## YSF Thematic Publication 2024

# *Climatic changes, impacts, vulnerability, mitigation and adaptations; Sri Lankan perspective*

*Young Scientist Forum (YSF)*

*National Science and Technology Commission Sri Lanka*

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**Young Scientist Forum (YSF)**
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Chapter e-book

# *Climatic changes, impacts, vulnerability, mitigation and adaptations; Sri Lankan perspective*



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**PREFACE**

The Young Scientists Forum (YSF) has been hosted by National Science and Technology Commission (NASTEC) of Sri Lanka since 2000, to provide an opportunity for young scientists in the country to voice their opinions on science and technology related issues. The YSF currently consists of more than 500 members representing diverse disciplines. Steering Committee (SC) of YSF started publishing a Thematic Publication from 2022 as one of the annual activities of YSF. The theme of the e-book for 2024 "Climatic changes, impacts, vulnerability, mitigation and adaptations; Sri Lankan perspective"

The purpose of this thematic publication is to provide a comprehensive assessment of climate change vulnerability and adaptation strategies specific to Sri Lanka. Understanding the vulnerability of Sri Lanka to climate change and identifying effective adaptation strategies is crucial for ensuring the country's sustainable development and the well-being of its population. This thematic publication provides following deliverables under four main themes namely: Agriculture & Livestock, Fisheries, Coastal & Water Resources, Infrastructure & Technological Development and Renewable & Green Energy

Given that the mandate of NASTEC is to advise the government in making policies on science and technology related aspects, SC firmly believes that this would be a golden opportunity for young scientists to raise their opinions and perspectives in a more critical, different and comprehensive manner.

This thematic publication on climate change vulnerability and adaptation in Sri Lanka will provide a comprehensive understanding of the country's climate-related challenges and opportunities. By assessing vulnerability, analyzing impacts, evaluating adaptation strategies, and proposing policy recommendations, this publication will contribute to the body of knowledge on climate change adaptation and facilitate evidence-based decision-making. It will serve as a valuable resource for policymakers, researchers, and practitioners working towards building a climate-resilient future for Sri Lanka.

Editorial Board
YSF Thematic Publcation-2024

## Message from the Chairman /NASTEC

As the Chairman of the National Science and Technology Commission (NASTEC), it gives me great pleasure to see that the Young Scientists of Sri Lanka who have gathered under the Young Scientists Forum (YSF) of NASTEC and addressing the issues that are currently prevailing in both Sri Lanka and the World as a whole such as the Climate Change Impact. Climate Change is one of the key subjects that were recently discussed at the 9$^{th}$ Biennial Conference on Science and Technology by NASTEC. It is very encouraging to see the younger scientific generation also giving attention on mitigating such an important concern. This thematic e-publication under the title "Climatic changes, impacts, vulnerability, mitigation and adaptations; Sri Lankan perspective" is one of their efforts in educating the scientific community to mitigate this global wide adverse situation. This is their third consecutive chapter e-publication in recent years and I am proud to see all these publications have addressed most important subjects that affect the country in recent years.

Going through this publication, I have observed many interesting topics that thoroughly discuss the issues and policy gaps observed in the fields of Agriculture and livestock, Fisheries, coastal and water resources, Infrastructure and Technological Development, Renewable and green Technology, etc. related to climate change aspects encountered in the current Sri Lankan perspective and the proposals in policy and strategic approaches to find solutions to the existing problems.

Sri Lanka has many resourceful and talented young scientists, both within the country and abroad, in universities, S&T institutes, private industries and organizations, whose knowledge and expertise can be used to bring about these proposed sustainable strategic solutions to take the country to a socioeconomically and environmentally better state from the current predicament and to meet the expected SDG goals.

I would like to thank and congratulate all the chapter authors of this publication for their contributions of innovative solutions expressed in this book and to Prof. Nayana Gunathilaka, Editor-in-Chief and the Editorial Committee of YSF for taking initiative to compile such a comprehensive publication.

**Prof. Veranja Karunaratne**
Chairperson
National Science and Technology Commission

## Message from the Acting Director/NASTEC

I am pleased to deliver this message to the E-book published by the National Science and Technology Commission's (NASTEC) Young Scientists Forum for 2024. This e-book is focused on the Climatic changes, impacts, vulnerability, mitigation and adaptations under Sri Lankan perspective. The aim of this thematic publication is to provide a comprehensive outlook on how different sectors could work together to seek solutions for the climate change impact considering the individual sectoral approaches/strategies.

Sri Lanka is bound to meeting the UN Sustainable Development Goals (SDGs) by 2030 and one of these goals include Goal 13: Climate Action. Sri Lanka has also increased their commitment to achieving the Nationally Determined Contributions (NDCs), which is the achievement of the long-term goals of the Paris Agreement, and has outlined targets in an Implementation Plan till 2030 with the support from the United Nations Development Programme (UNDP)'s Climate Promise Phase II Project. Therefore, considering the greater need of meeting these goals related to climate change, the launching of such a publication by YSF, which highlights the existing policy gaps and necessary policy needs, can be considered as a timely project.

NASTEC, as the government's policy advisory body for science and technology affairs including climate change and mitigation, will use the review findings to identify gaps and recommend policy initiatives to address them. This e-book will also provide a wealth of information for readers who wish to conduct further research in specific topics.

This E-book consists of 18 chapters, each with a different topic linked to the main title under several sub-sectors such as Agriculture, Fisheries, Renewable Energy and Technological Development. The YSF Editorial Committee along with expert reviewers has thoroughly evaluated these Chapters to ensure that the main title's major components were covered. Therefore, this publication will deliver great service for research and development and also for policymakers in finding effective policy interventions for the current climate change impact. Furthermore, this E-book will be helpful for instilling scientific thinking in the general public.

It is my pleasure to express my gratitude to the Chairman and all members of the YSF Steering Committee, with special thanks to the Editor-in-Chief, Prof Nayana Gunathilaka, for their tireless effort in making this E-book a reality. I also express my gratitude and congratulate all the young scientists who contributed chapters to this E-book.

**Geethani S. Kannangara**
Actg. Director/ CEO

## Message from the Chairperson/YSF

As the Chairman of the Young Scientists Forum (YSF), it is with great pleasure to bring this message to the 3rd E-book thematic publication compiled by the YSF of the National Science and Technology Commission (NASTEC). The thematic E-book insights into the "Climatic Changes, Impacts, Vulnerability, Mitigation, and Adaptations: Sri Lankan Perspective". It aims to provide a comprehensive overview of the climatic changes specific to Sri Lanka, exploring their impacts, vulnerabilities, and the strategies adopted for mitigation and adaptation.

The issue of climate change is one of the most pressing challenges of our time, with far-reaching consequences for the environment, society, and economy. In the Sri Lankan context, the impact of climatic changes is increasingly evident, affecting various facets of our lives, from agriculture and biodiversity to infrastructure and public health.

This thematic E-book consisted of 19 book chapters, delving into the multifaceted aspects of climatic changes in Sri Lanka under the four main themes; Agriculture & Livestock; Fisheries, Coastal & Water Resources; Infrastructure & Technological Development and Renewable & Green Energy. Each chapter with different topics pondered scientific thoughts and perspectives that can significantly contribute to the richness and depth of this compilation.

I deem that this valuable contribution will not only enhance the knowledge base within our scientific community but also foster meaningful discussions and inspire future research and policy initiatives.

I wish to take this opportunity to compliment all the authors for bestowing their perceptions on the thematic topics that committed thorough addressing of climatic changes in Sri Lanka, and I am in debt to all the reviewers who kindly and thoroughly cooperated in reviewing and improving the chapters, that determinedly contributed to the high quality of the final published chapters in the e-book.

One last note of my appreciation to Prof. Nayana Gunathilaka, Editor-in-Chief and the Editorial Committee of the e-book and the YSF steering committee for compiling and promoting this e-book and extending their invaluable support to find solutions for a sustainable and resilient future.

**Prof. Kalpa W. Samarakoon**
Chairperson YSF- 2023

## Acknowledgements

The Young Scientist Forum of the National Science and Technology Commission of Sri Lanka expresses its gratitude to all those involved in the publication of this chapter e-book. We recognize and appreciate the invaluable contributions of everyone who played a role in bringing this book to fruition. The chapter authors are acknowledged with sincere gratitude for generously sharing their knowledge and experience, contributing significantly to this e-book. Special thanks go to the chapter reviewers, who dedicated their valuable time to reviewing and providing valuable suggestions, thereby enhancing the quality of the content in the chapters. We extend our appreciation to the editorial committee members for their devoted efforts in the editorial process, despite their busy schedules. We would also like to thank Ms. R.M.A.S.D. Rajakaruna, a past student of the Faculty of Science, University of Kelaniya, Sri Lanka who is presenting studying for her postgraduate studies at Faculty of Silviculture and Forest Engineering, Transilvania University of Brasov, Romania for the valuable contribution provided by creating the cover page of the thematic publication. Additionally, we would like to thank the members of the YSF Steering Committee for their continuous encouragement, which played a crucial role in turning this endeavor into a unique and accomplished reality.

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# **SECTION 1-** AGRICULTURE AND LIVESTOCK

# Effects of Climate Change and Adaptation Strategies on Food Security in Sri Lanka

# Effects of climate change and adaptation strategies on food security in Sri Lanka

R.M.A.S.D. Rajakaruna[1*], B.G.N. Sewwandi[2], M.M.M. Najim[2]

## Abstract

The impacts of climate change have a major influence on the food security of a country. Sri Lanka is a developing nation that is severely affected by the shifts in climate. Therefore, this book chapter aims to analyze the effects of climate change on food security from a Sri Lankan perspective. The agriculture, livestock, and fisheries sectors play crucial roles in the food production of Sri Lanka, which is jeopardized by various climate change-related factors. Extreme weather events, increases in temperature, and precipitation fluctuations affect agricultural productivity and enhance pest and disease outbreaks. The livestock industry is more vulnerable to climate change due to the sensitivity of animals to the stresses caused by fluctuations in climate. Reduction of forage quality, heat shock, loss of optimum environmental conditions, spread of diseases, and disease dynamics due to climate change can decline the growth of animals, reduce production and accelerate the mortality rate. Climate impacts such as sea level rise, increase in sea surface temperature, and degradation of ecosystems reduce the yield from fisheries. Therefore, the adaptation strategies that are crucial for overcoming the adverse impacts of climate change on food security are discussed in this study to achieve climate resilience in the agriculture, livestock, and fisheries sectors in Sri Lanka.

**Keywords:** Agriculture, Climate resilience, Food production, Livestock, Nutrition

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## Introduction

The climate is the long-term weather patterns in a geographic location. Climate is a crucial factor that controls the survival of life on Earth. Global climate is affected by many climate phenomena, such as the El-Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) [1-2]. Nevertheless, human-induced changes in global climate have become more dominant in the present world than natural factors. The primary sources of human-induced climate change are emissions due to energy use, urbanization, and land use changes [3]. The effects of climate change can be seen throughout the world. Biodiversity has been affected by climate change. Some animal species shift their climatic niches as a response to climate change, while some species are led to extinction [4]. An increase in global mean temperature has adversely impacted coastal resources, forestry, marine ecosystem productivity, and terrestrial ecosystem productivity [5]. FAO et al [6] have identified climate extremes as a major driver of food insecurity and malnutrition since severe and frequent climate extremes disrupt food supply chains, especially in developing countries.

World Food Summit [7] has declared that food security exists when all people, at all times, have physical and economic access to sufficient, safe, and nutritious food that meets their nutritional requirements and food preferences that are essential for their lives to be active and healthy. The four pillars of food security have been identified as availability, access, utilization, and stability. Food availability is the availability of sufficient amounts of food of good quality. Access is access by people to sufficient food sources for obtaining appropriate foods for a nutritious diet. Utilization is the process of utilizing food to meet all physiological needs through a healthy diet, access to clean water, sanitary conditions, and health care. Stability means having access to enough food without being cut off by cyclical or unexpected shocks [8].

Nevertheless, ensuring global food security has become more challenging due to the rapid increase in population [9]. The world population is expected to increase to 9.7 billion by 2050 [10]. Especially, vulnerable groups such as women are more susceptible to food insecurity due to their significant contribution to the production and preparation of food and their lower dietary intake as household food managers [11-12]. Children also face various health, nutritional, and developmental problems due to household food insecurity [13]. Therefore, food insecurity has become a serious issue that affects the health, nutrition, and behavior of individuals. It exacerbates the susceptibility of people to cardiovascular diseases, nonalcoholic fatty liver disease, and advanced fibrosis [14-16]. A study by Kim-Mozeleski et al [17] found that higher smoking prevalence is induced by the psychological distress related to food insecurity. Long-term food insecurity, such as limited access to food and low nutrient intake, causes mental health problems, including depression, anxiety, and behavioral changes in both children and adults [18-20].

The climate change impacts on food security could be severe in developing countries [21]. Sri Lanka is an island in the Indian Ocean that experiences four monsoon seasons annually. They are the Northeast monsoon, Southwest monsoon, first inter monsoon, and second inter monsoon. The Northeast monsoon occurs from December to February. Southwest monsoon occurs from May to September, providing rainfall to the Southwestern part of the country. The first inter-monsoon occurs from March to April. The second inter-monsoon occurs from October to November [22]. The land area of Sri Lanka has been divided into three zones: wet zone, dry zone, and intermediate zone, according to these rainfall patterns [23-24].

Agriculture, livestock, fisheries, and aquaculture are the main food production sectors in Sri Lanka that are greatly influenced by climate change. Although Sri Lanka is a country with low greenhouse gas emissions, it is considered a highly vulnerable country to climate change. Climate change can directly affect food security in many pathways. Agricultural and fisheries productivity could vary over climate change, leading to adverse effects on livelihoods, income generated, and elevation of food prices. Climate-induced disease burdens could hinder food utilization by people. Esham et al [25] have found that climate-related issues threaten food security in Sri Lanka, reducing agricultural productivity, food loss along supply chains, low resilience of the rural poor community to climate change, and higher malnutrition levels among children. Therefore, the aim of this study is to analyze the literature related to the impacts of climate change on food security and available adaptation strategies from a Sri Lankan perspective and to suggest measures to improve the current knowledge and facilities to combat the harmful impacts of climate change on food security in Sri Lanka.

## Agriculture

Agriculture is the most vulnerable sector to climate change due to its high sensitivity to climate variations. Climate change disrupts soil fertility, irrigation, and plant growth and enhances the infestation of pests and diseases [26]. In addition to the pressure of the increasing global population, climate change has reduced global food security by decreasing agricultural productivity. South Asia is highly affected by rainfall variability, elevating temperatures, and extreme climatic events such as droughts, floods, heat waves, and storms. In contrast, agriculture causes climate change by emitting considerable amounts of greenhouse gases [27]. Many crops in South Asia would experience a large reduction in yields with increasing temperatures, while changes in precipitation patterns could induce failure in rainfed agriculture [28].

For example, crop production in Sri Lanka could be taken. Wickramasinghe et al [29] have found that agriculture in the Northern and Eastern parts of Sri Lanka shows high vulnerability to climate change due to droughts, while agriculture in the Northern and Eastern coastal zones is highly vulnerable to floods. In addition, Central highlands have been identified as vulnerable to landslides. Water scarcity is a serious problem for agriculture in Sri Lanka. Farmers face difficulties in irrigation due to a lack of rainfall and increased periods of droughts, which are expected to enhance in the future [24]. De Silva et al [23] have found that the average irrigation water requirement for paddy production in Sri Lanka will increase by 23% due to a lack of rainfall in the wet season by 2050.

An increase in temperature could also increase the water consumption by crops, especially in the dry zone of Sri Lanka [23]. A study conducted by Jayathilaka et al [30] in a mid-country wet zone has shown that the decrease in annual rainfall and an increase of temperature by 1.4°C from 1980 – 2007 in the particular area has led to an increase in yield and the areal extent covered by coconut and tea plantations. A rise in atmospheric temperature causes increased plant respiration rate and evapotranspiration [26]. Gunathilaka et al [31] have studied how weather variations affect tea production in Sri Lanka. The results of the study have shown a negative correlation between tea production and an increase in both rainfall and average temperature. An increase in average temperature by 1 °C would reduce tea production by 4.6%, while an additional 100 mm of annual rainfall could decrease tea production by 1%.

The climate in Sri Lanka has shown a statistically significant decrease in long-term annual precipitation and an increase in long-term average annual temperature. Variations in mean rainfall intensity during monsoon seasons have been correlated with the El-Niño-Southern Oscillation (ENSO) [32]. ENSO is well known for influencing global crop production, especially rice production, by inducing anomalies in rainfall and temperature [33]. Some studies show that Sri Lankan agriculture is also affected by ENSO [34-35]. There are two agricultural seasons in Sri Lanka, namely, Yala (April–September) and Maha (October–March). According to a streamflow study in the Kelani River, the streamflow in the La Niña phase was 32% higher than that in the El Niño phase during the Yala season. In the Maha season, during the El Niño phase, the streamflow enhanced from October to December and reduced from January to February. The management of agriculture heavily depends on in-season rainfall and streamflow, which is affected by ENSO [35]. For instance, farmers may grow flood-resistant varieties in the Maha season and drought-resistant short-term varieties in the Yala season, which is water-constrained. Another study showed that the El Niño phase causes an increase in the average Maha rice production and a decrease in Yala rice production due to rainfall anomalies during the Maha season. Nevertheless, there is a potential for flooding during Maha cultivation [34]. It is also important for irrigation managers to increase the carryover storage to overcome water deficits in the January to April period caused by the El Niño phase. Chithranayana and Punyawardena [36] have observed high spatial variability in rainfall in Yala and Maha seasons due to climate variations causing a lack of water available for cultivation, leading to a reduction of cropland extent to half.

Crop vulnerability to pests, diseases, and invasive species has been enhanced due to changes in weather patterns due to climate change in Sri Lanka [37-38]. A higher frequency of extreme weather events caused by climate change could lead to the emergence of infectious diseases in plants. For instance, dry weather favors insect vectors and viruses, while wet weather favors fungal and bacterial pathogens [39]. Studies have found that the main crops such as paddy, tea, and coconut cultivated in Sri Lanka are highly sensitive to climate change-induced pest, disease, and invasive species outbreaks, which leads to higher investments in controlling those harmful impacts [23], [37], [40]. These factors reduce agricultural production in many areas of Sri Lanka. A study by Kariyawasam et al [41] used climatic suitability maps to assess the vulnerability of croplands to invasive plant species. The study has found that areas including vegetable, fruit, tea, rubber, coconut, home gardens, and grasslands are susceptible to invasive plant species, indicating negative impacts on food production in Sri Lanka. Out of all croplands, coconut plantations are more vulnerable to invasion, while aquatic agricultural lands such as paddy fields are more likely to be invaded by *Eichhornia crassipes* and *Salvinia molesta* under current climatic conditions in Sri Lanka. In addition a relatively high climatic suitability has been shown by south and western parts of Sri Lanka for establishment of invasive plant species [42]. A study by Ratnayake et al [43] has found that crop wild relatives that are important in supplying genetic materials for the development of crop varieties with higher yields has become vulnerable to climate change due to reduction of land area with suitable environmental conditions. In future this could severely affect Sri Lankan agriculture leading to food insecurity.

Rural poor people, who comprise more than 75% of the poorest people in the world, are vulnerable to climate change because they live in fragile ecosystems and practice rainfed agriculture on which their entire livelihood depends [44]. Smallholder farmers have been more vulnerable to climatic stresses in addition to the economic constraints they face by pursuing agriculture in a developing country like Sri Lanka. Lack of water for irrigation has been identified as the main climate-related issue for small-scale crop cultivation in Sri Lanka, according to a study conducted by Esham and Garforth [45] in Rathnapura District, Sri Lanka. Small retail stalls and open-air markets with no refrigeration facilities in Sri Lanka are exposed to temperature rises, exacerbating post-harvest food losses due to climate change [25]. Abeysekara et al [46] have found that climate-induced reductions in crops will increase the prices of agricultural products, leading to a reduction in food consumption within the next few decades. A study conducted by Menike and Arachchi [47] has found that smallholder farmers in Sri Lanka show a high responsiveness to climate variations and reduce the effects of rainfall, temperature, and wind through adaptation measures. According to that study, the decision-making for implementing climate adaptations has been proportional to the family size, education level, access to loans, and access to information through electronic media. Gunatilake [48] has found that household food security in rural farming households in some areas of Sri Lanka is vulnerable even to mild droughts because of the reduction of food production due to crop damage by droughts. Suresh et al [49] have studied that farmers who adapt to climate change receive a higher average rice yield compared to non-adaptors in the Batticaloa district, Sri Lanka. In that study, education has been identified as the main driver for implementing climate adaptation measures in agriculture, indicating the importance of providing climate adaptation awareness for farmers.

Labor demand for agriculture, such as the tea plantation sector, has limited crop-switching opportunities and long pre-harvesting seasons, varying with the effects of climate change. According to a study by Gunathilaka et al [50], a decrease in labor demand has been observed in the south-west monsoon, the north-east monsoon, and the second inter-monsoon owing to higher rainfall and increased cloud cover that reduces tea growth and amount of tea leaves harvested. Higher rainfall also discourages worker turnout. Nevertheless, the same study has found a positive relationship between labor demand and rainfall in the first inter-monsoon due to relatively low rainfall during this season, which occurs mainly in the evenings, leaving the daytime sunny. The same study has estimated a reduction of 2.5% in overall labor demand for tea production by 2050 due to an increase in rainfall.

Coastal agriculture is easily affected by climate change compared to inland farming because coastal ecosystems undergo frequent changes due to climate change and anthropogenic stressors [51]. Climate-related hazards in coastal areas include sea level rise, floods, storm surges, increased coastal erosion, seawater intrusion, and elevation of ocean acidity and sea surface temperature. Sea level rise has been found to be the main climatic factor that affects coastal farming. In addition, frequent flooding of salt water and rising soil and water salinity in coastal areas lead to the abandoning of coastal farmlands [52].

Carbon fertilization is the increase in the rate of photosynthesis in plants due to the increase in carbon dioxide ($CO_2$) in the atmosphere. Mendelsohn [53] studied that a 3% increase in net crop revenue occurs in Asian agriculture due to carbon fertilization when considering both loss and gain of crop net revenues due to a 1.5°C rise in temperature. Nevertheless, the same study also evaluated a 13% loss in net crop revenue with a 3°C rise in temperature, indicating the vulnerability of agriculture to a rise in temperature. In contrast, photosynthesis has been enhanced, with increased $CO_2$ concentration in the atmosphere leading to higher plant growth and productivity [26]. The studies conducted by De Silva et al [23] and Droogers [54] in the Walawe river basin, Sri Lanka, have found that climate change also has positive impacts on agriculture. A rise in crop growth and an increase in average yields have occurred due to increased $CO_2$ levels and precipitation. Nevertheless, the same study indicates the possibility of reducing agricultural yields due to frequent extreme climate events.

## Livestock

Climate change severely affects livestock production and food security. Global warming has been identified as playing a major role in determining livestock output than precipitation patterns. Heat stress induced by variations in weather, temperature, humidity, and wind speed directly affects dairy and beef production. Meat and meat products, which include poultry, pig, cattle, goat, and sheep, are one of the main protein sources consumed in Sri Lanka [55]. Higher temperatures reduce the feed intake and fertility of animals while enhancing mortality and susceptibility to diseases [56]. The reproductive performance of cows has been decreased by climate change by exacerbating embryonic death and reduction in implantation [57]. About 1 ˚C increase in global temperature could induce a 9.7% average reduction in beef production. Livestock production in tropical agriculture-dependent countries with low-income levels is more vulnerable to climate change [58]. A study conducted by Carvajal et al [59] has found that the cattle population in tropical zone is highly vulnerable to heat stress due to difficulty in controlling temperature and humidity in the tropical zone. According to a study by Craine et al [60], elevated temperatures have led to a decline in forage quality, protein, and energy availability, which limit the performance of cattle due to nutrient deficiencies.

Nevertheless, some tropical cattle possess better tolerance and resistance traits for overheating, such as slick and light color coat types [59]. Native breeds of tropical countries and their crossbreeds can be used to improve production at high temperatures [57]. The temperature humidity index (THI) is used to determine the extent of heat stress in animals [61]. A study by Gamameda et al [62] has also found that local cattle and their crossbreeds have the highest capability to cope with high THI levels in Sri Lanka. In that study, local cattle were able to produce the same production level of milk from THI 80 to 83 while other cow breeds such as Friesian cows and Jersey cows showed a decreasing trend in milk production with THI value. Therefore, the promotion of local breeds for milk production could be effective as an adaptation to climate change.

Feng et al [63] have found that income generated by livestock has increased with the increase in a long-term increase in precipitation while it has decreased with the long-term rise in temperature. With the decrease in rainfall, a declining trend in cattle population has been observed by Megersa et al [64], indicating possible negative impacts of climate change on pastoral systems. Nevertheless, Rajakaruna and Warnakulasooriya [65] have studied parasitic infections such as *Ascaris lumbricoides*, *Fasciola* sp. *Schistosoma* sp. and *Isospora* sp. in dairy cattle have been increased due to high rainfalls compared to low rainfall periods in Kandy District, Sri Lanka.

In high-temperature environments (> 26 ˚C) with high humidity, poultry production (eggs and meat) is reduced with the massive mortality rates due to the absence of sweat glands in birds that makes them unable to tolerate those harsh conditions [66]. Reduced feed intake, increased susceptibility to diseases, and inferior product quality are adverse effects of environmental stress in birds [67]. Pest infection is a huge problem faced by the poultry industry due to climate change, which induces the need to use disinfection agents for poultry houses and to protect animals from diseases spread by pests. For instance, breeding locations of mosquito larvae are destroyed, and insecticides are applied to eliminate mosquito infections when the climate favors the spreading of mosquitoes in tropical countries [68].

## Fisheries and Aquaculture

Low-latitude regions are expected to have reduced vertical mixing and reduced nutrient recycling in the oceans, which would lead to a reduction in fish production. Extreme climate events could have severe impacts on both inland and marine fisheries. Climate change negatively affects marine fisheries by declining the size and age of fish populations and decreasing the biodiversity of marine ecosystems. Inland fisheries could be pressurized by changes in rainfall [69]. Shifts in the distribution of the yield of marine species and marine net primary productivity occur due to climate change [70]. Sri Lanka is an island surrounded by the Indian Ocean which is rich with many marine and coastal resources. Fisheries are one of the major economic activities that are essential for both the economy and food safety of the country. It provides food, nutrition, and livelihoods for millions of people around the world [71]. Direct effects of climate change on fisheries include changing growth, productivity, reproductive capacity, mortality, and distribution of fish stocks [72].

Inland fisheries provide high-quality, affordable food for people who are vulnerable to food insecurity due to poverty throughout the world while providing millions of livelihood opportunities globally [73]. Inland water bodies are already heavily stressed by agricultural activities, deforestation, and increasing development activities in watershed areas. Therefore, climate impacts are an additional burden on inland water bodies reducing the productivity of fisheries. Community-based fisheries in Sri Lanka are affected by climate change and the frequency and severity of natural disasters [74]. A reduction of fish catch and catch per unit in inland reservoirs occur due to the migration of fish to newly inundated areas created by heavy rainfall [75].

Changes in ecosystems occur due to climate change, including changes in environmental variables such as temperature, dissolved oxygen, and dissolved carbon dioxide levels, creating unfavorable conditions for marine organisms which lead to changes in marine food webs and productivity [76], [77]. It negatively affects fisheries economies. In addition to that, ocean conditions are severely affected by extreme weather events, inducing adverse impacts on fisheries and aquaculture [78]. Coastal zones are highly vulnerable to climate change. The climatic stresses in the coastal zone that affect fisheries and aquaculture include floods, droughts, high salinity levels in soil, sea level rise, and cyclones [79]. During the tsunami disaster of 2004, marine fisheries in ten out of fourteen coastal districts were severely damaged, including damages to fishing boats, fishing communities, livelihoods, and infrastructure [80]. Variability in weather and increasing frequency and extreme weather events induced by climate change have severe effects on fish and fish products by habitat destruction, such as loss of coral reefs, changing fish migration patterns, and growth of fish stocks [73], [81], [82]. According to climate change projections of RCP 8.5 (representative concentration pathway) from the Intergovernmental Panel on Climate Change (IPCC), it is expected to have a 7% - 12.1% decrease in total maximum fish catch potential in exclusive economic zones from 2000 to 2050 [73]. A decline in yellowfin tuna catch has been observed by Sambah et al [83] with the increase in sea surface temperature in the Indian Ocean. The rate of pathogenic bacteria occurrence in the marine environment increases at high temperatures induced by climate change [73]. Pathogens cause mass mortalities in many marine species, such as plants, corals, fish, and mammals [72].

Shrimp farming is a popular aquaculture sector in Sri Lanka. It is also affected by climate change. For instance, Jayasinghe et al [71] have shown how different climate-related consequences negatively affect the shrimp culture in Sri Lanka. Cyclones could cause damage to the infrastructure and also cause cross-contamination of ponds, leading to the spread of diseases. Higher water evaporation in culture ponds during prolonged drought periods and the temperature rises cause salinity stresses on shrimp culture systems that reduce yields and enhance disease outbreaks. Coastal flooding could also damage shrimp farming infrastructure and could introduce predators and pathogens to culture systems. Asia is the main source of shrimp production that faces different extreme climate events, such as cyclones, sea-level rise, high salinity, floods, and droughts [84]. Climate change directly affects the water quality used in shrimp farming [85]. A study by [86] has found that environmental parameters such as high salinity, temperature, and pH induce the occurrence of vibriosis in shrimp farms, reducing shrimp yield.

## Climate adaptation strategies

Climate change is unavoidable, and adaptation to its adverse effects is essential. More adaptation measures can be improved and utilized to reduce the impact of climate change and enhance food security in Sri Lanka. The Climate Change Secretariat of the Ministry of Environment is the main national initiative for addressing climate change impacts in Sri Lanka. It is the National adaptation plan for climate change impacts in Sri Lanka 2016 – 2025, prepared in line with the guidelines of the United Nations Framework Convention on Climate Change (UNFCCC) provides a holistic approach to implementing climate adaptation strategies in all the most vulnerable sectors, including agriculture, livestock, and fisheries to ensure climate resilience in Sri Lanka [87]. It guides the authorities in developing policies, institutional setup, resource distribution, technology development, and capacity building in those sectors. Further, the draft National Policy on Climate Change 2023, which is the updated version of the National Climate Change Policy of Sri Lanka in

2012 has also addressed food security through related climate adaptation strategies to promote practices such as climate-smart agriculture and climate-smart animal husbandry and enhance the dissemination of climate information [88-89].

Climate resilience of agriculture can be achieved by various adaptation measures. Crop diversification is an effective method that involves cultivating more than one species of crops in a given area. It ensures the resilience of agricultural systems of smallholder farming, leading to the stabilization of food stocks and household food security [90]. Rainwater harvesting can be used to cope with the reduction of rainfall and increasing irrigation water requirements [91]. Utilization of water-conserving irrigation technologies such as micro-irrigation, sprinkler irrigation, low-pressure pump irrigation, and channel irrigation can significantly contribute to managing agricultural water demand [92]. Crop residue retention in fields can improve soil physical, chemical, and biological properties and also reduces large amount of $CO_2$ emitted by burning of crop residues [93-94]. Therefore, productive crop residue management is essential to combat climate stresses on agriculture. The development of stress-tolerant crop varieties can improve agricultural productivity, improve resilience, and reduce carbon emissions. Nevertheless, further research needs to be conducted to determine the magnitude of climate change impacts on crops depending on the variety, geographical zone, and production demand [95]. Remote sensing and meteorological services play a major role in collecting reliable and timely information on the impacts of climate variations on agriculture. Remote sensing contributes to the efficient use of natural resources, assessment of potential yield, and management of pests and diseases in agriculture [96]. Capacity building of agricultural communities is crucial for knowledge-based disaster risk reduction and adaptation to climate variations [97-98].

The climate change impacts on livestock systems could be minimized by research and development of climate-tolerant species [99]. Local breeds of cattle and poultry are known to have more resistance to high temperatures and arid environments that have the potential to overcome the decline of livestock production due to climate change [100-101]. For instance, in Kerala, India, maintaining heat and tropical disease-resistant smaller native cows is more cost-effective for smallholder farmers than maintaining imported Holstein cattle stressed by tropical environmental conditions [102]. Genetic improvements in local breeds could be used to enhance meat and milk production. To overcome the lower quality and quantity of forage for livestock, techniques such as intercropping that intensifies both soil fertility and forage yield could be used [103]. Continuous animal health monitoring is essential for effective control of climate-related pest and disease outbreaks [104].

Climate change adaptation methods such as genetic improvements and provision of locally available feed for fish could be utilized to reduce the effects of climate change on fisheries. Establishing marine protected areas and protecting existing ones could assist in restoring marine fish stocks and prevent degradation caused by climate change [105-106]. Restoration and conservation of mangroves could improve the buffer against severe climate events such as tsunamis, cyclones, and floods [107-108]. Proper financial mechanisms and disaster risk response by the government can reduce the effects of extreme climate events on food security [109].

## Conclusion

Climate change is a major factor that affects the food security of Sri Lanka. Agriculture is a highly sensitive sector to climate change impacts. Changes in rainfall patterns, increase in temperature, climate-related pest and invasive species outbreaks, extreme climate events such as floods and droughts can severely affect the agricultural productivity of the country. Smallholder farmers and laborers are easily affected by climate variations. Nevertheless, some studies have shown an increase in crop yield with an increase in $CO_2$ concentration in the atmosphere. Climate impacts such as heat stress, water scarcity, extreme climate events, and climate-induced pest and disease outbreaks reduce livestock production. Both inland and marine fisheries are affected by climate change. Changes in ecosystem health due to climate change negatively affect marine fisheries by creating unfavorable conditions. Extreme climate events, sea level rise, and increased sea surface temperature lead to the reduction of fish catch. The available normative instruments, such as the National adaptation plan for climate change impacts in Sri Lanka and the National Policy on Climate Change, provide a holistic approach to climate adaptation strategies to ensure food security in Sri Lanka. Climate resilience in agriculture, livestock, and fisheries can be achieved by following effective adaptive measures suggested by previous studies. Nevertheless, capacity building, dissemination of climate information, and conducting future research towards climate resilience at the local level are crucial to determine and overcome the adverse impacts of climate change on food security in Sri Lanka.

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## Conflict of Interest
The authors have declared that no competing interests exist.

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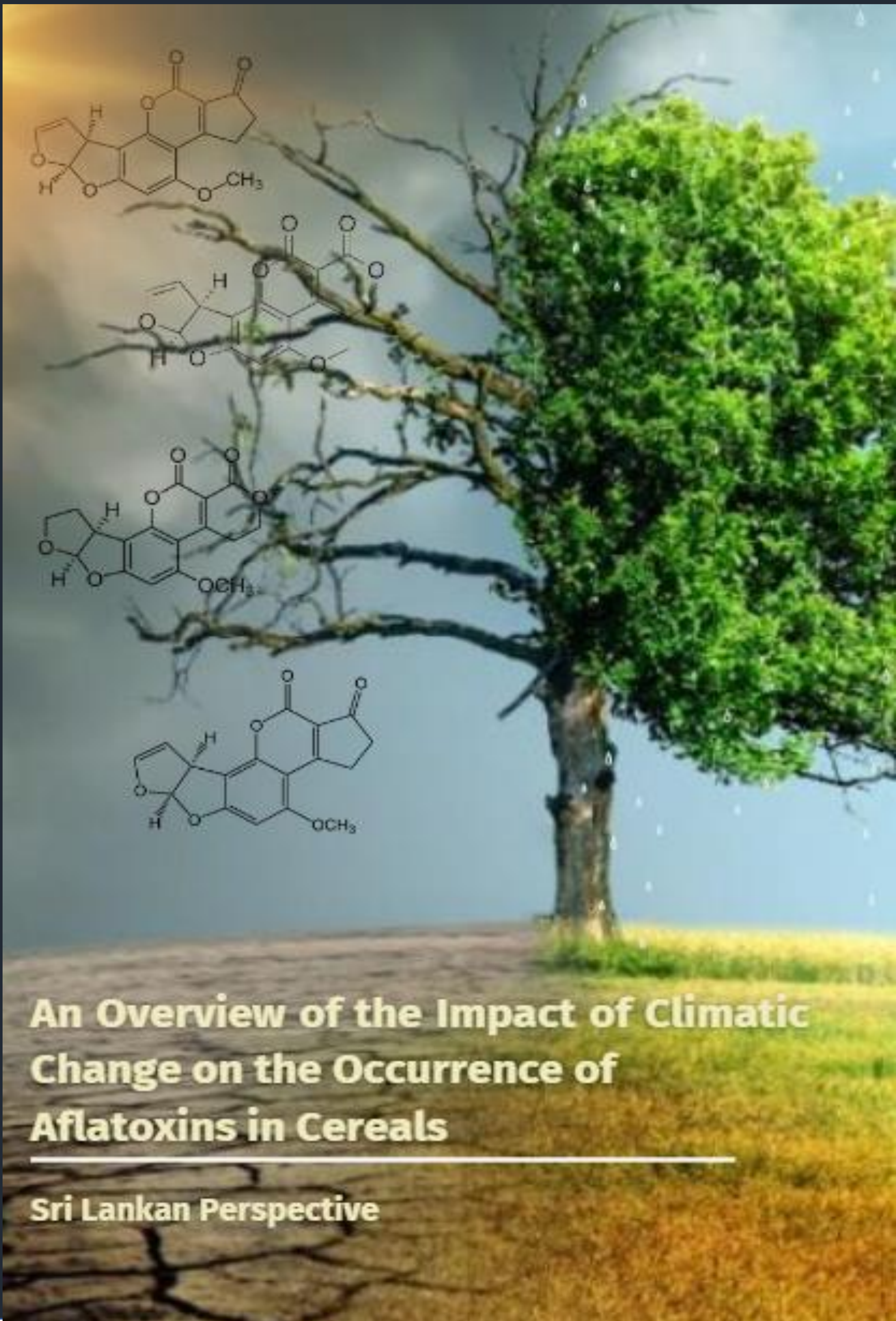

# An Overview of the Impact of Climatic Change on the Occurrence of Aflatoxins in Cereals

## Sri Lankan Perspective

# An overview of the impact of climatic change on the occurrence of aflatoxins in cereals: Sri Lankan perspective

M.R.P. Chasna, D.U. Rajawardana*, P.N.R.J. Amunugoda

## Abstract

Aflatoxins, a group of toxic and carcinogenic metabolites, are primarily produced by *Aspergillus flavus* and *Aspergillus parasiticus* which are prominent in hot humid tropical climates similar to Sri Lanka. Climate changes can positively impact the presence of aflatoxigenic fungi and aflatoxin production in cereals and cereal-based products, among which rice and corn are the most common victims. In Sri Lanka, rice is the main staple food, and corn is consumed in high amounts due to its high protein content by pregnant and breast-feeding mothers, and children and is also used as a main animal feed. The fungal growth and aflatoxin production in cereal crops depends on several factors, including weather and climate. Changes in weather and climate such as increased temperature, heavy rainfalls, and droughts are the modulating factors of *Aspergillus* growth and subsequent aflatoxin production. Prolonged exposure to aflatoxins leads to acute and/ or chronic "aflatoxicosis" in humans with teratogenic, genotoxic, immunosuppressive, and mutagenic effects. Thus, considering the importance of aflatoxins in the food chain, the maximum allowable limits for aflatoxins in foods have been established by various governments including the European Commission. However, in Sri Lanka, the regulation for aflatoxins in cereals is still at the drafted level. To alleviate the harmful effects of these toxins on the health of humans and animals, the development of a safe, stable, and effective multifaceted approach to combating contamination of food with aflatoxins is necessary. Thus, this chapter analyses the impact of climate change on the occurrence of aflatoxin in cereals, primarily in corn and rice respective to Sri Lanka, and the possible prevention strategies to assure food quality and safety.

**Keywords:** Aflatoxins, Aflatoxigenic fungi, Cereals, Climate, Food quality and safety

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## Introduction to mycotoxins

### *Mycotoxins*

Mycotoxins are secondary toxic metabolites produced by filamentous fungi, which contaminate foods and feeds, causing numerous negative health effects in humans and animals and also causing huge economic losses throughout the value chain [1-2]. Prolonged exposure to these low molecular weight compounds can cause a range of symptoms and illnesses in humans, both acute and chronic, ranging from cold and flu-like symptoms to immune deficiency, organ failure, cancer, and even death [3]. This exposure can occur through skin contact, inhalation, or ingestion [4], and the high-risk categories including young, elderly, and those with compromised immune systems are more vulnerable to the negative health effects of mycotoxins [5].

The early estimates from the Food and Agriculture Organization (FAO) [4] stated that mycotoxin contamination affected 25% of global crops, and the more recent estimates suggested that this may be increased to 60–80%. The role of weather and climate is significant in all factors associated with mycotoxin contamination as presented in Figure 1 [1].

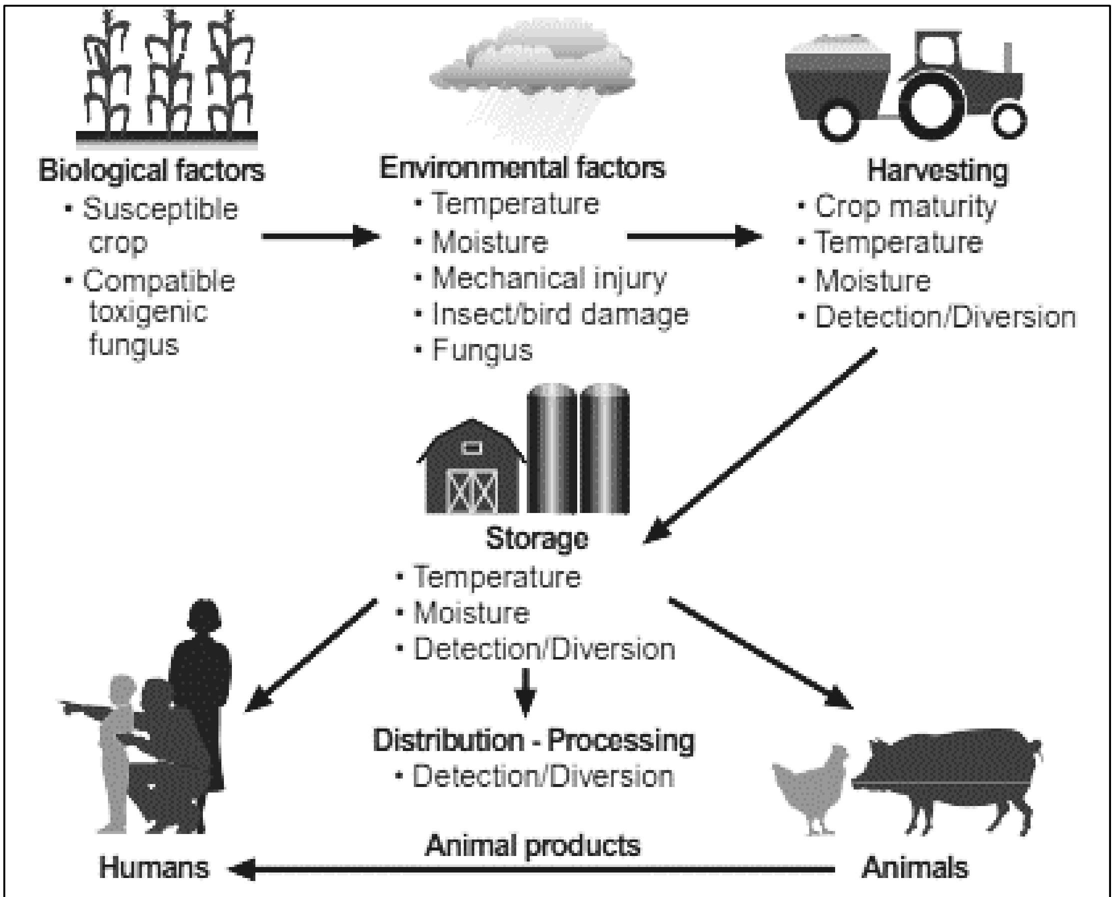


**Figure 1.** Factors affecting mycotoxin occurrence in the food chain (Source: Krogh, 1978)

Mycotoxins can be grouped according to their global occurrence, toxicity, and economic impact, and they contaminate a range of foods, feeds, and water systems [2]. Different groups of mycotoxins and their affected commodities are summarized in Table 1.

**Table 1.** Group of mycotoxins and affected commodities (Source: Frisvad *et al.*, 2019)

| Mycotoxin | Commodity |
|---|---|
| Aflatoxins | Corn, wheat, copra, peanuts, milk, eggs, nuts, figs |
| Citrinin | Cereal grain (corn, wheat, rice, barley) |
| Cyclopiazonic acid | Corn, peanut, cheese |
| Ochratoxin A | Cereal grain (corn, wheat, oat, barley), coffee, cocoa, grapes |
| Patulin | Apple juice, moldy feed |
| Penicillic acid | Stored corn, cereal grain, dried bean |
| Penitrem | English walnut, hamburger bun, beer |
| Sterigmaatocystin | Green coffee, grains, hard cheese, peas |
| Trichothecenes | Corn, wheat, barley, oats, commercial cattle feeds |
| Zearalenone | Corn, water system |

### *Aflatoxins*

Among mycotoxins, aflatoxins are considered as one of the most important groups due to their toxicity, global occurrence, and economic impact. As of now, around twenty aflatoxins have been identified, where aflatoxin B1 (AFB1) is the most frequently detected aflatoxin in agricultural commodities. The other three most common naturally occurring aflatoxins are aflatoxin B2 (AFB2), aflatoxin G1 (AFG1), and aflatoxin G2 (AFG2) [2], [7]. Aflatoxins have the highest acute and chronic toxicity of all mycotoxins and have numerous negative health effects on humans and animals, where aflatoxins B1, B2, G1, G2, and M1, M2 are of public health importance as they frequently contaminate food intended for human consumption [8]–[10]. The toxicity levels of aflatoxin decrease in the form of B1>G1>B2>G2 [11], where AFB1 is the most powerful, dangerous, and abundant toxin [12], moreover the heterogeneity of AFB1 makes its risk more challenging [13].

The four main aflatoxin types (AFB1, AFB2, AFG1, and AFG2) are primarily produced by toxigenic strains of the *Aspergillus* fungi [2], [7], which are one of the most important food spoilage organisms that dominate the food supply chain in areas with wet and warm climates [14]. While the genus *Aspergillus* has more than 200 species, only less than twenty species are known to produce aflatoxins, the toxic and carcinogenic metabolites. *Aspergillus flavus* and *Aspergillus parasiticus* are the two dominant species that produce aflatoxins [15-17] in or on foods, and to a lesser extent, these toxic metabolites are produced by *Aspergillus bombycis*, *Aspergillus ochraceoroseus*, *Aspergillus nomius*, *Aspergillus astellatus* and *Aspergillus pseudotamari* [5]. Major toxins produced by *A. flavus* are AFB1, and AFB2 whereas, *A. parasiticus* produces two additional toxins named AFGI and AFG2 [12], [18-19].

Exposure to aflatoxins may lead to aflatoxicosis with teratogenic, genotoxic, immunosuppressive, and mutagenic effects [20]. Among aflatoxin-related health outcomes, liver carcinogenicity and child health threats have been recognized as increasingly important by the European Food Safety Authority (EFSA) [21]. The International Agency for Research on Cancer (IARC) has grouped AFB1, AFB2, AFG1, AFG2, and AFM1 as Group 1 human carcinogenic compounds, and among them, AFB1 has the most pronounced toxic and carcinogenic effects [20]. However, the potential health impacts depend on several factors such as age, gender, the amount of ingested aflatoxins, and the prior health status of an individual [21]. To date, several aflatoxin outbreaks have happened all over the globe, and the major outbreaks were listed in Daily Mirror by Prof. Deepal Mathew on May 2021 as below summarized [22].

**Table 2.** Major aflatoxin outbreaks (Source: Mathew, 2021)

| Year | Country/ region | Affected commodity | Aflatoxin outbreak/ consequences |
|---|---|---|---|
| 1974 | India (Gujarat and Rajasthan) | Maize | 106 estimated deaths |
| 2003 | Kenya | Maize | 120 confirmed deaths |
| 2013 | Many countries in Europe | Milk | N/A |
| 2014 | Kenya | Maize flour | Five brands of maize flour were recalled due to contamination with aflatoxins |
| 2021 | USA | Pet food | N/A |
| 2021 | Sri Lanka | Coconut oil | Contamination of coconut oil imported from Malaysia with aflatoxins |

The above list indicates that the frequency of aflatoxin outbreaks has been increased in the 21st century. The Commission of the European Communities reported [23] that AFB1 has no threshold level below which no tumor would develop. Thus, only a zero level of exposure can vouch for no risk. The maximum allowable limits for aflatoxins in food and feed have been established by various governments to protect human and animal health. Among them, the most rigorous maximum allowable levels are set out for AFB1 and total aflatoxins (sum of AFB1, AFB2, AFG1, and AFG2) by the European Commission [24-25].

## Global climate change and Sri Lankan perspective

Climate is both a complex and interactive system that consists of the atmosphere, water bodies, land surface, and living beings [26], and the internal dynamics of this system can be significantly influenced by various external factors resulting in several changes inside the system [27]. Human-driven or anthropogenic forces have become the key reasons, over the natural processes, for the climate changes today [28]. Climate change is defined as a change in average weather conditions on Earth that persists over an extended period, which means climate change is a significant fluctuation in the prevailing state of average weather patterns that lasts over several decades or longer [29]. Over geological time, the Earth's climate has been constantly changing contributing to several variations all over the world [27].

### *Climate Change in Sri Lanka*

No country is immune to the impact of climate change, and the situation in Sri Lanka is not different from the global context. Sri Lanka has been drastically affected by many climate change challenges [30], and the Science Community in Sri Lanka has shown ample evidence for the issue [31]. Although Sri Lanka seems somewhat distant from other countries and nestled amid the Indian Ocean, it is predominantly vulnerable to climate change owing to its unique geographical location [30]. It leads to several impacts, mainly including rising temperatures, changes in precipitation patterns, and an increase in extreme weather events

[32-33]. The Institute of Policy Studies of Sri Lanka (IPS) stated that the intensity and frequency of these extreme weather events due to climate change have increased significantly within the country [33].

Moreover, the World Bank Group (WBG) reported that Sri Lanka regularly experiences a very high temperature with an average maximum of 32℃ leading to a 4% annual probability of severe droughts [28]. Climate changes can occur due to many reasons such as natural or anthropogenic forces. Among these two categories, anthropogenic forces have become the key reasons for the occurrence of these climate changes in Sri Lanka. Accordingly, many challenges can incur significantly due to the devastating impacts of climate change, and the impacts related to aflatoxins are highlighted in the below conceptual framework (Figure 2) [28].

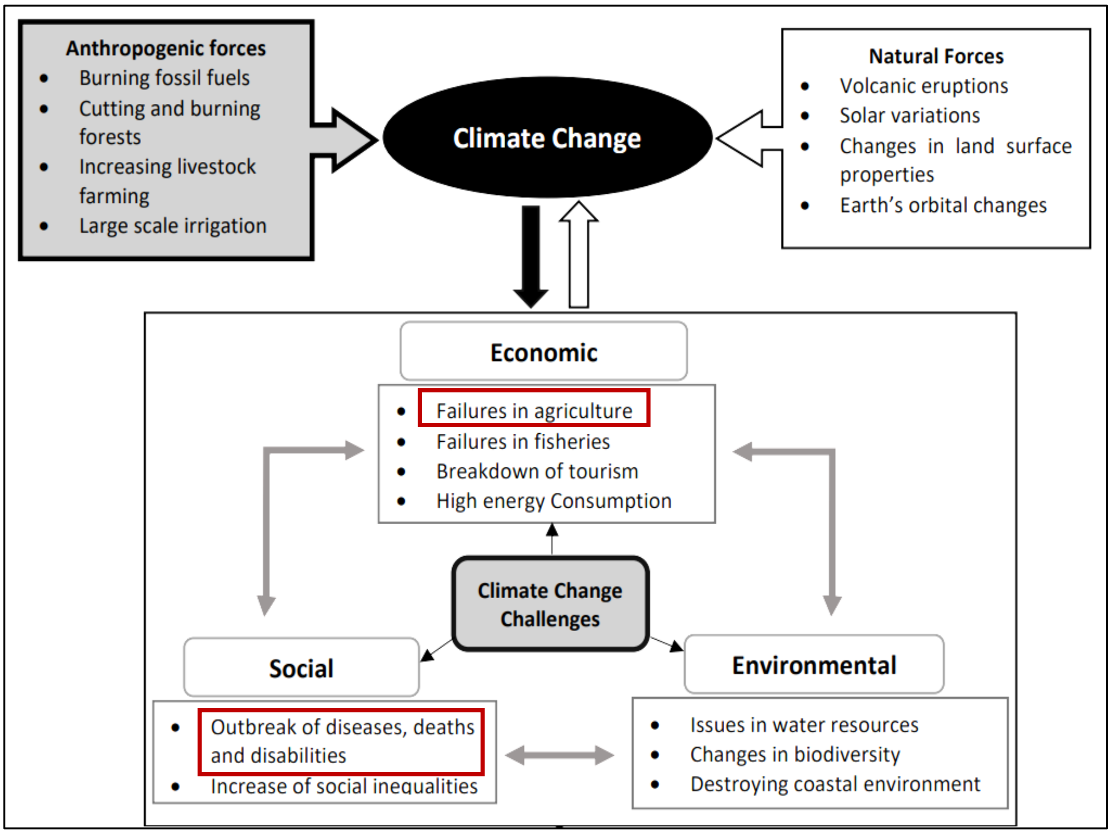


**Figure 2.** Climate change challenges (Source: Dasandara *et al.*, 2021)

### *Effects of climate change patterns on aflatoxins*

Aflatoxins are difuranocoumarin molecules that are produced by the polyketide pathway of fungi [8], and the production depends on certain factors such as the nutritional composition and genetic susceptibility of the host plant, moisture content, humidity, water activity, aeration, temperature, acidity level, fungal population, and physical condition of the crop [15]. However, meteorological conditions such as climate change are the most important factor in the production of aflatoxins [1]. The effect of climate change on the occurrence of aflatoxins is extremely complex and involves many factors including weather and other agronomic factors such as soil type [34]. Weather, especially changes in precipitation patterns and an increase in average global air temperatures with more extreme events such as heat waves, droughts, and extreme precipitation [35] play an important role in fungal infection and aflatoxin production in crops [1]. Fungi can affect crops at several stages, including pre-harvest, harvest, transportation, and storage [36]. However, only one stage is enough for the aflatoxin contamination [1]. Climate change influences the prevalence of fungal species that infect cereal crops, and produce mycotoxins [37]. The population of aflatoxin-producing fungi associated with cereal crops and soils varies with climate. These fungi survive poorly under cool conditions (temperature < 20℃), whereas the population of *A. flavus* in warmer regions (temperature > 25℃) is high, where *Aspergillus* sp. are common throughout crop surfaces, soils, and air [38].

The climate also influences the type of aflatoxin-producing fungi, as a result, these fungi are different in different geographical locations [39]. Where high temperatures and dry conditions favor the growth and dispersal of spores of *A. flavus,* drought together with high temperatures favors the production of aflatoxins in fields [14]. Hence, a change in temperature towards the higher temperatures will tend to increase aflatoxin contamination. Crops grown in warmer climates have a higher chance of infection by *A. flavus* and*,* an aflatoxin-producing fungi, while in some regions, infection only occurs when temperatures rise and is associated with drought [40]. Therefore, it can be stated that climate change has a profound effect on both the growth of aflatoxin-producing fungi and relative aflatoxin production. Paterson and Lima [1] suggested that a major risk in developed countries will be in temperate zones when temperatures tend to increase greater than 30℃. Thus, Sri Lanka as a tropical country with an average maximum temperature of 32℃ is more vulnerable to aflatoxin contamination.

### *Adverse effects of aflatoxins*

The presence of aflatoxins in foods is recognized as a global food safety concern by the World Health Organization (WHO) since they exhibit several toxic effects on humans. Exposure to aflatoxins can lead to “aflatoxicosis” that could be acute or chronic, and the toxic effects exhibited by aflatoxins depend on several factors such as age, gender, dosage, exposure duration, and nutritional status of individuals [18],[41]. Acute aflatoxicosis is prevalent when individuals are exposed to food contaminated with high doses of aflatoxins, and the symptoms include abdominal pain, vomiting, diarrhea, pulmonary edema, cerebral edema, anorexia, fatty liver, acute hepatitis, jaundice, depression, and photosensitivity [18],[41]. Acute poisoning is more prevalent in developing countries such as Sri Lanka due to the increased risk of contamination of staple food, lack of food security, absence of aflatoxin awareness, and lack of regulatory limits [42].

On the other hand, chronic aflatoxicosis is caused by being exposed to low doses of aflatoxins for an extended period which results in immune suppression and cancer [42]. According to toxicological studies, aflatoxins have been demonstrated as mutagenic compounds that can alter DNA leading to changes in chromosomes and mutations in genetic codes [43], and thus, aflatoxins are classified as "Group 1 carcinogen to humans" by the IARC. Additionally, chronic exposure to aflatoxins can result in decreasing immunity through decreased antibody production, reduced cell-mediated immunity, and decreased resistance to fungal, bacterial, and parasitic secondary infections [41], [44]. Aflatoxins can also lead to liver diseases such as cirrhosis and hepatomegaly [44]. Unfortunately, exposure to aflatoxins may lead to low birth weights since the exposure can occur in the uterus through the trans-placental pathway, and in children, it may affect growth since exposure is higher in children due to their low body weights.

Due to aflatoxin contamination, the food products cannot be consumed or exported leading to financial losses, and it is most common in developing countries. Additionally, the crop yield will be reduced due to fungal infection [35], [45], [46].

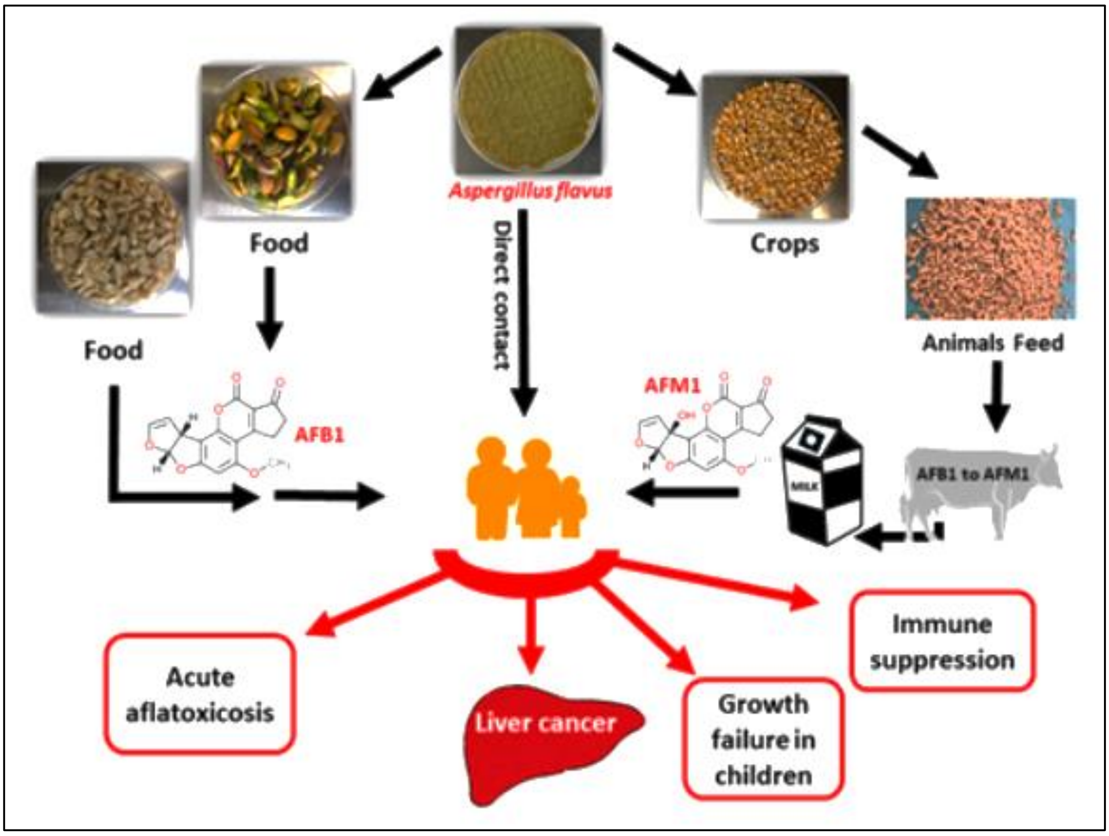


**Figure 3.** Adverse effects of aflatoxins on human health (Source: Gunawardena, 2021)

## Occurrence of aflatoxin in cereals: Sri Lankan context

The occurrence of aflatoxins and their outbreaks were reported in several foods worldwide including vegetable oils, nuts, cereals, and dairy products. In Sri Lanka, such occurrences have been reported since the early 1980s [36]. High humidity and high temperature, almost always present in tropical countries, are known to favor the growth of aflatoxigenic fungi and mycotoxin contamination, especially aflatoxins and fumonisins [36], [48]. The climate of Sri Lanka is in general inductive to fungal attacks and mycotoxin production, in addition to other factors, such as the prevalence of pests, irrigation systems, droughts, agricultural practices, and storage techniques. The most common foods for human consumption worldwide are cereals and cereal-based products, among which rice and corn are the most commonly contaminated by aflatoxins [36], and it is more frequent. In Sri Lanka, aflatoxin B1 is the predominant mycotoxin contaminating most agricultural produce including cereals [49]. Prof. Deepal Mathew reported on Daily Mirror on May 2021 that, food crops are contaminated in either pre-harvest or post-harvest stages, and when considering pre-harvest contamination, crops commonly affected are maize, cottonseed, and peanuts. Post-harvest contamination occurs mainly in coffee, rice, and spices [22].

### *Maize*

Maize is one of the most important crops in the world after wheat and rice in terms of production, consumption, and trade, hence aflatoxin contamination in maize has important ramifications for both health and global trade [35]. Maize (*Zea mays* L.) was introduced to Sri Lanka during the 16$^{th}$ century and due to its high energy value, high protein content, and low cultivation cost, it became popular among Sri Lankan farmers and consumers [7]. However, the maize grown in Sri Lanka is unfortunately not safe from aflatoxin contamination, and with no regulation on aflatoxin levels found in maize in local markets, the Sri Lankan population is at risk of dangerous levels of aflatoxin exposure [50].

Maize crops grow in warm climates and are prone to infection by *A. flavus*, a greenish-yellow to yellowish-brown powdery mold, which causes diseases like "*Aspergillus* ear" and "kernel rot of maize" on corn (Figure 4) with the production of aflatoxins [7]. Toxin production and fungal populations in maize depend on several factors that stress corn plants [51] including the low moisture content of the soil, high daytime maximum temperatures, high nighttime minimum temperatures, and nutrient-deficient soils [52], [53]. Moreover, infection occurs when temperature rise is coupled with drought conditions [36], [40], [54]. With increasing temperatures and more erratic rainfall predicted, climate change will likely impact aflatoxins occurrence in Sri Lanka in terms of their type and concentration. These changes may negatively impact the quality and quantity of maize grown and therefore raise key issues for human health, food safety, and food security [50].

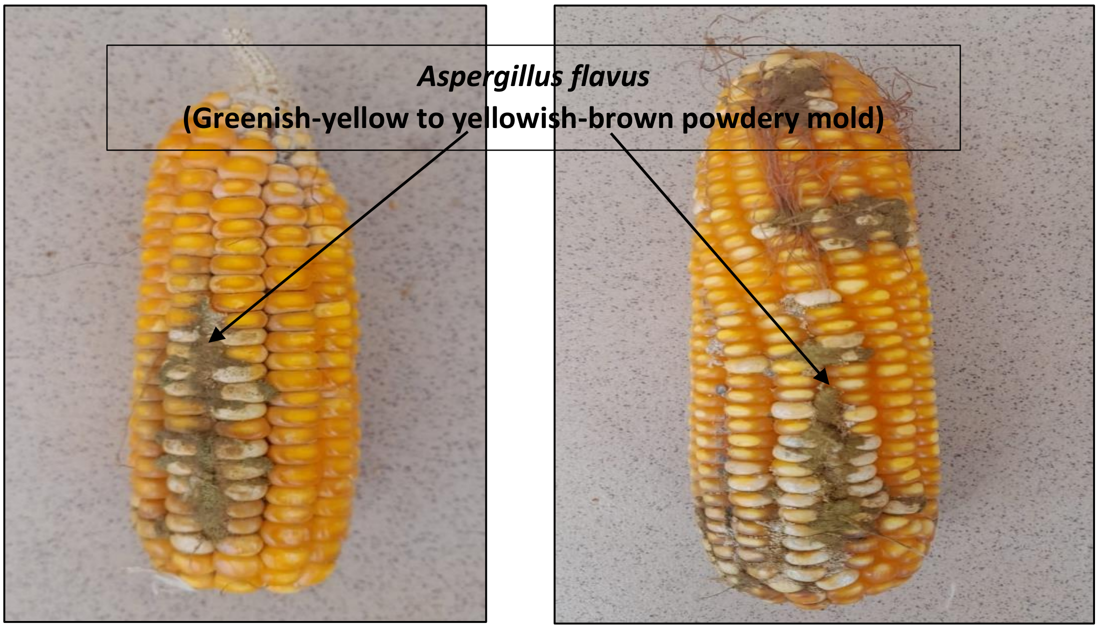


**Figure 4.** Kernel rot of maize

Though corn is one such agricultural produce highly susceptible to aflatoxin contamination, fewer scientific studies have been conducted on aflatoxin in corn in the Sri Lankan context. According to the Food and Drug Administration (FDA), the toxic level of total aflatoxin from corn consumption is limited to 20 ppb [36]. Jayaratne *et al* [55] conducted a research study on aflatoxin in corn in the Anuradhapura district, where they found, that out of 60 samples collected from the minor-scale corn-grown field, fifteen corn samples had exceeded the acceptable level of aflatoxin B1 while 22 samples were free of aflatoxin B1 and 23 samples were within the acceptable level; hence concluded that the presence of aflatoxin B1 in corn is not habitually distributed throughout the Anuradhapura district.

***Rice***

Rice, *Oryzae sativa* L. is the staple food in Sri Lanka which is widely produced and consumed throughout the country, and approximately 95% of domestic rice requirements are fulfilled by the country's national production. Rice is more susceptible to aflatoxin contamination, and it is generally caused by the improper drying of rice grains leaving a high moisture content of more than 14%. The *Aspergillus* fungi consequently degrade the quality of the grains while also discoloring them. Bandara *et al* [56] stated that aflatoxin contamination of rice, even at low levels, could be disastrous as the average Sri Lankan rice consumption per day is particularly high [56-57]. Although this is a crucial health concern, Sri Lanka as a developing country has very scarce data sources and studies in this regard.

The tropical climate in Sri Lanka provides favorable conditions for fungal growth, furthermore, the poor storage conditions of paddy for months aggravate mold growth. In Sri Lanka, generally, the temperature and relative humidity of storage is quite high and estimated at 27℃ and 78%, respectively. As a result, rice especially parboiled rice is more susceptible to aflatoxin contamination, and it has been reported in several instances from Sri Lanka and a few other South-East Asian countries [58].

Paddy is milled either without parboiling as raw rice or after parboiling as parboiled rice, and Dr. Prasanna J.P. Gunawardena reported in the Daily FT on April 2021 that, in Sri Lanka, rice is mostly consumed as parboiled rice [47]. Parboiling is a process where paddy is soaked in water overnight followed by pre-heating with the husk itself, and then it is sun-dried and then passed through a rubber roll sheller to remove the husk and a polisher to remove the outer bran layer [19]. Improper sun drying of pre-heated paddy can lead to high moisture contents which favors mold growth [56], [59-60].

In commercial parboiling, paddy is soaked in water in large concrete tanks, and this water is often reused due to practical issues, which causes high contamination. In the household level process, paddy is washed and preheated in clay or copper pots and followed by sun drying in open areas. The gelatinized starch within the parboiled rice is more susceptible to fungal growth than the starch in raw rice, hence it can be stated that parboiled rice is a more ideal substrate for fungal growth and aflatoxin production [56], thus more attention and close monitoring needed on parboiling practices [19]. Moreover, Bandara *et al* [56] stated that the levels of aflatoxin B1 and G1 in parboiled rice were significantly higher than in raw milled rice. During the storage, rice is packed in jute or polythene bags and then stacked in warehouses with poor ventilation for a longer period which may further increase the growth of *Aspergillus* fungi and aflatoxin production [56], [60].

## Climate change and aflatoxins: Sri Lankan perspective

*Aspergillus* species are very diverse and can adapt to a wide range of environmental conditions [61], however, they are mainly found in hot humid climates typically in tropical and subtropical regions, most significantly between 40°N and 40°S latitudes [62]. Sri Lanka, as a tropical island that lies in between these latitudes [63] (Figure 5), has favorable growth conditions for *Aspergillus* fungi.

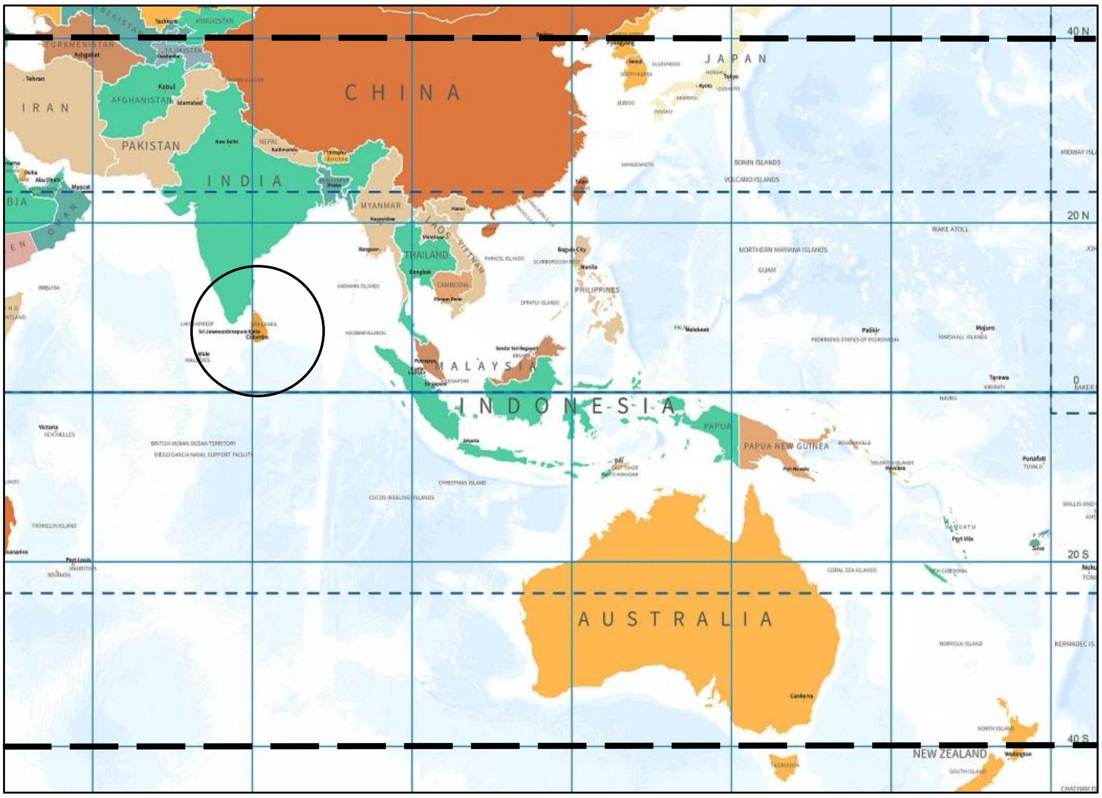


**Figure 5.** The geographical location of Sri Lanka

Aflatoxin contamination in foods depends on the genetic factor of crops as well as microclimate, including product moisture content, water activity ($a_w$), relative humidity, temperature, pH value, and substrate composition, where aflatoxin contamination is promoted due to stress or physical damage to the crop especially due to drought episodes, insect infestation, rain showers during pre-harvest stage, poor harvest timing, insufficient drying before storage, and poor storage practices [16], [42]. Additionally, Stepman [64] reported that the crops are fungal contaminated particularly under certain conditions such as dry weather at the onset of crop maturity.

The optimum growth temperature for *Aspergillus* fungi is generally 28℃–37℃ with a high humidity of above 80% [55]. However, the growth patterns differ between different strains of *Aspergillus* sp., for example, the optimal growth temperature for *A. flavus* and *A. parasiticus* are 33℃ and 35℃, respectively [66]. As reported by Pleadin *et al* [20] that the optimum conditions for the growth of aflatoxigenic fungi and the production of aflatoxins are the temperature of 35℃ and the $a_w$ of 0.95, and the temperature of 33℃ and the $a_w$ of 0.99, respectively. However, Lizárraga-Paulín *et al* [16] stated for the *Aspergillus* sp., the optimal growth happens at a temperature of 25℃ with a minimum $a_w$ of 0.75, and their secondary metabolites production starts at 10–12℃ with the most toxic metabolites produced at 25℃ with the $a_w$ of 0.95.

Global warming is expected to induce an increase in global temperatures by 1.5–4.5℃ by the end of the 21st century [67], along with an increase in the accumulation of carbon dioxide, increase in precipitation, the dominance of extreme weather conditions such as heat waves, and an increase in the incidence of flooding and droughts [68], where droughts are considered as an important trigger for the biosynthesis of aflatoxins. The sudden change in precipitation and drought patterns followed by increased humidity, temperature, and $CO_2$ levels will directly affect the expression of the regulatory and structural genes implicated in aflatoxin biosynthesis [69], and elevated $CO_2$ levels can further lead to aflatoxin contamination [70]. According to Medina *et al*. [70], AFB1 production was stimulated under elevated $CO_2$ levels, especially when coupled with drought.

Nowadays, it can be observed an unpredictable weather profile throughout the country with sudden rainfall, drought, and heat stress. According to the climate risk country profile (CRCP) issued by the World Bank Group, Sri Lanka is recognized as vulnerable to climate change impacts, ranked 103 out of 181 countries. For upcoming years, projected temperature rises are very likely to push ambient temperatures over 30℃ on a much more regular basis, and to considerably increase the frequency of temperatures over 35℃. Moreover, the incidence of permanent heat stress is likely to increase significantly in Sri Lanka, and the research suggests an increase in the frequency of drought events in South Asia [71]. Thus, these expected climate changes may positively induce the production of aflatoxins in cereals.

### *Pre-harvest effects*

Developing crops are supposed to be resistant to infection by *A. flavus* and subsequent aflatoxin contamination unless environmental conditions favor the fungal growth and crop susceptibility, where fungal infection often follows drought stress and insect injuries. High temperature and drought, which often occur during the growing season are likely to contribute to poor kernel development [51], and in corn, *Aspergillus* fungi are associated with cob [72] in the field at the time of crop maturity (39). A tan sooty black, greenish, or greenish-yellow mold grows on and between corn kernels, and the damage is most common near the tip of the ear. Silk infection in corn (Figure 6) is favored by high night and day temperatures, and sometimes the susceptible maize genotypes got infected with *Aspergillus* sp. at the time of silking. The infection goes through the silk to the developing grains; however, it remains latent and causes decay at the time of crop maturity in the form of cob rot. In some cases, the grain remains infected but does not show any symptoms [35]

**Figure 6.** Silk infection in corn cob

Late harvesting of maize and cultivating under nitrogen stress conditions generally produce aflatoxins before harvest than maize grown under good management practices and supplied with adequate nitrogen. Such contaminated grain may again be spoiled at the time of poor storage conditions [35].

### *Harvest effects*

The moisture level in the grains is the main indicator for identifying the harvesting time, and grains that will be dried after harvest are generally preferred to be harvested when the moisture content has dropped below 35% or 30% [73]. Climate change can lead to early maturing of the crop, and create favorable conditions for *Aspergillus* sp. infestation and aflatoxin production at the time of harvest, where the thriving of the fungi is most severe when crops are caught by rain just before or during harvest. Here, initially, dry seed develops water content conducive to contamination, and coupled with optimum temperature, fungal infection can be increased with the production of aflatoxins [35].

### *Postharvest effects*

Drying is an important stage in aflatoxin control following harvest, thus upon reaching adequate moisture content, crops are safely placed in storage. However, with the dominance of extreme weather conditions, such as high humidity, reaching adequate moisture content before storage would be hard to achieve. The sudden patterns of rainfall, precipitation, and dew can lead to the failure of the drying procedures specifically if sun drying is performed in open fields [74]. It is essential to control temperature and relative humidity during storage at levels below 10℃ and 70%, respectively, which would be challenging in traditional storages prevalent in Sri Lanka in climate change scenarios [75]. Therefore, under uncontrolled storage conditions, pest attacks can be increased leading to the increased growth and multiplication of different bacterial and fungal species especially in the presence of elevated temperatures and humidity. The xerophilic molds that start the deterioration process in stored grains can grow at low water activity, and these molds cannot be detected on freshly harvested grains as they occur in very low numbers. The contamination of xerophilic fungi commonly occurs when the grains are placed in silos or sheds, and during transport. As these molds grow and establish their metabolic activities, subsequently create favorable microenvironments for the *Aspergillus* fungi, where *A. flavus* in particular, only grows when the relative humidity is above 85% or moisture content in the grain is above 16% [35]. Moreover, increased water evaporation and condensation could lead to damp conditions that support the growth of *Aspergillus* sp., and subsequent aflatoxin production [75]. Therefore, with climate change, aflatoxin contamination is expected to increase during storage.

## Aflatoxin control

Aflatoxins are heat-stable chemical compounds that decompose at temperatures ranging from 237 to 306℃ [76], thus not destroyed during standard cooking. Unfortunately, there is no single step found so far to eliminate aflatoxin contamination from foodstuffs, but there are numerous control strategies practiced all over the world. Aflatoxin control can be done mainly at two points along the supply chain which are pre-harvest and post-harvest stages.

### *Preharvest strategies*

Pre-harvest control primarily focuses on preventing toxin formation by reducing or eliminating fungal growth on crops [77]. It is recommended to plant crop populations that are resistant to *Aspergillus* sp. growth and follow good crop production practices. Balanced fertility programs, timely irrigation to reduce drought stress, and minimizing insect damage reduce fungal growth on crops. Moreover, crop rotation can be practiced to reduce fungal growth and subsequent aflatoxin production [35]. Coupled with technological advancements, organic and biological farming practices can be used to overcome aflatoxin contamination in fields. For example, bio-controlling *Aspergillus flavus* strains with a nutrient-supplying carrier can be used to out-compete wild aflatoxigenic strains [55].

### *Postharvest strategies*

Reducing the risk of aflatoxin contamination after harvest can be done by following proper drying and storage practices despite the unpredictable weather events as below discussed.

<u>*Drying and storing of maize:*</u>

The moisture content and the temperature of the maize kernels affect the fungal infection; thus, the grains should be further dried to reach a maximum of 13.5% moisture content when long storage is intended. The infected seeds and the foreign matters should be removed before storing the kernels, and the grains should be safely packed in bags and the quality of those grains better to be checked periodically. Moreover, silos can be used for storing maize, however, it should be thoroughly cleaned and sanitized before placing the new grains, and good aeration is essential inside the silos. The silo's floor should be covered-paved, smoothed, cleaned, and dried with moisture insulation [73].

<u>*Drying and storing of rice:*</u>

Drying is the most critical step after harvesting a rice crop. When paddy is harvested, it may contain up to 25% moisture, resulting in mold development during storage. Thus, the paddy grains should be dried as soon as possible after harvesting - ideally within 24 hours. Delays in drying, incomplete drying, or ineffective drying will lead to fungal infection. The farm-level drying is mostly done through sun drying if the weather is in favorable conditions. However, to avoid weather risks, other mechanical drying methods (e.g. Heated air drying, In-store drying, and Solar drying) can be practiced [78]. Rice grain is hygroscopic and in open storage systems, the grain moisture content will eventually equilibrate with the moisture content of the surrounding air. Moreover, high relative humidity and high temperatures typically present in humid tropical countries lead to the absorption of more water which in turn results in high final moisture content. To reduce these risks, proper storage practices can be followed as below discussed [78].

<u>*Bag storage:*</u>

In Sri Lanka generally, rice grain is stored in 40−80 kg bags made from either jute or woven plastic, and depending on the size of storage, these bags are normally formed into a stack (Figure 7). When using bag storage, the following steps should be taken into consideration [78].

- Jute and plastic bags should not be stacked higher than 4 m and 3 m respectively.
- Bags should be stacked under a cover (e.g. under a roof, in a shed or granary, or under waterproof tarpaulins.)
- A one-meter gap should be left between and around stacks and a 1.5 m clearance between the top of the stack and the roof.
- Bags should be stacked on pallets or on an above-ground structure to avoid the possibility of absorbing moisture from the floor.

- In traditional storage, bags are stacked in outside granaries, which have been constructed from timber, mud, or palm leaves.

**Figure 7.** Bag storage of rice in Sri Lanka (Source: Warakapitiya, 2017)

*Commercial bulk storage:*

Commercial bulk storage, such as silos is not a very common storage practice in Sri Lanka as the moisture migration inside the silo can lead to building hot spots. The silos range in size from 20−2,000 ton capacity, and they can be more easily sealed for fumigation [78].

*Hermetic storage systems:*

Sealed or hermetic storage systems are very effective in controlling grain moisture content, especially in tropical regions, where the airtight barrier between the grain and the outside atmosphere maintains the moisture content of the stored grain as the same as when the storage was sealed. In hermetically sealed storage systems grains are placed inside an airtight container, which stops water movement between the outside atmosphere and the stored grain [78]. However, these post-harvest strategies have shown to be ineffective in ensuring the elimination of aflatoxin-producing fungi. Thus, decontamination techniques are subsequently required to reduce the risk of aflatoxin contamination [81].

### *Aflatoxin removal*

As reported by Dr. Prasanna J.P. Gunawardena in the Daily FT in April 2021, the removal or inactivation of aflatoxin in food and feedstuff is a major global concern [47]. Aflatoxins can be removed from contaminated foods and feed through physical, chemical, and biological means. However, the treatment has its limitations, since the treated products should be safe for human consumption. Furthermore, the novel processing technologies involving a microwave, UV rays, pulsed light, electrolyzed water, cold plasma, ozone, electron beam, or gamma irradiation in combination with biological, physical, chemical, or genetic engineering models have the potential to improve the efficiency of aflatoxins decontamination.

## Regulations and limitations

Since the discovery of aflatoxins in the 1960s, many countries have implemented regulations to protect consumers from the harmful effects of these toxins, and the permissible aflatoxin levels in foods were determined using toxicological data, food consumption data, data on the level and distribution of aflatoxins in goods intended for human consumption, and data on analytical methodology [82]. Prof. Deepal Mathew reported in the Daily Mirror on May 2021 that, consumption of food containing 1mg/kg or higher of aflatoxins is likely to cause aflatoxicosis, and consumption over 1-3 weeks of AFB1 dose of 20 – 120 mg/kg body weight per day can lead to acute toxicity and can be potentially lethal [22].

According to the Commission of the European Communities, the maximum levels of AFB1 and total aflatoxins (AFB1, AFB2, AFG1, and AFG2) for all cereals and all products derived from cereals, including processed cereal products should not be beyond 2 µg/kg and 4 µg/kg respectively. The maximum level of AFB1 and total aflatoxins set for maize and rice to be subjected to sorting or other physical treatment before human consumption or use as an ingredient in foodstuffs should not be beyond 5 µg/kg and 10 µg/kg, respectively. The maximum aflatoxin level for processed cereal-based foods and baby foods for infants and young children is set to 0.1 µg/kg. Moreover, the maximum aflatoxin level for dietary foods for special medical purposes intended specifically for infants is set to 0.1 µg/kg [23]. On the other hand, in Sri Lanka, the Food Control Administration Union has drafted a regulation for aflatoxins in cereals, and the maximum allowable levels are the same as in the Commission of the European Communities [83]. However, there is sufficient evidence that demonstrates that this amount does not do enough to protect everybody, especially people living in developing countries, where cereals (e.g. Rice) are consumed in high amounts and immunity is already low for other reasons. Moreover, there are some limits to implementing these regulations in Sri Lanka, which are listed below [47].

1. Most farmers do not know about the existence of aflatoxins, let alone the grave risks associated with their consumption, and therefore are not concerned about their mitigation.
2. Quantitative analysis of aflatoxins is optional for locally consumed foods, but mandatory for crops designated for export to meet international regulatory standards. Therefore, producers do not give importance to the aflatoxin level in food which are locally sold.

## Policy recommendations

1. Drives can be arranged at local, regional, and national levels to raise consumer awareness on the adverse effects of aflatoxins in cereals, as the aflatoxins may not only be present in maize but also Sri Lankan staple food, rice.

2. The national regulation for aflatoxins in cereals is still at the draft level, and it is the same as in the Commission of the European Communities. However, the permissible limits of aflatoxins in cereals should be re-considered, because people living in developing countries like Sri Lanka consume rice daily and in higher amounts, and immunity is low when compared to developed nations.

3. The aflatoxin level for imported cereals, especially maize should be included in the Food (Cereals, Pulses, Legumes, and Derived Products) regulation/Standards.

4. Implementing good agricultural practices (GAPs), good manufacturing practices (GMPs), good transporting practices (GTPs) and good storage practices (GSPs) for aflatoxin control should be generalized among the food chain, thus knowledge transfer programs can be organized starting from the grass root level.

5. Market mechanisms to inspect aflatoxins levels in cereals and regulate quality should be introduced at the local or regional level.

Actions are required at local, regional, and national levels to reduce aflatoxin prevalence and exposure in Sri Lanka [47].

## Conclusions

Aflatoxin contamination is prevalent in warm humid climates similar to Sri Lanka and may be severe during drought episodes. The literature search conducted in this study highlighted knowledge gaps on climate change and aflatoxin production in corn and rice respective to Sri Lanka. Projected climate change effects will influence primary agricultural systems and thus food security, directly via impacts on yields, and indirectly via impacts on its safety, with aflatoxins considered as crucial hazards. Understanding the impact of climate may allow the development of improved management practices, better allocation of monitoring efforts, and adjustment of agronomic practices in anticipation of climate change. To fill the gaps and develop predictive models, further research studies will be needed to effectively predict the level of risk of aflatoxins in economically important staple food crops and to understand whether they are resilient enough to tolerate the expected climate changes.

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## Conflict of Interest

No conflict of interest exists.

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# Smallholder Vegetable Farmers' Adaptation to Climate Change and Determinants of Decision on Adoption: a Sri Lankan Experience

# Smallholder vegetable farmers' adaptation to climate change and determinants of decision on adoption: A Sri Lankan experience

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## Abstract

Smallholder vegetable farmers are highly dependent on rainfall and temperature. Vegetable production in the country dropped by 9.1% due to adverse weather conditions in 2017. This study explored the factors affecting smallholder vegetable farmers' choices of adaptation to climate change. Data were collected from 150 respondents selected using multi-stage random sampling using a structured questionnaire. A Climate change adoption index was developed using Weighted Principle Component (WPC) method. Multiple Linear Regression model was used to identify the factors affecting adaptation strategies. According WPC, six climate adaptation strategies were identified. Climate change is an important problem in the area and many smallholder vegetable farmers have low adaptive capacity. Majority of the farmers (over 50%) perceived that temperature and rainfall have been increasing in the area during the last two decades. Mostly used adaptation strategies by the farmers were crop rotation, irrigation and use of drought tolerant crop varieties while micro irrigation and use of trenches were the least used adaptation strategies in the area. Choice of an adaptation strategy is affected by various factors such as farmers' gender, age of the farmer, farming experience, income, land ownership, contact with Extension agents and distance to market. This study recommends to develop tailored programs meeting the diverse needs of population segments. Future government policies should strengthen adaptive capacity of farmers through better access to climate-information. Providing opportunities for non-farm income activities that are less sensitive to climate and making farmers aware of those opportunities is important to overcome their vulnerability to changes in the climate.

**Keywords:** Adaptation strategies, Climate change, Limitations, Smallholder vegetable farmers

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## Introduction

Climate change is an inevitable phenomenon and a global challenge. According to the Fourth Assessment Report of the UNIPCC [1] project, even with the existing mitigation strategies, the climate will change. It is assessed that global mean temperature will rise from 1.8 – 4.0 $^{0}$C by the end of the 21$^{st}$ century [2]. South Asia is the highest vulnerable region to climate change among other Asian sub-regions [3]. The livelihoods of rain-fed farmers are more sensitive and vulnerable to climate change than irrigated farmers because they fully or partially depend on fluctuating rainfall for agricultural activities.

Sri Lanka is an agriculture-based developing country. Agriculture contributed 6.9% to the Gross Domestic Production (GDP) and over 25% of the population is employed in the agriculture sector [4]. The climate of Sri Lanka is mainly influenced by changes in air temperature, rainfall patterns, and extreme weather events [5]. Based on the ecological parameters (rainfall, soil type, and topography), Sri Lanka is divided into three agro-climatic zones: wet zone, intermediate zone, and dry zone. Agriculture in the dry zone is reported to be highly vulnerable to the impacts of climate change. Dry zone farmers have recently faced numerous challenges due to changes in the rainfall pattern, drought, and flood incidents which are additional challenges to dry zone agriculture.

The rural smallholder food producers are severely affected by climate change as they have a low adaptive capacity to climate change [5]. Living in the dry zone have made these producers highly dependent on natural resources despite the other challenges such as small farm size, poor technology, low capitalization, poor infrastructure, and inadequate institutional support limit their capacity to adapt to climate change.

Next to rice, the vegetable subsector is the most important sector in agriculture. As with rice, vegetables are cultivated throughout the country and a large number of farmers are engaged in vegetable cultivation. It contributes around 7.2% to total agricultural production, which is around 0.5% of the GDP in Sri Lanka [4]. Main vegetables grown in Sri Lanka can be classified into two categories such as up- country vegetable and low-country vegetable. Up-country vegetables are mainly cultivated in the central part of the country and low-country vegetables are cultivated low land area in dry zone. Major vegetable producing districts are Nuwara- Eliya, Badulla, Kandy, Matale, Kurunegala and Anuradhapura. These districts contribute more than 50% to the total vegetable production in the country.

One of the major problems faced by the vegetable farmers in dry zone is the gradual reduction of their Yala season vegetable production. [5] mentioned that vegetable production dropped by 9.1 % to 1.5 million metric tons in 2017. Production of low-country and up-country vegetables decreased considerably due to adverse weather condition that prevailed throughout the year.

Anuradhapura is a district which is located in the North Central province of Sri Lanka. Among the land use in Anuradhapura 19% used for vegetable cultivation. There are about 15000 numbers of small holders in Anuradhapura district. Anuradhapura district is selected because it is one of the major low country vegetable cultivation districts in the country. According to the census data, Yala season low country vegetable production in Anuradhapura district gradually decreased during 2001- 2015 years. Rainfall pattern and temperature are major climatic factors which affect vegetable production. Meteorological department data highlighted the fluctuation of rainfall amount and pattern in past 20 years which is negatively affecting the vegetable farmers in Anuradhapura district.

Actions taken to moderate, cope, or take advantage of experienced or anticipated changes in climate are called climate adaptation. Adverse effects of climate change can be greatly reduced due to the proper implementation of adaptation strategies. Some examples of adaptation strategies are planting according to rainfall variability, using micro-irrigation, crop diversification, using improved crop varieties, soil conservation, and deducing irrigation depth [5]. The use of climate-smart agricultural practices depends on several factors such as perception, socioeconomic factors, and perceived difficulty of adoption. However, in Sri Lanka, studies on factors affecting the adoption of climate-smart agricultural practices are lacking [5].

Adaptation to the adverse impacts of climate change is necessary. Socio-economic, cultural, political, institutional, geographical, and ecological factors influence adaptation [6]. Further, the perception of farmers on climate change is very important for adapting to the impacts of climate change [7]. There is a strong relationship between climate change perception and the degree to which climate-induced risks and opportunities affect the farmers and their livelihoods. Adoption to adaptation strategies largely depends on the perception of farmers towards climate change [8]. The perception which is related to experiences of natural and environmental factors varies individually. Even the perceptions of climate change are not necessarily consistent with measurable reality; they are involved to adequately reflect real challenges. However, no adaptation or maladaptation is the result due to misconceptions about climate change and its associated risks and accordingly increasing the negative impact of climate change.

However, in Sri Lanka, studies on factors affecting the adoption of climate-smart agricultural practices are lacking [5]. Identifying factors affecting adoption is important to make implementation plans and to develop policies. This study investigated how these drivers influence farmers' decision-making concerning climate change adaptation. Understanding the relative importance of these factors will help farmers easily employ viable adaptation practices and to overcome crop production constraints.

The general objective of this study was to assess the drivers of farmers' choice for adaptation practices for climate change in the Anuradhapura District. This main objective was divided into three sub-objectives as identifying and characterizing adaptation strategies employed by smallholder farmers to manage the adverse effects of climate change, to determine the factors that influence smallholder farmers' choice of adaptation, and to identify limitations for adopting climate smart agricultural practices.

## Methodology

### Profile of the study area

This study was carried out in Anuradhapura district which is the largest administrative district in Sri Lanka. Anuradhapura district contributes to low country vegetable production in a wider extent and is more vulnerable to climate change impacts than other vegetable growing districts. The district is located at 350km North the capital of the country. Anuradhapura has two distinct seasons including a long dry season (March-October) and a rainy season (November to February). Further, the rainfall pattern makes two distinct cropping seasons: Yala and Maha. Maha is the main cultivation season in Anuradhapura and Yala is the subsidiary cultivation season [9]. The average annual temperature is 26.5 °C | 79.7 °F and the average annual rainfall is 1255 mm | 49.4 inch. Compared to other administrative districts in Sri Lanka, Anuradhapura has more extreme weather events such as droughts. This study was conducted in three divisional secretariat divisions in Anuradhapura district: Galenbidunuwewa, Medawachchiya and Thambuththegama which are identified as the most vulnerable divisions for climate change.

## Sampling procedure

Target population of this study was smallholder vegetable farmers in Anuradhapura district. Multi-Stage sampling techniques which included a combination of sampling techniques was used to select GN divisions (lowest level administrative units) and farmers. In the first stage, based on the data of high vulnerability areas to climate change 3 Divisional Secretariat Divisions (DSD) were selected purposively. In the second stage five Agrarian Service divisions (ASD) were selected from the above three DSD randomly. The third stage involved random selection of three GN divisions in each selected ASD. Accordingly, 15 GN divisions were selected. Ten vegetable farmers were randomly selected from the list of farmers in each chosen GN division. Totally, 150 respondents were used for the study.

## Data collection methods

This study employed both primary and secondary data collected from quantitative data collection methods. Primary data were mainly gathered by a field survey using a pre-tested structured questionnaire. The questionnaire was pre-tested using ten respondents for validity and appropriateness. Based on the limitations identified at the pre-test, the questionnaire was modified and revised before the actual interviews. The questionnaire consisted of five main sections. The first section of the questionnaire focused on the general and socio-economic characteristics of the farmers. The second section asked questions about the access to climate/weather information. The third section of the questionnaire collected information about perception about climate change. The fourth and fifth sections asked questions about farmers' adaptation options and limitations for adaptation respectively. Include the questionnaire and refer to it. Both published and unpublished data sources were used to collect secondary data such as government department, books, web sites and journal articles. Data related to climate change in Anuradhapura district, data on annual rainfall, maximum and minimum temperature were collected from the Department of Meteorology, Sri Lanka.

## Descriptive data analysis

Demographic and socio-economic data of this study are presented as descriptive statistics such as frequency, percentage, graphs, figures and tables. For these analysis Microsoft excel 2010 and Statistical Package for Social Sciences (SPSS) were mainly used.

## Econometric analysis of data

### *Multiple linear regression model*

Multiple linear regression model was used to determine the factors that influence smallholder farmers' choice of adaptation and barriers. The linear regression model can be expressed as follows;

$$\boldsymbol{Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8 + \beta_9 X_9 + \beta_{10} X_{10} + \beta_{11} X_{11} + \beta_{12} X_{12} + \beta_{13} X_{13} + \beta_{14} X_{14} + e}$$

$\boldsymbol{Y_i}$ = number of adaptation strategies (dependent variables)

$\boldsymbol{\beta_0}$ = Intercept

$\boldsymbol{\beta_1} \dots \dots . . \boldsymbol{\beta_{14}}$ = regression coefficients

$\boldsymbol{X_1} \dots \dots . \boldsymbol{X_{14}}$ = gender, age, marital status, household size, education level, employment, farming experience, distance to input market, distance to output market, land ownership, farm income, extension contact, organization membership and getting credit (independent variables)

***e*** **=** error terms

***Climate data analysis***
Trends of rainfall and temperature in Anuradhapura district during last decade (1997-2017) were analyzed using descriptive statistical methods.

## Results and Discussion

### Socio-economic characteristics of respondents
Descriptive results revealed that majority (81%) of the respondents were male while 19% were female respondents. This implies that both male and female respondents are engaged in vegetable production in the area. Normally male headed households can be seen than female headed households in Sri Lanka and therefore, male dominated agriculture is normal assumption. Further, it revealed that higher contribution of smallholder vegetable production was given by male farmers while some female farmers were interested to vegetable cultivation in small scale level in Anuradhapura district. The mean age of respondents was 50 years. Monthly income from farming varied between LKR. 500,000.00 and LKR. 4,000.00. The mean farming experience of farmers was 22 years. Majority (71%) of the respondents have completed secondary education. More than half of the respondents (78%) totally depend on agriculture as fulltime farmers while only 22% were part time farmers.

### Perception of farmers on climate change
On a dichotomous scale ("yes/no" response) the respondents were asked to state whether or not they had experienced changes in the climate within the past 20 years. After their response, the respondents were again asked their perceived experience with six climate change effects in Sri Lanka to which they could state their experience as decrease, increase or no change. The results in Figure 1 shows that the majority of the respondents (74%) perceived that amount of rainfall has changed during main rainy seasons while about 52% of respondents have observed a change in the onset of rainfall during last few years. About 49% of respondents expressed that recurrence of drought increased with time. As noted by [10] agricultural production is particularly vulnerable to irregular or extreme conditions of climate such as more frequent droughts and deviations from "normal" growing season conditions.

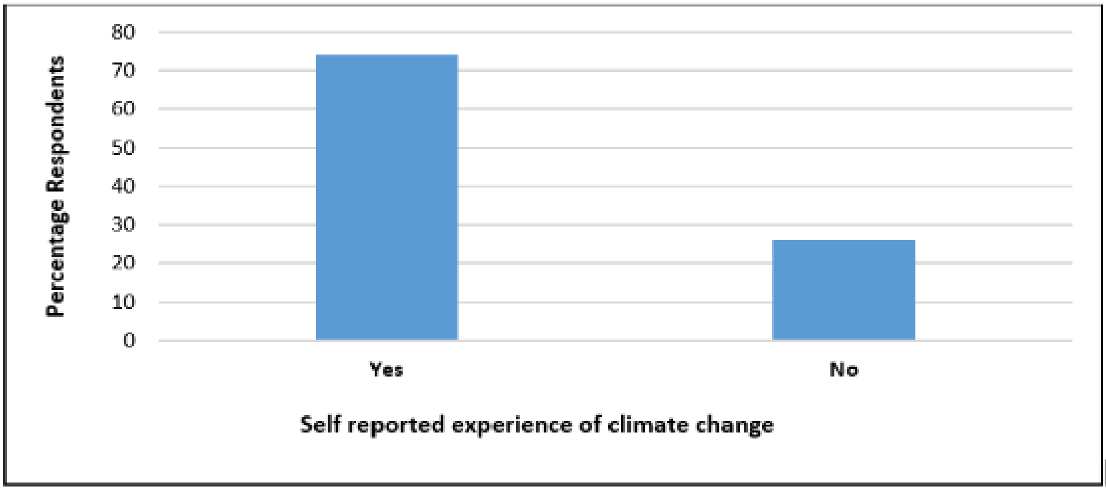


**Figure 1.** Self-reported experience of climate change

## Perceptions on the trend of rainfall and temperature in the past 20 years

According to the Table 1, more than half (64%) of the respondents perceived that there was an increasing trend of rainfall during past 20 years. Few numbers (26%) of respondents mentioned that rainfall was fluctuating while only 4% of respondent perceptions were it was constant. The majority of the (56%) respondents mentioned that temperature was increasing with time and 35% of respondent ideas were temperature has been fluctuating during period.

**Table 1.** Perceived changes in temperature and rainfall during last 20 years

| **Climatic event** | **Percentage (%) Respondents indicating their experience over the last 20 years** | | | | |
|---|---|---|---|---|---|
| | **Increasing** | **Decreasing** | **Fluctuating** | **Constant** | **No idea** |
| Temperature | 56 | 0 | 35 | 7 | 2 |
| Rainfall | 64 | 0 | 26 | 4 | 6 |

Majority of the respondents indicated that they had experienced an increase in the temperature and rainfall in their areas during the last 20 years. This is evident that farmers in the area have taken adaptive measures to overcome the changes in climate over the last twenty years.

## Trend of rainfall in Anuradhapura district during last two decades

To verify respondents' perceptions regarding the rainfall and temperature, annual rainfall data for the last 20 years were obtained from the Meteorological Department of Sri Lanka for Anuradhapura district and presented in Figures 2 and 3. Trend distribution of annual rainfall in Anuradhapura district observed an increasing trend. According to the Figure 2, during 2005, 2009, 2013 and 2016 annual rainfall has decreased. Rainfall has gradually increased from 2013 to 2014 while it has decreased drastically in 2016 year.

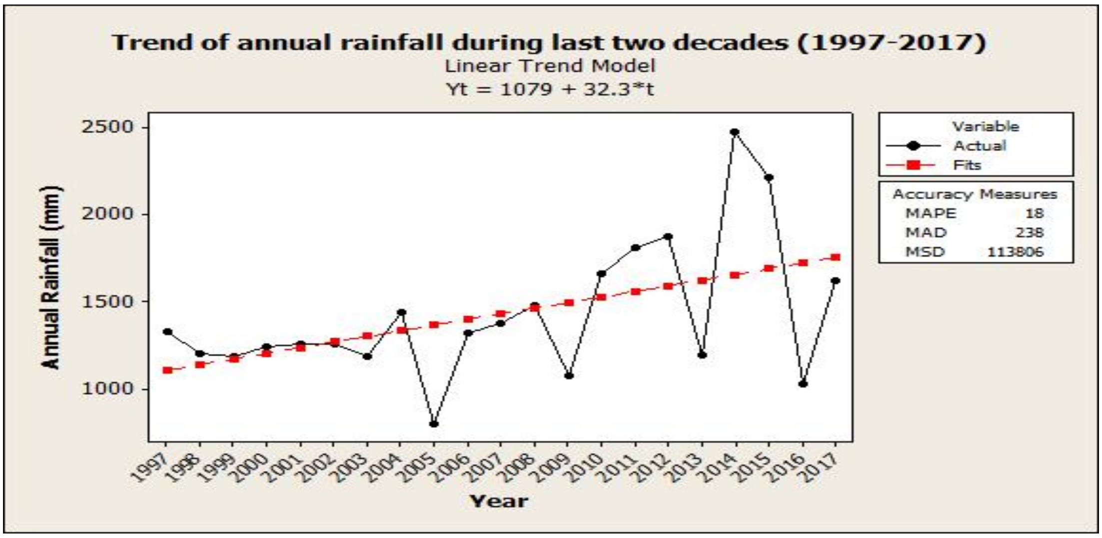


**Figure 2.** Trend of annual rainfall in Anuradhapura district

## Trend of temperature in Anuradhapura district during last two decades

As for temperature, an increasing trend was observed during 1998- 2017 years. In 1999, temperature has drastically reduced. After that it shows fluctuating results up to 2005. From 2006 to 2008, temperature was decreased and temperature was lowest in 2008.

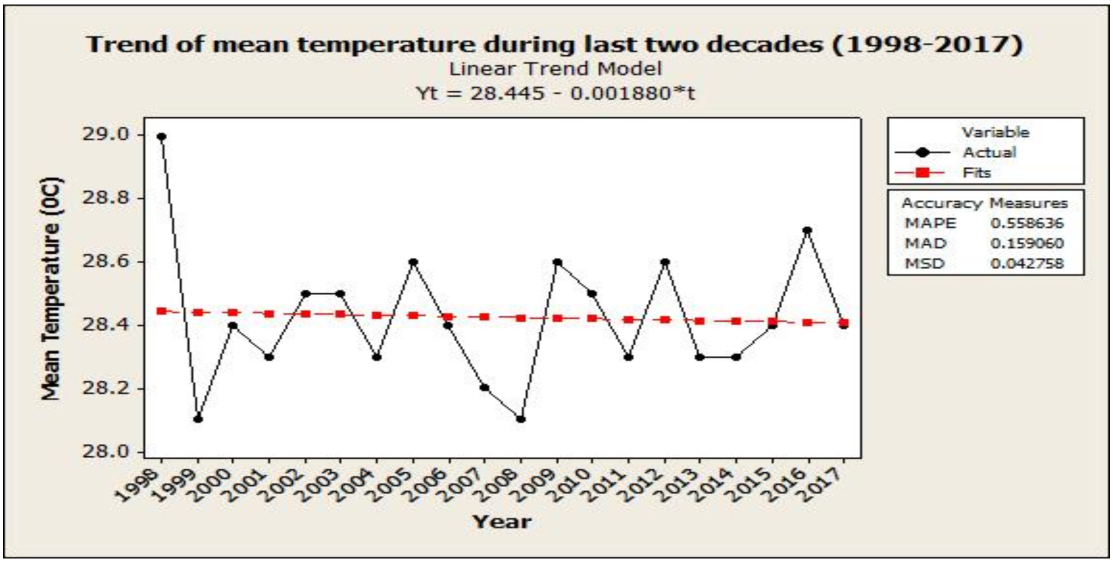


**Figure 3.** Trend of mean temperature in Anuradhapura district

## Adaptation strategies adopted by smallholder vegetable farmers

An Adaptation Strategy Index was (ASI) developed to assess different adaptation strategies used by farmers which held relative importance to others as suggested by [11]. The respondents were given different adaptation strategies and were asked to grade through a four-point rating scale to rate the importance of each strategy to their cultivation. Following index formula used by [11] & [12] was used to calculate the relative importance of adaptation strategies.

**ASI = ASn × 0+ ASl × 1 + ASm × 2+ASh × 3**

**ASI =** Adaptation Strategy Index

**ASn =** Frequency of farmers rating adaptation strategy as having no importance

**ASl =** Frequency of farmers rating adaptation strategy as having low importance

**ASm =** Frequency of farmers rating adaptation strategy as having moderate importance

**ASh =** Frequency of farmers rating adaptation strategy as having high importance

According to the study, all respondents used at least one or more adaptation strategies to overcome the adverse effects of climate change impacts (Table 2). According to the results, mostly used adaptation strategies were crop rotation (84%); followed by more irrigation (77%), use of drought tolerant crop varieties (57%), mixed cropping (56%) and having trees for shading (53%). Avoidance of flood prone areas (17%), introduction of micro irrigation (15%), use of fertilizer (13%) and building trenches (11%) were the least adopted strategies. It further revealed that respondents combined different adaptation strategies to regulate its negative effects on their cultivation. The variation of adaptation strategies used by the respondents may be due to difference in their socio-economic conditions and available information regarding that strategy.

According to the observations and focus group discussions had with the respondents, it was noted that the crop management strategies used by the respondents in the area were crop rotation, mixed cropping, use of drought tolerant crop varieties, change of planting date, having trees for shading, shifting of harvesting period and planting of cover crops. Even though farmers practice crop rotation as an adaptation strategy to climate change but only a few farmers had a wide knowledge of the benefits of the crop rotation such as increasing soil nutrients, increasing yield, reducing the spread of pest and diseases in the growing season. Respondents used drought tolerant crop varieties like cassava, green gram, cowpea and maize to reduce their vulnerability to climate change in drought prone areas. In addition, some farmers have changed varieties of vegetables with high market demand in place of new hybrid ones that are resistant to drought and pest and diseases. Further the respondents also mentioned that they preferred short term varieties over long term varieties due to less probability to suffer from drought or flood and can get income in short time. It indicates that when selecting vegetable varieties farmers consider not only market advantages but also climate risk.

**Table 2.** Climate change adaptation strategies adopted by respondents

| Adaptation strategy | Frequency | Percentage (%) |
|---|---|---|
| Use drought tolerant crops | 85 | 57 |
| Use organic fertilizer | 19 | 13 |
| Mixed cropping | 84 | 56 |
| Crop rotation | 126 | 84 |
| Change of planting date | 75 | 50 |
| Diversification to non-farm activities | 49 | 33 |
| ? trees for shading | 80 | 53 |
| More irrigation | 115 | 77 |

| | | |
|---|---|---|
| Mulching | 68 | 45 |
| Planting of cover crops | 22 | 15 |
| Shifting harvesting period | 34 | 23 |
| Avoidance of flood prone areas | 26 | 17 |
| Introduce micro irrigation | 23 | 15 |
| Building trenches | 16 | 11 |

(Multiple responses)

**Ranked order of adaptation strategies to climate change (Adaptation Strategy Index)**
The ranking of different adaptation strategies to climate change as ranked by the respondents are presented in Table 3. Out of 14 adaptation strategies, crop rotation ranked the first and thus the most important. Practice of more irrigation was identified as the second-ranked adaptation strategy. This was seen as a viable method to increase the yield of production in places with poor rain and high occurrence of droughts. The third most important adaptation strategy as ranked by the respondents was the use drought tolerant crops. Building trenches and avoidance of flood prone areas were ranked as the least important adaptation strategies by the respondents. This is most likely due to rare occurrence of flood and water logging condition during vegetable production period.

**Table 3.** Ranked order of the adaptation strategies to climate change

| **Adaptation strategy** | **Importance** | | | | **Adaptation strategy index** | **Rank** |
|---|---|---|---|---|---|---|
| | high | Medium | low | no | | |
| Crop rotation | 106 | 39 | 2 | 3 | 398 | 1 |
| Irrigation more | 94 | 37 | 14 | 5 | 370 | 2 |
| Use drought tolerant crops | 81 | 45 | 21 | 3 | 354 | 3 |
| Mixed cropping | 57 | 43 | 23 | 27 | 280 | 4 |
| Mulching | 50 | 49 | 28 | 23 | 276 | 5 |
| Put trees for shading | 52 | 37 | 41 | 20 | 271 | 6 |
| Change of planting date | 51 | 32 | 41 | 26 | 258 | 7 |
| Introduce micro irrigation | 32 | 54 | 29 | 35 | 233 | 8 |
| Diversification to non-farm activities | 43 | 29 | 37 | 41 | 224 | 9 |
| Use organic fertilizer | 27 | 36 | 43 | 44 | 196 | 10 |
| Shifting of harvesting period | 16 | 31 | 63 | 40 | 173 | 11 |
| Planting of cover crops | 19 | 16 | 53 | 62 | 142 | 12 |
| Building trenches | 16 | 16 | 19 | 99 | 99 | 13 |
| Avoidance of flood prone areas | 15 | 11 | 17 | 107 | 84 | 14 |

**Adaptation strategies categorization using weighted principle component analysis (WPCA)**
The weighted principal component analysis method was used to categorize similar adaptation strategies in this study. To make sure the indicators are standardized, suitable variables were chosen first. For this research, the extracting from the first component of PCA was used as the weights for the variables. The weighted value for each variable varied between -1 and +1 and their sign (+ or -) of the variables indicate the direction of relationship with other variables used to create the respective index. Finally, an adoption Index for each farmer was calculated.

From the weighted principle component analysis, different principal components were extracted across all the climate variability stresses as presented in Table 4. Accordingly, five climate adaptation categories were identified namely; crop diversification, changing crop calendar, soil and water conservation, flood prevention and irrigation.

**Table 4.** Climate adaptation categories according to the results of PCA

**Component Matrix[a]**

| Adaptation Strategy Used | Rotated Component 1 | 2 | 3 | 4 | 5 | Categorization |
|---|---|---|---|---|---|---|
| Use drought tolerant crop varieties | | 0.703 | | | | Crop Diversification |
| Mixed cropping | | 0.611 | | | | |
| Crop rotation | | 0.662 | | | | |
| Change of planting date | | | 0.566 | | | Changing crop calendar |
| Shifting harvesting period | | | 0.635 | | | |
| Mulching | 0.703 | | | | | Soil and water conservation |
| Planting of cover crops | 0.870 | | | | | |
| Use organic fertilizer | 0.560 | | | | | |
| Put trees for shading | 0.603 | | | | | |
| Avoidance flood prone areas | | | | 0.649 | | Flood prevention |
| Building trenches | | | | 0.797 | | |
| Irrigation more | | | | | 0.605 | Irrigation |
| Introduce micro irrigation | | | | | 0.681 | |

Extraction Method: Principal Component Analysis.

**Econometric estimation of factors influencing smallholder vegetable farmers' adaptation to climate change**

Multiple Linear Regression model was used to identify the factors affecting smallholder vegetable farmers' adaptation to climate change. The contingency coefficient test was used first, to check collinearity among the independent variables. No correlation was diagnosed between the independent variables used in this study. Then, multiple linear regression model was employed to determine the factors that influence smallholder vegetable farmers' choice of adaptation strategy to climate change effects with 14 explanatory variables. From the Multiple linear regression model, variables that are significant at less than or equal to 10% significance level are discussed as follows.

**Gender of farmer**: This variable significantly and positively affected use of soil and water conservation measures and use of irrigation practices as adaptation strategies. This implies that adoption of these strategies was more followed by male respondents than the female respondents [13] also found similar results.

**Age of farmer:** The results show that age of farmer was positively and significantly ($p<0.05$) influence the of choice of crop diversification and soil and water conservation practices. It also revealed that the use of flood prevention strategy to minimize negative impacts of climate change has positive and significant ($p>0.1$) relationship with age of the farmers. This implies that for every additional year in age of the household head, the probability of adapting to crop diversification and soil and water conservation is increased with compared to adopting changing crop calendar, irrigation and off farm activities.

**Marital status:** Marital status of respondents increases the probability of choosing irrigation practices against climate change impacts at 0.05 significance level ($p<0.05$).

**Household size:** The finding of the regression model was negatively and significantly ($p<0.1$) related to the use of off-farm activities as an adaptation strategy. This implies that with the increasing size of the family, the probability of farmers' adoption of off farm activities decreases. It can be assumed that large family size is able to take up various adaptation strategies than small family size which are labor intensive.

**Employment:** This positively and significantly ($p<0.1$) influenced farmers' decision to adapt to off farm activities. This implies that being a full-time farmer increases the probability of adopting off farm activities. Because full time vegetable farmers who had already suffered from adverse effects of climate change, would have no motivation to on farm adaptation strategy.

**Years of farming experience:** The coefficient of farming experience was significantly ($p<0.05$) and positively related to adoption of climate change adaptation measures using irrigation practices. The number of years one has spent in farming gives an indication of the practical knowledge he/she has acquired. Therefore, it could be assumed that highly experienced farmers tend to have more skills and knowledge in overcoming negative impacts of climate change.

**Distance to input market:** This variable significantly ($p<0.05$) and negatively affect the use of soil and water conservation techniques. This could be due to the fact that better access to markets enables farmers to obtain information on climate change and other important inputs they may need if they are to change their practices to cope with predicted future climate risk [14].

**Land ownership:** The ownership of the land of the responder has positive and significant ($p<0.1$) impacts on the use of crop diversification practices as an adaptation strategy. This implies that if the farmer is the owner of the land there is a possibility of increasing the adoption of crop diversification practices such as the use of drought tolerant crop varieties, mixed cropping and crop rotation.

**Farm income:** The results of the model indicated that farm income has positive and significant ($p<0.05$) impacts on adoption of irrigation practices. This is because when the main source of income in farming increase, farmers tend to apply micro irrigation practices such as drip irrigation and sprinkler irrigation. And also results shows that a negative relationship between farm income and choosing soil and water conservation techniques at 0.1% significance level.

**Contact with agricultural extension:** This positively and significantly ($p<0.1$) influenced farmers' decision to adapt to crop diversification as adaptation to climate change and variability while it has negative and significant ($p<0.05$) relationship with soil and water conservation practices. With increased information on climate change and adaptation techniques, farmers would choose to adapt climate adaptation strategies. As noted by [15] , "extension services provide informal training that helps to unlock the natural talents and inherent enterprising qualities of the farmer, enhancing his ability to understand and evaluate and adopt new production techniques leading to increased farm productivity". According to the study, selected crop diversification practices were use of drought tolerant crop varieties, mixed cropping and crop rotation. This implies that better awareness of these adaptation practices are needed to adopt them. Mulching, planting of cover crops, use organic fertilizer and shade trees were identified as soil and water conservation techniques used by the farmers through the study.

**Organization membership:** Being a member of farmer organization negatively and significantly ($p<0.05$) influence the choice of adopting off farm activities. The possible reason could be that through farmer organization provide information on farming, credits and resources that can be used when adapting to climate change. Education level of the farmer, distance to output market and availability of credit had no significant influence on adaptation to climate change.

**Table 5.** Multiple linear regression estimates for the choice of adaptation strategies

| Variables | Strategy | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Crop diversification | | Soil, water Conservation | | Changing crop calendar | | Flood prevention | | Irrigation practices | | Off farm activities | |
| | Sig. | Coe. | Sig. | Coe. | Sig. | Coe. | Sig. | Coe. | Sig. | Coe. | Sig. | Coe. |
| Gender | 0.49 | -0.063 | 0.034 | 0.181 | 0.75 | -0.029 | 0.83 | 0.02 | 0.085 | 0.149 | 0.32 | 0.091 |
| Age of farmer | 0.01* | 0.296 | 0.044 | 0.217 | 0.93 | 0.01 | 0.09 | 0.196 | 0.395 | 0.092 | 0.528 | -0.072 |
| Marital status | 0.84 | -0.018 | 0.311 | 0.083 | 0.38 | 0.078 | 0.50 | -0.059 | 0.043 | -0.169 | 0.91 | 0.01 |
| Household size | 0.29 | 0.097 | 0.661 | -0.038 | 0.87 | 0.015 | 0.46 | 0.069 | 0.91 | -0.01 | 0.062 | -0.172 |
| Education level | 0.15 | 0.13 | 0.615 | 0.042 | 0.46 | 0.068 | 0.54 | -0.056 | 0.659 | -0.038 | 0.237 | 0.107 |
| Employment | 0.80 | 0.024 | 0.102 | -0.15 | 0.43 | -0.08 | 0.21 | -0.126 | 0.892 | 0.013 | 0.067 | 0.181 |
| Experience of farmers | 0.36 | -0.106 | 0.279 | -0.117 | 0.72 | -0.043 | 0.45 | -0.088 | 0.045* | -0.221 | 0.904 | 0.014 |
| Distance to input market | 0.589 | 0.16 | 0.039** | -0.569 | 0.404 | -0.254 | 0.889 | 0.042 | 0.728 | -0.097 | 0.338 | 0.281 |
| Distance to output market | 0.227 | -0.132 | 0.662 | -0.044 | 0.124 | -0.173 | 0.345 | -0.105 | 0.678 | -0.043 | 0.289 | -0.115 |
| Land ownership | 0.04* | 0.18 | 0.414 | -0.073 | 0.95 | 0.006 | 0.11 | 0.154 | 0.692 | -0.036 | 0.608 | -0.049 |
| Farm income | 0.10 | 0.146 | 0.067 | -0.154 | 0.33 | -0.089 | 0.83 | 0.02 | 0.048** | 0.169 | 0.81 | 0.021 |
| Extension contact | 0.09* | 0.158 | 0.002** | -0.278 | 0.787 | 0.026 | 0.664 | -0.042 | 0 | 0.373 | 0.8 | -0.024 |
| Organization membership | 0.264 | 0.108 | 0.314 | 0.09 | 0.215 | 0.123 | 0.198 | -0.127 | 0.117 | -0.142 | 0.005** | -0.275 |
| Getting credit | 0.544 | 0.053 | 0.128 | -0.123 | 0.466 | -0.065 | 0.716 | 0.032 | 0.881 | 0.012 | 0.999 | 0 |

***, **= significant at 10%, 5% significant level, respectively**

**Abbreviations: Sig: Significance Coe: coefficient**

## Constraints to adopting climate smart agricultural practices

To identify limitations for adopting climate smart agricultural practices Problem Confrontation Index (PCI) was used. This has been widely used in similar studies to identify and investigate factors that hinder or constrain adoption practice [11], [16-17]. The respondents were asked to rate their perception of each constraint on a four-point Likert scale ranging from "not a problem" to "highly problematic".

**PCI = Pn × 0 +P1 × 1 + Pm × 2 + Ph × 3**

**PCI =** Problem Confrontation Index
**Pn =** Number of respondents who graded the constraint as no problem
**Pl =** Number of respondents who graded the constraint as low
**Pm =** Number of respondents who graded the constraint as moderate
**Ph =** Number of respondents who graded the constraint as high.

**Table 6.** Ranked of the constraints faced by respondents

| Constraints to adoption | Degree of constraints | | | | PCI | Rank |
|---|---|---|---|---|---|---|
| | High | moderate | Low | no problem | | |
| High cost of farm input | 68 | 66 | 14 | 2 | 350 | 1 |
| Lack of irrigation water | 61 | 42 | 30 | 16 | 297 | 2 |
| Poor awareness of adaptation practices | 45 | 60 | 17 | 28 | 272 | 3 |
| Less profit | 23 | 89 | 17 | 21 | 264 | 4 |
| Limited access to agricultural markets | 28 | 58 | 22 | 42 | 222 | 5 |
| Lack of access to timely weather information | 29 | 41 | 35 | 45 | 204 | 6 |
| Limited access to agricultural extension officers | 27 | 38 | 26 | 59 | 183 | 7 |
| Poor health | 35 | 29 | 19 | 67 | 182 | 8 |
| Inadequate farm labors | 17 | 37 | 36 | 60 | 161 | 9 |
| Lack of access to credit facilities | 20 | 36 | 24 | 70 | 156 | 10 |
| Limited farm size | 14 | 40 | 32 | 64 | 154 | 11 |

Table 6 summarizes the problems identified by respondents which constrain the adoption of climate smart agricultural practices. A ranking of the problems was conducted using a Problem Confrontation Index (PCI) with a PCI value of 350. High cost of farm input was ranked first and seems to be the most critical problem of the respondents in the region studied in terms of adoption of climate change adaptation strategies. Lack of irrigation water was ranked as the second most critical problem faced by the respondents. Poor awareness of adaptation practices, less profit and limited access to agricultural market were ranked the third, fourth and fifth most suffering problems, respectively. Additionally, the respondents also considered lack of timely weather information, limited access to agricultural extension officers and poor health as moderate constraints, while inadequate farm labors, lack of access to credit facilities as and limited farm size were the lowest constraints.

## Conclusions

The results this study show that the majority of the farmers have experienced a change in the climate for the last two decades in terms of extended dry periods and declining rainfall. As a result of that the vegetable production of the area has been severely affected and the farmers have been practicing several adaptation strategies to overcome the negative impacts of climate change for their cultivation. Mostly used adaptation strategies by the farmers were crop rotation, irrigation and use of drought tolerant crop varieties while micro irrigation and use of trenches were the least used adaptation strategies in the area. Choice of an adaptation strategy is affected by various factors such as farmers' gender, age of the farmer, farming experience, income, land ownership, contact with Extension agents and distance to market.

## Recommendation

The study recommends strengthening agricultural extension services, providing irrigation facilities and promoting rural micro-finance institutions to facilitate choosing appropriate adaptation strategies. Moreover, analysis of adaptation practices and constraints at farmer level will help facilitate government policy implementation. Programs on climate adaptation strategies should consider the heterogeneity of the population and develop tailored programs meeting the diverse needs of different population segments. Further, future government policies need to focus on strengthening smallholder farmers' adaptation capacity through providing access to climate related information.

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Include if necessary. If not, you have to indicate this as not applicable.

## Conflict of interest

Authors have declared that no competing interests exist.

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# Sustainable Livelihoods of Agrarian Communities in a Changing Climate:

## A Special Reference to Rice Farmers in the Dry Zone of Sri Lanka

# Sustainable Livelihoods of Agrarian Communities in a Changing Climate: A Special Reference to Rice Farmers in the Dry Zone of Sri Lanka

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## Abstract

This chapter explores agrarian communities' challenges and adaptive strategies, explicitly focusing on rice farmers in the dry zone of Sri Lanka in the face of a changing climate. The chapter uses the Sustainable Livelihood Framework (SLF) as a conceptual lens to highlight the interplay of various livelihood assets, including human, natural, social, financial, and physical assets, in shaping resilience and sustainability. The chapter emphasizes integrating traditional knowledge with modern technological interventions to foster climate resilience. It highlights vital strategies, including community-based adaptation initiatives, integrating local knowledge, capacity building, early warning systems, climate-resilient infrastructure development, livelihood diversification, natural resource management, and implementing finance and crop insurance mechanisms. The chapter also stresses the importance of collaborative efforts involving NGOs, government entities, and private sector institutes in amplifying the impact of these strategies. Drawing on empirical research and case studies, the chapter offers a comprehensive overview of the adaptive measures employed by rice farmers in the dry zone, emphasizing the need for context-specific, integrated, and collaborative approaches. The insights provided serve as a valuable reference for similar agrarian communities worldwide, navigating the challenges of climate change to ensure sustainable livelihoods.

**Keywords:** Climate change, Community-based adaptation, Sustainable Livelihood Framework, Resilience, Sustainability

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## Introduction

Climate, which refers to the typical weather patterns in a particular area over a defined period, significantly influences the characteristics of diverse regions in Sri Lanka [1], [2]. The island is mainly divided into three main climatic zones: the Wet Zone, the Dry Zone, and the Intermediate Zone. The dry zone, which covers about two-thirds of the island, is semi-arid and characterized by seasonal changes. Its distinct features, such as ancient tanks, reflect a rich history in agriculture [3], [4]. The northeast monsoon largely shapes this region's climate, leading to a specific rainy season from October to January and a long dry period from May to September, unlike the more regular rainfall in the Wet Zone [5-8]. In contrast to the semi-arid climate of the dry zone, the wet zone in the southwestern region, the central hill region, and the intermediate zone surrounding the central hills offer different climatic conditions. The dry zone's relatively high temperatures and low humidity contrast with the humid south and west of Sri Lanka. Its tropical mixed evergreen and thorn forests add to the ecological variety [2],[4],[5]. The climate in the dry zone has significantly impacted its farming methods throughout history. Archaeological evidence reveals complex irrigation systems over two thousand years old, showing how people have adapted to the climate there. These ancient systems underscore the area's strong agricultural background and reliance on monsoon rains for successful farming [10],[6]. However, this historically adaptive agricultural system now faces unprecedented challenges due to emerging global climate change patterns.

A noticeable shift towards more extended droughts, inconsistent rainfall, and increased instances of extreme weather, such as droughts and flash floods, marks a deviation from the traditionally reliable monsoon cycles important for farming [12-13]. Unpredictable rainfall affects the planning of agriculture and the region's irrigation water management. The area is also experiencing higher average temperatures than before, influencing its ecosystem, the growth cycles of crops, and the rate at which water evaporates [4]. The frequency and severity of extreme weather events, including unusual flooding and intense droughts, are rising. While floods can provide water, they often harm crops and interrupt agricultural activities. On the other hand, prolonged droughts challenge the availability of water and the survival of crops. These changing climate conditions are becoming more regular, indicating a need to reassess the farming and water management methods that have existed for centuries [11],[14]. This evolving climate scenario disrupts agricultural practices and leads to a range of environmental challenges that further complicate the situation.

Altered rainfall patterns, increased temperatures, and more extreme weather events are causing various environmental issues. Prolonged droughts and unpredictable rainfall have led to water scarcity. This scarcity impacts the agricultural water supply, leads to soil degradation, and reduces biodiversity. Changes in rainfall disrupt the hydrological cycle, affecting surface and groundwater [9]. Climate change also causes soil erosion and nutrient depletion, decreasing agricultural productivity. Elevated temperatures lead to higher evaporation rates, further limiting crop availability. While flash floods temporarily relieve water scarcity, they also cause soil erosion and damage agricultural infrastructure. These challenges, especially significant in a region reliant on agriculture, underline the urgency of addressing climate change in the dry zone [11],[14]. The profound impact of these environmental changes on the dry zone's agricultural sector, particularly rice farming, poses significant challenges to the livelihoods of local communities and the cultural heritage sustained for centuries.

In the dry zone, agriculture, especially rice farming, plays a central role in the communities' social, cultural, and economic aspects. Rice cultivation, a tradition of over two thousand years, is an economic activity and a critical cultural element, involving a significant portion of the population and shaping local customs. This form of agriculture, essential to the region's economy, stimulates associated industries and contributes to about 60% of the country's rice production [10],[15]. Traditional rice farming methods in the dry zone have evolved to match the historical climate patterns. Small Tank Cascade Systems (STCS) have effectively managed water across different seasons. These systems represent crucial adaptations to the region's unique climatic conditions, vital for sustaining rice farming despite climatic changes. However, recent climate shifts are challenging these systems, disturbing the alignment with monsoon cycles, affecting crop yields, and leading to crop failures [11],[14]. The resilience of these farming communities has become more critical than ever as they must adapt and ensure the continued sustainability of rice farming, a practice deeply ingrained in the region's identity. The test of changing climate conditions for these existing rice farming practices introduces further complexities into the cultivation process, emphasizing the critical need for adaptation and resilience.

The interaction between climate change and rice farming in the dry zone of Sri Lanka is intricate. Climate change considerably impacts rice farming, leading to altered planting schedules, greater risk of pests and diseases, and variable water supply. These changes cause unpredictable crop yields, upsetting the farming calendar established over centuries. The inconsistency of rainfall and higher temperatures necessitate changes in agricultural methods, compelling farmers to adjust to these environmental shifts. The once reliable monsoon patterns, essential for timing rice cultivation, now present a challenge [11],[14]. This disturbance extends beyond agricultural concerns, affecting the farming communities' livelihoods, economic security, and cultural and social traditions. Climate change puts rice farming, deeply connected to local customs and societal frameworks, at risk. Additionally, the rising occurrence of extreme weather conditions such as droughts and floods aggravates these issues, damaging crops, decreasing yields, and endangering the region's food security and economic well-being [12-13]. Given these profound impacts, there is an increasing focus on developing sustainable livelihood strategies to help these communities adapt to the ever-changing agricultural landscape.

In response to the challenges climate change poses in agriculture, sustainable livelihoods have become essential for adaptation. This approach aims to increase the resilience and adaptability of farming communities, helping them maintain their livelihoods amid environmental shifts. The sustainable livelihood framework emphasizes diversifying income sources, improving resource access, and effectively managing risks and vulnerabilities. In the dry zone, this involves developing sustainable agricultural practices that are resilient to climate variability and thus capable of preserving the socio-economic and cultural integrity of the region [16-17]. These frameworks promote a comprehensive understanding of the connections between climate, agriculture, and society. Thus, shifting towards adaptive and enhanced agricultural practices grounded in sustainable livelihood principles becomes critical for the future of rice farming in dry zones. It is important to reassess and modify these practices, focusing on short-term solutions and long-term strategies to sustain rice farming under evolving climate conditions. Additionally, integrating these strategies with broader community development initiatives is vital. Further, adapting to climate change-related shifts involves more than just altering farming techniques; it requires a holistic approach that combines sustainable livelihood frameworks with resilient agricultural methods. Therefore, this chapter aims to explore these aspects in depth. It provides an in-depth overview of the effects of climate change on rice farming in the dry zone and the strategies aligned with the sustainable livelihood frameworks to maintain this sector.

## The sustainable livelihood framework (SLF)

The Sustainable Livelihood Framework (SLF) is used as the conceptual framework to explain and quantify the contribution of different types of livelihood assets pertaining to achieving livelihood outcomes since SLF focuses on possibilities, constraints or capability to act in order to escape poverty and vulnerability, which determined by the assets in material non-material terms [18-19].

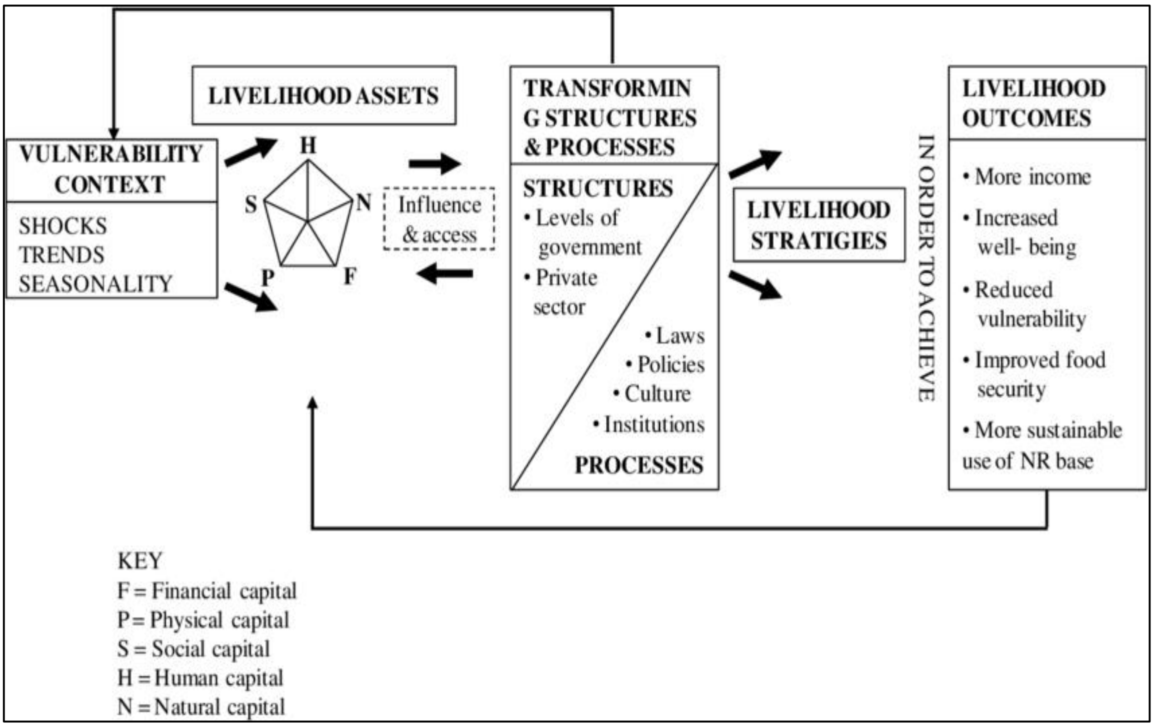


**Figure 1**. Sustainable Livelihood Framework (SLF) (Source: Silva et al., 2004)

## SLF and the Livelihood capitals

The SLF contains livelihood assets assuming their importance in 1) supporting the individuals' ability to escape poverty, 2) balancing the diversity and number of assets, 3) determining livelihood options and 4) transforming the assets into livelihood outcomes. The SLF is composed of five categories, which are presented in a pentagon. The centre point of the figure, where all lines meet, represents zero access to assets, while the outer perimeter represents maximum access to assets. On this basis, different shaped pentagons can drown for different communities or social groups within a community. The rationale behind the selection of these five categories is the belief that people require a range of assets to achieve positive livelihood outcomes. In contrast, the desired outcomes cannot be achieved with a single capital endowment alone [20-21].

I. **Human capital:** Human capital is considered the ability of people to practice specific livelihood strategies. This ability is determined by skills, knowledge, good health, and the ability to labour. At the household level, human capital is a factor in the amount and quality of labour available.

II. **Social capital:** Social capital is defined as having access to social networks and connectedness, which give people the ability to work together with others. Human relationships of trust, reciprocity, and exchange facilitate cooperation and membership of more formalized groups. Social capital can help reduce the 'free rider' problems associated with public goods. An increment in social capital can be effective in improving the management of common resources and the maintenance of shared infrastructure.

III. **Natural capital:** Natural capital signifies the stock of natural resources that people can use. Natural capital varies from public goods such as cleanliness and biodiversity up to private goods like access to land, access to natural resources like water and fertile soil, and access to livestock. Natural capital is significant to those who derive all or part of their livelihood from resource-based activities (farming, fishing, gathering in the forest, mineral extraction). For instance, paddy farmers in Sri Lankan dry zone need much of this natural resource to conduct their occupations.

IV. **Physical capital:** Physical capital consists of the produced goods and services that a human provides. Examples are access to infrastructure such as roads and railways, but also access to shelter or public services like clean drinking water and electricity. Access to these resources is crucial in reaching well-being and prosperity.

V. **Financial capital:** Access to financial resources, such as income and savings (bank deposits or liquid assets such as jewellery and livestock), is an essential element for livelihood development. It can be converted into other types of assets and can be used for the direct achievement of livelihood outcomes.

## Livelihood strategies and outcomes

Livelihood strategies refer to the activities deployed by households to generate a means of living. According to Ellis [22], livelihood activities can be divided into natural resources and non-natural resource-based activities. Natural resource-based activities include the collection of resources from forests, food and non-food cultivation, livestock rearing, and non-farm activities. Non-natural-based activities include rural trade, other rural services (vehicle repair), and rural manufacturing. Livelihood outcomes are the achievements or outputs of livelihood strategies. For instance, more income, increased well-being, reduced vulnerability, improved food security, and more sustainable use of natural resources are these examples.

### Vulnerability context and impact on livelihoods

The vulnerability context can be interpreted as being the external environment. Thus, it has no control over and has a direct impact on an individual's asset status and livelihood outcomes. For a better understanding, the vulnerability context can be further subdivided into three areas: trends, shocks, and seasonality [20]. Table 1 shows some examples of trends, shocks and seasonality.

**Table 1.** The possible vulnerabilities due to the dynamics in the external environment

| | |
|---|---|
| Trends | 1. Population trends<br>2. Resource trends<br>3. National /international economic trends<br>4. Trends in governance (including politics)<br>5. Technological trends |
| Shocks | 1. Human health shocks<br>2. Natural shocks<br>3. Economic shocks<br>4. Conflict<br>5. Crop/livestock health shock |
| Seasonality | 1. Price changes<br>2. Production changes<br>3. Health status change<br>4. Natural resource availability changes |

**How to use SLF for the betterment of communities**

As a fact of evidence, the sound principles of development are reflected by Sustainable Livelihood Development. Such principles are mainly linked to 1) Asset building (financial, natural, human, physical, social); 2) Livelihoods (comprises of assets, capabilities, and activities necessary for means of living); 3) Reducing exposure to shocks and stress and 4) Sustainability enhancement [23]. Against this backdrop, SLF has been helpful in identifying such links. For instance, Dang et al. [24] adopted SLF to analyze the impact of the China Grain for Green Programme (GGP) on the participant's livelihoods in China. Udayakumara and Shrestha [25] employed SLF to explore livelihood impacts due to the construction of *Samanalwewa* Hydroelectricity Reservoir, Sri Lanka. Aberathne et al. [26] applied SLF to investigate the effects of culture-based fishing on the livelihood of two fishing communities in the *Puttalam* district in Sri Lanka. Moreover, UNDP, FAO, and IFAD have used SLF for the purpose mentioned above since the 2000s. Therefore, SLF can be used to monitor the progress of existing climate adaptation regarding the achievement of livelihood outcomes by paddy farmers in the dry zone of Sri Lanka.

## Climate adaptation in paddy farming in the dry zone of Sri Lanka

Agricultural practices and the livelihoods of paddy farmers in the dry zone of Sri Lanka have been profoundly affected by climatic challenges. In particular, these challenges include extended drought periods, erratic rainfall, higher temperatures, and an increased frequency of extreme climatic events [17], [27-29]. These factors, along with the region's low annual precipitation and high evaporation rates, make paddy farming particularly vulnerable to water scarcity [29-30]. This region's paddy farming requires climate adaptation to address water scarcity, optimize planting schedules based on rainfall patterns, and integrate traditional knowledge with modern strategies to ensure sustainability [17],[30]. Climate adaptation in paddy farming involves improving water use efficiency, adjusting cropping schedules, and promoting traditional practices, all of which contribute to boosting resilience against climatic challenges and ensuring sustainable agricultural productivity [30]. Farmers can better navigate climate change in the dry zone through these adaptation measures while maintaining environmentally sustainable practices.

Historically, paddy farmers in the dry zone of Sri Lanka have adapted to harsh climates by employing many traditional practices. Water availability during dry spells has been ensured by ancient tank cascade systems, used for over 2000 years, which collect, store, and distribute rainfall and runoff [11]. Home gardens, which serve as multi-functional land-use systems, are also recognized for their resilience to climate change and contributions to food security [31]. Adaptation has been supported by cultivating indigenous rice varieties that are drought-tolerant, supplemented by introducing other drought-tolerant crops [32]. This integration of ancient knowledge and modern technology has evolved [11]. It has not only strengthened agricultural resilience but also safeguarded livelihoods. Diversification strategies have reduced dependence on paddy alone, ensuring livelihood sustainability amidst climatic uncertainties [17]. It emphasizes how tradition and modernity interact in shaping the adaptive capacities of agrarian communities in dry areas of Sri Lanka.

Paddy farmers in the dry zone of Sri Lanka have adopted a range of modern adaptation strategies in order to sustain their livelihoods. Among these measures are stress-tolerant rice varieties, precision agriculture, efficient water management systems such as drip irrigation, and rainwater harvesting [32]. Furthermore, the restoration and maintenance of traditional irrigation systems, such as village tanks and tank cascade systems, have been crucial to effective water management [11]. Agro-well-based agriculture incorporating agroforestry characteristics offers flexibility in adapting to changing climatic conditions [29]. Agricultural technology and climate science advances have significantly boosted these strategies, giving farmers a better understanding of weather patterns and soil health [11]. To encourage the adoption of climate-resilient practices, government agencies and non-governmental organizations provide extension services, training, agricultural inputs, and financial assistance [33]. Community-based organizations are vital to sharing knowledge and taking collective action as climate-induced challenges grow. These multi-tiered support structures accelerate climate-resilient paddy farming practices in the region.

Several case studies from the dry zone of Sri Lanka shed light on successful adaptation practices among paddy farmers. According to Esham & Garforth [17], smallholder farmers need feasible adaptation approaches, emphasizing the need to mainstream climate change adaptation policies into national development plans. Bebermeier et al. [11] highlight how farmers in the Anuradhapura district utilized traditional water storage systems in combination with modern drip irrigation techniques to enhance water efficiency. In Sri Lanka, traditional and modern practices coexist in harmony, as discussed by Abeywardana et al. [10]. This illustrates the importance of contextualized adaptation strategies recognizing the socio-cultural and historical fabric within which agrarian communities operate [10],[17]. Based on these studies, integrating traditional practices with modern technological interventions may be necessary for effective adaptation in climate-vulnerable regions. With these insights, similar agroecological zones worldwide can develop more effective climate adaptation strategies.

The integration of climate adaptation practices has significantly influenced paddy farming productivity, income levels, and food security in the dry zone of Sri Lanka [28]. Despite adverse climatic conditions, drought-resistant rice varieties and efficient water management, including traditional village tank cascade systems, have enhanced crop yields [11],[27]. Farm income levels have increased, fostering economic stability, although making climate adaptation profitable remains challenging [16]. In addition to improving food security, these strategies have reduced toxic elements in rice and improved public health [34]. These benefits have led to greater resilience to climate change and other external shocks. Enhanced water use efficiency, improved soil health, and diversity of crop varieties have provided farming communities with a more substantial buffer against climate change [17]. In the dry zone of Sri Lanka, climate adaptation practices undeniably contribute to a more sustainable and resilient agricultural landscape.

There are several challenges that paddy farmers face in the dry zone of Sri Lanka when adopting climate adaptation practices. Finance constraints constitute a significant barrier to acquiring modern agricultural technologies and infrastructure for efficient water management and soil conservation [17]. Paddy production in the dry zone is especially vulnerable to water shortages [16]. There is a knowledge gap where farmers may need more information or training to implement new adaptation strategies effectively [35],[36]. Institutional factors, including poverty and marginal land, can complicate adopting climate-smart practices [37]. Developing river basin management projects integrating traditional knowledge, such as the Mahaweli Development Program, can enhance climate adaptation and resilience [30]. The tank cascade systems are resilient to climatic fluctuations and buffer climate change effects in the dry zone [11]. In order to steer paddy farming towards a more resilient path amidst changing climatic conditions, climate-smart agricultural practices such as drought-tolerant crop varieties and water-saving irrigation techniques will be imperative.

Policy interventions grounded in empirical research are necessary to improve climate adaptation in paddy farming in Sri Lanka's dry zone. As one of the recommendations, tank cascade systems should be restored and managed since they have historically been recognized as sustainable measures for watershed management and have been increasingly emphasized for their role in drought and flood mitigation [11],[38]. Furthermore, adjusting rice planting dates can lead to water savings, suggesting that farmers must be guided in optimizing planting schedules [39]. Adopting adaptation practices, such as cultivating drought-tolerant crop varieties and diversifying crops, has been identified as crucial, and thus, policies should promote their adoption [32]. Climate change adaptation should also be incorporated into national agricultural policies, particularly for the dry zones [17]. Traditional knowledge should be merged with technological advancement in analyzing climate adaptation practices to highlight the value of a combined approach. Altogether, in the face of climatic adversity in the dry zone of Sri Lanka, a multi-tiered, collaborative approach, supported by supportive policy frameworks, can significantly accelerate the transition towards more resilient and adaptive paddy farming systems.

## Strategies for enhancing climate resilience in paddy farming

### Community-based adaptation initiatives

Community-based adaptation (CBA) initiatives are essential for building climate resilience at the grassroots level. These initiatives empower communities to identify their unique climate vulnerabilities, develop locally appropriate solutions, and enhance their adaptive capacity. Based on many published CBA frameworks developed to build farmers' climate resilience, here are some key strategies that focus on implementing community-based adaptation initiatives. Eight strategies explained in this section (Figure 2) are directly linked with the social, human, natural, physical, and financial capital of a sustainable livelihood framework.


**Figure 2.** Strategies of community-based adaptation initiatives for building climate resilience of farmers.

## Community engagement and participation

As a community that is regularly dealing with diverse climatic challenges, it is essential to get involved in all stages of adaptation planning and decision-making in order to build a climate-resilient action plan. It facilitates getting an idea about the exact scale of the vulnerability and capacities through their definitions. Through local community understanding, adopting, and applying the various participatory tools and techniques, researchers will be able to build up a more practical climate-resilient action plan for a particular agrarian community. There is much evidence available in other regions of the world that explains the success of such involvement [40-41]. The ultimate objective of enhancing community involvement is to ensure that the diverse voices of vulnerable and marginalized groups are well recognized. Therefore, it is essential to build sustained partnerships among researchers and particularly vulnerable farming communities to build trust and develop contextualized information [42].

## Local knowledge integration

Every community is comprised of different values, beliefs, identities, goals, and social networks, which directly outline perceptions and actions on building the climate resilience of the farming community. Also, it is reported that indigenous peoples' holistic view of community and the environment is a significant resource for adapting to climate change [43]. Therefore, any engagement processes that ignore the socio-cultural context within which stakeholders are embedded may fail to guide adaptive responses. Therefore, taking insights from traditional agricultural technologies when developing policies will ensure long-term sustainability. Hence, it is mandatory to integrate indigenous knowledge into community-based adaptation initiatives.

The dry zone of Sri Lanka also has a unique paddy farming culture, which comprises many specific agricultural practices that are orally transmitted from generation to generation. For instance, the village tank system is well-designed to address the issue that arises due to water shortages, which are very common in the dry zone of the country. Also, *Bethma* and dry seed farming (*Kakulam govithena*) are the best adaptation strategies in traditional agriculture.

However, later on, most of the policymakers and administrative parties neglected the indigenous practices and prioritized the popularizing of only modern agricultural activities with the expectation of rapid agricultural development in the area. However, that could be the leading cause of the existing poor climate resilience of paddy farmers in the dry areas of the zone, even though many projects were introduced in the last decades. Therefore, when developing such action plans in Sri Lanka to uplift the paddy farmers' resilience, it is better to integrate local knowledge. Through the integration of indigenous knowledge into the planning of community-based adaptation initiatives, social and human capital is strengthened in order to achieve climate resilience for agriculture.

### Capacity building

Rural communities are the most vulnerable to adverse climatic conditions [44]. The need for more access to modern technology and knowledge sources like formal or informal education and training further aggravates this. Universities and research stations have a more significant role to play in this regard by extending their support to strengthen climate resilience. This can include training programs/ farmer school programs on climate-resilient agricultural practices, disaster risk reduction techniques, and livelihood diversification skills [45]. Further facilitating knowledge sharing and learning among communities, encouraging them to exchange experiences and best practices with neighbouring communities and regions, will also be beneficial.

### Early warning systems

The establishment and strengthening of early warning systems is essential to provide communities with timely information about impending climate-related hazards, such as floods, droughts, or storms [46]. This system enables the farmers to take the necessary agricultural management practices at proper periods based on the weather pattern. Also, this helps farmers prepare early for extreme weather conditions and avoid unnecessary agricultural losses and damage.

However, this type of technological improvement may not be successful in the actual farmer's field conditions at initial levels, as farmers are not very familiar with such conditions. However, this can be solved by linking the indigenous and modern knowledge systems. Dry zone paddy farmers have their weather forecasting approach through understanding the natural signs. For instance, if weaver birds build their nests at higher levels of trees, farmers expect significant rainfall, and the tank water level will be high. Suppose farmers can be convinced by matching the indications of the early warning system and natural signals. In that case, it will facilitate the proper utilization of this kind of advanced technological improvement by rural farmers.

### Climate-resilient infrastructure

Technological innovation is essential in climate-proofing national and community-level infrastructure [45]. Invest in climate-resilient infrastructure, such as flood defences, rainwater harvesting systems, and drought-resistant crop varieties, to enhance the community's ability to withstand climate impacts. The well-established climate-resilient infrastructure in the dry zone of Sri Lanka is rainwater harvesting through the construction of water tanks as an adaptation strategy to conserve excess water for dry periods. However, many of these tanks are now depleted due to the sedimentation. Therefore, it is essential to establish proper maintenance procedures as we had in a traditional community (*Pangukariya*). It is reported in Bangladesh that bamboo structures are utilized to prevent riverbank erosion, while in Nepal, we also have different rainwater harvesting methods.

### Livelihood diversification

Livelihood diversification has long been used and promoted as a strategy for increasing incomes and managing and diversifying risk among poor and vulnerable households (45). This can be achieved either through changing agricultural practices as per changing weather patterns or diversifying the number of income generation methods. As experts predict, dryer areas will become dryer, and the agriculture sector will be affected severely due to climate change [47]. In such conditions, farmers can change livelihood patterns by cultivating drought-resistant paddy varieties instead of regular varieties or applying modified moisture conservation practices. Similarly, the weather forecast predicts that water availability for irrigation will be inadequate. In that case, farmers may cultivate other field crops such as Mungbean (*Vigna radiata*), Blackgram (*Vigna mungo*), and Soybean (*Glycine max*), which can be managed with minimum water quantities. This was practiced only in several areas in the dry zone, with the majority of the farmers trying hard to continue cultivation with existing water availability or giving up paddy cultivation. Therefore, through proper extension services, farmers should be aware of diversification strategies that can be applied to build climate resilience.

The second method of livelihood diversification is to focus more on secondary income generation methods, such as seeking labour opportunities and engaging with other livelihood pathways. This will further link to investments and human capital, including education, health and job growth [48]. However, more than livelihood diversification is needed to build the climate resilience of farmers, and if it does not happen properly, it can even increase their vulnerability [49].

### Natural resource management

Human activities are exacerbating natural changes in the climate [43]. Farmers must adjust strategies for the new weather conditions repeating for several subsequent seasons to sustain crop production under the climate change scenario. In water-stressed areas and for resource-poor farmers, resilient rice production systems involving better crop establishment methods, improved water, weed and nutrient management practices, and utilization of microbial resources have been found to be very successful [50].

### Finance and crop insurance

Providing microfinance in the agricultural sector is one of the critical strategies for building climate resilience among farmers. It has more significant potential to strengthen the small-scale farmers who are responsible for global agricultural production to a greater extent. The role of micro-finance in improving livelihood assets is threefold [51].

a) Direct income effects
b) Indirect income effects (i.e., education and training)
c) Non-pecuniary effects (i.e., more robust social networks and increased confidence)

However, most financial resources for climate actions come from public sectors and are used for large-scale mitigation actions. Microfinance bundled with insurance can be another good adaptation measure [51]. When considering the Sri Lankan context, a public sector entity is offering farmer insurance services for paddy rice, maize, and livestock. In total, during the year 2012, the Agricultural and Agrarian Insurance Board (AAIB) provided LKR100 million (approximately US$740,000) in compensation to farming families affected by droughts and floods [52].

**Potential collaborations: Role of NGOs, governments, and international bodies**

Both state and non-state entities have a dual role in shaping responses to climate change. On the one hand, they experience the tangible effects of climate change as both institutions and individuals. On the other hand, they serve as catalysts for change. These entities engage with one another within specific socio-economic and political contexts, identifying and prioritizing key concerns, devising strategies, collaborating with internal and external stakeholders, mobilizing resources, and ultimately designing and implementing climate response initiatives. Effective coordination among various levels of government, community-based organizations, domestic and international non-governmental organizations (NGOs), international development partners, scholars (including academics), the media, and the private sector is essential for achieving improved outcomes.

In the context of Sri Lanka, national non-governmental organizations (NGOs) like Practical Action and *Janathakshan Ltd* collaborate with government agencies to provide support in terms of financing, training, and the adoption of Climate-Smart Agriculture (CSA) practices within farming communities across various agricultural systems. It is worth noting that there is currently no systematic and all-encompassing insurance or loan program in place for farmers, as highlighted by the World Bank in 2015.

The UN International Fund for Agricultural Development (IFAD), Food and Agriculture Organization (FAO), Oxfam, and other institutions provide support for the agricultural sector. Several international and national institutions, such as the UN Development Programme (UNDP), USAID Development Grants Program (USAID GDP), Japan International Cooperation Agency (JICA), and the Nordic Development Fund (NDF), provide support for the agricultural sector in general [52].

**Policy recommendations and support mechanisms**

In developing policy recommendations and support mechanisms for sustainable livelihoods in the context of climate change, it is essential to integrate the principles of the Soil Conservation Act (Chapter 450) with the unique needs of rice farmers in the dry zone of Sri Lanka. This integration should focus on promoting soil health through a blend of short-term and long-term strategies, including tillage, erosion control, surface protection, efficient irrigation, nutrient management, soil amelioration, and biological manipulation. These practices are crucial for enhancing crop resilience against climate-induced stresses such as drought, inundation, and salinity. The dynamic nature of climate change necessitates adaptive management of these soil conservation measures. It is essential to understand individual capacities and expected soil utilization returns, aligning public interests with individual stakeholder capabilities. This includes farm infrastructure, natural resources, and environmental considerations. The Sustainable Livelihood Assessment Framework (SLFA) plays a critical role in this context. Policymakers and practitioners should employ the SLFA to design and evaluate soil management practices at an individual level, allowing for the customization of soil conservation strategies to meet the specific needs of rice farmers in the dry zone.

Furthermore, the National Adaptation Plan for Climate Change (NAPCC) 2016-2025, with its comprehensive plan to safeguard the vulnerable agriculture sector, must be implemented effectively. This requires commitment and competency from agrarian communities and agricultural institutes. However, disparities among individuals and communities can hinder the implementation of adaptive measures, especially when they require investment or initiation without additional support from government agencies. To address this, supportive activities, such as the recently initiated Agriculture Sector Modernization Plan, should be implemented. These activities should be closely linked with the SLFA to capture the capacities and strengths of individuals, serving as a benchmark for decision-making regarding climate change impact mitigation.

Finally, ensuring the effectiveness of climate policy requires alignment with other critical sectoral policies, including energy, infrastructure, industry, agriculture, natural resources, health, and environmental considerations. Policies, strategies, and mechanisms should be formulated and enhanced to achieve coherence across sustainable development, economic growth, food security, public health and safety, climate change adaptation and mitigation, environmental stewardship, and disaster risk reduction objectives. This holistic approach will ensure that policy recommendations and support mechanisms are comprehensive, practical, and tailored to the specific needs of rice farmers in Sri Lanka's dry zone.

***Case Study 01: FAO's Save and Grow Project in Sri Lanka 2019-2022***

In response to the challenges posed by climate change in Sri Lanka's dry zones, where erratic rainfall and prolonged dry spells historically affect rice cultivation, the vulnerability of dry zone rice cultivation to climate change is evident due to its heavy reliance on abundant water resources. The FAO's Save and Grow project in Sri Lanka was a crucial initiative aimed at supporting the transition to more productive and resilient smallholder farm systems while simultaneously reducing greenhouse gas emissions in rice production.

The project was operated from 2019 to 2022 and was executed by the Food and Agriculture Organization (FAO) with the generous support of Germany's Federal Ministry of Food and Agriculture. Over this timeframe, the project effectively trained more than 1,130 farmers and service providers in six villages within the Anuradhapura district. Notably, one of these villages, known as the "CSA village," rigorously followed climate-smart agricultural practices. It served as a live demonstration for researchers, and insights gained were integrated into subsequent training programs. Ongoing monitoring enabled adaptive management and refinements to agronomic procedures.

Recognizing the need for modernization and mechanization, the project procured agricultural machinery, rigorously tested it under local conditions and made it readily available to farmers. Collaborative efforts between the government and small entrepreneurs during this period enabled farmers to gain improved access to sustainable production inputs, output markets, and essential services. This collaboration empowered farmers to sell higher-quality produce on stable markets at better prices, strengthening their economic resilience. As per information from the Rice Research and Development Institute, the implementation of novel water management techniques allowed farmers to decrease the overall irrigation demands for rice farming by 10 to 20 per cent. Consequently, this enabled them to reserve water for upcoming crop seasons. Additionally, they initiated land preparation early in the rainy season, optimizing land use. During the dry season, beneficiaries expanded their irrigated land by 15 per cent through training in the alternate wetting and drying technique, conserving water during the primary growing season. The community experienced its highest water capacity on record at the end of the dry season, attributed to practices such as early planting, rainwater utilization, and the alternate wetting and drying technique. Furthermore, by employing soil testing kits and leaf colour charts and applying fertilizer precisely to parachute trays, farmers reduced fertilizer usage by 27 per cent. These outcomes signify not only improved resource efficiency but also increased crop yields and sustainability, benefitting both the farming community and the environment.

Mr. P. Sisilarathna, a dedicated father of three, assumes the vital role of being the sole provider for his family, comprising eight members residing in Meegassegama village. Mr Sisilarathna actively engaged in the training provided by this project and subsequently implemented the acquired practices within his agricultural endeavours. The introduction of these novel agronomic techniques has resulted in commendable enhancements in crop yields while concurrently achieving notable reductions in resource inputs, encompassing seed paddy, fertilizer, agrochemicals, labour utilization, and water requirements.

The success of this project can be attributed to a combination of factors, including robust collaboration between government agencies, research institutions, and the local community. The training and capacity-building efforts targeted at farmers were instrumental in the adoption of climate-smart practices. Moreover, the project's provision of resources, such as agricultural machinery and sustainable inputs, played a pivotal role. The innovative water management and farming techniques introduced empowered farmers to optimize resource usage, while precise agricultural practices further reduced the environmental footprint [53-54].

***Case Study 02: Climate-smart practices for intensive rice-based systems in Bangladesh (2016-2018)***

Bangladesh, with its geographical location in the tropics, extensive floodplains, low elevation above sea level, dense population, and limited economic and technological resources, is considered one of the most vulnerable nations to the impacts of climate change [55-58]. As a result, climate change has significantly and persistently affected crop production in Bangladesh, an economy heavily reliant on agriculture [59].

Bangladesh, as a rice-producing nation where traditional rice production techniques were water-intensive, relies on continuous standing water irrigation. This practice significantly increased the cost of cultivation and greenhouse gas (GHG) emissions. Rice cultivation was responsible for approximately 25% of total estimated methane emissions in Bangladesh, making it the third-largest methane source after domestic wastewater and livestock. The significant challenges included high water usage, the cost of electricity or diesel pumps, and environmental impacts due to emissions [60].

To address the issue mentioned above, the Asian Development Bank collaborated with the International Rice Research Institute to implement a climate-smart rice cultivation approach in Bangladesh. This approach mainly involved the use of alternate wetting and drying (AWD) technology and a new rice variety, BRRI Dhan 75, to showcase the benefits of climate-smart farming practices. The project validated several climate-smart agricultural (CSA) practices in farmers' fields, including mechanized AWD technology for rice cultivation, rice varieties suitable for AWD, and diversified rice-based cropping systems with high-value crops.

A pilot project was initiated in the Korerhat and Nurpur areas of Bangladesh. In the transplanted aman season (November-December), BRRI Dhan 75 was introduced. Subsequently, an off-season mustard variety (BARI Sorisa 14) was cultivated before planting another rice variety (BRRI Dhan 28) in the following boro season (April-May). The on-farm participatory project covered a total of 30 hectares (15 hectares in each village) and involved training 474 participants, including extension workers and farmers, through five organized training programs from 2016 to 2017. Training focused on technology utilization, the environmental impact of agricultural practices, environmentally friendly rice seed processing and preservation, benefits of AWD irrigation over continuous standing-water methods, GHG emission reduction during rice cultivation, enhanced benefits from climate-smart cropping, and AWD implementation with an emphasis on irrigation scheduling.

The project in Bangladesh received technical support from IRRI and BRRI in the Gazipur district, with financial assistance from the Asian Development Bank in the Muhuri Irrigation Project area. Collaboration also occurred with the Ministry of Agriculture, BWDB, DAE, and BARI, along with support from the Bangladesh Agricultural Research Council and the Muhuri Irrigation Project. The private sector contributed to improvements in machinery.

The adoption of climate-smart practices resulted in a 52% to 61% increase in farmers' income in these areas. AWD technology consumes approximately 22% less water compared to continuous standing water irrigation. Depending on rice varieties and seasons, GHG emissions were reduced by 13% to 41% under AWD compared to continuous standing water, with the most significant reduction occurring during the *boro* season. Among rice varieties, BRRI Dhan 75 exhibited the lowest GHG emissions at 44 kg/ha, while BRRI Dhan 11 had the highest emissions at 50 kg/ha. Additionally, the yield of the new BRRI Dhan 75 variety was 20% higher at 5.11 t/ha compared to the regular varieties used by farmers during the transplanted *aman* season (BRRI Dhan 11 and BRRI Dhan 49), which yielded 4.26 t/ha.

Based on the experience gained throughout the project, several essential requirements have been identified for the scaling up of climate-smart agricultural technologies in Bangladesh. These requirements include the need to invest in the development, validation, and widespread dissemination of suitable climate-smart agricultural technologies. Additionally, conducting surveys and generating evidence regarding the adoption and impact of these technologies is crucial for informed decision-making. To support these efforts, it is essential to establish knowledge management support and information-sharing platforms that facilitate the exchange of valuable insights and best practices. Providing farmers with the necessary support and incentives for adopting climate-smart agricultural technologies is another critical aspect of this initiative. Moreover, ensuring access to high-quality seeds and efficient seed multiplication processes will play a pivotal role in enhancing agricultural productivity and resilience. Linking farmers and farmers' groups to rice and grain value chains is essential to creating sustainable market opportunities. Lastly, a comprehensive review of government policies and priorities is needed to align activities and promote the widespread adoption of climate-smart agricultural practices in the region. These collective measures aim to foster a more sustainable and climate-resilient agricultural sector in Bangladesh [55].

In conclusion, the insights gleaned from the successful climate-smart rice cultivation project in Bangladesh provide a valuable blueprint for the enhancement of rice farming practices within the Sri Lankan dry zone.

## Conclusion

In the context of a rapidly changing climate, the agrarian communities, particularly the rice farmers in the dry zone of Sri Lanka, face multifaceted challenges that threaten their sustainable livelihoods. With its unique climatic and historical significance, the dry zone has been a cornerstone for rice production, contributing significantly to the nation's food security. The Sustainable Livelihood Framework (SLF) offers a comprehensive lens to understand the interplay of various livelihood assets and their role in achieving positive outcomes. The integration of traditional practices with modern technological interventions, as evidenced by the coexistence of ancient tank cascade systems with contemporary irrigation techniques, underscores the importance of a holistic approach to climate adaptation. Community-based adaptation initiatives incorporating local knowledge, capacity building, and early warning systems emerge as pivotal strategies. Furthermore, the role of finance, especially microfinance and crop insurance, is paramount in sustaining resilience. Collaborative efforts involving NGOs, government bodies, and international organizations can strengthen the impact of these strategies. As the world struggles with the impacts of climate change, the experiences and adaptive strategies of the rice farmers in the dry zone of Sri Lanka offer invaluable insights. These lessons, rooted in tradition and modernity, can guide similar agrarian communities in similar regions, emphasizing the need for context-specific, integrated, and collaborative approaches to ensure sustainable livelihoods in the face of climatic adversities.


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## Competing interest

Authors declare that they have no any competing interest.


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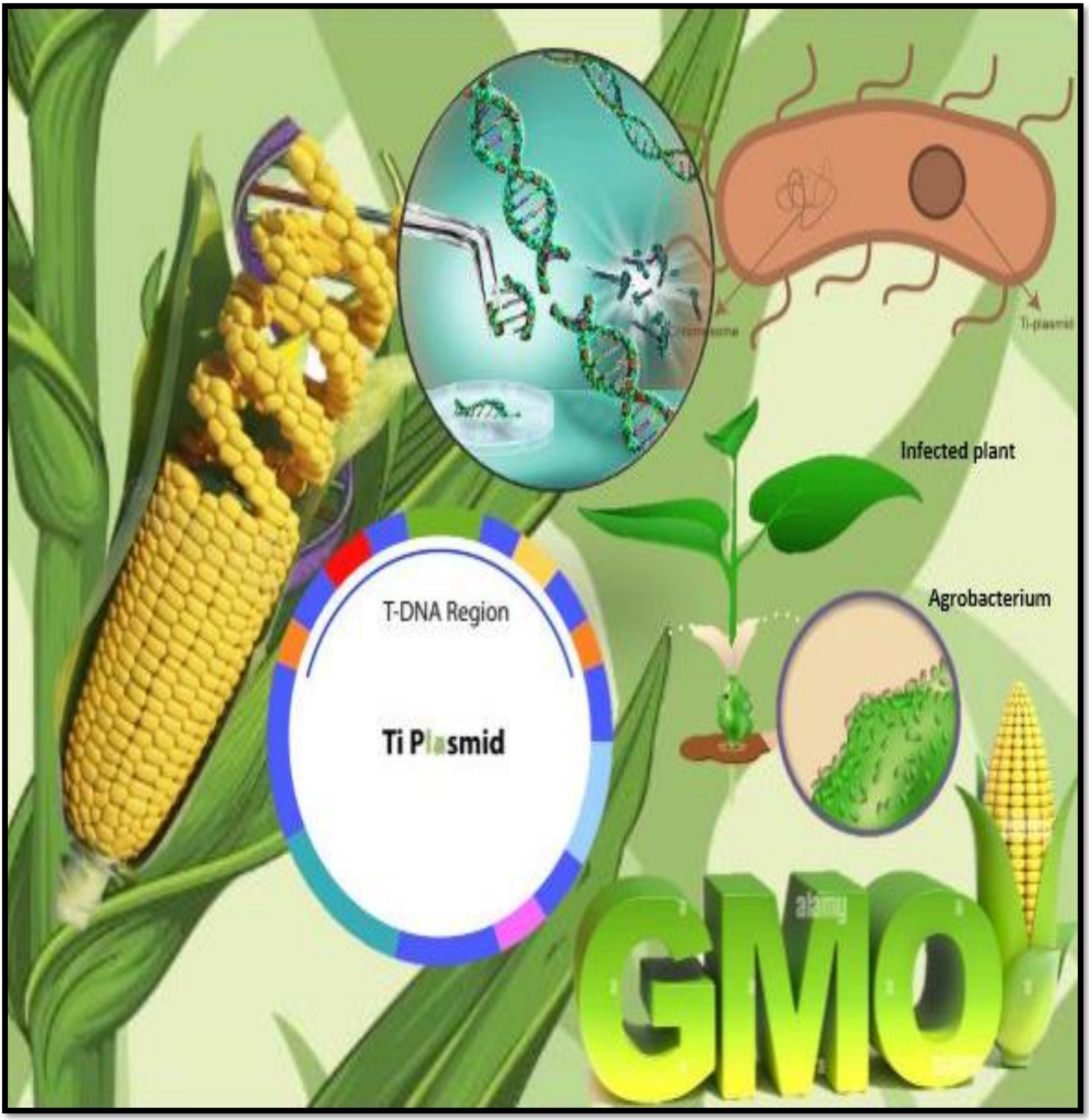
# Prospects and Challenges in *Agrobacterium* Mediated Genetic Transformation of Maize to Tackle Climate Change; Sri Lankan Perspective



# Prospects and challenges in *Agrobacterium* mediated genetic transformation of maize to tackle climate change; Sri Lankan perspective

M.N.F. Nashath, A.N.M. Mubarak*, A.D.N.T. Kumara

**Abstract**

An efficient plant transformation technique is considered as an essential requirement in developing genetically modified (GM) maize plants that can encounter a wide range of biotic and abiotic stresses caused by climate changes. Compared to different plant transformation methods, *Agrobacterium*-mediated transformation is perceived to be cheap, simple, and has stable gene integration with minimum rearrangements. Accordingly, this method serves as the best option for developing countries in the continents of Asia and Africa. In light of these, *Agrobacterium*-mediated gene delivery into maize has been constantly improved, making it as a foremost technology not only in genetic engineering but also in genome editing over the past decades. This can be further enhanced by practicing advanced and novel techniques during the transformation procedure. *Agrobacterium*-mediated transformation of maize plants and the subsequent recovery are affected by several factors including maize genotypes, explant types, bacterial strains, vector systems, and co-cultivation medium. Ensuring optimal conditions would increase efficiency and effectivity of the transformation procedure. Moreover, as a developing nation, biosafety regulations in Sri Lanka are evolving to keep pace with advancements in biotechnology and international standards. However, Sri Lanka face multiple challenges in implementing the guidelines and policies. Addressing these challenges are crucial not only for protecting the environment and public health, but also for promoting innovation, trade, transparency, and trust. Though some of the farmers are cultivating traditional maize varieties in Sri Lanka, majority of the farmers cultivate imported hybrid varieties. Hence, by performing efficient gene transformation technique, traditional maize varieties can be improved to have high yield, tolerant to climatic changes and resistant to pest and disease.

**Keywords:** *Agrobacterium,* bacterial strain, GM maize, plant transformation*, Zea mays* L.

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## Introduction

Maize (*Zea mays* L.), one of most salient cereal crops, is globally grown with broad applications, including human consumption, animal feed preparations, bio-fuel formulations, chemical applications, and medicinal purposes. It is the second most cultivated cereal crop in Sri Lanka, and occupies 5.6 % of the total cereal cultivation area [1]. During *Maha* season, it is frequently cultivated in dry and intermediate zones of the country as rain-fed cultivation [2]. In Sri Lanka maize is mainly utilized in poultry industry and for the production of Samaposha/Triposha.

Though the maize production increases throughout the country, it is not sufficient enough to meet the domestic requirement and larger portion of maize is yet imported from other countries [3]. This might be due to poor quality inputs mainly of seeds used in cultivation and associated adverse climate and soil conditions. In sometimes, regardless of quality of inputs used, stresses either biotic or abiotic also adversely affect plant growth and development. Even though, number of management practices are applied by farmers desired level of expectation is not met for requirement thus arises the necessity for other alternatives in which cultivation of tolerant/resistant varieties with higher yield receives much attention through breeding and genetic improvement options. Hybrid maize varieties contribute 95 % of total cultivation and since country's hybrid seed production does not attain self-sufficiency and gap prevails, about 1200 MT of maize seeds are imported annually to assure maize production (Ministry of Agriculture). Hence, the imported hybrids seeds are high in cost and not affordable to poor farmers and also the landraces which is being cultivated by local farmers from eastern regions exhibit comparatively better performance than the existing commercial varieties. In accordance with recent data, 819 maize accessions are stored in Plant Genetic and Resource Centre, Gannoruwa in Sri Lanka, and 35 of them are landraces [4].

The growth and yield of maize plants have been significantly reduced as a result of climate change effects risking the food security all over the world [5]. Maize, a staple crop for billions of people around the world, is extremely sensitive to temperature and precipitation patterns, making it highly vulnerable to the effects of changing climate. Rising temperatures can cause an array of issues for maize farmers. Extreme heat, for example, during the flowering stage can cause poor pollination and reduced kernel formation, resulting in poorer yields [6]. Furthermore, constant high temperatures can worsen water stress, making it more difficult for maize plants to acquire moisture required for optimal growth. Zhao *et al*. [7] conducted an experiment to investigate the influence of climate change on main crop yields and discovered significant production losses of 6 %, 3.2 %, 3.1 %, and 7.4% in wheat, rice, soybean, and maize, respectively. According to Schlenker and Roberts [8], maize yield increased at an ideal temperature of 29$^{o}$C, but it decreased as the temperature rose further. Similarly, it was discovered that for every 1$^{o}$C increase in temperature over the optimal development temperature, maize yield reduced by 8.3% [9]. İncrease in pest and disease attack is another critical impact of the climate change. This alarming situation pose a serious threat to Sri Lankan maize production. Hence, climate change adaptation measures are critical for mitigating the effects of maize agriculture. These may include the development of heat-tolerant maize varieties, improved irrigation and soil management practices, and the application of climate-resilient farming strategies.

## Genetic engineering of maize plant

Even though various conventional methods, including introduction, selection and hybridization are practiced for maize crop improvement, these traditional methods are laborious, time and space consuming and developing critical agronomic traits in heterotic groups is difficult due to their incompatibility [10]. Genetic engineering/ modification has been a successful molecular technique that is extensively utilized in improving various traits such as tolarence to herbicide and resistance to insects in different crops [11]. İt is considered to be the fastest adopted crop technology in recent times. The development of transgenic crops is regarded as a crucial solution to a number of climate change-related challenges, as its commercialization is known to contribute to a reduction in global $CO_2$ emissions [12]. They are intended to adapt to ever-changing environmental variables, such as temperature and rainfall fluctuations, as well as increased insect infestations.

International Services for the Acquisition of Agri-Biotech Applications has reported that based on the present pattern, it is anticipated that the adoption rate of GM crops with biotech traits will continue to rise, especially in developing nations. Large and small scale farmers in developed and under-developed nations that have produced transgenic crops commercially have reaped enormous multiple advantages, as seen by the historically quick adoption of transgenic crops over the early five years from 1996 to 2000. The worldwide extent of genetically enigneered crops accelerated by more than 25 times between 1996 and 2000, owing to the contributions of a total of fifteen nations, 10 industrial and 5 developing [13]. The worldwide distribution of transgenic crops was estimated as 44.2 million heactares in 2000 and 1.7 million hectares in 1996 [14].

Genetically modified maize was first commercialized in 1996 and currently grown by farmers in 14 countries in 58.9 million hectares. Next to soybean, maize is the highest adopted biotech crop all over the world and due to it comparatively low rate of adoption (30.7 %) and huge cultivated area it has the highest potential of expansion [15]. Currently, GM maize is grown in Asian and African countries including South Africa, the Philippines and Vietnam. The genetically engineered "MON87460" transgenic maize is a popular drought-resistant crop [16]. Hybrid maize "DroughtGardTM" has been designed, produced, and released for farming in the United States in 2013 and is thought to reduce water necessary for cultivation by limiting leaf growth, particularly during its crucial blooming stages [17].

## Plant transformation

The application of transgenic techniques in crop improvement programs crucially needs an efficient plant transformation method. Plant transformation is a process of inserting exogenous DNA or gene into a plant genome and the transformation of maize has been documented in several studies *via* electroporation [18], particle bombardment [19], poly ethylene glycol [20], silicon carbide whiskers [21] and *Agrobacterium* [22]. Considering the above mentioned methods, transformation through *Agrobacterium* is highly recommended for gene transferring into a numerous range of crops including maize. This method is considered to be the most efficient [23], reliable, simple, cheap [10], stable [24] and primarily it has the ability to integrate low copy of relatively larger DNA segments into recipient cells with minimum rearrangements, resulting in a high-quality transgenic crop [25].

## Agrobacterium-mediated transformation

*Agrobacterium tumefaciens* and *Agrobacterium rhizogenes* are soil-borne bacteria which infect plants and form crown galls and hairy root diseases in host plants. The molecular principle behind the transformation technique is that a portion of large $T_i$ (Tumor induction) or $R_i$ (Hairy root induction) plasmid (200 – 800 kbp) present in the *Agrobacterium* being delivered and integrated into the host plant genome [26]. The transferred DNA is called as T-DNA which consiss of two types of genes. They are oncogenes, responsible for auxin and cytokinin synthesis and disease formation and the other genes encode for opines synthesis and responsible for T-DNA transfer [27]. Upon infection, T-DNA specific genes are expressed inside plant cells. As a result, the growth hormones, amino acid derivatives and opines catabolized by the inciting *Agrobacterium* will be over-produced. Subsequently, the successful penetration of *Agrobacterium* results in crown gall tumors or hairy root formation in plants [28]. *Agrobacterium* acts as an excellent carrier to introduce foreign DNA into plants through this mechanism and this plant transformation involves bacterial colonization, bacterial virulence system induction, attachment of bacteria with plants, T-DNA transfer complex fromation and finally transferring and integration of T-DNA into the plant genome [23] (Figure 1).

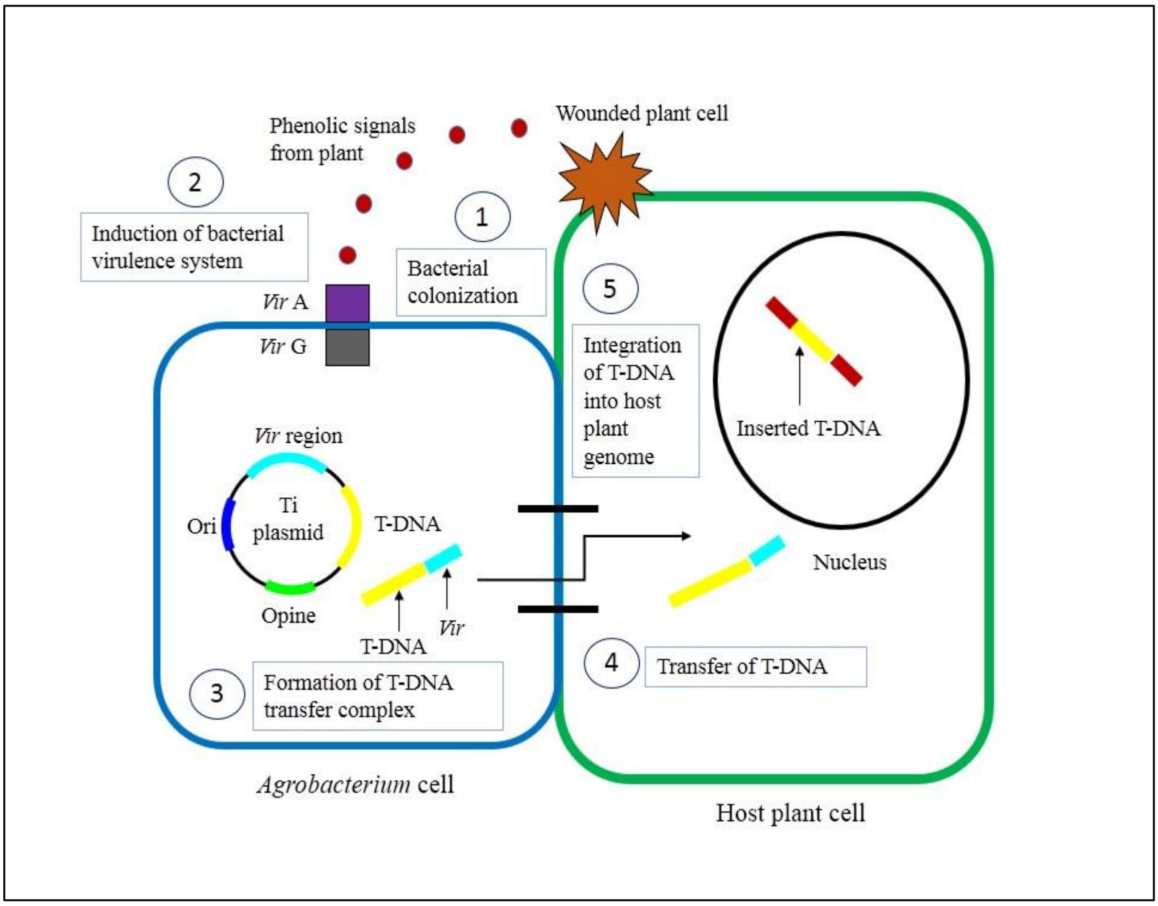


**Figure 1.** *Agrobacterium*-mediated plant transformation process (Source: Modified from Hwang *et al*.., 2017).

After the successful transformation of dicotyledonous plants using *Agrobacterium* in the early 1980s, many efforts were taken in monocotyledonous species [29]. Earlier, it was believed that monocots cannot be transformed using *Agrobacterium* as they are not affected by *Agrobacterium* in natural conditions due to their recalcitrant nature to regeneration [30]. However, the advancement in plant regeneration and comprehensive research on T-DNA transfer has led to the transformation of monocots using *Agrobacterium* successfully. Ishida *et al*. [31] reported the initial successful *Agrobacterium*-mediated genetic transformation in maize using immature embryos and this method was further improved constantly in subsequent studies over the past years.

## Factors affecting *Agrobacterium*-mediated transformation of maize plants

*Agrobacterium*-mediated transformation of monocotyledonous plants and their subsequent recovery are affected by several factors. Based on previous studies plant genotype, type of explant and its development stage, bacterial strain and its concentration, binary vector selection, inoculation and co-cultivation condition and appropriate promoters and selectable markers strongly impact the *Agrobacterium*-mediated transformation efficiency in maize [32].

Nevertheless, maize plant transformation is still under concern due to the genetic variability, different responses of *in vitro* cultures and the compatibility of genotype with *Agrobacterium* strains resulting in comparatively low transformation frequency [10].

## Choice of maize genotypes

Well-responsive maize genotypes in tissue culture is known to be a crucial factor in *Agrobacterium*-mediated transformation [24]. During tissue culture, most maize genotypes generate less compact and less re-generable type I callus. Type II callus, in contrast, is friable, fast-prolifering and distinctly re-generable [33]. In earlier studies, maize model genotypes including A188, Hi-II (A188 x B73) and H99 have performed excellently in *Agrobacterium*-mediated transformation [31] [34-36]. A188 and Hi-II genotypes are responsible for the production of type II callus and possess high plant regeneration and embryogenic callus induction frequency [37]. A188 is an amenable temperate inbred maize which resulted in 30 % transformation efficiency [31] while Hi-II has also been transformed successfully with 12 – 18 % of efficiency in previous studies [22] [38]. However, due to their poor agronomical value, backcrossing transgenes into local maize genotypes is considered to be time-consuming and expensive [39-40]. Thus, there was a need to broaden the array of maize genotypes that could be transformed efficiently through *Agrobacterium*.

Lupotto *et al*. [39] transformed some cross lines of A188 and other agronomically important inbred maize *via Agrobacterium* while Huang and Wei [41] transformed four lines of inbred maize (9046, Mo17, 414 and Qi319) and obtained transformation frequency of 2.4 to 5.3 %. Moreover, Hiei *et al*. [42] increased the efficiency of maize inbreds transformation process using heat treatment and centrifugation prior to infection. Frame *et al*. [43] studied the transformation efficiency of maize inbred lines called B104, B114, and Ky21 and obtained a 2.8 to 8 % frequency. They further elevated the frequency of B104 by doing some modifications to the culture media. Following that, scientists did several modifications to the culture media with the concern of increasing the transformation efficiency of various maize genotypes.

There are many previous literatures in maize transformation that employed temperate genotypes with lower attention to tropical maize genotypes. However, it has been proven that tropical maize genotypes also can be transformed *via Agrobacterium*. Valdez-Ortiz *et al*. [44] observed that LPC13, tropical maize can produce type II calli and successfully transformed it with 5.41 – 6.82 % of transformation efficiency using *Agrobacterium*. Omar *et al*. [45] reported that among several tropical maize genotypes, IL3 was the most susceptible for transformation outperforming the A188 temperate genotype by 31.7 % and 5.82 % transformation frequencies respectively (Table 1). *Agrobacterium*-mediated transformation efficiency of six inbred and two hybrids of tropical maize was evaluated by Ombori *et al*. [10] by examining factors like *A. tumefaciens* strain, vector types and co-cultivation period. However, Abhishek *et al*. [46] reported that maize in tropical region is less responsive to *in vitro* regeneration after transformation using *Agrobacterium* and to overcome this issue, *in planta* transformation protocols which are not dependent in tissue culture were initiated for tropical maize through *Agrobacterium* infection in recent studies.

## Co-cultivation medium: composition and modifications

The optimum growth and morphogenesis of different plant tissues strongly depend on their nutrient requirement. Furthermore, tissues from various plant parts may also have distinct growth demands [47]. Hence, the selection of an appropriate co-cultivation medium and its components is crucial for successful tissue culture and the subsequent gene transformation [48]. According to Carvalho *et al.* [49], the efficient friable callus formation in maize immature embryos differs depending on the selection of the co-cultivation medium. Several culture media, *viz* N6 [50], MS

[51], LS (Linsmaier and Skoog) and D media are utilized in gene transformation of maize [43], [36] [38]. Du *et al*. [48] found out that LS and MS media worked well compared to N6 and D media in the absence of any antioxidants. The same results were obtained by Ishida *et al.* [31] in which they observed no positive transgenic plants in the N6 medium. However, in another experiment, half the strength of N6 basal salt in combination with 0.4 g/l L-cysteine and 0.15 g/l dithiothreitol (DTT) antioxidants brought a high transformation frequency (18 %) compared to other salt and antioxidant concentrations [38]. Salt concentrations of the co-cultivation medium influences gene transferring by affecting the growth of *Agrobacterium* [52]. Nevertheless, the cause for improved transformation frequencies under low concentration is unknown while the lower salt levels (10 % and 30 %) had detrimental impacts on transformation [48]. Supplementing co-cultivation media with antioxidants like L-cysteine, DTT, proline and polypyrolidone has proved to improve the *Agrobacterium* transformation in maize. Frame *et al*. [43] studied the use of L-cysteine in modified salt medium and concluded that maize inbred lines can be efficiently transformed when MS is used in tissue culture medium instead of N6 salts (Table 1).

Scientists have found out that the removal of factors like ethylene that negatively affect *Agrobacterium* and plant interaction has significantly increased the transformation efficiency. Hence, they used ethylene biosynthesis inhibitors (aminoethoxyvinylglycine) and ethylene perception inhibitors ($AgNO_3$ and silver thiosulphate) to improve the T-DNA transferring procedure [53]. Another alternative technique is the application of ACC deaminase that can break down the ethylene precursor and α keto-butyrate [54]. Songstad *et al*. [55] tested the function $AgNO_3$ in maize tissue culture for the first time and found out that $AgNO_3$ has the ability to increase the plant regeneration frequency by reducing the ethylene effect. Valdez-Ortiz *et al*. [44] observed a 20-25% rise in the number of maize embryos producing callus in the induction media added with 15 mg/l $AgNO_3$. They also explained that the addition of $Ag^+$ ions improves somatic embryogenesis by increasing the internal Abscisic acid levels. In addition to that, it is also found that 5 – 10 mg/l $AgNO_3$ favoured type II callus formation from immature embryos [56]. Moreover, improved somatic embryogenesis by adding different concentrations of $AgNO_3$ in co-cultivation mediums such as 1.8 – 18 mg/l [57] and 15 mg/l [49] has been reported in previous studies. However, $AgNO_3$ concentrations of more than 20 mg/l tended to decrease the embryogenic callus production due to toxicity [44].

Several other modifications in the cultivation media have been done in recent studies. Sato *et al*. [58] used both mutant acetolactate synthase and Bispyribac-sodium herbicide to select transformed Japanese inbreds line whereas Akoyi *et al*. [59] suggested that *Agrobacterium* transformation in tropical maize inbreds can be facilitated by incorporating Dicamba growth regulators in the co-cultivation medium. Cho *et al*. [40] combined cytokinin, glucose and copper in the co-cultivation media to optimize the transformation method for PHR03 (a recalcitrant commercial maize elite inbred).

### Choice of explants

According to the existing literatures on maize transformation mediated by *Agrobacterium*, a wide range of explants were successfully transformed in many attempts. These explants include immature zygotic embryos, silks, leaf, seedling derived maize callus, embryogenic callus, plumular meristem cells, shoot apices and shoot apical meristem. Among these, freshly isolated maize immature zygotic embryo (1.2 mm - 2.0 mm) has been identified as increasingly amenable to *Agrobacterium* [34-35], [60],[44]. Though immature zygotic embryos are considered to be effective in callus induction, they have some major drawbacks such as sensitivity to environmental changes [42], dependency in plant developmental stage [28], need of a good facility for quality determination, high cost and time-consuming [61].

Optimization in transformation protocol has facilitated using callus as an explant for transformation. According to Du *et al*. [61] the embryogenic callus of several cereals including rice and maize could be effortlessly produced from embryo or the scutellum at the immature stage of embryo. The high potential in receiving exogenous DNA, stable integration and sensitivity to the screening agent have made embryogenic callus as a better explant option. Further, when embryogenic callus was used as an explant, the time taken to obtain maize transgenes was shortened from eight to three months. However, Abdel-Rahman and Widholm, [62] said that immature embryos from a very few maize genotypes only can form embryogenic callus. Meanwhile, Sidorov *et al*. [63] revealed that embryogenic callus generated from maize seedlings can also be transformed in the same way as callus derived from immature embryo. When seedling-derived callus are used as explants, immature embryos are not required. Hence, seedling derived callus can be employed instead of the conventional immature embryos or immature embryos-derived callus in transformation [64].

Grimsley *et al*. [65] revealed that maize shoot apical meristems can be readily transformed with maize streak virus using *Agrobacterium tumefaciens*. In another study, Gould *et al*. [66] obtained peak viral infection in shoot apical meristematic tissues of maize compared to other tissues used in the study and concluded that because of the compatible nature of *Agrobacterium*, maize, and maize streak virus, the inoculated meristematic tissue recorded the largest degree of viral infection. Sairam *et al*. [67] and Kant *et al*. [68] also succeeded in gene transformation of maize shoot apical meristems (Table 1). Maize apical meristem is morphologically plastic allowing it to create multi-shoots and somatic embryos without depending on the genotypes [67]. A major benefit of using shoot apical meristems is, plantlets similar to their parents can be developed when there are no modifications through differentiations [69]. Moreover, when shoot tips are used as explants, no donor plants are needed for immature embryo development and the multi-shoot producing ability of maize seedlings makes this transformation method appropriate for a wide array of genotypes [70]. Despite these several benefits of shoot apices as explant, transformation efficiency remains relatively low [71]. Leaf material is also one of the desirable explant resources, for a variety of reasons. Leaves can be readily generated in large quantities from germinating seedlings in a short time span, and they allow numerous consecutive rounds of selection and regeneration for the development of maize organelle transformation technology [72].

## Choice of *Agrobacterium* strain

In order to utilize the unique capability of *Agrobacterium* bacteria as a natural genetic engineer, many efforts have been taken to remove oncogenes characteristics of the bacteria and manipulate it [73]. The $T_i$ plasmids are generally big in size and there are no unique restriction sites in which selected genes could be cloned in the T-DNA region. Since inserting a foreign gene directly into that region, replacing oncogenes was found as a complex procedure, a binary vector system was developed by scientists based on the principle where the T-DNA region and the virulence (*vir*) genes can be divided into two non-identical replicons [23]. The binary vector was formed by the replicon consisting the T-DNA, whilst the *vir* helper was formed by the replicon containing the *vir* genes [74]. AGL0, GV3101 MP90, EHA101, EHA105, NT1 and LBA4404 are some of the developed *Agrobacterium* strains that contain non-oncogenic *vir* helper plasmids [75] [76]. These plasmids have a completely or partially deleted T-region so that they cannot incite tumors inside the host plant cell. Moreover, these plasmids are small, can be easily manipulated and consist of multiple unique restriction sites [74].

Cho *et al*. [40] compared the efficiency of transformation of four *Agrobacterium* strains (LBA4404, EHA105, AGL1 and GV3101) in maize and obtained the highest transformation frequency of 23.3

% when using AGL1 strain. Valdez-Ortiz *et al*. [44] evaluated LBA4404, EHA101 and EHA105 strains and the results established that EHA101 and EHA105 strains performed better by producing at least 30 % of GUS-positive embryos while LBA4404 strain resulted in zero GUS staining. In another study, AGL1, EHA101, C58rifC1 and LBA4404 bacterial strains containing pIG121-Hm standard binary plasmid were tested in *Agrobacterium*-mediated maize transformation and from this study, it was revealed that the *Agrobacterium* strain EHA101 and AGL1 were more effective showing 90 % and 87 % of GUS expression than C58rifC1 and LBA4404 strains [70] (Table 01). The better transformation of EHA105 strain compared to LBA4404 and GV3101 was proved by Huang and Wei [41] as well. Hence, it can be concluded that agropine types AGL1, EHA101 and EHA105 are the most suitable bacterial strains for an effective *Agrobacterium* transformation in maize plants. Moreover, presently scientists are working on increasing the transformation efficiency of *Agrobacterium* using several molecular strategies including up-regulating its *vir* gene expression level, applying *vir* genes inducers and using ternary and super-binary vector systems [77-78].

### Standard and super binary vectors

*Agrobacterium*-mediated transformation of higher plants is employed with either standard or super binary vectors. A standard binary vector system is consisted with T-DNA borders, multiple cloning sites (MCS), marker and reporter genes, the origin of replication for both *Escherichia coli* and *Agrobacterium* and other necessary elements [73] (Figure 2). On the other hand, a super binary vector is constructed by introducing virulence genes such as *virB*, *virE*, and *virG* additionally from the pTiBo542 plasmid to a standard binary vector for an enhanced transformation frequency and a wide range of the host for bacteria [79] (Figure 3).

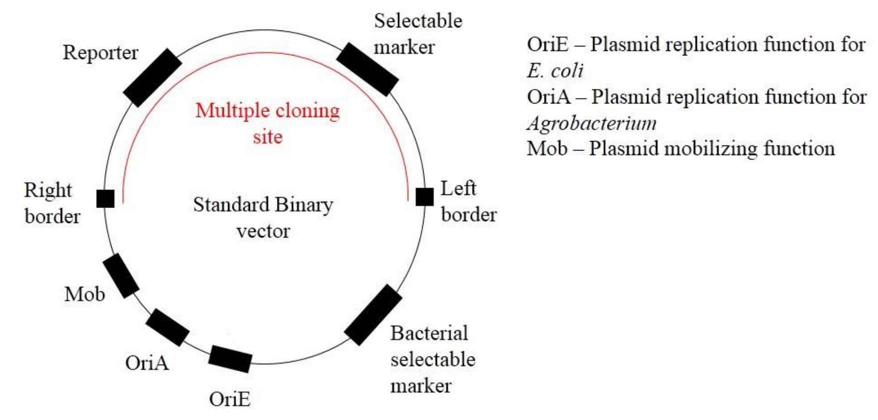


**Figure 2.** Components of a standard binary vector (Source: Modified from Komari *et al*., 2006).

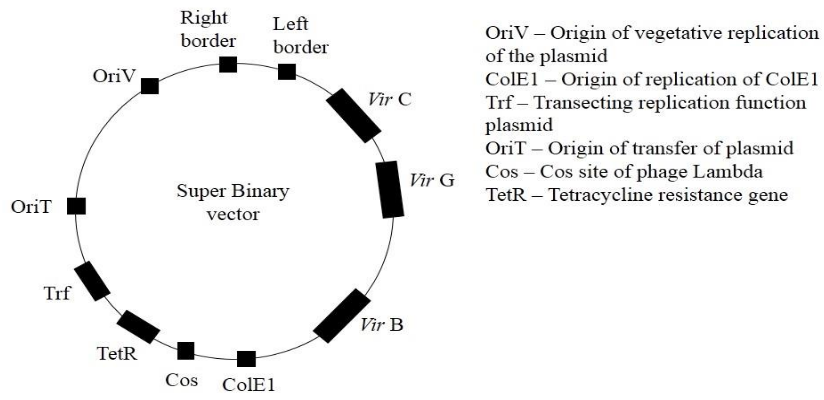


**Figure 3.** Components of a super binary vector (Source: Modified from Komari *et al.*, 2006).

The MCS are developed from standard cloning vectors like pUC8/9, pUC18/19, and pBluescript. Promoters for constitutive gene expression are used to express the selectable markers in calli, cells or germinating embryos in order to facilitate the plant transformation. The most repeatedly utilized promoter for monocotyledonous plants including maize is the 35S promoter, actin gene promoter of rice [80] and ubiquitin gene promoter of maize [81]. Marker genes used in vector systems are selected based on the host plants and in maize, the phosphinothricin resistance gene (*bar*) is considered to be efficient [82]. Other than these, plant selectable markers and bacterial selectable markers are also important components of the vector system. Genes that express resistance to kanamycin, tetracycline, gentamycin, spectinomycin, hygromycin and chloramphenicol are some commonly used bacterial selectable markers whereas Nos-nptII and 35S-hpt are some of the plant selectable markers for both *E. coli* and *Agrobacterium* [73].

*Vir* genes encode proteins that contribute for T-DNA processing and successive transferring into the plants [83]. Virulence loci such as *virC* and *virF* are the main determinants of the host range and in maize, the *virH* locus is considered to involve in the transformation procedure [84-85]. *Vir* genes are activated by the phenolic compounds, induced by wounding. Hence, in order to increase the bacterium and plant interaction, scientists have added these phenolic compounds externally into the induction media [48], [10]. A stable gene transfer by *Agrobacterium* utilizing a standard binary vector in maize was initially reported by Gould *et al*. [66]. Following him, fertile and stable transgenic maize using EHA101 strain having standard binary vector was produced by Frame *et al*. [22] with lower transformation efficiency (5.5 %) even under the improved co-culture conditions. Conversely, transformation frequencies ranging from 33 % to 51 % had been recorded in previous studies through super binary vectors [86],[35]. However, very few studies have used super binary vectors to establish repeatable *Agrobacterium* transformation in maize. Construction of a standard binary vectors is easier than that of super binary vectors because, during the assembling of super binary vectors, the gene of interest (GOI) is co-integrated into a large plasmid through homologous recombination [31] (Table 1). In contrast, the development of a standard binary vector system does not necessitate this extra move allowing it a simple option to introduce a GOI into an *Agrobacterium* strain [22]. Furthermore, public laboratories can easily finance standard binary constructs to study transgenic maize. Even though using standard binary vectors have several advantages, *Agrobacterium*-mediated transformation frequency remains low compared to super binary vectors, even in improved medium conditions [61].

**Table 1.** Summary of genotypes, explants, vector type, bacterial strains and transformation efficiency in previous *Agrobacterium*-mediated maize transformation studies

| S/N | Genotype | Explant | Media | Vector | Bacterial strain | Transformation efficiency | References |
|---|---|---|---|---|---|---|---|
| 1 | NA | Shoot apices | NA | Standard | C58 | NA | Grimsley *et al*. [87] |
| 2 | NA | Coleoptilar node of mature embryos | MS | Standard | LBA4301 and LBA4301ros | NA | Grimsley *et al*. [65] |
| 3 | Funk's G90 hybrid | Shoot apices | MS | Standard | EHA1 | NA | Gould *et al*. [66] |
| 4 | A188, bxlbx, W23 and 880254A | Meristematic tissue of immature embryo | MS | Standard | C58 | NA | Schlappi and Hohn, [28] |
| 5 | A188, W117, W59E, A554, W153R'H99, BMS | Immature embryo | N6 | Super | | 5–30 % | Ishida *et al*. [31] |
| 6 | Hi-II | Immature embryo | N6 | Super | A281 | 32.8–50.5 % | Zhao *et al*. [86] |
| 7 | Lo1054, Lo1056, Lo951, Lo881, A188 and B73 | Immature embryos | N6 | Standard | C58C1, EHA101, LBA4404 and EHA105 | NA | Lupotto *et al*. [88] |
| 8 | A188 | Immature embryo | LS | Standard | LBA4404 | 30 % | Negrotto *et al*. [34] |
| 9 | A188 | Immature embryo | NA | Standard | LBA4404 | NA | Taniguchi *et al*., [89] |
| 10 | Hi-II | Immature embryo | MS and N6 | Standard | EHA101 | 5.5 % | Frame *et al*. [22] |
| 11 | Hi-II | Immature embryos | N6 | Standard | LBA4404 | NA | Miller *et al*. [90] |
| 12 | Hi-II | Immature embryo | N6 | Super | LBA4404 | 40 % | Zhao *et al*. [35] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 13 | R23, LH 74 × A 641, LH 262 × LH 252, LH 198 × LH 227, FR 1064 × FR 1064, SDMS × LH 185, and LH 176 × LH 177 DMS | Shoot apical meristem | MS | Standard | EHA105, LBA4404, and GV3101 | 60 – 87 % | Sairam *et al*. [67] |
| 14 | (Pa91 _ H99) _ A188 | Immature embryos | MS | Standard | ABI strain | 18.9 % | Zhang *et al*. [60] |
| 15 | LH198 X Hi-II | Immature embryos | NA | Standard | ABI strain | 3 – 13.4 % | Huang *et al*. [91] |
| 16 | Five elite inbreds and their crosses with A188 | Immature embryos | NA | Standard | EHA105 | NA | Lupotto *et al*. [39] |
| 17 | A188, R91 and A188 X R91 | Embryogenic calli | MS | Standard | LBA4404 | 3.4 % | Danilova and Dolgikh, [92] |
| 18 | 9046, Mo17, 414 and Qi319 | Immature embryos | N6 | Standard | EHA105, LBA4404 and GV3101 | 2.4 - 5.3 % | Huang and Wei, [41] |
| 19 | AT-3 | Pistil filaments (silk) | NA | Standard | GV3101 | 6.8 % | Chumakov *et al*. [93] |
| 20 | B73, B104, B114, H99, Mo17, W64, Oh43, A188, Mp420, GT-Mas:gk and Ky21 | Immature embryos | MS and N6 | Standard | EHA101, LBA4404 and C58Z707 | 2.8–8 % | Frame *et al*. [43] |
| 21 | A188, A634, H99, W117, W59E and Oh43 | Immature embryos | N6 | Standard | LBA4404 | 0 – 29.6 % | Hiei *et al*. [42] |
| 22 | Hi II | Immature embryo | MS | Standard | EHA101 | 10.3 % | Horn *et al*. [94] |
| 23 | H99, LH198×HiII, PHA ((Pa91×H99)×A188), KHI and LI, L2, L4, L9, and L9×L5 | seedling derived maize callus | MS | Standard | ABI | 2 – 11 % | Sidorov *et al*. [63] |
| 24 | Qi 319 and Ye 515 | Embryogenic callus | MS | Standard | LBA4404 | 40.2 % | Yang *et al*. [95] |
| 25 | A188, A634, H99 and W117 | Immature embryo | LS | Super | LBA4404 | 51.7 % | Ishida *et al*. [36] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 26 | LPC13 | Immature embryo | N6 | Standard | EHA10, EHA105 and LBA4404 | 5.41 – 6.82 % | Valdez-Ortiz *et al*. [44] |
| 27 | Kenyan tropical inbred lines (TL21, TL22, TL23 and TL18)<br>Sudanese inbred lines (IL1 and IL2)<br>CIMMYT inbred lines (CML216 and CML244) | Immature embryo | N6 and LS | Standard | EHA101 | 20-30 % | Anami *et al*. [96] |
| 28 | Hi-II A X Hi-IIB | Immature embryo (F2) | N6 | Standard | LBA4404 and EHA101 | 18 % | Vega *et al*. [38] |
| 29 | Hi-II | Type II embryogenic calli | MS | Standard | C58C1 | 0.60 % | Kim *et al*. [97] |
| 30 | A188 | Immature embryo | N6, MS, LS and D | Standard | LBA4404 | 3.2 – 15.9 % | Du *et al*. [48] |
| 31 | S61, B73, Mo17 and A188 | Immature embryos | MS and N6 | Standard | EHA101, EHA105 and LBA4404 | 6.45 % | Takavar *et al*. [98] |
| 32 | Hi and B104 | Immature embryo | N6, MS | Standard | EHA101 | 6.4 % | Frame *et al*. [99] |
| 33 | CG62 | Shoot apical meristem | MS | Standard | EHA101 | 62 % | Kant *et al*. [68] |
| 34 | IL1, IL3, IL15, IL16, IL28, IL38, IL42, IL43, Hudiba-1, Hudiba-2, Mojtamma-45, A188 and KAT | Immature embryos | NA | Standard | EHA101 | 31.7 % | Omar *et al*. [45] |
| 35 | CML78, CML216, CML331, TL18, TL27, MU25, A188 maize inbred, H627 and PTL02 hybrid line | Immature embryo and embryogenic callus | MS | Standard | EHA101, AGL1, LBA4404 and GV | 1.4 % | Ombori *et al*. [45] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 36 | (CG69, CG59, CG65, CG68, CG101, CG94, CG37, CG102, CG103, CG74 and CG93) and (He344, K10 and Longfu746) | Shoot apices | MS | Standard | AGL1, EHA101, C58rifC1 and LBA4404 | 2 %. | Cao *et al*. [70] |
| 37 | PHR03 | Immature embryos | PIA | Standard | LBA4404, AGL1, EHA105 and GV3101 | 57.1 % | Cho *et al*. [40] |
| 38 | Hi II A X Hi II B | Immature embryos | MS and N6 | Standard | EHA101 | NA | Lee and Zhang, [100] |
| 39 | HKI 163 | Plumular meristem cells of germinating seeds | N6 | Standard | EHA105 | 4 % | Abhishek *et al*. [46] |
| 40 | L3 tropical elite maize | Immature embryos | N6 | Standard | EHA101 | 1.1 – 3 % | Souza *et al*. [101] |
| 41 | B104 | Immature embryos | MS | Standard | EHA101 | 4 % | Raji *et al*. [102] |
| 42 | Hi-II | Embryogenic callus | N6 | Standard | EHA105 | 30.39 % | Du *et al*. [61] |

**NA:** Not Available

## *Agrobacterium*-mediated gene transformation in maize genome editing

The genome-editing technique is a novel advancement in genetic science. It has been demonstrated that the target DNA double-stranded break (DSB) increases the gene-editing frequency by more than a thousand times and it acts as a primary breakthrough in genome modification [103]. Hence, these DSBs can be utilized in site-specific genome alterations to enhance agronomic traits using a natural DNA repair procedure in crops. During the last two decades, several classes of nucleases that can generate DSBs at predetermined regions have been formed. They include zinc-finger nucleases (ZFNs), customized homing endonucleases (meganucleases), transcription activator-like effector nucleases (TALENs), and CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) -associated (Cas) proteinse [104] and are utilized to enhance gene editing in different species including plants. Because of its great precision, adaptability, simplicity and low cost, CRISPR is considered as a promising technique in genome editing [105].

CRISPR technology was developed based on the bacterial immunity system to fight against viral infections [106]. A nuclease enzyme (Cas9) directed by a guide RNA (gRNA) containing the site-specific sequences and selectable marker genes can reach a designated target in the host genome. This complex of protein creates the CRISPR-Cas9 gene-editing system. These reagents could be delivered to the plant cells as a part of a single plasmid or separately by traditional transformation methods like biolistics or *Agrobacterium* [107]. Cas9 facilitates gene editing by causing a site-specific DSB in DNA. This method is considered to be a breakthrough in the manipulation and creation of living modified organisms because it permits the *in vivo* DNA modification at the targeted location with remarkable accuracy [108].

Despite several advances, *Agrobacterium* remains the preferred gene delivery method in CRISPR/Cas gene-editing owing to its simplicity, less invasive nature, reproducibility and the stable DNA vectors used in this system [109]. CRISPR technology is utilized for several applications that include target mutagenesis [110], transcriptional reprogramming [111], precise gene replacement [112], epigenome editing [113], base editing [114] and disease treatment [115]. Though the fundamentals of CRISPR-Cas9 genome editing are already well-known, it has been found out that species differences can lead to a range of outcomes in regards to resolution, efficiency, accuracy, and structure of DNA modification [116]. Different aspects, such as the selection of target site, properties and qualities of endonucleases and gRNA, DSB type and different plant species and parts will result in variations in the mutations created [117].

In a research comparing the TALENS and CRISPR technologies in gene editing of maize protoplasts, Liang *et al*. [118] obtained 13.1 % efficiency from CRISPR and 9.1 % from TALENS. In comparison to meganucleases, Svitashev *et al*. [103] found out that CRISPR technology can create a 10 to 20 times higher mutation frequency in maize plant. Furthermore, multiplex gene-editing technique in maize utilizing a tRNA-processing system was demosntrated by Qi *et al*. [119]. It was discovered that the method of tRNA–sgRNA (transfer RNA-single guide RNA) had greater editing efficiency than the simplex editing system. Char *et al*. [120], described target mutagenesis with high frequency in maize using *Agrobacterium*-mediated CRISPR/Cas9. In their research, the gRNA/Cas9 constructs were transformed into *Agrobacterium* strain EHA101 and immature maize embryos of Hi-II were infected with that in order to develop the 'ISU Maize CRISPR'. In a new research, Zhang *et al*. [121] harnessed CRISPR/Cas9 to generate semi-dwarf maize plants through gene editing by transforming immature embryos with *Agrobacterium* tumefaciens strain LBA4401 harboring pBUE411-2gR-GA vector.

## Need of transgenic maize in Sri Lanka

One strategic approach to the issues posed by climate change in Sri Lanka could be the cultivation of transgenic maize. Significant effects of climate change have been felt by the nation, including more frequent extreme weather events, higher temperatures, and unpredictable rainfall patterns. Transgenic maize, which has undergone genetic modification to display characteristics like resilience to pests and drought, can be an essential tool for climate adaptation. The productivity of maize, which is a main crop grown extensively in Sri Lanka, is under risk due to changing weather patterns. Because of climate change, longer droughts are becoming more frequent, yet transgenic maize cultivars are resilient. Additionally, they are resistant to diseases and pests, which might spread in environments with changed conditions. Transgenic maize can also address issues faced in food security by providing increased yields and nutritious value. Ensuring a stable and dependable maize crop is essential to maintaining the population's food supply as extreme weather events become more frequent. Transgenic maize can also reduce the demand for artificial fertilisers and pesticides, encouraging environmentally responsible and sustainable farming methods. This can lessen the detrimental effects conventional farming practises have on the environment, which fuel climate change.

It is vital to take into account the possible hazards and apprehensions linked to transgenic crops, encompassing regulatory, ecological, and economical aspects. A thorough evaluation of these concerns ought to be implemented alongside any endeavours to establish genetically modified maize farming in Sri Lanka. This would guarantee that the technology's advantages can be fully utilised while reducing any possible downsides.

## Transgenic crop cultivation and biosafety regulations in Sri Lanka

Sri Lanka has designed Biosafety regulations related to the handling, usage, importation, exportation, and release of genetically modified organisms (GMOs) and genetically engineered products to ensure the safety of human health and the environment. The Cartagena Protocol on Biosafety is an international treaty under Convention on Biological Diversity (CBD) that addresses the safe transmission, handling, and use of living-modified organisms (LMOs) developing from modern biotechnology [122]. Sri Lanka has signed the Cartagena Protocol on Biosafety in 2000 and ratified in 2004, committing to adopting its requirements to regulate and ensure the safe handling and trading of genetically modified organisms (GMOs) and genetically engineered goods [123]. The Ministry of Mahaweli Development and Environment (MoMDE) created the National Policy on Biosafety in accordance with the Protocol, and the Sri Lankan Cabinet of Ministers adopted it in 2005. The National Biosafety Framework (NBF) of Sri Lanka operates on a precautionary premise, with two basic goals. First, it tries to assess the current biosafety status of the country, including regulations, legislation, and administrative procedures relating to genetically modified organisms (GMOs). Second, it seeks to identify areas in need of improvement, such as legislative gaps, limitations in administrative or enforcement processes, or other flaws in the biosafety framework. By pursuing these dual goals, Sri Lanka hopes to analyze its current biosafety status as well as develop a path for improving its capacity to manage GMOs and ensure biosafety [124].

The Food Act, which was established in 2007 for legislation of GM food, makes it permissible to import and consume GM food in Sri Lanka [125]. Nevertheless, the nation forbids the cultivation of GM crops for consumption or livestock feed. Importers need prior authorization and must submit a risk assessment by regional authorities to import genetically modified food or feed. In order to properly inform customers about genetic modification, GM foods sold in Sri Lanka must also bear the proper labeling. A labeled GM food product is not yet available on the market because no importers have been given permission to deliver GM food into Sri Lanka. However, it is anticipated that GM food may eventually reach the Sri Lankan market given the global development of GM food and improvements in safety evaluation methods. As a result, efforts are being made in Sri Lanka to create a biosafety framework for GM foods in order to make decisions based on the available data and safeguard human health and the environment from any risks [126].

### Barriers in policy development related to genetic engineering and suggestions to overcome them

Sri Lanka's biosafety regulations are evolving to keep pace with advancements in biotechnology and international standards. However, there are several acts related to biosafety, a country like Sri Lanka face multiple challenges in implementing the guidelines and policies. Some of the issues faced by the Sri Lankan government include insufficient enforcement capacity, lack of skilled human resources at all stages of implementation, financial issues, the need for stronger national and regional partnerships, and lack of communication with stakeholders [124]. Adoption of biosafety standards may be hampered by a lack of public understanding and awareness of GMOs and their possible effects on human health and the environment. In addition to these, preparing for and responding to potential biosafety emergencies, such as accidental releases or contamination, requires planning and resources.

Addressing these issues would necessitate a collaborative effort from governments, regulatory agencies, scientists, industry players, and civil society. It frequently requires a careful balance of encouraging scientific innovation, guaranteeing food security, and protecting human health and the environment. Furthermore, ongoing capacity building, increased public education, and international collaboration can all help Sri Lanka effectively establish and enforce biosafety rules.

## Conclusions

*Agrobacterium*-mediated transformation of maize plants is influenced by various aspects such as different genotypes, explant types and development stages, binary vector selection and co-cultivation conditions. It is proven that *Agrobacterium*-mediated gene transferring into maize plant has been constantly studied and improved based on the needs. Moreover, it has become as one of the foremost technologies for transgenic miaze production and maize genome editing. Introducing more advanced and novel techniques during this transformation procedure can further help to overcome the barriers and increase the transformation efficient in both developed and developing countries including Sri Lanka. Furthermore, more attention has to be put into creating adaptable maize transformation techniques that do not depend on genotype and can be applied in any laboratories worldwide.

While adopting its biosafety legislation policies, Sri Lanka is confronted with issues related to stakeholder communication, budgets, labour skills and enforcement capacity. Due to the low level of public awareness of GMOs, it is crucial to plan ahead for biosafety emergencies. Building capacity, educating the public and collaborating with other countries are essential for Sri Lanka to successfully adopt to transgenic maize cultivation.


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## Conflict of interest

The authors declare that there is no potential conflict of interest.

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# Research and Development to Mitigate Climate Change Impacts on Food Security in Sri Lanka

# Research and development to mitigate climate change impacts on food security in Sri Lanka

D. Padukkage[1*], C. M. Nanayakkara[2]

## Abstract

Food security in terms of production and achieving self-sufficiency in agricultural sector is less discussed yet needs special attention in climate change adaptation strategies of Sri Lanka. Being the most climate sensitive sector, agriculture is significantly affected by the climate change and results in serious issues in agricultural production of food crops and animal production. Hence, the relative contribution of agricultural sector to the national economy has reduced to around 10 percent of GDP during recent decades. Increases in temperatures, changes in precipitation patterns, extreme weather events, and reduction in water availability, etc. result in reduced agricultural productivity leading to lowered food availability, access to food, and food quality. In order to face the climate changes, research and development (R&D) can be directed to address the critical research needs of the sector. Development of climate change resilient varieties (paddy, horticulture, etc.) and breeds (livestock and poultry) that can tolerate heat stress, drought and floods and resistant to diseases and pest attacks is the need of the hour to mitigate risks caused by climate change. Diversifying food sources and agricultural production techniques to reduce climate change driven risks require research facilities, and skilled and trained human resources. Hence improving the capacity of research institutes is a timely need. Further, advanced R&D on restoring nature to absorb more carbon, reducing plastic and polythene usage, solutions for reducing the effect of future climate changes, etc. are critical for establishing food security. This chapter aims to suggest R&D interventions to be focused and possible policy interventions in order to reach food security under a changed climate.

**Keywords:** Agricultural production, Climate change, Food security, National economy

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# Introduction

## Climate change: The global scenario

The climate change, as per the United Nations, is referred to 'long-term shifts in temperatures and weather patterns' [1]. During the past 65 years, significant global challenges have been encountered due to climate change which is considered as the ultimate outcome of global warming [2]. Greenhouse gas emissions due to human actions (Figure 1) such as combustion of fossil fuels (Figure 2), industrialization, use of certain fertilizers in farming, etc. directly influence and trigger the climate change which in turn threaten the stability of the earth functions and human existence. While all nations are affected by the impacts of climate change over the components of environmental, ecological and socio-economic aspects, mainly developing countries are more vulnerable due to lack of adaptive capabilities [3-4].

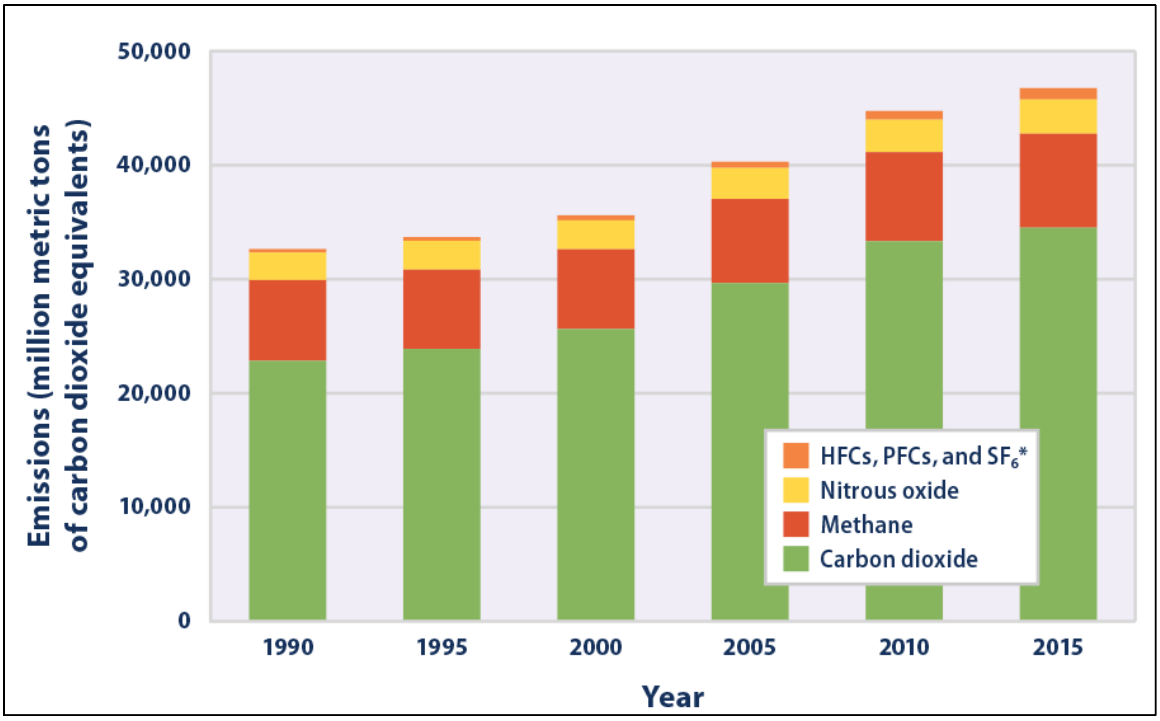


**Figure 1.** Human-caused emissions over time for individual greenhouse gases. (Source: United States Environmental Protection Agency, 2021)

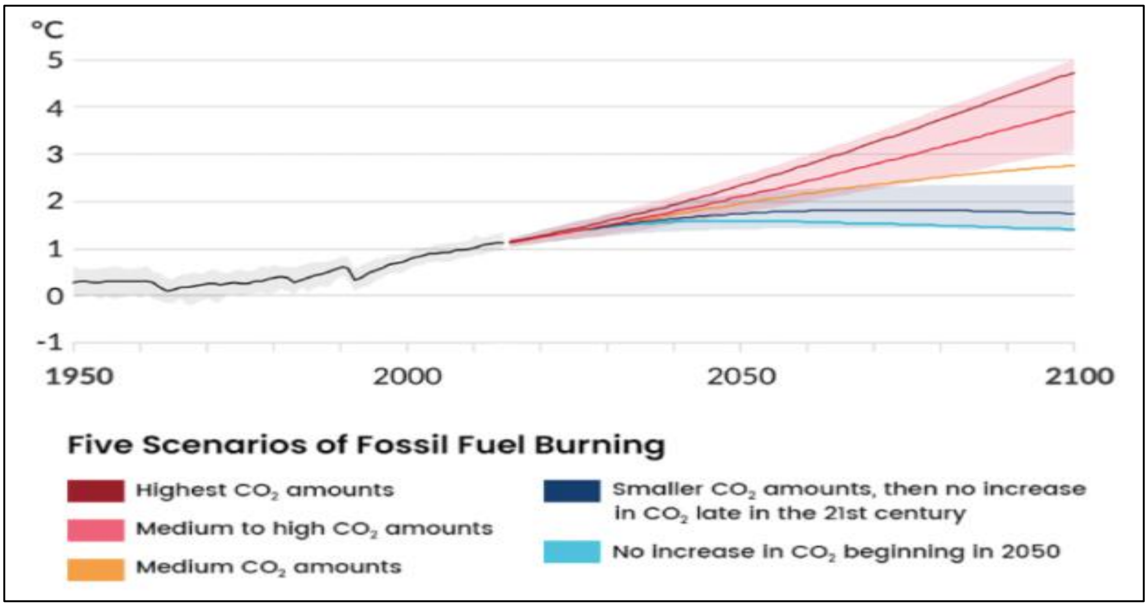


**Figure 2.** Projected temperature increase (°C) due to combustion of fossil fuel. (Source*:* IPCC, 2021)

The future consequences of heightened temperatures and continuous global warming (Figure 3) require debate and immediate action. Irregular weather patterns, which involves changes in temperature, precipitation, pressure and humidity levels, elevated sea level due to retreating of ice glaciers, flooding and cyclone hazards are considered as most important global effects of climate change [7-8]. With the onset of industrial revolution, these effects amplified to an uncontrollable level and it is important take immediate steps to control and mitigate these devastating impacts.

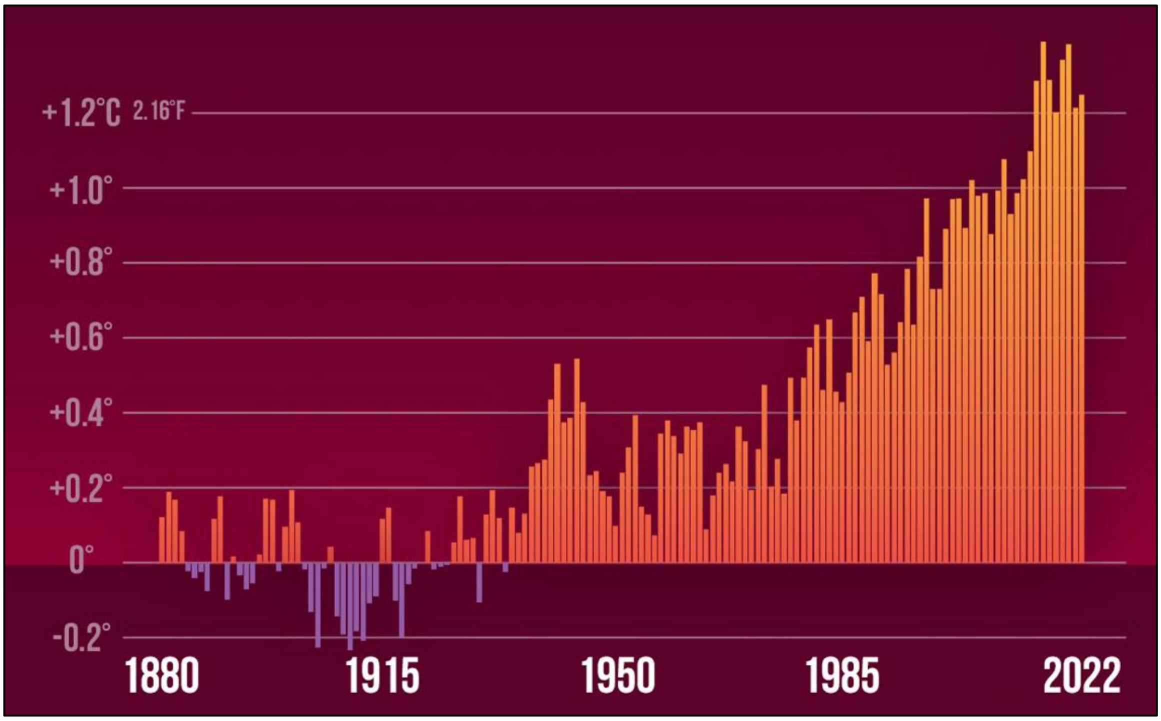


**Figure 3.** Global Average Temperature Anomalies, departure from 1881-2022.
(Source: https://climateknowledgeportal.worldbank.org/themes/cckp/images/logo2.png)

## Status of climate change in Asia

Being the largest continent extending to the polar region, Asia contributes considerably to the global climate change. In Asian region, extreme weather conditions caused by climate change impacts have been reaching to a threatening level that will cause more socio-economic and environmental disruptions in the future. According to the World Meteorological Organization (WMO) State of the Climate in Asia 2022 report [10], during 1991–2022, Asia recorded double the warming trend during 1961-1990 period which is reported faster than global average [1]. The estimated mean temperature of Asia in 2022 was 0.73 °C [0.63–0.78] which is above the 1991–2020 average. Sea surface temperature of Asian region recorded a rate of more than 0.5 °C per decade which is approximately three times faster than the global warming rate. Due to glacier melt in Tibetan Plateau, which has 100,000 $km^2$ of glacier coverage and which contains the largest volumes of ice outside of the polar regions, sea level has been rising across Asia higher than the global mean rate (GMSL) during 1993–2022 (3.4 ± 0.3 mm per year).

As per the WMO State of the Climate in Asia 2022 report [10], the economic losses associated with 81 weather, climate and water-related disasters in Asia in 2022, of which over 83% were flood and storm events: Pakistan (over US$ 15 billion), China (over US$ 5 billion) and India (over US$ 4.2 billion). More than 50 million people were affected and more than US$ 36 billion in economic damages were recorded due to climate change associated extreme weather events in Asia (Figure 4).

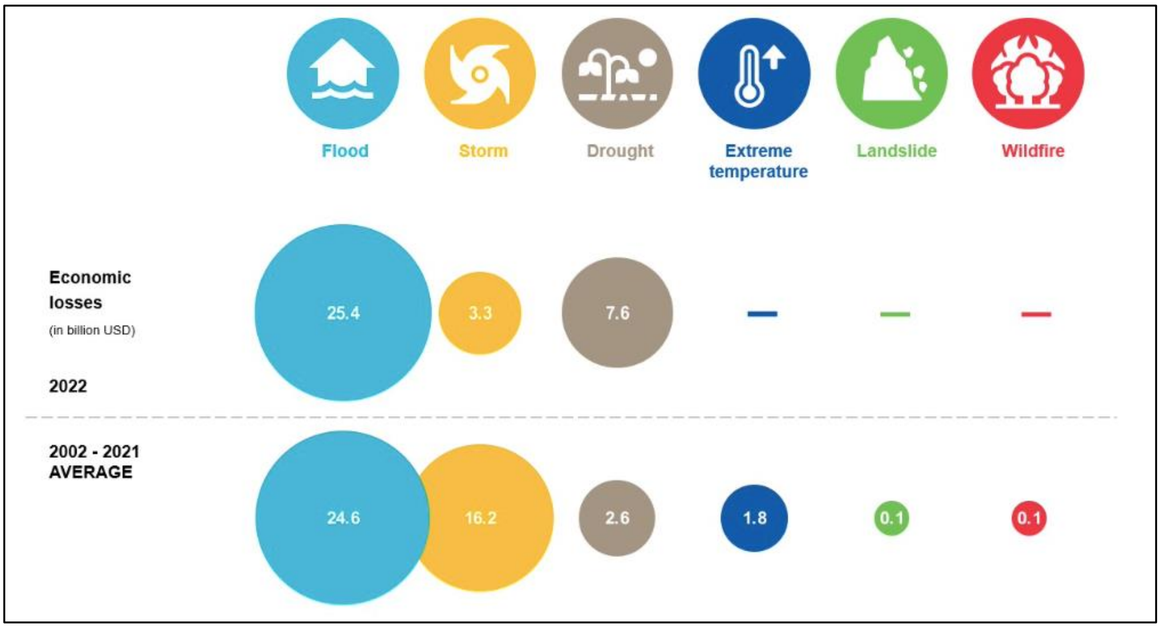


**Figure 4.** The economic losses associated with climate change in Asia during 2021-2022. (Source: WMO, State of the Climate in Asia 2022 report, 2022)

## Status of climate change in Sri Lanka

Sri Lanka is a tropical nation which is highly vulnerable to adverse impacts of climate change. Climate change can cause more frequent and intense extreme weather events, such as cyclones, floods, and droughts, rising temperatures, changes in precipitation patterns, rises in sea level and these events can have significant impacts on agriculture, and communities. Given its coastal geography, Sri Lanka is susceptible to the impacts of sea level rise that can result in coastal erosion, saltwater intrusion into fresh water sources and coastal lands, and threats to coastal area.

There are unique rainfall patterns in Sri Lanka with notable spatial variations. Sri Lanka has two major seasons with respect to monsoon rains, the *Maha season* associated with northeast monsoon (September–March) and the *Yala season* associated with the southwest monsoon (May–August). Sri Lanka has a unique rainfall pattern with notable precipitation zones, namely, wet zone (mean annual rainfall of over 2,500 mm), intermediate zone (between 1,750 mm and 2,500 mm), and dry zone (less than 1,750 mm). A decreasing trend of annual precipitation is estimated at around 7% [11]. The variability of climate and the frequency of extreme events has been on the increase in Sri Lanka [12]. Precipitation remains linked to the El Niño Southern Oscillation (ENSO), and El Niño events typically increasing the precipitation associated with the northeast monsoon.

Sri Lanka is one of the hottest countries in the world with an average temperature of around 27 °C–28 °C, and increasing to around 35 °C during the hottest months. Sri Lanka experiences an annual probability of severe droughts of about 4% as a result of these adverse increases in temperature level [13]. Increase in average temperatures, leading to heatwaves and changes in weather patterns can be experienced due to climate change emphasizes that temperature rise has accelerated toward $20^{th}$ century. Over the 20th century, Sri Lanka experienced warming of around 0.8°C [11] which determines that the temperature rise reported in Sri Lanka was estimated 0.16°C of warming per decade between 1961–1990 [12]. An annual probability of severe droughts of about 4% is experienced as a result of these adverse increases in temperature level [13].

The average annual loss from natural disasters in Sri Lanka is estimated at USD 0.38 billion over the long term [12]. Ninety-six percent of these natural disasters in Sri Lanka are cause by the adverse impacts of climate change and the country has become the fourth most climate change affected country in 2016 [13].

## Climate change impact

### Climate change impacts on agriculture sectors and agro-ecosystems

Agriculture is one of the largest contributors to global warming which is responsible for 30-40% of all greenhouse gas emissions and which in turn is significantly impacted by climate change [14]. Agricultural productivity is highly affected by climate change with response to extreme weather conditions such as flooding (Figure 5), drought (Figure 6) and forest fires [15-16]. Agriculture is a major component of developing countries' economy and livelihood of majority of population and therefore, climate change impacts on agricultural sector challenges the peoples' quality of life and overall economy [14]. A rise in temperature from 1 to 3.7 °C is forecasted at the end of this century and severe negative impacts on crop growth and production are expected [17]. Therefore, several short-term and long-term management and administrative approaches and measures for mitigation and adaptation of climate change are required to tackle the disruptive effects of climate change (Figure 7).

**Figure 5.** Paddy cultivation in Pamburana area, Sri Lanka destroyed due to extreme weather during December 2019. (Source: Adapted from Karunaratna, 2019, *Daily Mirror*)

**Figure 6.** Agricultural lands affected by long-term drought in Sri Lanka.
(Source: https://www.hirunews.lk/english/151722/hydro-power-generation-dropped-to-12-percent-as-dry-weather-hits-many-parts-island)

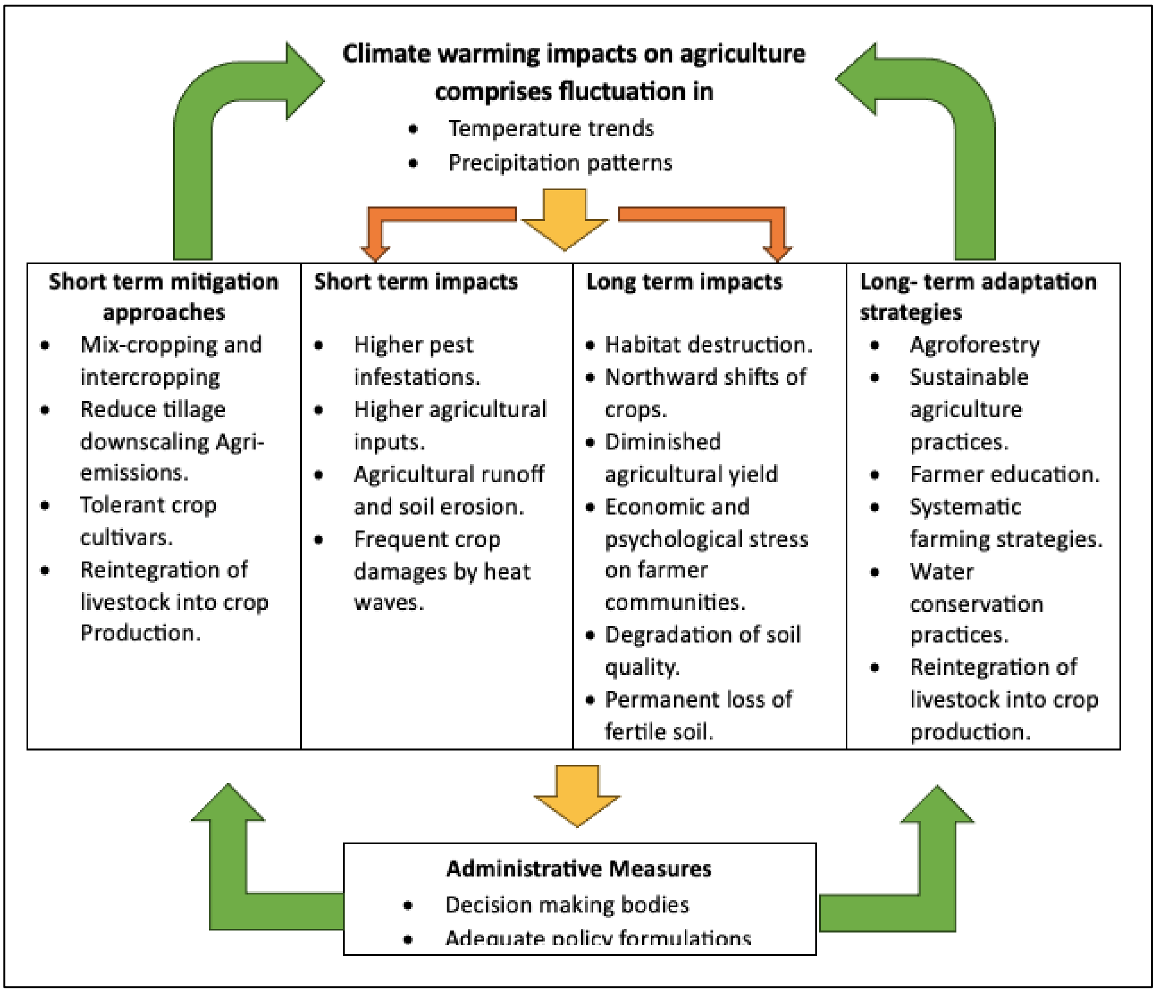


**Figure 7.** Potential impacts of climate change on agriculture sector and the appropriate mitigation and adaptation measures to overcome its impact. (Source: Adapted from Abbass *et al*., 2022)

When the growth and conditions optimal for plant (light, water and soil), animal and ecosystem functions are not conducive anymore due to climate change, less productivity of species, or even species extinction could occur i.e. Native varieties of vanilla in South and Central America are at highest risk of extinction, while wild cotton is second on the list, followed by avocados, and then wild potatoes [20]. In agriculture, crops, livestock, forestry, fisheries and aquaculture are both directly and indirectly affected by climate change that cause economic and social consequences on agricultural production leading to negative impacts on food security and nutrition. The direct impacts are mainly caused by elevated temperature levels and less water availability and affect agricultural production through changes in other contributory factors such as density of pollinators, pests, disease vectors, invasive species, etc. These impacts are easier to predict and well projected for main staple crops. Indirect affects play a major role in less controlled environments such as forestry and fisheries, and are much more difficult to project due to the high number of interacting parameters.

The agriculture sector is impacted by more than 25% of all damage and loss from major climate-related disasters such as drought, floods, cyclones and tropical storms [1]. Therefore, the importance of agriculture and food system resilience is highly emphasized by the parties of the Paris Agreement and globally considered as a top priority of mitigation and adaptation [21].

## State of global and national food security

According to the widely accepted definition by World Food Summit, 1996 [22] "Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" [23]. Four dimensions of food security are highlighted, namely: availability of food (level of food production, stock levels and net trade), accessibility (economic and physical access), utilization (usage and assimilation in human body) and stability of the above three dimensions. On average, 750 million of world population are undernourished (Figure 8) and due to this widespread food insecurity, it is projected that almost 600 million people will be chronically undernourished in 2030 [24]. According to the World Bank, the number of people suffering acute food insecurity increased from 135 million in 2019 to 345 million in 82 countries by June 2022.

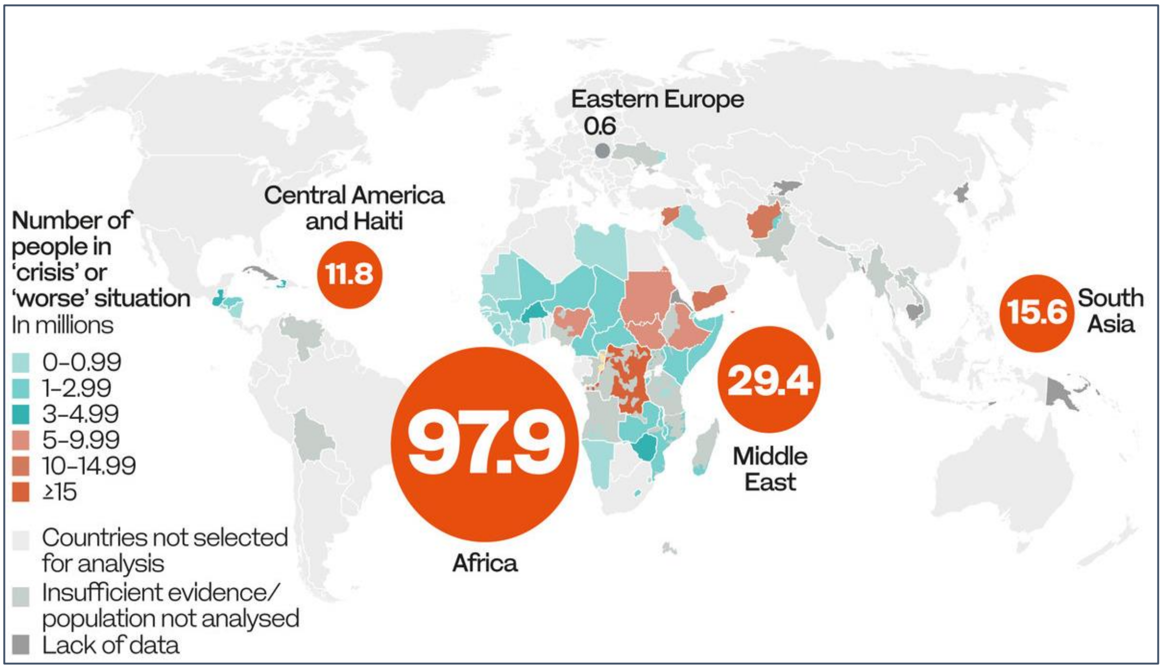


**Figure 8.** Global Report on Food Crisis, 2022.
(Source: https://www.arabnews.com/node/1971861/middle-east)

During 2022, 6.2 million people in Sri Lanka became food insecure as a result of economic crisis with high food inflation rate and Sri Lanka has been recognized as a 'hunger hotspot' among 48 countries (Figure 8) designated by the World Food Programme [26]. The risk of climate change also threatens the food security of the country. Agricultural yields are highly affected by increasing temperature, extreme and prolonged heat conditions, droughts, floods, landslides, abnormalities and changes in climatic patterns and seawater intrusion etc. causing missing and fluctuating cropping seasons result in loss of crop harvests, decline in crop productivity, food quality and nutritional values and increased pest attacks and unknown pests, diseases and invasive species emergence. Traditionally, medicinally and culturally important plant varieties, wild food varieties, pollinators such as bees, butterflies and other insects are endangered and result in high decrement in the density of biodiversity. These impacts create vulnerable challenges in access to food, price hikes, food scarcity, hunger, malnutrition and food insecurity increasing poverty and rural indebtedness. Past government decision on banning import of agrochemical such as chemical fertilizer and weedicide affected on food security of Sri Lanka negatively. Following are few consequences faced by food security of Sri Lanka.

1. **Crop yield reduction:** When alternative methods or inputs are not readily available or adopted by farmers, banning chemical fertilizers and weedicides lead to a decline in crop yields. This affected the overall production of food crops.
2. **Farmers' livelihoods:** Farmers who have been reliant on conventional agrochemicals may face economic challenges during the transition to alternative methods. There should be a need for support and training to help them adapt.
3. **Food price increase:** Reduced agricultural productivity may lead to an increase in food prices when supply was not met demand. This affected food access for certain segments of the population.
4. **Short-term challenges:** The transition away from conventional agrochemicals resulted in short-term challenges in terms of adapting farming practices, finding suitable alternatives, and achieving optimal yields.

It is essential to consider the specific context, policies, and support mechanisms in place when assessing the impact of such decisions on food security. Government initiatives to promote sustainable and resilient agricultural practices, provide education and support to farmers, and ensure a smooth transition are crucial in mitigating potential negative consequences on food security. Additionally, monitoring and adapting policies based on the outcomes observed over time are important for achieving a balance between environmental sustainability and food production.

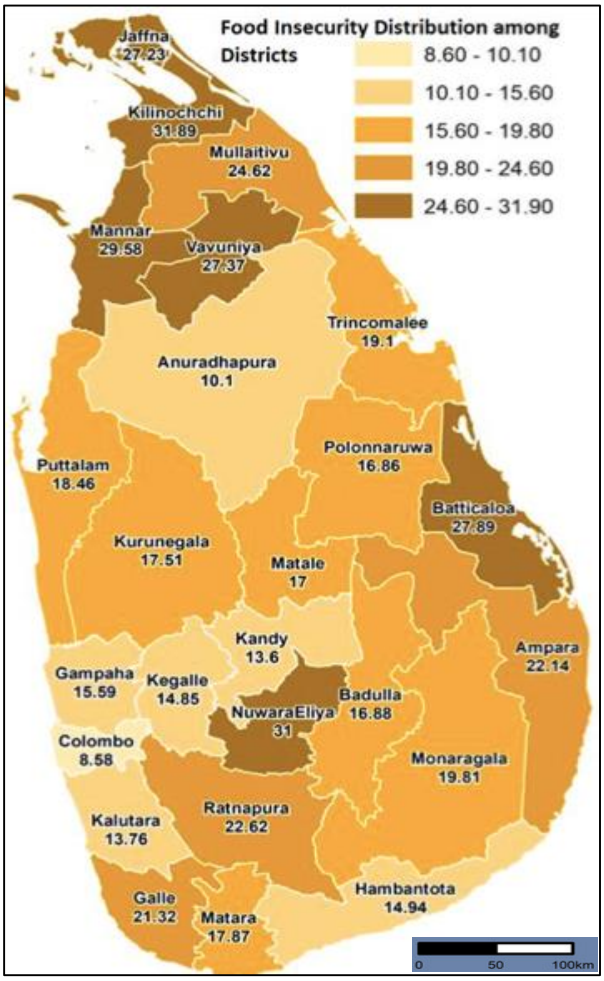


**Figure 9.** Food insecurity distribution among districts in Sri Lanka. (Source: WFP Sri Lanka, Country Brief, July 2023)

## Climate change impact on food security in Sri Lanka

Due to the consequences of extreme weather patterns, and environmental disasters, food production and supply are declined and have become uncertain considerably [27]. Rising temperatures, increased drought conditions, decrease in soil fertility, and floods or storms cause heavy loss of crop production (Figure 10 & 11). Food insecurity poses significant impacts on health, livelihood and financial status of small farmers and nutrition among vulnerable populations. A direct impact on food security is caused by climate change as global warming progresses [28] and resultant extreme weather conditions such as flood and drought incidents are becoming increasingly severe and variable in Sri Lanka that adversely affects agricultural productivity and thereby the livelihood of farmers during last ten years in Sri Lanka [29].

Sri Lanka experienced its worst drought conditions during 2016 which caused 40% decline in paddy harvest in early 2017 followed by heavy rain patterns during May 2017 that deteriorated food crop production of the country than in other countries [29- 30]. According to [31] in 2017, 229,560 households became food insecure, including rain-fed farmers and agricultural labourers being the most affected. In the 2017 Global Climate Risk Index, Sri Lanka was ranked the second worst as floods, heavy rain and landslides during 2017 caused 246 deaths and displacement of more than 600,000 people [32]. Increased frequency of drought conditions and heat stress due to temperature increase at a rate of 0.2°C per decade, increased ambient mean minimum and mean maximum temperatures, increased number of warm days and warm nights, decreased number of cold days and cold nights and increased frequency of extreme hot days are adversely affecting food security of Sri Lanka [30],33]. According to [34], Sri Lanka reported much higher and more frequent severity of weather-related disasters such as floods, landslides, droughts and storms which caused 74% of the total disaster occurrences during 1990–2018 [35]. It is reported by the [36] in 2018, that many climate hotspots in Sri Lanka specially the areas located around agricultural areas are at high risk due to increase in temperature, changes in rainfall patterns, seawater rise as a result of extreme weather events such as La Niña and El Niño extremes [36-38].

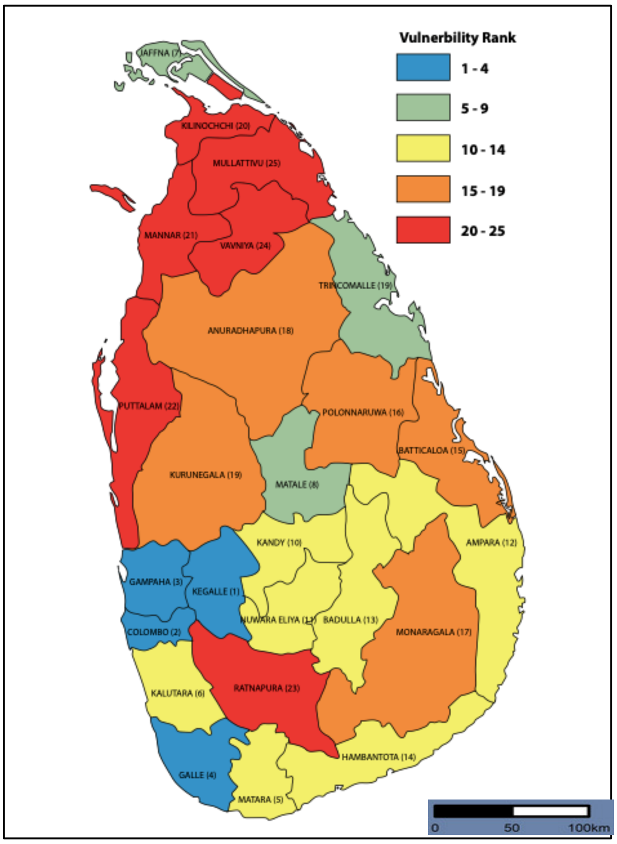


**Figure 10.** Climate Change Induced Vulnerability at District Level. (Source: Punyawardena *et al.*, 2013)

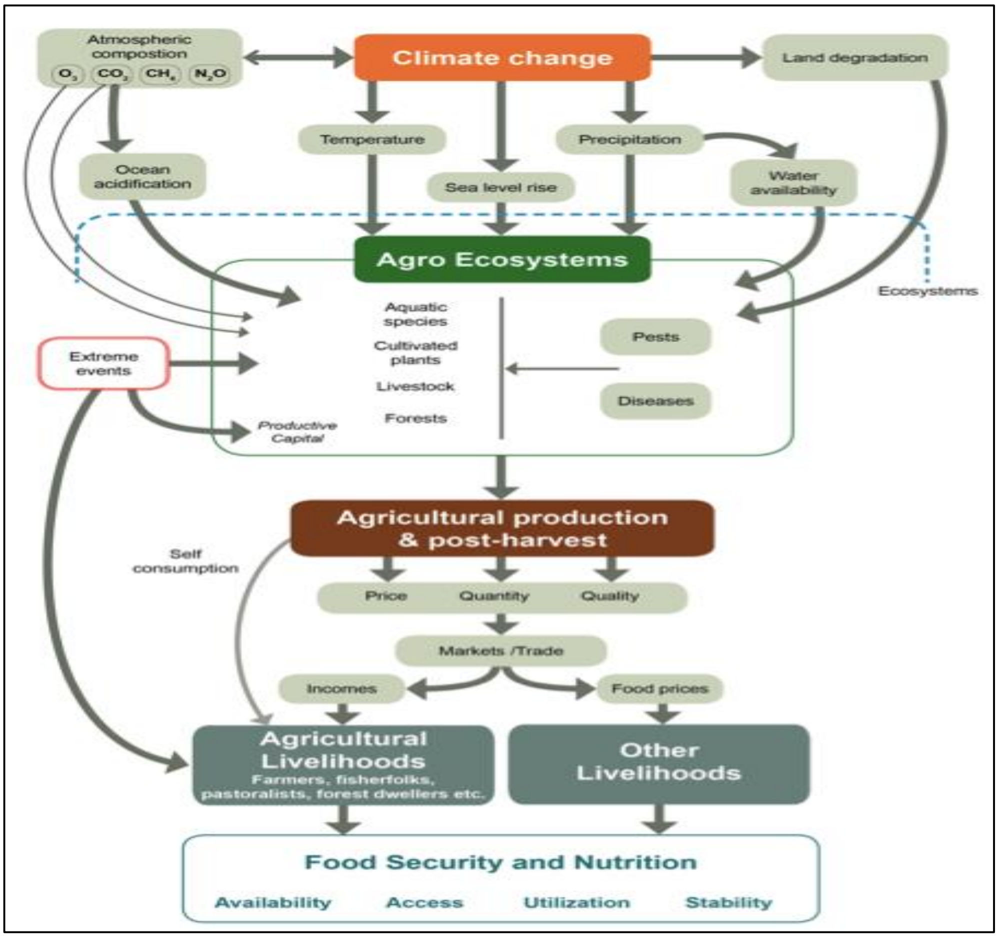


**Figure 11.** Effects of climate change on food security and nutrition. (Source: FAO, 2015)

Major greenhouse gases namely, Carbon dioxide ($CO_2$), Methane ($CH_4$) and Nitrous Oxide ($N_2O$) emitted during agricultural activities have a direct impact on climate change. Nitrogen fertilizers, flooded rice fields, soil management, land conversion, biomass burning, increased mechanization, high agro-chemical usage, livestock production and manure management etc. have been identified as contributing factors of agriculture-related activities on climate change [41]. Approximately from 5% to 10% of the overall contribution to global warming is due to livestock industry related activities as fossil energy is utilized throughout the high-intensity animal productions in modern agriculture [41-42].

Deforestation due to agricultural expansion is causing higher carbon emissions. When a large proportion of the soil carbon is lost as plants and dead organic matter during the burning of agricultural crop waste such as cereal straw, sugar cane stubble and rice straw, it contributes approximately one third of the total global $CO_2$ emissions. Nevertheless, most farmers tend to burn large quantities of crop residue, which results killing of insects and other pests and disease-causing organisms and neutralizes soil acidity and at the same time $CO_2$ is released to a considerable extent [41]. Being the most significant gas emitted during agricultural activities especially in fertilizer usage and water management, Methane ($CH_4$) is reported to release from paddy fields (91%), animal husbandry (7%) and the burning of agricultural wastes (2%). Nitrous Oxide ($N_2O$) emissions are mainly due to nitrogen fertilizer usage, legume cropping and animal waste. During fertilization, crop takes up most of the nitrogen, but the rest of nitrogen is denitrified and diffused into the atmosphere, which contributes to global warming.

In order to mitigate the impacts of climate change effects on food security as discussed above, the governments and non-governmental organizations need to develop strategies to minimize and mitigate the contributory factors to climate change and identify methods for enhanced food production, availability and access. These strategies should focus on investment in developing agricultural infrastructure facilities, crop diversification, land use planning, food preservation, diversification of food sources, and specially research and development on controlling and minimizing contributing factors of agriculture-related activities on climate change. Research on climate-informed food and training for local farmers on sustainable agriculture methods and management practices in order to ensure unthreatened global food security.

## Research and development interventions for establishing four dimensions of food security to mitigate climate change in Sri Lanka

As per [23] in 2006, four dimensions of food security, namely ensuring availability of food, accessibility, proper utilization and ensuring stability are highlighted and R&D with regard to food security should be focused to accomplish these four dimensions while mitigating climate change. Table 1 illustrates the major impacts of climate change on agricultural sector and food security of Sri Lanka and R&D actions to mitigate the impacts.

**Table 1.** Major impacts of climate change on food security and R&D actions to mitigate the impacts

| No. | Major impacts on agricultural sector | Reason | R&D actions to mitigate impacts |
|---|---|---|---|
| 1 | Reduced or reversed yield increase & reduced crop growth [43] | Changes in optimum climate requirement for optimal plant growth: temperature, atmospheric carbon dioxide ($CO_2$), and the frequency and intensity of extreme weather: floods and droughts | • Investigate, develop and introduce high yielding climate change resistant varieties with tolerance to biotic and abiotic stresses (climate change tolerant crops: ex: drought tolerant, flood tolerant, salt tolerant, etc.) and increased nutritional value using conventional and molecular techniques.<br>• Develop pest and disease resistant crop breeds<br>• Cultivation, conservation and promotion of traditional and local seeds and planting materials, community seed banks and seed exchanges, and the free distribution of seeds and planting materials<br>• Research and promotion of traditional crop varieties, food processing methods and food preservation methods<br>• Manipulation of plant microbiome, especially rhizosphere engineering to mitigate plant stresses, increase nutrient availability and control pests and diseases.<br>• Restoring soil health in agricultural lands<br>• R&D to develop water conservation measures Promote vertical gardening, hydroponic systems, and protected agriculture |
| 2 | Reduced or loss of nutritional value and quality of crops [43]. Especially in terms of monoculture practices. | Rising levels of atmospheric carbon dioxide reduce the concentrations of protein and essential minerals in most plant species. Increased pesticide usage due to increased pest pressures. While there are benefits to monoculture, such as simplified management and increased efficiency in harvesting, it also comes with certain challenges that can impact the health of the soil and the crops themselves, i.e. nutrient depletion, pest and disease buildup, soil structure degradation, changes in microbial communities, decreased biodiversity, genetic uniformity & nutrient imbalances | |
| 3 | Crop losses due to extreme weather conditions | Increased intensity of extreme weather conditions: floods and droughts, pest and disease outbreak | |
| 4 | Increase of distribution of weeds and pests under extreme climate [43] | Many weeds, pests, and fungi thrive under warmer temperatures, wetter climates, and increased $CO_2$ levels. Understanding the plasticity of weeds, pests, and fungi is crucial for effective management and control strategies. It highlights the need for integrated pest management (IPM) approaches. | |
| 5 | Increasing vulnerability to diseases in livestock: Increase the prevalence of parasites and diseases [44] | Heat stress, earlier onset of spring and warmer winters | |

| | | | |
|---|---|---|---|
| | | | • Use of internet of things for the precise application of agriculture inputs<br>• Develop smart apps aiming the farming community to access agriculture supply chain<br>• Promote smart farming (agricultural drones, livestock monitoring solutions, smart green houses, etc.)<br>• Develop community-based water harvesting and distribution systems and rainwater harvesting systems<br>• R&D on application of mulch, Jeewamurtham and biochar, and non-tilling practices<br>• Develop and promote silage and hey production<br>• Promote techniques of fodder production and conservation<br>• R&D on strengthening vaccination programmes<br>• Develop pest forecasting system<br>• Conduct research on parasites and diseases<br>• Develop disease resistant breeds (Focus: livestock and poultry)<br>• R&D to promote integrated pest management |

| | | | |
|---|---|---|---|
| | | | • Develop and introduce soil conservation measures such as SALT farming, contour farming, non-chemical fertilizer and pesticides (i.e., neem seed extract), live fences, crop rotation<br>• Research on promotion of soil organic matter<br>• R&D on bioremediation of wastewater, soil, air and food<br>• Crop diversification and multi-cropping<br>• Research on the application of agroecological, organic and natural farming methods<br>• Develop and introduce polytunnel and greenhouse farming, home gardens, agroforestry, reforestation<br>• The minimization of shifting cultivation<br>• The reduction of firewood use for cooking, the use of efficient cookstoves, the prevention of forest fires, the use of agricultural and forest residues for organic fertilizer or mulching<br>• Research on the use of agrotechnology (e.g., drip irrigation and sprinkling)<br>• Reduce usage of synthetic fertilizer and agrochemicals while researching and introducing biofertilizer with high growth impacts on crops and natural materials-based agrochemicals (pesticides, fungicides and weedicides) |

| | | | |
|---|---|---|---|
| | | | • R&D on natural and ecofriendly composting and fertilization methods ex: worm compost, bokashi method<br>• Develop efficient cookstoves in order to reduce usage of firewood, the prevention of forest fires, the use of agricultural and forest residues for organic fertilizer or mulching<br>• Research on crop modeling to access future climate change impacts<br>• R&D on ecofriendly and healthy methods increasing fruit longevity and reducing post-harvest crop losses |
| 6 | Reduced fertility of livestock | Heat stress and other extreme weather events | • R&D and promotion of animal husbandry with high yielding animal breeds with resistant to stress factors<br>• Investigate, develop and introduce high yielding climate change resistant livestock forage varieties with tolerance to biotic and abiotic stresses<br>• R&D on alterative animal feed formulations |
| 7 | Reduced livestock production (meat, eggs and milk etc.) and quality | | |
| 8 | Reduced grain and forage quality and quantity in livestock feed | Longer, intense droughts, resulting from higher summer temperatures and reduced precipitation, Increases in carbon dioxide ($CO_2$) | |
| 9 | Decline in productions in fisheries sector: Changes in temperature and seasons can affect the timing of reproduction and migration that affect the lifecycle and increase the likelihood of disease. | Changes in temperature and seasons, water sources gradually becoming acidic due to increases in atmospheric carbon dioxide ($CO_2$) [45] | • R&D on mangrove reforestation<br>• R&D on coastal conservation and develop shore shoreline management plans<br>• Research on conserving coral reefs, and related marine biodiversity |
| 10 | Marine disease outbreaks [46] | Higher water temperatures and higher estuarine salinities | |

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|---|---|---|---|
| 11 | Competition with other species over food and other resources | Migration of aquatic species for new habitats to avoid extreme weather events | • Research on safety and less pollutant fishing and transportation methods in water sources<br>• R&D on water conservation and water purification methods, renovation of minor water tanks, village tanks and irrigation channels<br>• Develop and implement a continuous programme for monitoring shoreline changes<br>• Study impacts of sea level rise on costal habitats over short-, medium- and long-term horizons<br>• Identify, declare, collect information and prepare maps on vulnerable areas to extreme events and inundation<br>• Conduct awareness programmes on sea level rise and extreme events to coastal communities to empower them for facing the risks of climate change<br>• Research on ecofriendly alternatives for polythene and plastics<br>• Research on alternative energy sources to reduce heavy consumption of non-renewable natural resources such as fossil fuel and to reduce heavy $CO_2$ and methane production (ex: wind, solar and sea tide energy)<br>• Mapping the areas prone to climate change impacts: on severity, time and duration of extreme weather conditions |
| 12 | Destruction of sensitive ecosystems and losing animal and plant habitats [39, 40] | Water sources gradually becoming acidic due to increases in atmospheric carbon dioxide ($CO_2$) [45] | |
| 13 | Implications in safety, distribution, and consumption of livestock and aquaculture products [46, 47, 48] | Climate-induced changes in pests, parasites, and microbes: increase in the use of parasiticides increase the risk of pesticides entering the food chain or lead to evolution of pesticide resistance [46, 47, 48] | |

| | | | |
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| | | | • R&D on sustainable management techniques for effective usage of natural resources<br><br>• Training and development of Sri Lankan young scientists, school children and local farmers on above aspects<br><br>• Adjust cropping calendars according to climate forecasts<br><br>• Develop systems for timely issuing and communicating of climate information to farmers<br><br>• Develop research institute capacity for conducting research on climate change impacts and tolerant varieties/breeds and climate resilient farming methods<br><br>• Develop and prepare adaptive management programmes for climate sensitive ecosystems and prepare recovery plans for highly threatened ecosystems and species |

**Compliance of R & D actions to promote food security to National Policies and Plans**

Climate change has been recognized as a key challenge faced by Sri Lanka and certain strategies, action plans and projects for overcoming climate change are presented in relevant policy documents as mentioned below. Critical issues of climate change are addressed, coordinated and controlled through actions implemented through these policies and plans [49]. These existing plans or policies covers climate change adaptation as a special focus area in a limited manner and however, they are focused on addressing specific issues of respective sectors.

- National Action Plan for Haritha Lanka Programme which has given more weight to actions targeting mitigation (i.e. reducing GHG emissions), in areas of infrastructure vulnerability, land use zoning, rainwater harvesting, increase of vectors and food security.
- Sri Lanka Comprehensive Disaster Management Programme 2014-2018 (SLCDMP) on disaster risk management has been identified separately as a cross–cutting need of adaptation
- National Action Programme for Combating the Land Degradation of Sri Lanka (NAP- CLD) has recognized climate change as a factor that can intensify the degradation of land resources in future highlighting issues such as soil erosion and landslides in up- and mid-country wet zone (upper watershed) areas.
- The Coastal Zone Management Plan (CZMP) has recognized climate change as a factor that can intensify the degradation of coastal resources in future concerning coastal erosion, coastal pollution and degradation of coastal habitats.
- The National Physical Plan 2011-2030 (NPP) has identified global warming as a concern that can affect physical development activities of the country and covers some aspects of disaster risk management.
- Sri Lanka Water Development Report 2010 (SLWDP) has identified climate change as a major driver of change in the water resources sector.
- National Agriculture Policy has identified 'Assuring food security' and 'Ensuring environment sustainability' as two major pillars of the policy in making and recognized 'Natural resource management & climate change adaptation' as a key strategic/intervention area that cover soil conservation, water management, agriculture climate forecast and disaster risk reduction.

These policies and mitigation approaches are to be delivered through the joint efforts of key stakeholders namely, Government sector (Line ministries and line agencies and central government and provincial councils), Private sector (Corporate sector and SMEs) and Civil society organizations. Further, the academics, researchers and other knowledge makers and local community-based organizations have a major role to implement and monitor responsibilities of the plan in their professional and occupational capacities.

## Suggestions and recommendations

Sri Lanka is an agriculture-based country and over 80% of its food producers are small-scale farmers [29]. Although the food security of the country largely depends on productions of agriculture, livestock and fisheries, the national accounts of agricultural sector's share has been declining due to the government less priority in policy level and as the government policies are more favorable towards the industry and service sectors. When targeting large-scale agro-industrial approaches, promoting food security needs to be ensured applying proper agro-ecological practices to cater to the demand of increasing population while mitigating climate change impacts.

Mitigating climate change impacts on food security requires a multidisciplinary approach. Among these disciplines, research and development of cross-cutting areas play an important role which accommodates following aspects,

(a) Identification of critical research needs,
(b) Improving research facilities, increasing funding for R&D,
(c) Institutional development and coordination,
(d) Collaborating with international research institutes and agencies for funding,
(e) Technology and knowledge transfer,
(f) Standardization of methodologies and processes of food production following international standards,
(g) Establishing protocols for quality assurance of food,
(h) Formation of government and institutional policies, rules and regulations aligning with food safety and security and resource mobilization,
(i) Facilitating and promoting market research for food,
(j) Research and exploration on local traditional knowledge on food security,
(k) Enhancing R&D results and output dissemination to scientific and local communities,
(l) Involving participation of farmer community, university and school children and local community in education, training and awareness programmes on R&D and climate change disaster risk and information management,
(m) Contributing to policy, laws and regulations formation by relevant authorities.

## Conclusions

Considering the above approaches, R & D actions to mitigate impacts discussed in section 03 of this chapter and summarized in table 01 have to be implemented aligning with these requirements. The existing policies require transformations and reforms aligning those to current and emerging needs. Further, cooperation among government officials, institutes and extension services (ex: Agricultural extension officers and instructors) need to be strengthened at policy level and proper and timely awareness about climate change impacts and mitigating approaches are required to be streamlined and reached to the upper to lower level of governmental and non-governmental officials and smaller to larger scale farmers. Moreover, to obtain food security and sustainability, it is crucial to comply with interventions in vulnerable communities. Providing employment opportunities to tackle poverty, hunger, and malnutrition, ensuring the right to food, safeguards the rights of small-scale food producers, and consumers. As discussed and highlighted in this chapter, it is important to recognize challenges on food security from climate change, and to search for corrective measures with more focus on reinforcing R&D nationally. Disseminating knowledge, skills and techniques in order to achieve food security and sovereignty of the country through a holistic approach and change in attitudes, lifestyle and behaviour to build adaptive capacity of the community are essential and important in current scenario of mitigating climate change and ensuring food safety.


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## Conflict of interest

Authors have declared that no competing interests exist.

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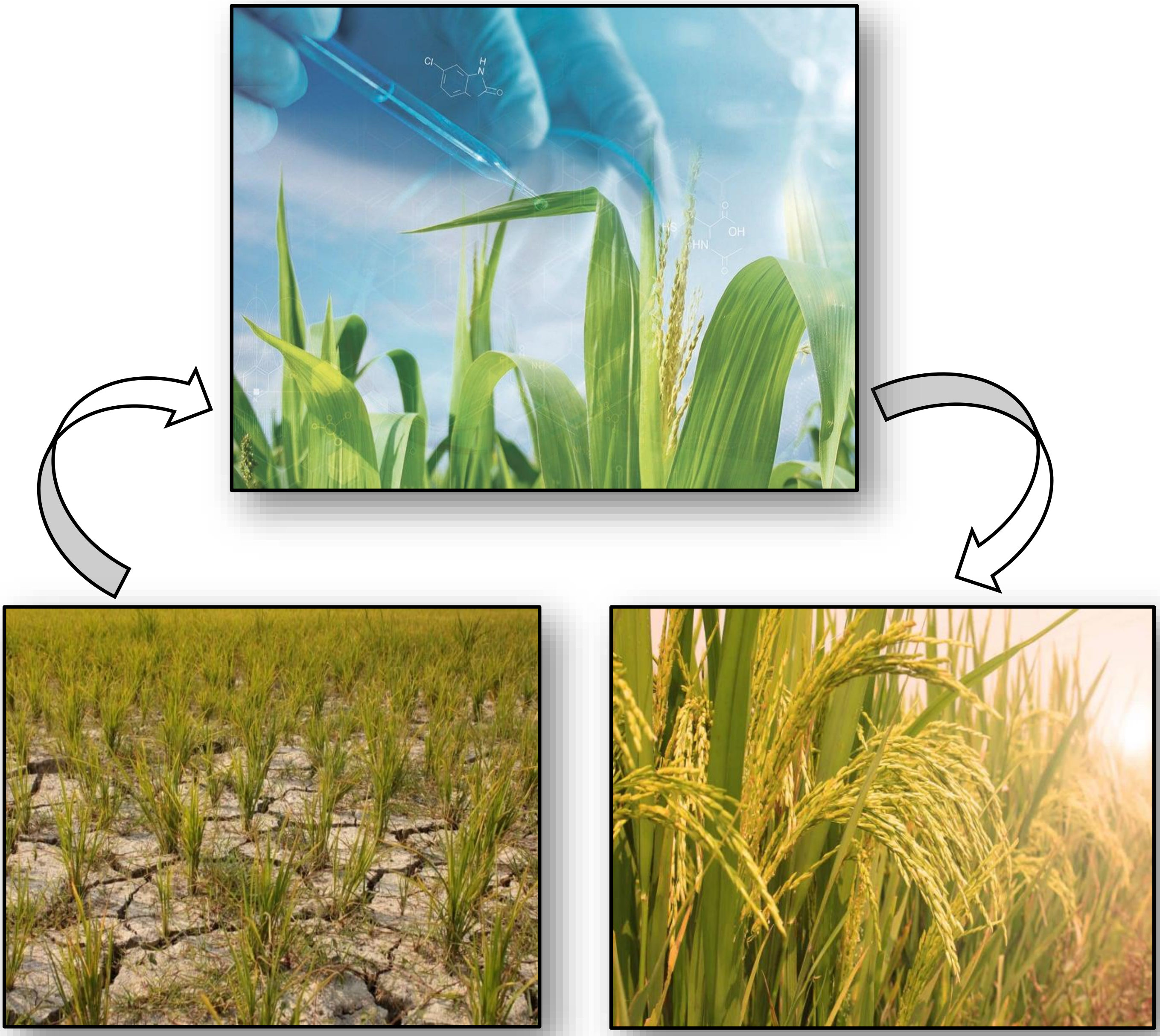
# A Comprehensive Approach to Develop Rice Varieties to Cope with Climate Change Impacts



# A comprehensive approach to develop rice varieties to cope with climate change impacts

P.V.N.N. Ranasinghe, Mapa S.T. Mapa*

**Abstract**

Rice is the major staple crop of Asia and any deterioration of rice production systems through climate changes would seriously impair food security in this continent. Compare to the other crops, rice is much prone to various abiotic and biotic stresses due to its semiaquatic phylogenetic origin. Abiotic stresses including high temperature and humidity, drought, salinity, flooding, ion toxicity, soil acidity etc. are known to influence the occurrence of biotic stresses such as weed, pests and diseases. All these stress conditions are adversely affected on rice cultivation which leads to reduce the potential yield. Over the decades' different traditional strategies like natural selections, breeding techniques use to adapt the rice varieties to different environmental conditions in different regions. Advanced technologies have led to create stress-tolerant rice varieties through the genetic engineering. Recently developed advanced rice varieties are widely use in the world which are having multi resistance characteristics for extreme conditions and able to give high yields. One such example is RD6 "BC4F4 132-12-61" rice variety from Thailand which resisted to blast disease and tolerated salt stress while giving high yield. Even though Rice Research and Development Institute developed, improved abiotic resistance rice varieties, traditionally most of the farmers are cultivate only few popular rice varieties in Sri Lanka which is the major barrier in order to overcome the drastically changing adverse weather conditions. Therefore, having locally adapted higher range of rice varieties and suitable newly developed rice varieties in the world and adopt them into local cultivation are the major solutions. Further, socioeconomic implications and adequate recommendations for making policies are significant as a comprehensive approach to mitigating abiotic and biotic stresses in changing climates in Sri Lanka.

**Keywords:** Rice varieties, Stress resistance, Abiotic/biotic stress, Climate changes

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## Introduction

Many Asian countries, especially in Southeast Asia, rice (*Oryza sativa* L.) plays a significant role in meeting dietary needs by covering a substantial portion of the food requirements. In Sri Lanka, rice has traditionally been a staple food and a major component of the diet of the vast majority of Sri Lanka's population of 23.1 million. Sri Lanka domestic rice consumption requires a volume of around 3.5 to 4.0 MMT of rice per year [1]. Approximately 800,000 farmers and their families depend directly on paddy, which is grown on 30% of the land area [2].

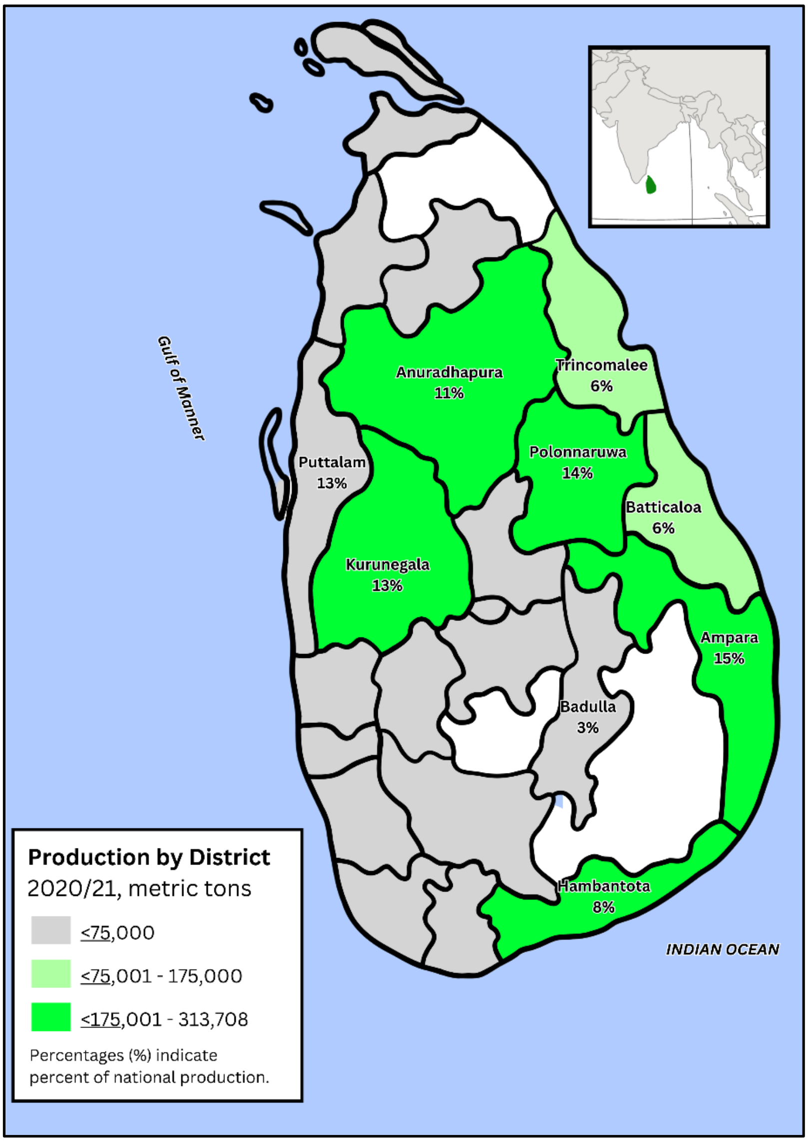


**Figure 3.** Annual rice production by districts in 2020/21

(Source: Sri Lanka Ministry of Agriculture; https://ipad.fas.usda.gov/countrysummary/Default.aspx?id=CE&crop=Rice )

Figure 1 presents statistical data from the Sri Lanka Ministry of Agriculture on Sri Lanka's total rice production by districts in 2020/21. The key findings highlight significant contributions to annual rice production from districts such as Ampara, Hambanthota, Kurunegala, Anuradhapura, Polonnaruwa, Batticaloa, and Trincomalee. These districts play a crucial role in sustaining and boosting Sri Lanka's overall rice output, reflecting their vital contributions to the nation's agricultural landscape and self-sufficiency in rice production. Rice is naturally adapted to grow in flooded or waterlogged conditions with average temperature between 20 °C and 27 °C. Average 175—300 cm annual rainfall is the most suitable for the paddy cultivation [3]. This adaptation has made rice more susceptible to certain abiotic and biotic stresses in changing climates, compared to other crops that have evolved in different environments [4].

Climate change is considered as the leading environmental problem in 21st century, and research efforts have increasingly concentrated on assessing the potential consequences of climate change. Current Sri Lanka mean annual temperature is about 27 °C in the lowlands and 15 °C in the central highlands, but according to the regional climate model projections for future temperature proposed consistent enhancement of 1.0 °C – 1.1 °C in 2030, 1.3 °C – 1.8 °C in 2050, and 2.3 °C – 3.6 °C in 2080. Along with increase temperature, it predicts 5%–10% increase precipitation by the end of the 21st century [5]. Global warming and the changing climatic conditions lead to the concurrence of multiple abiotic and biotic stresses individually or in combination [6-7]. Agriculture is a key affected focus area since it has direct connection to the climate [8]. Abiotic and biotic stresses reported to have significant negative impact on rice crop survival, growth, development and yield in most parts of the world, especially the Asia and Africa [9-10]. Abiotic stress is an environmental factor that is placed on plants, as a result of variation of physical or chemical stress. Plants are subjected to a variety of abiotic stresses, all of which have an impact on crop yield around the world (Table 1). These include basically high temperature and humidity, drought, salinity and flooding [11].

**Table 3.** Major abiotic stress conditions and their effects on rice cultivation

| Stress condition | Brief introduction and/or Harm cause to rice crops |
|---|---|
| High temperature and humidity | ***<u>Developmental stage sensitivity</u>:***<br>Rice's response to high temperatures varies based on developmental stages. Ex: Heat tolerance during booting may not correlate with flowering tolerance, Extreme heat during vegetative stages may not significantly affect the reproductive stage [12].<br><br>***<u>Vegetative phase tolerance:</u>***<br>During the vegetative phase, rice is relatively tolerant to elevated temperatures (around 35 °C daytime and 25 °C nighttime). Beyond these temperatures, reduced growth, fewer tillers, and lower dry weight may occur. High temperatures can disrupt photosynthesis by affecting thylakoid organization and membrane stability [12-13].<br><br>***<u>Transpiration cooling:</u>***<br>Efficient transpiration cooling is crucial in mitigating high-temperature impacts.<br>Closely related to relative humidity, lower humidity enhances transpiration cooling.<br>Higher humidity reduces the effectiveness of transpiration cooling [12].<br><br>***<u>Pollen sensitivity:</u>***<br>Rice pollen is highly sensitive to temperature and humidity. Viability is lost within 10 minutes after shedding.<br>Spikelets with over 20 germinating pollen grains tend to remain fertile under high temperatures. |

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| | Heat-tolerant rice varieties show slower reductions in pollen activity, germination, and floret fertility [12].<br><br>***<u>Impact on ripening:</u>***<br>High temperatures during rice ripening reduce grain weight, filling, and quality. Resulting in a higher percentage of chalky rice, smaller grains, and reduced amylase content. Heightened demand for assimilates during grain filling contributes to these issues [11].<br><br>***<u>Night temperature impact:</u>***<br>High night temperatures, especially minimum temperatures, have been linked to reduced yields.<br>Demands more comprehensive studies to address this emerging challenge [12]. |
| Drought | ***<u>Factors driving:</u>***<br>Rising temperatures, frequent El Niño events and reduced rainy days [14].<br><br>***<u>Types of drought in agriculture:</u>***<br>Catastrophic: Severe, with profound consequences like famine.<br>Chronic: Less severe but leads to substantial production losses.<br>Inherent: Linked to increasing water scarcity and competition, despite irrigation [12-13].<br><br>***<u>Effects on crop yield:</u>***<br>Drought occurs when soil moisture is insufficient for crop water requirements.<br>Yield losses in reproductive stage more than vegetative stage. Genetic basis of grain formation failure during flowering stage is a major concern [12].<br><br>***<u>Specific impact on rice cultivation:</u>***<br>Reduction in spikelet fertility, viable pollen production, panicle exertion, pollen shed, and embryo development. Decreased grain yield during fertilization and initiation of grain filling [13-14].<br><br>***<u>Simultaneous high temperature and drought stress:</u>***<br>Significant negative impact on rice cultivation, especially under upland conditions.<br>Expected increase in frequency and intensity due to climate change [13].<br><br>***<u>Combined drought and high temperature stress effects:</u>***<br>Affects rice physiology more than individual stresses.<br>Particularly during reproductive stage (flowering and grain filling). Limits photosynthesis due to reduced stomatal conductance, leading to biomass decrease.<br>Evokes unique transcriptome, metabolome, and proteome responses in rice [13].<br><br>**<u>Phenotyping considerations:</u>**<br>Specific developmental stages affected by combined drought and heat stress. |

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| | Varied stress intensities during different stages.<br>High temperatures during anthesis particularly sensitive, leading to spikelet sterility.<br>Longer durations of combined stress result in greater yield reductions [13]. |
| Salinity | ***<u>Salinity threat due to climate change:</u>***<br>Indirect factors driving salinity are rising temperatures and sea level rise. (Elevated temperatures contribute to sea level rise). Projections suggest a 3.58 °C temperature increase could lead to a substantial 1000 mm sea level rise. Coastal wetland inundation and heightened salinity result from increased sea levels [12].<br><br>***<u>Groundwater salinity and agricultural practices:</u>***<br>Over half (55%) of total groundwater is naturally saline [11].<br>Improper water and fertilizer use in irrigated agriculture exacerbate salinity. Secondary salinization and increased brackish groundwater prevalence occur [12].<br><br>***<u>Challenges in salinity conditions:</u>***<br>Rising temperatures promote salt deposition on the soil surface through capillary action. Salt becomes difficult to leach below the root zone [12].<br><br>***<u>Impact on rice cultivation:</u>***<br>Significantly affects rice growth and yield. Salinity stress can reduce rice grain yield from 20 to 100% depending on severity and duration.<br>High soil salt levels hinder water uptake, causing osmotic stress, ion toxicity, and disrupted nutrient uptake [15-16].<br><br>***<u>Effects on morpho-physiological parameters:</u>***<br>Inhibited seed germination, Stunted root and shoot growth, Reduced tiller and grain numbers per plant, decreased pollen viability and delayed seed setting, Sterile spikelet occurrence and poor leaf area development [17].<br><br>***<u>Biochemical and physiological changes:</u>***<br>Growth inhibition and yield losses result from biochemical and physiological changes. Main effects on rice plants include reduced water potential, impaired nutrient uptake, and direct toxicity from sodium ($Na^+$) and chloride ($Cl^-$) ions [17-16].<br><br>***<u>Altered physiological characteristics and biochemical indicators:</u>***<br>Ion uptake, total cation, and osmotic stress are altered by salt stress. Changes in relative growth rate and transcription efficiency occur.<br>Biochemical indicators such as proline, anthocyanins, peroxidase activity, calcium and potassium concentrations, chlorophyll, and hydrogen peroxide are affected [17-16]. |
| Flooding (Submergence) | ***<u>Historical association of rice with flooding:</u>***<br>Rice plants evolved from aquatic species. Thrive in swampy monsoonal environments [18]. |

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| | ***Role of floods in rice cultivation*:**<br>Provide essential water and nutrients to rice plants [18].<br><br>***Destructive nature of flooding:***<br>Excessive or prolonged flooding can be detrimental.<br>Considered one of the most destructive natural calamities [18].<br><br>***Climate change impact on flooding:***<br>Increased concerns due to climate change. Rice in extreme rainfall events and intensification of tropical cyclones [18].<br><br>***Major types of flooding patterns:***<br>Submergence: Short-duration flooding lasting less than three weeks.<br>Stagnant Flooding: Varies in water depth, from medium-deep to deep.<br>Flooding During Germination: Occurs in areas where rice is directly seeded [18].<br><br>***Adaptations to deep water conditions:***<br>Deepwater rice varieties have evolved to elongate rapidly to keep part of the plant above water.<br><br>***Effects of flooding on rice plants:***<br>Oxygen deprivation, reduced photosynthesis, inhibited nutrient uptake, and hindered growth.<br>Submergence during reproductive stage leads to poor grain setting, spikelet sterility, and yield loss [19].<br><br>***Specific challenges with submergence:***<br>Submergence during germination becoming more relevant with the adoption of direct-seeded systems.<br>Devastating effects on rice plants, impacting oxygen supply, photosynthesis, nutrient uptake, and growth [18, 19]. |

Biotic stresses in rice cultivation refer to the various harmful living organisms like weeds, pests, and diseases in plant ecosystems that can negatively impact on rice plants, leading to reduced yields and crop losses. The abiotic stressors can weaken the natural defenses of plants, compromise their overall health, and create favorable conditions for the proliferation of pests and pathogens. This interplay between abiotic and biotic stresses underscores the complex relationship in plant health and agricultural productivity [20].

Biotic stresses escalate as climate change influences the distribution and behavior of pests and pathogens like the brown plant hopper and rice blast etc., expanding their ranges and increasing infestation risks. Altered life cycles of these pests and diseases, along with shifts in weed growth patterns, introduce asynchrony with crop growth stages and threaten rice production. Changes in host-pathogen interactions due to environmental shifts may also lead to increased disease outbreaks in rice crops [21-22]. Some of the most common biotic stresses affecting rice cultivation are shown in Table 2.

**Table 4.** Most common biotic stress conditions and their effects on rice cultivation

| Category | Examples | Harm cause to rice crops | References |
|---|---|---|---|
| Insect pests | "Rice stem borer" | With its destructive moth larvae burrowing into rice stems, reduces yield and weakens plant structures | [4], [23] |
| | "Rice hispa beetles" | Damage leaves, leaving behind characteristic "windowpane" damage | [4], [23] |
| | "Brown plant hoppers" | Weaken rice plants, transmit viral diseases and can lead to hopper burn symptoms | [10], [4], [23] |
| | "Sap-sucking insects" | | |
| Diseases | "Rice blast" | Affects leaves, stems, and grains, causing characteristic lesions and reducing yields | [10], [4] |
| | "Sheath blight" | Attacks the sheaths and leaves of rice plants, leading to reduced photosynthesis and yield losses | [10], [4] |
| | "Bacterial leaf blight" | Affects leaves and can cause blighting and necrosis, reducing the quality of rice crops | [4] |
| | "Rice tungro virus" | Significantly reduce rice yields and reduce the grain quality | [4] |
| Weeds | "Echinochloa" species | Compete with rice plants for resources such as water, nutrients, and sunlight and reduce yields by shading rice plants and depriving them of essential resources | [24] |
| | "Cyperus" species | | [24] |
| | "Sphenoclea zeylanica" | | [24] |
| Parasitic nematodes | Root-knot nematode | Damage rice roots, leading to reduced water and nutrient uptake, stunted growth, and yield loss | [25] |
| Rodents | Rats and mice | Cause post-harvest losses by consuming rice grains during both field and storage phases | [26] |

Worldwide rice farming is practiced in various diverse ecological zones. The rice cultivation systems in different growing areas are mainly depends on various factors such as available water, soil type, and the prevailing monsoon. Therefore, rice production faces various constraints in various ecology of rice cultivation (Table 3) [10].

In agriculture, upland areas are known for their reliance on rainfall as the primary source of water for crops, as they are usually not well-suited for irrigation due to their elevation and terrain. Upland farming often faces challenges such as limited water availability, susceptibility to erosion. In addition, there are three types of lowlands which are differ from the depth of the water table and the degree of reliance on rainfall as a water source. Shallow lowlands have a relatively shallow water table, while deep lowlands have a much deeper water table. Medium lowlands fall somewhere in between of those two. Anyhow, all the three types are rain fed and do not have access to artificial irrigation systems. This may cause the occurrence of specific stresses in those areas. Rain fed shallow lowland areas are challenged by the lack of assured irrigation, recurrent droughts, and susceptibility to diseases like blast and bacterial leaf blight. Rain fed medium lowlands contend with added complexities, including intermittent flooding and pests like brown plant hoppers and gall midge. Rain fed deep lowlands are vulnerable to abiotic stresses such as floods and salinity, as well as biotic stresses like bacterial leaf blight and pests. In contrast, irrigated ecosystems benefit from controlled water access through artificial irrigation systems, alleviating many water-related constraints faced by rain fed systems [10].

**Table 3.** Rice production constraints in various ecologies of rice cultivation

| Ecosystem | Source of water | Constraints |
|---|---|---|
| Upland | Rainfall | Drought, blast, weeds, low soil fertility, Fe toxicity, soil nematode problem, lodging |
| Rainfed Shallow Lowland | Rainfall, water table | Lack of assured irrigation, frequent drought, blast, bacterial leaf blight |
| Rainfed Medium Lowland | Rainfall, water table | Lack of assured irrigation, drought, flood, drought and flood in same or different season, bacterial leaf blight, brown plant hopper, gall midge |
| Rainfed deep Lowland | Rainfall, water table, flood water | Lack of assured irrigation, fragile and low productivity, Prevailing abiotic stresses such as flood, salinity, Biotic stresses such as bacterial leaf blight, gall midge, brown plant hopper |
| Irrigated | Irrigation | Salinity, bacterial leaf blight, brown plant hopper |

Rice crop faces multiple stresses during different stages of its growth and development. It was reported that around 70% reduction in yield due to the occurrence of abiotic stresses at different stages of growth and development [6]. Therefore, it is really important to analyze the abiotic and biotic stresses effect on rice crop. Climate change has a significant impact on rice cultivation as it can stimulate both biotic and abiotic stresses, making rice production more challenging. In order to address this challenging situation in Sri Lanka, our researchers and farmers have been going through several adaptation strategies.

## Adaptations strategies for abiotic and biotic stresses in Sri Lanka

Climate change adaptation in agriculture involves a multifaceted approach to mitigate the impacts of shifting climate patterns. Farmers and communities in Sri Lanka adopt various strategies, including introducing stress resistant rice varieties and seed improvements through genetic modifications, selecting climate-resilient rice varieties, adjusting planting schedules, and changing crop and seed choices. Efficient irrigation practices and income diversification are critical components of adaptation, along with considering migration in response to climate-induced stresses. Capacity-building initiatives provide farmers with the knowledge and skills to implement effective strategies, while community-based approaches and government policies support collective resilience efforts. Ongoing research and innovation are essential to develop and refine climate-resilient farming techniques, ensuring the sustainability of agricultural systems in the face of evolving climate challenges [26]. Rice Research and Development Institute (RRDI) and other researchers in Sri Lanka have been working for years and already introduced several stress tolerance rice varieties and several other strategies to adapt these adverse impacts of climate change on rice cultivation.

### *Genetically modified rice varieties*

In response to the challenges posed by climate change in Sri Lanka's agriculture, significant efforts have been invested in genetic modifications of rice to enhance its resilience. RRDI and other research institutions have spearheaded the introduction of stress-resistant rice varieties through biotechnological methods. This involves identifying specific genes responsible for traits like drought tolerance, pest resistance, and increased nutritional content. Using genetic engineering techniques, these genes are introduced into the rice genome, and the resulting modified plants undergo rigorous testing and evaluation in controlled environments and field trials. The goal is to develop rice varieties that can thrive in the face of evolving climate patterns, contributing to sustainable and resilient agricultural systems.

The genetic modification process encompasses the isolation of target genes, their introduction into rice cells, selection of transformed cells, regeneration into whole plants, and thorough testing before regulatory approval. Advanced technologies like CRISPR-Cas9 offer precise gene editing capabilities, enabling scientists to make specific changes to the rice genome without introducing foreign genes [28]. While genetic modifications hold promise for climate adaptation, the deployment of such crops requires careful consideration of environmental impact, regulatory approval, and ongoing collaboration between scientists, policymakers, and local communities to ensure responsible and effective implementation. Following are number of examples of stress tolerance rice varieties recommended by the Department of Agriculture, Sri Lanka from 1958 to 2021 (Table 4).

**Table 4.** Recommended rice varieties in Sri Lanka (Source: RRDI rice verities- Department of Agriculture Sri Lanka

| **Recommended regional / stress resistance characteristics** | **Examples** |
|---|---|
| Drought resistance | Bg 251(GSR), Bg 250, Bg 301, Bg 314, Bw 266-7, Bw 267-3, Bw 351, Bg 359, Bw 364, Ld 365, Ld 368, Ld 371, Bw 372, Bg 377, Bw 100, Bw 451, Bw 453 |
| Submergence resistance | Bw 302, Bw 272-6b, Bg 750, Bg 455 |
| For general cultivation | Ld 253, At 313, H 10, Bg-34-8, Bg 276-5, Bg 300 , At 303, Bg 304, Bg 305, At 306, At 307, At 308, At 309, At 311, H7, Bg 34-6, Bg 94-1, Bg 94-2, Bg 350, Bg 352, Bg 357, Bg 358, Bg 360, Bw 361, At 362, Bw 363, , Bg 366, Bw 367, Bg 370, Bg 381 IP, At 373, Bg 374, H 4, H 8, Bg 11-11, Bg 90-2, Bg 379-2, Bg 400-1, Ml 273, Bg 403, Ld 408, Bg 450, Bw 452, Bg 454 |
| Iron toxic soil | Bw 267-3, Bw 361, Bw 363, Bw 364, Bw 367, Bw 372, Ld 66, Bw 100 |
| Mineral soil | Bw 351 |
| Salinity | Bg 310, At 353, At 354, Bg 369, Bw 400, At 401, Bw 451 |
| Acidic soil | Ld 66, Bw 400 |

### ***Other strategies***

Several adaptation strategies against abiotic and biotic stresses are practiced in Sri Lankan rice production (Table 5).

**Table 5.** Climate change adaptation strategies for rice production in Sri Lanka
(Source: RRDI rice verities- Department of Agriculture Sri Lanka)

| Adaptation type | Examples of application |
|---|---|
| Share loss | Encourage farmers to diversify individual cropping, to share risk |
| Bear loss | Where losses cannot be avoided or adaptation cost exceeds benefit |
| Mitigate the effects: structural and technological | Increase reservoir capacity<br>Implement water efficiency schemes |
| Mitigate the effects: legislative, regulatory and institutional | Change land-use planning practices<br>Change water allocation practices |
| Avoid or exploit changes in risk | Move rice crop to lower-risk areas<br>Promote other agricultural crops<br>Change cropping calendar |
| Research | Refine relationships between variations in climate, water resources and crop yield. Improve reliability and/or resolution of future climate variability models |
| Education, behavioral | Increase farmer awareness of the need to take individual or communal action to prepare for climate change |

*Adaptation strategies for drought:*

Wet season rainfall will decrease over most of Sri Lanka according to the scenarios modelled. The months of January and February likely will be most affected, with the rains ending much earlier. This would lead to higher paddy irrigation requirements and lower water availability, increasing water stress. Local adaptation strategies are traditional approaches for resolving water stress, such as increasing water use efficiency, water harvesting and/or reducing cropped areas. Farmers are advised to consider earlier planting and shorter duration varieties to avoid the impacts of less rainfall in January and February [2].

The study conducted in Kurunegala district by Dharmarathna et al., 2014 on different rice planting date scenarios and found that advancing the planting date by 1 month led to increased rice yields compared to the base condition, while delaying the planting date decreased yields for all varieties. This suggests that adapting to climate change in Kurunegala could involve shifting the planting date by 1 month, serving as a non-costly strategy to mitigate potential climate impacts on rice production in the region [29]. Short-Duration Seeds: Utilizing short-duration seeds (At362," "Bg300," and "Bw362) particularly during the “Yala” season on lowland fields, reduces the likelihood of production loss due to wilting by approximately 5%. These seeds mature faster, allowing crops to complete their growth cycle within a shorter timeframe and better withstand water stress [30]. Crop Diversification: Diversification into alternative field crops, especially during the “Yala” season on lowlands, significantly lowers sensitivity to water stress by about 10%. This approach involves planting different crops alongside or in rotation with rice, providing farmers with a buffer against drought-related yield losses [27].

*Agroforestry*:
Planting agroforestry trees on lowland fields during the “Yala” season can reduce water stress sensitivity by approximately 7%, enhancing overall resilience to drought [30].

*Crop residue retention*:
Implementing improved crop residue retention practices in “Maha” lowland fields, involving the retention of crop residues for at least five years and enhancing decomposition rates, substantially decreases water sensitivity by about 15.5%. This approach enhances soil health, moisture retention, and overall drought tolerance [30]. These adaptation strategies have offered practical solutions for rice farmers to mitigate the adverse impacts of drought, promoting sustainable rice cultivation in challenging water-stressed environments [30].

Drought-tolerant rice varieties have emerged as crucial solutions to combat erratic rainfall patterns in Sri Lanka's rain-fed rice cultivation zones. Approximately 35% of rain-fed rice farmers face the challenge of insufficient water availability during the “Yala” season. To address this issue, Sri Lanka's Agronomy Division, RRDI has actively engaged in screening rice lines for moisture-stressed conditions since 2008, collaborating with international organizations like the International Rice Drought Tolerant Nursery (IRDTN) and the "Green Super Rice" project. Through these efforts, two promising rice lines, “Bg 10-9028” and “IRDTN 07-11”, were identified and underwent adaptability testing. “Bg 10-9028” was released as “Bg 251 GSR” in 2014, and “IRDTN 07-11” became “Bg 314” in 2020, designed specifically for rain-fed cultivation in Sri Lanka's dry and intermediate zones. These varieties offer varying maturity periods and yield potentials, providing adaptability to diverse environmental conditions and showcasing their potential to help farmers mitigate drought stress and minimize crop losses.

*Adaptation strategies for high temperature:*
With projections indicating decreased wet season rainfall and elevated temperatures, Sri Lankan rice growers adopt various measures. Recommending short-duration seeds, crop diversification, agroforestry, and improved crop residue retention practices serve to mitigate the adverse impacts of high temperatures on rice cultivation.

*Adaptation strategies for salinity:*
In response to the challenges posed by soil salinity in Sri Lankan paddy fields, several crucial strategies and measures have been proposed to safeguard rice production as follows. Firstly, there's a focus on Soil Health Management, promoting practices like proper tillage, effective land leveling, and the application of organic manure to enhance soil health and productivity in salt-affected paddy fields. Secondly, the introduction of salt-tolerant varieties is encouraged, such as “Pokkali” and “Nonabokra”, possess mechanisms to thrive in saline conditions, making them suitable for cultivation in salt-contaminated fields [30]. Additionally, efforts have been made to develop High-Yielding Dwarf Varieties (e.g., At 354, At 401, Bg 310, and Bg 369) that are both salt-tolerant and well-adapted to local conditions, offering improved grain yields compared to traditional salt-tolerant varieties [30]. Furthermore, ensuring the availability of quality seeds of salt-tolerant rice varieties and promoting self-seed production by farmers is emphasized, along with the establishment of seed production farms in major districts to meet demand.

Other key measures include the control of illegal sand mining to prevent saltwater intrusion, the construction and maintenance of Sea Water Restraining Bunds in vulnerable areas, efficient water distribution to mitigate excessive salt concentration, and the regulation of groundwater extraction to ensure sustainable use [31]. Leveraging technology such as weather advisory systems, Geographic Information System (GIS), and remote sensing aids in informed decision-making for planting seasons and identifying areas with salt accumulation, facilitating the implementation of best management practices for paddy cultivation [31]. Several key strategies are employed by rice growers in Sri Lanka to address these biotic stresses:

*Pest-resistant rice varieties:*
Farmers in Sri Lanka have been adopting pest-resistant rice varieties that are developed through breeding programs. For instance, varieties resistant to the brown plant hopper, a significant rice pest in the region, have been cultivated. These resistant varieties help reduce the damage caused by pests, leading to higher yields and enhanced food security [32].

*Integrated Pest Management (IPM) Practices:* IPM practices are widely promoted in Sri Lanka as a sustainable approach to pest management. Farmers are encouraged to use biological control methods, such as introducing natural predators of rice pests, alongside cultural practices like crop monitoring and the use of pheromone traps. These practices help reduce pesticide use and minimize negative environmental impacts [32].

*Crop rotation*:
It is an essential practice in Sri Lankan rice farming. By alternating rice cultivation with other crops, farmers disrupt the life cycles of pests and diseases. For example, planting leguminous crops in between rice cycles can help control nematode populations, which can damage rice roots [32]. Application of Pesticides or Biocontrol Agents: While sustainable practices are prioritized, the judicious application of pesticides or biocontrol agents is sometimes necessary to manage severe pest outbreaks. Integrated approaches ensure that pesticides are used sparingly and in a targeted manner to minimize environmental and health risks [32].

## Widely used adaptation strategies, techniques and new rice varieties in the world

Researchers have addressed the challenges of climate change by employing genomics-assisted breeding (GAB) to develop rice varieties that are resilient to various biotic and abiotic stresses, enhancing their suitability for sustainable and climate-smart rice production. The International Rice Research Institute (IRRI) is at the forefront of developing climate-smart rice varieties to address a spectrum of climate-related challenges. Their approach includes utilizing marker-assisted breeding techniques for precision and efficiency. In response to drought, IRRI and its national partners have developed a drought-tolerant rice variety named "IR74371-70-1-1", released as "Sahbhagi Dhan" in India, "Sukha Dhan 3" in Nepal, and "BRRI Dhan 56" in Bangladesh. This variety exhibits genetic drought tolerance and efficient soil moisture extraction, offer a yield advantage of 0.8 to 1.6 tons per hectare over other varieties during drought years. "Sahbhagi Dhan" maintains a favorable yield even in non-drought conditions and has shorter maturity duration, allowing for increased cropping intensity. These drought-tolerant varieties have the potential to uplift socio-economically disadvantaged farmers and enhance food security in rain-fed rice-dependent areas [33]. They're addressing the adverse effects of high temperatures on rice production by identifying heat-tolerant varieties and incorporating heat tolerance into elite lines. Cold tolerance, particularly vital during critical reproductive stages, is also a focus, with IRRI conducting breeding programs to develop cold-tolerant rice varieties.

IRRI has also tackled the problem of flooding, a major threat to rice crops, by incorporating the SUB1 gene, conferring submergence tolerance for up to 14 days. This innovation has resulted in varieties such as "Swarna Sub1" and "Samba Mahsuri", which boast yield advantages of 1–3 tons following flooding [34]. Furthermore, IRRI's efforts extend to salt-tolerant rice, exemplified by "BRRI Dhan 11", designed to thrive in saline conditions, potentially boosting rice productivity in salt-affected areas. Additionally, it is dedicated to addressing soil-related challenges, such as nutrient imbalances and toxicities, by identifying genetic donors for tolerance and breeding resilient rice varieties. Their comprehensive research and breeding programs aim to create climate-resilient and stress-tolerant rice varieties, ultimately enhancing food security for farmers in challenging environments [34].

Marker-assisted backcrossing (MAB) and pyramiding techniques have been successfully applied to enhance the tolerance of popular rice varieties like “Swarna”; to specific stressors, such as submergence and drought. Quantitative trait loci (QTLs) for traits like drought tolerance (qDTY12.1, qDTY3.1, and qDTY1.1), submergence tolerance (Sub1), and salinity tolerance (Saltol). Furthermore, pyramiding of resistance genes has proven effective against diseases like bacterial blight and blast, ensuring durable resistance. These innovative breeding strategies have resulted in the development of climate-resilient rice varieties [10].

Under the Stress Tolerant Rice for Africa and South Asia (STRASA) project at the IRRI, have developed notable rice varieties carrying combinations of 6 to 10 quantitative trait locus (QTLs)/genes. These varieties exhibit resilience to multiple stresses, including bacterial leaf blight, blast, brown plant hoppers, gall midge, drought, and submergence, while maintaining superior grain quality. These lines are adaptable to various environmental conditions and can serve as elite parental lines for future breeding efforts aimed at achieving high genetic gains. Additionally, researchers have focused on enhancing adaptability to direct-seeded rice (DSR) conditions, which are particularly relevant in the face of changing climate patterns and limited water resources. Traits like root characteristics, early vegetative vigor, uniform emergence, grain yield under DSR conditions, and lodging resistance have been combined with drought tolerance and resistance to biotic stresses using marker-assisted selection (MAS). The introduction of a multi-parent advanced generation intercross (MAGIC) population strategy further advances the exploration of multiple alleles' effects on grain yield, grain quality, and stress tolerance in rice breeding [10].

An ambitious breeding program was conducted in Thailand to enhance the resilience of the popular glutinous rice variety “RD6”, known for its aromatic qualities and soft texture. They aimed to address the dual challenges of blast disease and salt stress by employing gene pyramiding techniques through MAB. This innovative approach involved combining four blast resistance QTLs (qBl 1, 2, 11, and 12) with the “Saltol QTL” for salt tolerance [35].

The breeding process began with the cross between the RD6 introgression line (RGD07005-12-165-1), which carried the blast-resistant QTLs, and the salt-tolerant “Pokkali” variety. The resulting new rice variety, named "RD6 BC4F4 132-12-61”. This newly developed rice variety that not only retained the favorable agronomic traits of RD6 but also demonstrated resistance to blast disease and salt tolerance. This development has offered great potential for Northeast Thailand's farmers, providing them with an improved rice variety capable of thriving in regions affected by blast disease and salt stress [35].

Planning and Environmental Conservation in China have given the attention to land use planning in rice-growing areas, improving soil organic matter, reducing agricultural chemical use, and enhancing organic carbon storage in agricultural systems. This includes implementing measures like green manure cropping, protective lime amendment, straw management, and precision fertilization. The integration of rice productivity technology, soil organic carbon sequestration technology, and paddy Green House Gases (GHG) emissions reduction technology can promote sustainable development of the rice industry and mitigate climate warming effects [36].

Water-saving and drought-resistant rice (WDR) represents a pioneering rice variety which posses’ high yield potential and grain quality with a capacity to thrive in water-scarce and drought-prone conditions. This innovative rice type is the result of a strategic fusion of traits from both lowland

and upland rice ecotypes, each renowned for its adaptation to distinct soil water conditions, owing to their unique drought-resistant characteristics. Upland rice, which flourishes in water-limited environments, has been particularly effective due to its robust drought avoidance and resistance attributes, cultivated through a specialized bidirectional selection process [37].
In the development of WDR varieties, the selection of elite parent plants based on the genetic diversity including drought avoidance, tolerance, water use efficiency, and productivity, thereby mitigating potential trade-offs among these essential traits. Hybridization breeding, has enhanced complex traits like yield potential and drought resistance. In addition, its overall suitability has been developed by transferring and combining pest- and disease-resistant genes. Numerous registered WDR varieties are now available to farmers, demonstrating their adaptability to both irrigated and rain-fed ecosystems. To maximize the potential of WDR, crop management practices encompass water-saving cultivation methods in lowland paddy fields and dry seeding with aerobic cultivation in rain-fed fields, promoting resource-efficient and eco-friendly rice production in China [37].

A study conducted in South Bangladesh aimed to evaluate the suitability of various rice varieties for wet and dry seasons in coastal areas affected by climate change-induced salinity and waterlogging. They have utilized statistical models like Additive Main Effects and Multiplication Interaction (AMMI) and Genotype and Genotype-by-Environment Interaction (GGE) to assess genotype-environment interaction (GEI) effects on grain yield. From this study "BRRI dhan54" has identified as the most suitable variety for the wet season, while "BRRI dhan47" has preferred for the dry season across all sites, aligning with farmer preferences for higher yields. Modern rice varieties outperformed traditional ones, suggesting their promotion for wider adoption [38]. All these newly developed rice varieties are widely utilizing in worldwide farmers regardless of the climate conditions or pathogen attack and gain significant amount of increase yield while standing against to abiotic and biotic stresses.

## Limitations
There are many adaptation technologies along with several stress tolerance rice varieties available in Sri Lanka. But most of the Sri Lankan paddy farmers stick to limited number of varieties (Figure 2) throughout the whole time. This will be a major barrier in the adaptation against abiotic and biotic stresses of rice cultivation in Sri Lanka.

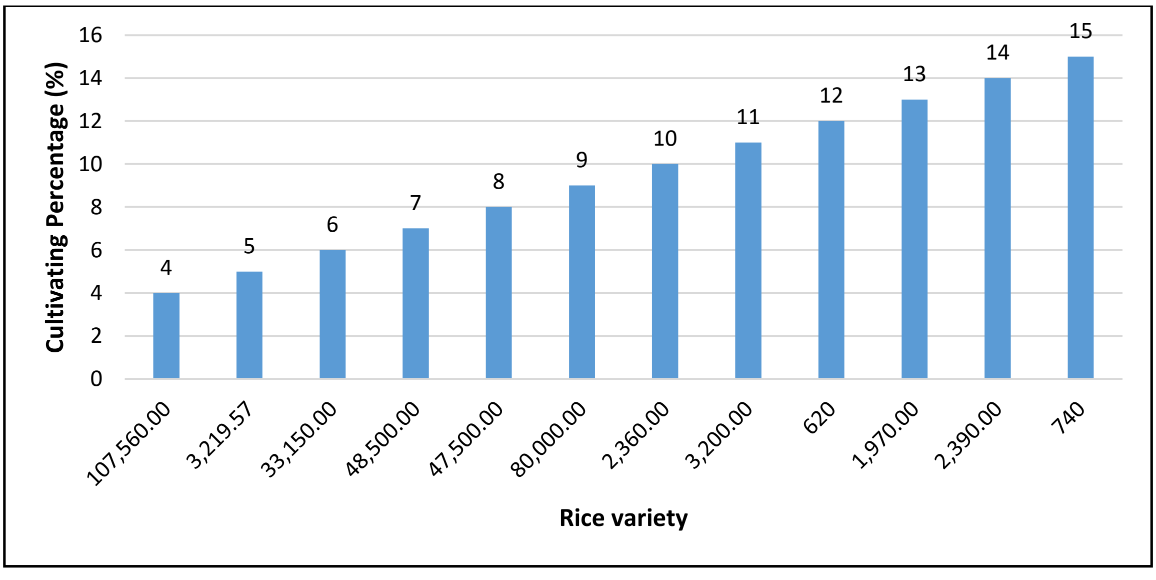


**Figure 2.** The most popular rice varieties in Sri Lanka – 2019 (Source: RRDI Socio Economics Aspects Cultivated Extents – Department of Agriculture Sri Lanka).

Many farmers adhere to traditional farming practices that have been passed down through generations. These practices often involve using specific rice varieties that have been cultivated in the region for a long time. Farmers may be resistant to change due to the familiarity and success they have had with these traditional varieties. In addition, farming is a high-risk occupation, and farmers may be risk-averse when it comes to adopting new varieties. They may fear potential crop failure or reduced yields if they switch to unfamiliar rice varieties. This risk aversion can be a significant barrier to the adoption of new and potentially more resilient varieties.

Some farmers may not be aware of the availability of newer, more stress-tolerant rice varieties. Access to information, education, and extension services may be limited in certain regions, preventing farmers from learning about and adopting improved varieties that could better withstand abiotic and biotic stresses. Farmers may face challenges in accessing seeds of new varieties. The availability of seeds for traditional varieties may be more widespread and accessible, while seeds for newer varieties may be limited or more difficult to obtain.

Some farmers choose rice varieties based on market demand and consumer preferences. If there is a consistent demand for a specific type of rice, farmers may be reluctant to switch to other varieties, even if those are more resistant to stresses. Certain rice varieties may be deeply ingrained in the cultural and culinary traditions of a region. Farmers may prefer growing rice varieties that are well-suited for local cuisines and traditional practices, reinforcing the continued cultivation of those varieties. The absence of financial or other incentives to adopt new varieties can discourage farmers from making changes. If there are no clear benefits, either in terms of increased yields, reduced input costs, or improved resistance to stresses, farmers may be less motivated to switch to new varieties.

To address these barriers, efforts should be made to provide education and extension services, improve access to seeds of stress-tolerant varieties, and create incentives for farmers to adopt new and resilient rice varieties. Collaboration between researchers, agricultural extension services, and local communities is crucial in promoting the adoption of improved agricultural practices. The most important factor is, diverse range of improved rice varieties and different strategies against abiotic and biotic stresses are introducing around the world. Respective government authorities have responsible to check the suitability of those novel rice varieties and advanced strategies in Sri Lankan contest. Then they have to work on the popularity of those latest strategies which can utilize against abiotic and biotic stresses in the ground level farmers.

## Socioeconomic implications in Sri Lanka

According to the Asian Development Bank assessing the costs of climate change and adaptation in South Asia report, dry and intermediate zones drought condition will have increased. Those zones consist the major rice cultivation areas. At the same time, they use regional climate model projections and forecast high cloud cover arising from the southwest monsoon circulation may limit solar radiation in the wet zone during the *yala* season (April–August) and in the dry zone during the *maha* season (October–January). Due to those climate changes rice production will significantly decrease in Sri Lanka (Figure 3) [5]. This will negatively effect on many sectors and food security will be in the jeopardy.

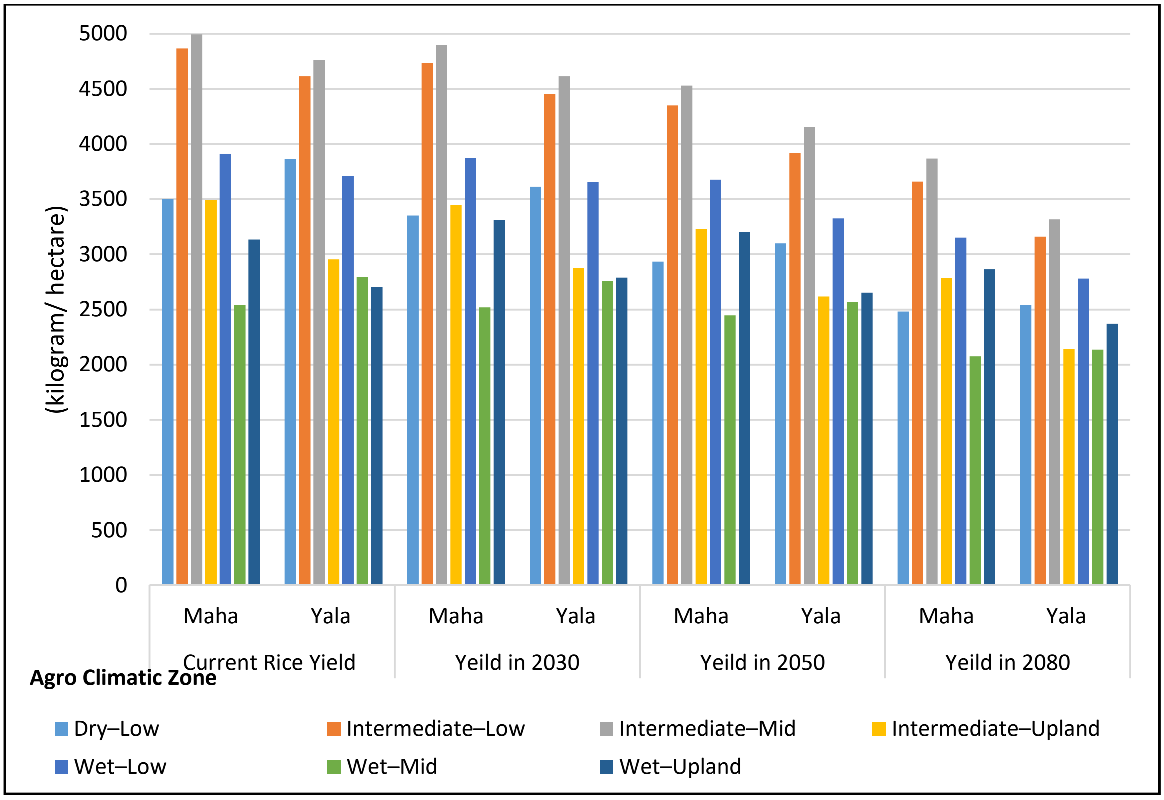


**Figure 3.** The impact of climate changes in rice production of Sri Lanka (Source: Ahmed, 2014). "Assessing the costs of climate change and adaptation in South Asia". Asian Development Bank)

The adoption and expansion of stress-resistant rice varieties affect the social and economic aspects of the country. Cultivating stress-resistant rice varieties in Sri Lanka can significantly boost the income and livelihoods of farmers while benefiting rural communities. These specialized rice varieties, developed to thrive under adverse conditions like drought, flooding, salinity, and pests, offer higher and more stable yields. As farmers adopt these varieties, they can achieve better production even amid unpredictable weather patterns, reducing risks associated with crop failure. This not only enhances food security within farming households but also contributes to community resilience by providing a consistent rice harvest. Moreover, increased farm profitability enables farmers to reinvest in agriculture, diversify income sources, and stimulate local economic development, ultimately leading to improved well-being in rural areas [39].

The availability of stress-resistant rice varieties in Sri Lanka holds substantial potential for enhancing food security. These specialized rice strains, resilient to adverse climate conditions, promise more stable rice production and a reduced risk of food shortages triggered by erratic weather patterns. Their higher yields contribute to increased rice availability in the market, fostering diversified food sources and enabling vulnerable populations to access a more nutritious diet. This leads to improved food affordability and resilience against climate-related shocks, benefiting not only small-scale farmers but also marginalized communities who are most vulnerable to food insecurity [40].

A compelling narrative of progress in global rice production unfolds through insightful analysis. The discernible upward trend in rice yield over time, combined with the expanding production areas worldwide, distinctly underscores a positive trajectory. This collective increase in rice production signifies agricultural advancement and serves as a clear indicator of the potential to fortify and enhance global food security. The correlation between expanded production areas and increased yield is unmistakable, contributing directly to a more robust and reliable food supply.

This optimistic pattern signifies a noteworthy step forward in addressing the challenges of food security, laying the foundation for sustained agricultural resilience on a global scale [41].

It also influences rural-urban migration patterns in Sri Lanka. When farmers have more reliable incomes due to these varieties, it can discourage migration to urban areas in search of employment. This could lead to the retention of the rural workforce, potentially revitalizing rural communities, preserving local traditions, and reducing the strain on urban infrastructure [42]. The expansion of stress-resistant rice varieties aligns with environmental sustainability goals by reducing the need for excessive pesticide use, promoting efficient resource utilization, and potentially minimizing land use changes. However, careful monitoring is necessary to ensure that sustainable agricultural practices are maintained and that the introduction of new varieties does not lead to unintended environmental consequences [43].

There may be socioeconomic disparities in access to stress-resistant rice varieties and associated agricultural technologies. It's important to ensure that smallholder farmers and marginalized communities have equitable access to these innovations. Barriers to access, such as affordability and knowledge gaps, should be addressed to promote inclusive adoption [44]. The shift towards stress-resistant rice varieties may lead to changes in labor demand in the agricultural sector. While there may be reduced demand for manual labor in some aspects of rice farming, there could be an increased need for specific skills related to the cultivation of these varieties, such as knowledge of their unique requirements and traits [45].

The adoption of stress-resistant rice varieties can influence rice markets, affecting prices and competition. While increased rice availability may stabilize prices, market dynamics can vary [46]. The adoption and expansion of stress-resistant rice varieties in Sri Lanka not only impact farmers but also hold significant implications for consumers. The increased availability of rice in the market, resulting from higher and more stable yields of stress-resistant varieties, plays a crucial role in influencing food accessibility and affordability for consumers. With a more consistent rice harvest, consumers are likely to experience a stabilized rice supply, potentially leading to more predictable and affordable prices.

Moreover, the diversified food sources facilitated by the higher yields of stress-resistant rice varieties contribute to a more nutritious diet for consumers. As these specialized rice strains offer resilience against adverse climate conditions, consumers can benefit from a continuous and varied supply of rice, reducing the vulnerability to food shortages triggered by erratic weather patterns. This improvement in food security at the production level directly translates into enhanced food accessibility and quality for consumers.

Additionally, the potential reduction in rural-urban migration, driven by increased income stability for farmers, can positively impact rural communities. Consumers in these areas may witness a preservation of local traditions and a sustained rural workforce, contributing to the overall well-being of rural communities. It's important to conduct thorough research and gather data to support the analysis of these socioeconomic implications. Additionally, engaging with stakeholders, including farmers, agricultural experts, and policymakers, can provide valuable insights into the potential effects of expanding stress-resistant rice varieties in Sri Lanka.

### Policy recommendations

The IRRI and other related collaborations play a pivotal role in advancing rice research in Sri Lanka. It is better to have well planned and improved policies which are integral to addressing the challenges posed by abiotic and biotic stresses in changing climates. Firstly, it needs to focus on securing adequate funding for research programs, fostering collaborations with national and international institutions, private sector partners, and government agencies. This strategic pooling of resources ensures a robust foundation for innovative rice variety development initiatives. In addition, through the international collaborations, newly developed successful, multi stress resistant rice varieties could trial on specific regions in Sri Lanka and analyze their suitability and productivity under the adverse climatic conditions.

Another factor is that, the prioritization of traits within IRRI's breeding programs are needed to guide by specific policies aiming at enhancing resilience. These policies may emphasize traits such as drought tolerance, disease resistance, and adaptability to varying climate conditions. Implements policies concerning seed production, quality control, and distribution, ensuring that stress-tolerant rice seeds are not only developed but also made accessible to farmers throughout the country.

Policies that promote the dissemination of research findings and knowledge about stress-tolerant rice varieties will be strengthening extension services. This involves extensive training programs for extension workers and initiatives to raise awareness among farmers, encouraging the widespread adoption of advanced rice varieties. Moreover, the integration of climate-resilient agriculture strategies into national policies aligns IRRI's research goals with broader initiatives aims at addressing the impacts of climate change on agriculture.

Continuous capacity building is another significant factor, that encompassing scientists, researchers, extension workers, and farmers. Training programs ensure that stakeholders stay abreast of the latest advancements in rice research, cultivation techniques, and sustainable agricultural practices. The robust monitoring and evaluation frameworks, systematically assessing the impact of research and policies over time will allow the success of strategies to ensure that intended goals are achieved effectively.

Lastly, active promotion of international collaboration, fostering partnerships with global research organizations and institutions is really important. The exchange of germplasm, research findings, and collaborative projects on an international scale accelerates progress in rice variety development, contributing to a collective effort in addressing the challenges posed by abiotic and biotic stresses in the dynamic context of changing climates.

## Summary

The rice production is a crucial factor for the many Asian nations, and even a small decrease in productivity could threaten food security. Climatic changes directly accelerate abiotic and biotic stresses, which may cause to decrease the rice production. Therefore, approaches to overcome abiotic and biotic stresses due to climate change are essential. Developing more tolerant crop varieties and improving crop management practices could be possible solutions for these increasing abiotic and biotic stresses. Most of other Asian countries who use the rice as one of their major staple crops are already adopted improved rice varieties in their field. But most of the Sri Lankan rice farmers are stick with few rice varieties especially reluctant to change their traditional seed collection. Current climatic pattern in Sri Lanka dramatically changing than past decays. Therefore, Sri Lankan rice crop cultivation system must adapt to traditional and advanced mitigating strategies in parallel to other Asian countries. The promotion of climate-resilient rice varieties that can withstand drought, flooding, salinity, and pests, efficient irrigation practices and etc. are some strategies could follow in Sri Lankan farmers. However, the Global trends are more tend to expand novel rice verities with combined stress resistance characteristics to withstand adverse climatic effects. Therefore, Sri Lankan rice crop cultivation system needs to expand the range of rice verities with the suitable analyzing techniques to comply with the regional specifications.

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## Conflict of interest

Authors have declared no conflict of interests exist.

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# Enhance the agriculture-based economy of Sri Lanka: A decision support tool including crucial climate forecast and optimal cultivation plan

# Enhance the agriculture-based economy of Sri Lanka: A decision support tool including crucial climate forecast and optimal cultivation plan

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## Abstract

Sri Lanka's agricultural practices are largely rain-fed, meaning they heavily rely on the natural precipitation patterns for irrigation rather than extensive irrigation systems. This makes rainfall a crucial determinant of crop success and overall agricultural productivity. As rural communities in Sri Lanka make a considerable contribution in terms of feeding a growing population, this chapter introduces a user-friendly decision support tool called as 'Smart Agro Planner' which contains a rainfall forecasting model and optimal cultivation plan for the agricultural officers of a village to make decisions on cultivation and deliver to the farming communities. This study introduces a new approach to forecast rainfall using Multiple Artificial Neural Network (ANN) model and newly introduced modified picture fuzzy numbers known as Sceptical Picture Fuzzy Numbers with its application in the proposed cultivation plan. The proposed cultivation plan provides details of which crops should be cultivated in which area and the best time for cultivation to get maximum profit and harvest considering uncertainty using fuzzy optimization. Sceptical Picture Fuzzy Goal Programming model was capable to obtain optimal results, which has 14% of increment in profit compared to the existing cultivation of a farming village using 24 crops. ANN model which is capable of forecasting rainfall with a mean squared error of 0.0547. This invention will contribute to enhance the economy and stabilize the food reserves in Sri Lanka.

**Keywords:** Artificial Neural Network, Cultivation plan, Fuzzy numbers, Rainfall forecasting, Rural Farming

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## Introduction

Agriculture plays a pivotal role in Sri Lanka's economy, with a significant portion of the population depending on agriculture for their livelihoods and it is making an enormous contribution to the economy of the nation. However, the industry also must deal with issues/ challenges including resource scarcity, changing climatic patterns, and the requirement for sustainable operations. To address these challenges and propel the agricultural sector towards greater resilience and productivity, the development of a comprehensive decision support tool becomes imperative to empower farmers and stakeholders in the agricultural value chain with actionable insights derived from the integration of crucial climate forecasts and optimal cultivation plans. By leveraging advanced technologies and data-driven methodologies, such a decision support tool seeks to revolutionize decision-making processes within the agricultural landscape of Sri Lanka including early detection of climatic changes.

Climate change is any change in climate over time, whether due to natural variability or because of human activity [1]. Climate change may cause risk at cultivation which may be unavoidable and unexpected [2-4]. The possible effects of climate change on agricultural production are not limited to crop cultivation. It will cause fluctuations in the quantity of the crop yields. As agricultural productivity is climate sensitive, forecasting climatic factors is important to maximize the harvest and plan and manage the cultivation [5]. Even though all the climatic factors have influenced on cultivation, rainfall is one of the major influential factors to Sri Lankan agriculture [6-7]. Rainfall forecasting is vital in agriculture, and it is a challenging task due to the uncertainty of natural phenomena [8]. Rainfall and its variability influence all sectors of agriculture in several ways. Rainfall variation adversely affects the quantity of the harvest. The rate of change of rainfall fluctuates with time. As it is changing with time, it is important to have an accurate rainfall forecasting model. Rainfall prediction is very important for decision makers in agriculture. Accurate information on rainfall is essential for the planning and management of cultivation [1]. A process of early recognition of rainfall is valuable for farmers as it is useful to make decisions that yield attractive benefits in the agriculture [9]. In the process of rainfall forecasting, it is required to consider what are the factors affecting rainfall [6].

According to Shaikh et al. in 2017, temperature, humidity, wind speed, air pressure, cloud percentage are some of the major factors affecting rainfall [10]. Hence, this study considered available meteorological factors: rainfall, temperature (TM), humidity (HD), wind speed (WS), air pressure (PS) and cloud percentage (CD) recorded in a surrounding metrological station located in Dompe Divisional Secretariat in Gampaha district in the model building process. Based on these climatic factors, rainfall forecasting models can be developed using artificial neural networks. Past studies have obviously indicated that ANN is a good approach and has a high potential to forecast rainfall and it has better accuracy than other models [11]. On the other hand, Artificial neural network (ANN) can be used for predictions as it has a capability of examining and determining the nonlinear behavior of the historical data used for prediction [12]. Artificial neural network is a type of data driven technique which refers the principle of biological neurons [13]. The most common neural networks used in predictions in past studies is the feed forward neural network. Back propagation is widely used algorithm for training feed forward neural network [10]. Therefore, in this study, ANN approach is being applied to forecast rainfall using other related climatic factors. Further, the novelty of this study is introducing the Multiple ANN model for rainfall forecasting. The Multiple ANN is a neural network which obtains values for the input variables from another ANN model. It is a collection of ANNs.

### Artificial Neural Networks for forecasting climatic factors

The data set contains monthly records of rainfall (mm), temperature (°C), wind speed (kmph), air pressure (mb), humidity (%) and percentage of clouds from January 2010 to December 2019 in

Dompe divisional secretariat, Gampaha district. The data set was divided into three parts and used for training (80%), validation (10%) and testing (10%) before applying to each model. The training data set was used for weight updating process in each model. A practical way to find an optimal point of better generalization and avoid over fitting is to set aside a small percentage of the training data (validation set). Finally, the performance of the models was evaluated using the unseen data set.

The relationship between variables and cross correlations were examined using suitable statistical techniques to identify the significant variables for forecasting models. Pearson and Spearman Rho correlation coefficients are two widely using statistical measures when measuring the relationship between variables. The Pearson correlation coefficient assesses the linear relationships between variables, while the Spearman correlation coefficient evaluates the monotonic relationships and hence this study continues with both coefficients. Table 1 represents the Person's and Spearman Rho correlations along with the p-value between rainfall and other selected climatic factors and cross correlations among them. These correlation coefficients were used to identify the significant factors affecting rainfall (i.e., p-value<0.05) and only the significant relationships are given in the Table 1. Non-significant correlations such as Temperarture_lag2, Temperature_lag3, Windspeed_lag2, Humidity_lag2, Cloud_lag2 were not considered further where 'Lag_1' represents the one month before value of the corresponding variable and 'Lag_2' represent a period of 2 month before value of the corresponding variable while 'Lag_3" represent a period of 3 month before value of the corresponding variable.

**Table 1.** Correlation and cross correlation between rainfall and other significant climatic factors

| Parameter | Correlation with rainfall | | | |
|---|---|---|---|---|
| | **Pearson's** | **p-value** | **Spearman Rho** | **p-value** |
| Temperature (c) | -0.114 | 0.001 | -0.122 | 0.03 |
| Wind speed (kmph) | -0.190 | 0.001 | -0.194 | 0.001 |
| Pressure (mb) | -0.279 | 0.001 | -0.281 | 0.001 |
| Humidity (%) | 0.326 | 0.001 | 0.310 | 0.001 |
| Cloud (%) | 0.386 | 0.001 | 0.401 | 0.001 |
| Temparature_lag1 | 0.248 | 0.001 | 0.243 | 0.001 |
| Windspeed_lag1 | -0.219 | 0.001 | -0.229 | 0.001 |
| Pressure_Lag1 | -0.130 | 0.02 | -0.130 | 0.007 |
| Presure_Lag2 | -0.048 | 0.04 | -0.056 | 0.03 |
| Pressure_Lag3 | -0.030 | 0.04 | -0.083 | 0.04 |
| Humidity_lag1 | 0.156 | 0.001 | 0.126 | 0.002 |
| Cloud_Lag1 | 0.242 | 0.001 | 0.246 | 0.001 |

According to the Table 1, temperature, wind speed and air pressure have negative correlation with rainfall while humidity and cloud percentage have positive correlation with rainfall. Lag 1 of temperature, wind speed, air pressure, humidity and cloud percentage were significantly correlated with rainfall while lag 2 and 3 of air pressure were also statistically significant. The procedure of training an ANN as a forecasting model is as follows: The data set was trained for several trials and observed the number of hidden layers and neurons in each hidden layer which captured the minimum error. There are some transfer functions used in neural networks. Log-sigmoid, tan sigmoid and pure linear are the most popular functions among them. Then the neural network was trained several times to cover all possible combinations of transfer functions by changing transfer function in layers. There are several backpropagation training algorithms available which are used to train neural networks. After selecting the training algorithm, the model was trained by changing model parameter: combination coefficient (μ) from 0.00001 to 0.01 until the minimum error was obtained. Different networks give different results with the same training functions and adaptive learning functions having the same number of neurons. Therefore, thousands of models were trained until reaching the minimum error in each forecasting model. With reference to Table 1, out of climatic factors temperature, air pressure, wind speed, humidity and cloud percentage are significantly correlated with rainfall. To obtain an accurate rainfall forecasting model it is important to consider those climatic factors to the ANN model. Though present values of the climatic factors (lag zero) are required it is very important to train individual ANN models to forecast each climatic factor separately. Then, obtained those forecasted values as input to the rainfall forecasting model. Hence ANN was developed for aforementioned climatic factors separately.

### Artificial Neural Networks for Temperature, Pressure, Cloud Percentage, Humidity and Wind speed forecasting models

As mentioned in the introduction ANN models are capable of forecasting time series data with minimum errors. Hence ANN models were trained with minimum errors measured using Mean Squared Error (MSE) and Normalized Mean Squared Error (NMSE). Table 2 illustrates the identified input combinations for each climatic factor along with MSE and NMSE.

**Table 2.** Performance of the models with different combinations of input variables

| Variables | Input combination of variables | MSE | NMSE |
|---|---|---|---|
| Temperature | TM_lag1, TM_lag2 | 0.2257 | 0.2364 |
| Pressure | PS_lag1, PS_lag2 | 0.2478 | 0.2130 |
| Cloud percentage | CD_lag1, CD_lag2 | 0.2485 | 0.2369 |
| Humidity | HM_lag1, HM_lag2 | 0.1457 | 0.1222 |
| Wind speed | WS_lag1, WS_lag2 | 0.1987 | 0.1803 |

* Temperature (TM), Wind speed (WS), Pressure (PS), Cloud percentage (CD), Humidity (HD), Temparature_lag1 (TML1), Windspeed_lag1 (WSL1), Windspeed_lag2 (WSL2), Pressure_Lag1(PSL1), Pressure_Lag2 (PSL2), Pressure_Lag3 (PSL3), Humidity_Lag1 (HDL1), cloud_Lag1 (CDL1), L1- lag 1, L2-Lag 2, L3-Lag 3

Input combination of all climatic factors were limited to its first and second lags which were obtained minimum mean squared error and minimum normalized squared error. Then, the number of hidden layers were changed from one to four for the models selected above and recorded results in Table 3.

**Table 3.** Performance of the models with different number of hidden layers

| No of hidden layers | Temperature | Pressure | Humidity | Wind speed | Cloud percentage |
|---|---|---|---|---|---|
| | | | MSE | | |
| 1 | 0.2257 | 0.2478 | 0.1458 | 0.1987 | 0.2485 |
| 2 | 0.2121 | 0.2490 | 0.1246 | 0.2082 | 0.2501 |
| 3 | 0.3641 | 0.2501 | 0.2781 | 0.2584 | 0.2634 |
| 4 | 0.3077 | 0.2687 | 0.3010 | 0.2672 | 0.3870 |
| | | | NMSE | | |
| 1 | 0.2364 | 0.2130 | 0.1221 | 0.1803 | 0.2369 |
| 2 | 0.2188 | 0.2568 | 0.1167 | 0.2071 | 0.2544 |
| 3 | 0.2789 | 0.2544 | 0.2498 | 0.2203 | 0.2578 |
| 4 | 0.3047 | 0.2614 | 0.2765 | 0.2644 | 0.3109 |

There are two hidden layers in the ANN build for forecasting the temperature and humidity while one hidden layer in the ANN build for forecasting the pressure, wind speed and cloud percentage which have minimum errors. Therefore, those models were used to further improvements. As ANN models developed to forecast temperature and humidity, captured two hidden layers, Table 4 (i) illustrates number of neurons required for those models in each layers.

**Table 4 (i).** Performance of the models with different number of hidden neurons under 1st and 2nd hidden layers

| Number of Neurons | | MSE | NMSE |
|---|---|---|---|
| **Layer 1** | **Layer 2** | | |
| **Temperature** | | | |
| 7 | 8 | 0.2780 | 0.3344 |
| 7 | 9 | 0.3881 | 0.3478 |
| 8 | 5 | 0.3748 | 0.3627 |
| 8 | 6 | 0.2165 | 0.2142 |
| 8 | 7 | 0.2740 | 0.2355 |
| 8 | 8 | 0.2783 | 0.3007 |
| 9 | 9 | 0.3578 | 0.3422 |
| 9 | 10 | 0.3047 | 0.3881 |
| 10 | 8 | 0.3742 | 0.3077 |
| 10 | 9 | 0.3904 | 0.3199 |
| 10 | 10 | 0.4369 | 0.4071 |

| **Humidity** | | **MSE** | **NMSE** |
|---|---|---|---|
| 10 | 9 | 0.1245 | 0.1169 |
| 10 | 10 | 0.1378 | 0.1346 |
| 10 | 11 | 0.1480 | 0.1631 |
| 10 | 12 | 0.1495 | 0.1385 |
| 11 | 11 | 0.1663 | 0.1451 |
| 11 | 12 | 0.1879 | 0.1602 |
| 12 | 10 | 0.1387 | 0.1300 |
| 12 | 11 | 0.1268 | 0.1278 |
| 12 | 12 | 0.1208 | 0.1143 |
| 13 | 10 | 0.2047 | 0.2382 |
| 13 | 11 | 0.2525 | 0.2366 |
| 13 | 12 | 0.2877 | 0.2361 |
| 14 | 10 | 0.3781 | 0.3408 |

It was observed that 8 and 6 neurons in first and second hidden layers respectively in the ANN build for forecasting the temperature has minimum error. Further, based on the minimum MSE and NMSE, it was identified that there are 12 neurons in both first and second layers in the ANN build for forecasting humidity. There was one hidden layer in ANN models developed for forecasting the pressure, wind speed and the cloud percentage. Table 4 (ii) illustrates the number of neurons required for the hidden layer in three models.

**Table 4 (ii).** Performance of the models with different number of hidden neurons under one hidden layer

| No. of Neurons in Layer 1 | Pressure | | Wind speed | | Cloud percentage | |
|---|---|---|---|---|---|---|
| | MSE | NMSE | MSE | NMSE | MSE | NMSE |
| 1 | 0.4369 | 0.4071 | 0.4028 | 0.3907 | 0.2485 | 0.2369 |
| 2 | 0.3047 | 0.3081 | 0.3999 | 0.3987 | 0.2301 | 0.2270 |
| 3 | 0.3748 | 0.3627 | 0.3666 | 0.3870 | 0.2280 | 0.2207 |
| 4 | 0.3904 | 0.3899 | 0.3904 | 0.3887 | 0.2358 | 0.2135 |
| 5 | 0.3858 | 0.3477 | 0.2908 | 0.2807 | 0.2178 | 0.2038 |
| 6 | 0.3783 | 0.3307 | 0.2783 | 0.2307 | 0.1938 | 0.1759 |
| 7 | 0.3578 | 0.3422 | 0.1925 | 0.1878 | 0.1578 | 0.1422 |
| 8 | 0.2778 | 0.2530 | 0.1723 | 0.1603 | 0.1778 | 0.1597 |
| 9 | 0.2863 | 0.2599 | 0.1987 | 0.1803 | 0.2163 | 0.2099 |
| 10 | 0.2301 | 0.2200 | 0.2047 | 0.2081 | 0.2201 | 0.2200 |
| 11 | 0.2280 | 0.2207 | 0.2748 | 0.2627 | 0.2345 | 0.2207 |
| 12 | 0.2208 | 0.2103 | 0.2904 | 0.2899 | 0.2423 | 0.2178 |
| 13 | 0.2347 | 0.2309 | 0.3858 | 0.3477 | 0.3904 | 0.3890 |
| 14 | 0.2351 | 0.2343 | 0.3783 | 0.3307 | 0.3858 | 0.3478 |
| 15 | 0.2423 | 0.2402 | 0.4280 | 0.4027 | 0.3583 | 0.3336 |

It was identified that there are 12, 8 and 7 neurons in hidden layers of the ANN build for forecasting the pressure, wind speed and cloud percentage, respectively based on the minimum error in each model. Selected transfer functions for each layer are illustrated in Table 5 (i) and (ii) for each climatic factor.

**Table 5 (i).** Performance of temperature and humidity forecasting models by changing transfer function in each layer

| Input hidden layer 1 | Hidden layer 1 to hidden layer 2 | Hidden layer 2 to output layer | Temperature | | Humidity | |
|---|---|---|---|---|---|---|
| | | | MSE | NMSE | MSE | NMSE |
| Log-sigmoid | Log-sigmoid | Log sigmoid | 0.2374 | 0.2345 | 0.1208 | 0.1142 |
| Log-sigmoid | Log-sigmoid | Pure linear | 0.2143 | 0.2113 | 0.1568 | 0.1332 |
| Pure linear | Log-sigmoid | Tan sigmoid | 0.2987 | 0.3014 | 0.2089 | 0.1987 |
| Log sigmoid | Tan sigmoid | Pure linear | 0.3780 | 0.3105 | 0.1187 | 0.1106 |
| Pure linear | Tan sigmoid | Tan sigmoid | 0.3328 | 0.3780 | 0.1356 | 0.1278 |
| Tan sigmoid | Tan sigmoid | Log-sigmoid | 0.3078 | 0.3792 | 0.1236 | 0.1158 |

It was identified that the transfer function of the Input layer to hidden layer 1 as log-sigmoid, hidden layer 1 to hidden layer 2 as log-sigmoid and hidden layer 2 to output layer as pure linear function for the ANN model build for temperature while the transfer function of the Input layer to hidden layer 1 as log-sigmoid, hidden layer 1 to hidden layer 2 as tan-sigmoid and hidden layer 2 to output layer as pure linear function for the ANN model for humidity depend on the minimum errors of the test set.

**Table 5 (ii).** Performance of pressure, wind speed and cloud percentage forecasting models by changing transfer function in each layer

| Input layer to hidden layer 1 | Hidden layer 1 to output layer | Pressure | | Wind speed | | Cloud percentage | |
|---|---|---|---|---|---|---|---|
| | | MSE | NMSE | MSE | NMSE | MSE | NMSE |
| Log-sigmoid | Log-sigmoid | 0.2208 | 0.2103 | 0.1880 | 0.1628 | 0.1578 | 0.1422 |
| Log-sigmoid | Pure linear | 0.2531 | 0.2178 | 0.1723 | 0.1603 | 0.1367 | 0.1178 |
| Log sigmoid | Tan sigmoid | 0.2147 | 0.2023 | 0.1971 | 0.1874 | 0.1369 | 0.1123 |
| Tan sigmoid | Tan sigmoid | 0.2387 | 0.2246 | 0.2144 | 0.2036 | 0.1378 | 0.1230 |
| Tan sigmoid | Log-sigmoid | 0.2439 | 0.2371 | 0.2470 | 0.2469 | 0.1056 | 0.1023 |
| Tan sigmoid | Pure linear | 0.2498 | 0.2475 | 0.2698 | 0.2580 | 0.1155 | 0.1369 |
| Pure linear | Pure linear | 0.2457 | 0.2498 | 0.3066 | 0.2907 | 0.2151 | 0.2036 |
| Pure linear | Tan sigmoid | 0.2689 | 0.2571 | 0.3874 | 0.3571 | 0.2378 | 0.2169 |
| Pure linear | Log-sigmoid | 0.2678 | 0.2419 | 0.3706 | 0.3412 | 0.2588 | 0.2274 |

According to Table 5 (ii), minimum errors yield the transfer functions for the input layer to hidden layer 1 and hidden layer 1 to hidden layer 2 are log-sigmoid and tan-sigmoid for the ANN model of pressure. The minimum errors yield the transfer functions for the input hidden layer 1 and hidden layer 1 to hidden layer 2 are log-sigmoid and pure linear for the ANN model of wind speed. Tan sigmoid and log-sigmoid transfer functions for the input hidden layer 1 and hidden layer 1 to hidden layer 2 yield minimum error for the ANN models of cloud percentage. Levenberg-Marquardt back-propagation algorithm yielded the minimum NMS and NMSE for all models. After several trials it was decided that 'trainlm' as the best algorithm which could converge faster (Table 6).

**Table 6.** Performance of the models with different backpropagation training algorithms

| **Climatic Factor** | | **traingd** | **traingdm** | **traingdx** | **traincgp** | **traincgf** | **traincgb** | **trainscg** | **trainbfg** | **trainbr** | **trainlm** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | MSE | 0.6877 | 0.5681 | 0.5478 | 0.4586 | 0.3587 | 0.4281 | 0.3018 | 0.3422 | 0.2512 | 0.2143 |
| | NMSE | 0.6238 | 0.5147 | 0.5781 | 0.4889 | 0.4132 | 0.4777 | 0.3746 | 0.3780 | 0.2503 | 0.2113 |
| Pressure | MSE | 0.5511 | 0.5238 | 0.4955 | 0.4080 | 0.3975 | 0.3288 | 0.2903 | 0.2701 | 0.2389 | 0.2147 |
| | NMSE | 0.5102 | 0.5147 | 0.4287 | 0.4436 | 0.3214 | 0.3182 | 0.2873 | 0.2863 | 0.2158 | 0.2023 |
| Humidity | MSE | 0.4876 | 0.4415 | 0.4369 | 0.3680 | 0.3588 | 0.3281 | 0.3023 | 0.2781 | 0.1220 | 0.1187 |
| | NMSE | 0.4025 | 0.4114 | 0.4125 | 0.3481 | 0.3132 | 0.3177 | 0.2987 | 0.2369 | 0.1208 | 0.1106 |
| Wind speed | MSE | 0.5397 | 0.6039 | 0.4189 | 0.3358 | 0.4389 | 0.6038 | 0.4128 | 0.2722 | 0.1839 | 0.1723 |
| | NMSE | 0.5333 | 0.5477 | 0.4122 | 0.3731 | 0.3708 | 0.5702 | 0.4632 | 0.2389 | 0.1733 | 0.1603 |
| Cloud percentage | MSE | 0.4587 | 0.3688 | 0.3555 | 0.2080 | 0.3981 | 0.2698 | 0.2477 | 0.1654 | 0.1189 | 0.1056 |
| | NMSE | 0.3022 | 0.3111 | 0.3207 | 0.1360 | 0.3236 | 0.2182 | 0.2301 | 0.1354 | 0.1366 | 0.1023 |

As given in Table 7, suitable value of combination coefficient (μ) for models were decided as 0.0001 for the ANN forecasting models for temperature, pressure, and wind speed. The suitable value of combination coefficient, for models were decided as μ = 0.0005 for cloud percentage ANN model and μ = 0.005 for humidity forecasting ANN model. With those adjustments in the model improving process, five forecasting ANN models were finalized for the forecasting temperature, pressure, humidity, wind speed and cloud percentage with the minimum error as highlighted in Table 7.

**Table 7.** Performance of the model with different combination coefficients

| μ | Temperature | Pressure | Humidity | Wind speed | Cloud percentage |
|---|---|---|---|---|---|
| | | | **MSE** | | |
| 0.00001 | 0.2143 | 0.2378 | 0.2236 | 0.2878 | 0.2933 |
| 0.00005 | 0.2047 | 0.2136 | 0.2174 | 0.1736 | 0.1368 |
| 0.0001 | 0.1036 | 0.1172 | 0.1975 | 0.1674 | 0.1103 |
| 0.0005 | 0.1558 | 0.1238 | 0.1548 | 0.1689 | 0.1014 |
| 0.001 | 0.1378 | 0.2147 | 0.1187 | 0.1723 | 0.1056 |
| 0.005 | 0.1890 | 0.1587 | 0.1136 | 0.1890 | 0.1123 |
| 0.01 | 0.2078 | 0.1996 | 0.2511 | 0.1990 | 0.1190 |
| | | | **NMSE** | | |
| 0.00001 | 0.2113 | 0.2017 | 0.2138 | 0.2278 | 0.2071 |
| 0.00005 | 0.2135 | 0.1789 | 0.2036 | 0.1789 | 0.1274 |
| 0.0001 | 0.1002 | 0.1023 | 0.1748 | 0.1520 | 0.1179 |
| 0.0005 | 0.1358 | 0.1311 | 0.1357 | 0.1587 | 0.1011 |
| 0.001 | 0.1477 | 0.2023 | 0.1146 | 0.1603 | 0.1023 |
| 0.005 | 0.1972 | 0.1508 | 0.1072 | 0.1823 | 0.1170 |
| 0.01 | 0.2041 | 0.1278 | 0.2236 | 0.1987 | 0.1136 |

Architectures of the ANNs developed for each climatic factor are described below where w: weight and b: bias of the network.

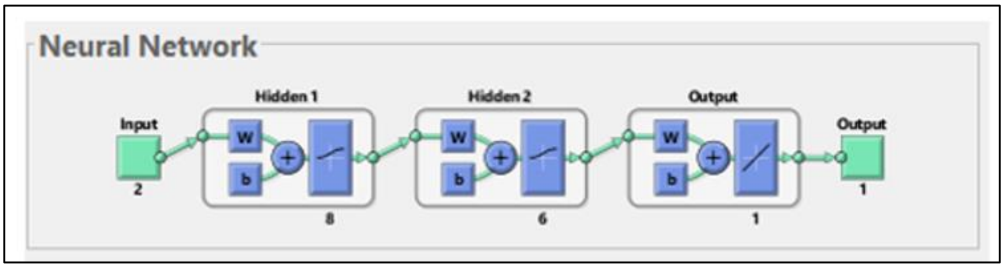


**Figure 1.** Architecture of the feedforward neural network for Temperature forecasting

The temperature forecasting model includes 2 input variables: TM_lag1 and TM_lag2. There are two hidden layers with 8 and 6 hidden neurons in layer 1 and 2 respectively as given in Figure 1. The transfer function of the Input hidden layer 1 as log-sigmoid, hidden layer 1 to hidden layer 2 as log-sigmoid and hidden layer 2 to output layer as pure linear function were suggested. The network is trained with ‘trainlm’ function. The optimal combination of coefficient is 0.0001 with 0.04 as the decreasing factor and 25 as the increasing factor.

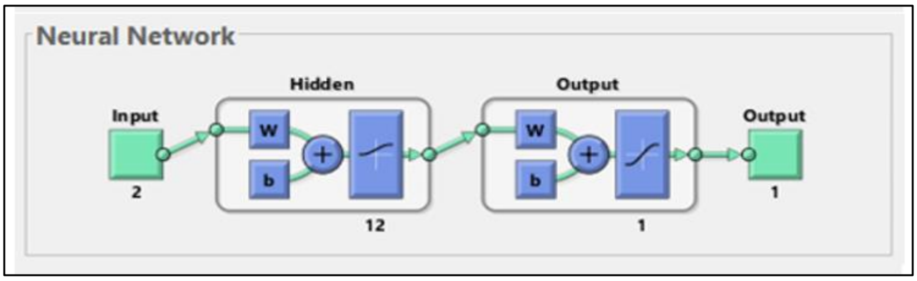


**Figure 2.** Architecture of the feedforward neural network for air Pressure forecasting

PS_lag1 and PS_lag2 are two input variables in the final model developed for pressure forecasting. There is one hidden layer with 12 hidden neurons (Figure 2). Minimum errors yield the transfer functions for the Input hidden layer 1 and hidden layer 1 to hidden layer 2 are log-sigmoid and tan-sigmoid for the ANN model of pressure. The 'trainlm' function is used to train the network. The optimal coefficient combination is: 0.0001 decreasing by 0.04 increasing by 25.

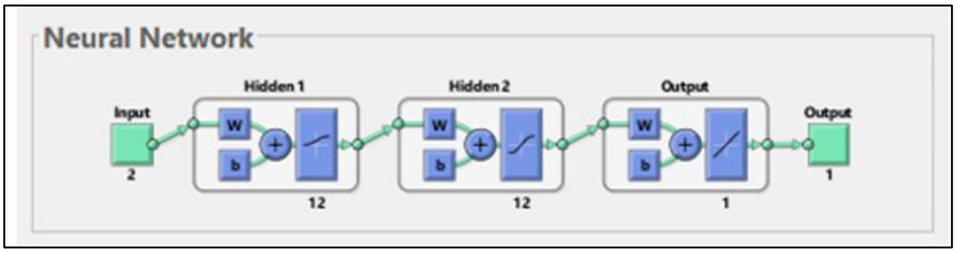


**Figure 3.** Architecture of the feedforward neural network for Humidity forecasting

Based on the NMSE of the test data set, the optimal model for forecasting humidity was selected after thousands of trials. HM_Lag1 and HM_lag2 are two input variables in the final model. As given in Figure 3, there are 12 hidden neurons in each of the two hidden layers. The transfer function of the input hidden layer 1 as log-sigmoid, Hidden layer 1 to hidden layer 2 as tan-sigmoid and hidden layer 2 to output layer as pure linear function for the ANN model for humidity were finalized. The 'trainlm' function is used to train the network. The optimum coefficient combination is 0.005 with a decreasing factor of 0.04 and an increasing factor of 25.

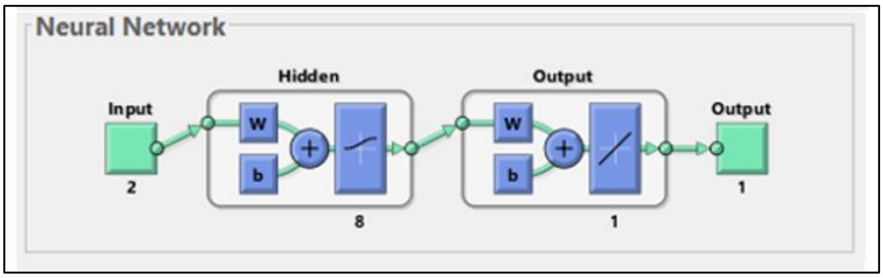


**Figure 4.** Architecture of the feedforward neural network for wind speed forecasting

WS_lag1 and WS_lag2 are two input variables in the model designed to forecast wind speed. There is one hidden layer with 8 hidden neurons (Figure 4). The minimum errors yield the transfer functions for the Input hidden layer 1 and Hidden layer 1 to hidden layer 2 are log-sigmoid and pure linear for the ANN model of wind speed. The 'trainlm' function is used to train the network. The optimal coefficient combination is: 0.0001 decreasing by 0.04 increasing by 25.

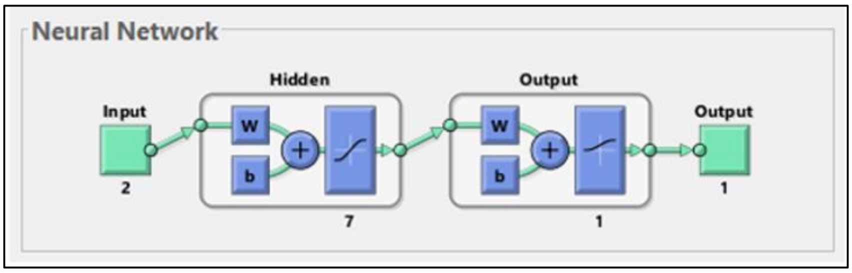


**Figure 5.** Architecture of the feedforward neural network for Cloud percentage forecasting

The final model, which comprises two input variables: CD lag1 and CD lag2, is used to forecast cloud percentage. There is one hidden layer with 7 hidden neurons as given in Figure 5. Tan sigmoid and log-sigmoid transfer functions for the Input hidden layer 1 and hidden layer 1 to hidden layer 2 are yield minimum error for the ANN models of cloud percentage. The 'trainlm' function is used to train the network. The optimum coefficient combination is 0.0005 with a decreasing factor of 0.04 and an increasing factor of 25.

Forecasted values and the actual values of the test set were plotted in Fig. 2 together to visualize the performance of the finally identified models in forecasting the climatic factors: temperature, pressure, humidity, wind speed and cloud percentage. According to Figure 6, it can be identified that the final feed forward neural network models are capable of forecasting given climatic factors with higher accuracy.

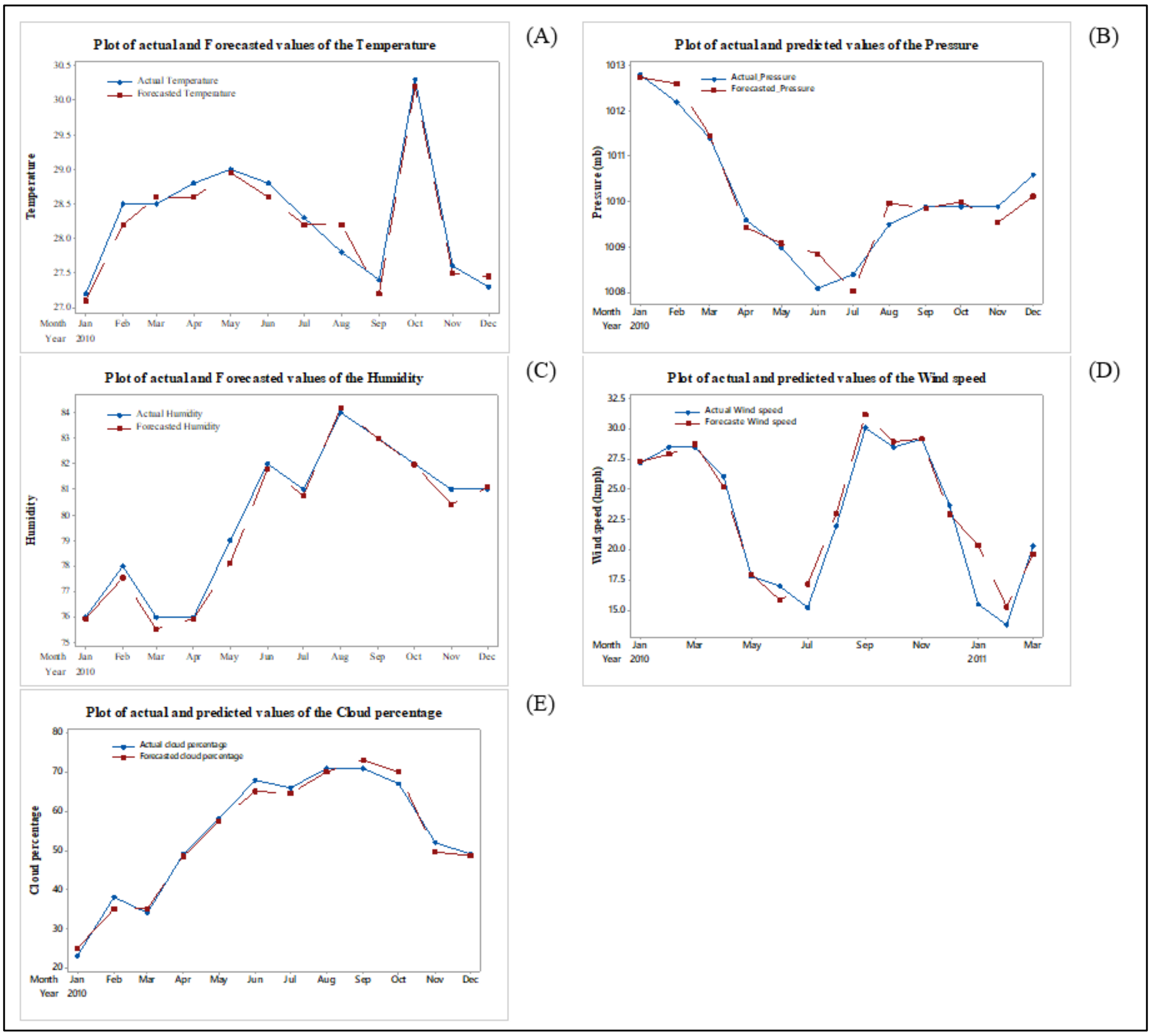


**Figure 6**. Plot of actual and predicted values of the climatic factors for the test set of (A) Temperature, (B) Pressure, (C) Humidity, (D) Wind speed and (E) cloud percentage

## Multiple Artificial Neural Network model for Rainfall Forecasting

Rainfall is correlated with many other climatic factors. Among them, temperature, air pressure, humidity, wind speed and cloud percentage were significant. Moreover, the model developed to forecast rainfall requires those climatic factors (Lag zeros) and lags. Hence, it was required the records of current month to forecast rainfall for next month and future. Then, forecasted values of the individual forecasting models for each climatic factor were used as recent inputs into the rainfall forecasting model, and it is a new approach which is a combination of ANNs for climate forecasting that has never done so far. Hence, it is known as the Multiple ANN model. According to the results of Table 1, there are 12 variables (Temperature, Wind speed, Pressure, Humidity, Cloud percentage, Temperature_lag1, Wind speed_lag1, Pressure_lag1, Pressure_lag2, Pressure_lag3, Humdity_lag1 and Cloud percentage_lag1) in the data set which are significantly correlated with the rainfall and those variables are used as inputs to the rainfall forecasting model. There are several possible combinations of 12 input variables and practically it is difficult to test with all combinations one by one. Thus, this study was carried out using the most important combinations based on correlation coefficients which indicate the associations between variables. Then variables were removed one by one and observed the MSE and NMSE as given in Table 8.

**Table 8.** Performance of the models with different combinations of input variables

| Input combination of variables | MSE | NMSE |
|---|---|---|
| TM, WS, PS, HD, CD, TL1, WS1, WSL2, PSL1, PSL2, PSL3, HDL1, CDL1 | 0.2504 | 0.2689 |
| TM, WS, PS, HD, CD, TL1, WS1, PSL1, PSL2, PSL3, HDL1, CDL1 | 0.2444 | 0.2158 |
| TM, WS, PS, HD, CD, TL1, WS1, PSL1, PSL3, HDL1, CDL1 | 0.2756 | 0.3541 |
| TM, WS, PS, HD, CD, TL1, WS1, PSL1, HDL1, CDL1 | 0.2950 | 0.2975 |
| WS, PS, HD, CD, TL1, WS1, PSL1, HDL1, CDL1 | 0.3901 | 0.4986 |
| WS, PS, HD, CD, TL1, WS1, HDL1, CDL1 | 0.3849 | 0.3120 |
| WS, PS, HD, CD, TL1, WS1, CDL1 | 0.3834 | 0.4739 |
| WS, PS, HD, CD, TL1, WS1, WSL2, PSL1, PSL2, PSL3, CDL1 | 0.3378 | 0.5438 |
| TM, WS, PS, HD, CD, TL1, WS1, CDL1 | 0.3380 | 0.4121 |

* Temperature (TM), Wind speed (WS), Pressure (PS), Cloud percentage (CD), Humidity (HD), Temparature_lag1 (TML1), Windspeed_lag1 (WSL1), Windspeed_lag2 (WSL2), Pressure_Lag1(PSL1), Pressure_Lag2 (PSL2), Pressure_Lag3 (PSL3), Humidity_Lag1 (HDL1), cloud_Lag1 (CDL1), L1- lag 1, L2-Lag 2, L3-Lag 3

According to the results in Table 8, the ANN model, with 12 inputs, exhibits the minimum error. Thus, this input set was used for further improvements of the model. The number of hidden layers were changed from one to four for the model selected above and the performance of the ANN models were recorded in Table 9. According to the results, minimum NMSE is recorded under two hidden layers while minimum MSE was recorded under one hidden layer. Thus, it was decided to proceed with the training of the neural network with both one and two hidden layers separately.

**Table 9.** Performance of the models with different number of hidden layers

| Number of hidden layers | MSE | NMSE |
|---|---|---|
| 1 | 0.2444 | 0.2689 |
| 2 | 0.2862 | 0.2174 |
| 3 | 0.3201 | 0.2541 |
| 4 | 0.3440 | 0.3957 |

Models with single hidden layer, number of neurons were identified by changing the number of neurons in the hidden layer from 1 to 20. In Table 9, the number of hidden layers from 1 to 4 are represented. Then considered two hidden layers and the most suitable number of neurons in each hidden layer were identified by changing the number of neurons in the first hidden layer from 1 to 20 while changing the number of neurons in second layer from 1 to 20 simultaneously. Then trained the model with one hidden layer for many trials and observed that the ANN model with 13 neurons in the hidden layer displayed the minimum error (Table 10).

**Table 10.** Performance of the models with different number of hidden neurons under one hidden layer

| Number of Neurons in the Hidden Layer | MSE | NMSE |
|---|---|---|
| 1 | 0.6447 | 0.6890 |
| 2 | 0.5298 | 0.5888 |
| 3 | 0.5127 | 0.5114 |
| 4 | 0.4389 | 0.5301 |
| 5 | 0.4011 | 0.5078 |
| 6 | 0.4712 | 0.5199 |
| 7 | 0.6882 | 1.6071 |
| 8 | 0.3784 | 0.6782 |
| 10 | 0.5299 | 0.5972 |
| 11 | 0.5972 | 0.8714 |
| 12 | 0.3678 | 0.3538 |
| 13 | 0.3001 | 0.2927 |
| 14 | 0.4102 | 0.3927 |
| 15 | 0.5245 | 0.3756 |
| 16 | 0.5189 | 0.4893 |
| 17 | 0.4156 | 0.6721 |
| 18 | 0.4718 | 0.5748 |
| 19 | 0.5921 | 1.3687 |
| 20 | 0.8670 | 2.5911 |

Then trained and observed the results of the neural network with two hidden layers. After multiple trials, it was discovered that the minimum error was captured by 13 neurons in the first hidden layer and 10 neurons in the second hidden layer (Table 11). As a result, the neural network will be trained using 13 and 10 neurons in the first and second hidden layers, respectively.

**Table 11.** Performance of the models with different number of hidden neurons in each layer under two hidden layers.

| Number of Neurons | | MSE | NMSE |
|---|---|---|---|
| Layer 1 | **Layer 2** | | |
| 10 | 11 | 0.4145 | 0.5145 |
| 10 | 12 | 0.6675 | 1.5961 |
| 10 | 14 | 0.3645 | 0.5712 |
| 11 | 12 | 0.6109 | 0.6098 |
| 12 | 10 | 0.5227 | 0.8385 |
| 12 | 11 | 0.3599 | 0.3387 |
| 13 | 09 | 0.4578 | 0.3785 |
| 13 | 10 | 0.2967 | 0.2563 |
| 13 | 11 | 0.7458 | 0.3482 |
| 13 | 12 | 0.7420 | 0.6998 |
| 14 | 10 | 0.4875 | 0.5207 |
| 14 | 11 | 0.4120 | 0.4868 |
| 14 | 12 | 0.5844 | 1.2998 |
| 15 | 12 | 0.8536 | 2.5782 |

The transfer function of the Input hidden layer 1 as log-sigmoid, hidden layer 1 to hidden layer 2 as tan-sigmoid and hidden layer 2 to output layer as pure linear function for the ANN model were finalized as given in Table 12.

**Table 12.** Performance of the models by changing transfer function in each layer

| Input layer to Hidden layer 1 | Hidden layer 1 to Hidden layer 2 | Hidden layer 2 to Output layer | MSE | NMSE |
|---|---|---|---|---|
| Log-sigmoid | Log-sigmoid | Log-sigmoid | 0.5372 | 0.3417 |
| Pure linear | Log-sigmoid | Log-sigmoid | 1.5879 | 0.4790 |
| Log-sigmoid | Tan sigmoid | Log-sigmoid | 0.8705 | 0.8702 |
| Tan sigmoid | Pure linear | Log-sigmoid | 0.6423 | 0.7410 |
| Tan sigmoid | Log-sigmoid | Log-sigmoid | 0.9457 | 0.9712 |
| Pure linear | Pure linear | Log-sigmoid | 3.247 | 4.2801 |
| Log-sigmoid | Pure linear | Log-sigmoid | 2.5834 | 0.9742 |
| Tan sigmoid | Tan sigmoid | Log-sigmoid | 2.1470 | 3.0271 |
| Log-sigmoid | Log-sigmoid | Pure linear | 0.2374 | 0.2272 |
| Pure linear | Log-sigmoid | Pure linear | 0.3455 | 0.3852 |
| Log-sigmoid | Tan sigmoid | Pure linear | 0.7205 | 0.9692 |
| Tan sigmoid | Pure linear | Pure linear | 0.7899 | 0.8454 |
| Tan sigmoid | Log-sigmoid | Pure linear | 5.3578 | 0.9712 |
| Pure linear | Pure linear | Pure linear | 7.1287 | 5.8702 |
| Log-sigmoid | Pure linear | Pure linear | 3.5874 | 2.8701 |
| Tan sigmoid | Tan sigmoid | Pure linear | 4.2876 | 5.2389 |
| Log-sigmoid | Log-sigmoid | Tan sigmoid | 0.6188 | 0.4279 |
| Pure linear | Log-sigmoid | Tan sigmoid | 2.6890 | 0.6387 |
| Log-sigmoid | Tan sigmoid | Tan sigmoid | 0.8678 | 0.9025 |
| Tan sigmoid | Pure linear | Tan sigmoid | 0.9155 | 0.6328 |
| Tan sigmoid | Log-sigmoid | Tan sigmoid | 0.8970 | 0.7458 |
| Pure linear | Pure linear | Tan sigmoid | 2.4777 | 1.0472 |
| Log-sigmoid | Pure linear | Tan sigmoid | 4.2891 | 0.9742 |
| Tan sigmoid | Tan sigmoid | Tan sigmoid | 4.1880 | 1.7781 |

According to Table 13, out of these training algorithms the model with the Levenberg-Marquardt back-propagation algorithm yield the minimum MSE and NMSE.

**Table 13.** Performance of the models with different backpropagation training algorithms

| Training algorithm | MSE | NMSE |
|---|---|---|
| Levenberg-Marquardt back-propagation | 0.0975 | 0.2058 |
| Bayesian Regularization back-propagation | 0.2967 | 0.2563 |
| BFGS Quasi-Newton back-propagation | 0.4822 | 0.6572 |
| Resilient Back propagation | 2.0070 | 2.4948 |
| Scaled Conjugate Gradient back-propagation | 0.6954 | 0.8405 |
| Conjugate Gradient with Powell/ Beale Restarts back-propagation | 0.6315 | 1.8077 |
| Fletcher-Powell Conjugate Gradient back-propagation | 0.5340 | 1.8725 |
| Polak-Ribiere Conjugate Gradient back-propagation | 0.6871 | 1.2224 |
| One Step Secant back-propagation | 0.7186 | 1.8494 |
| Variable Learning Rate Gradient Descent back-propagation | 0.6572 | 0.843 |
| Gradient Descent with Momentum back-propagation | 2.2034 | 3.4780 |
| Gradient Descent back-propagation | 1.1772 | 2.8145 |

In here value of combination coefficient (μ) was changed from 0.00001 to 0.01 and observed the change in errors of the test data set through MSE and NMSE as shown in Table 14.

**Table 14.** Performance of the model with different combination coefficient

| μ | MSE | NMSE |
|---|---|---|
| 0.00001 | 0.1282 | 0.3784 |
| 0.00005 | 0.0998 | 0.2758 |
| 0.0001 | 0.0547 | 0.0378 |
| 0.0005 | 0.0997 | 0.2874 |
| 0.001 | 0.0975 | 0.2058 |
| 0.005 | 0.1050 | 0.2148 |
| 0.01 | 0.2410 | 0.5782 |

The combination coefficient 0.0001 for Levenberg-Marquardt back-propagation algorithm yields the minimum error. Therefore, suitable value of μ for this model was finalized as 0.0001. With those adjustments the model improving process completed and finalized the multiple feed forward neural network model to forecast rainfall. The architecture of the final ANN model is given in Figure 7.

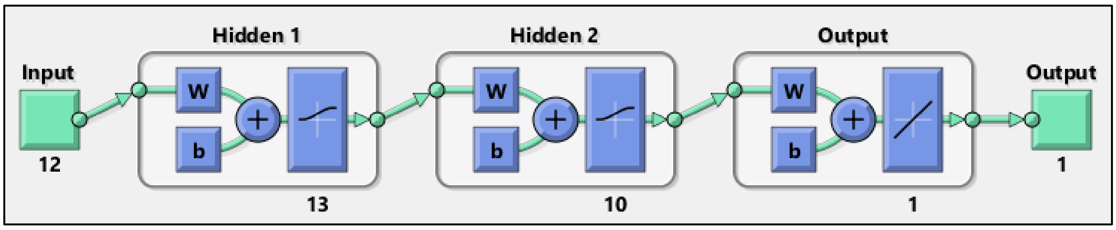


**Figure 7.** Architecture of the Feedforward Neural Network for rainfall forecasting model

The rainfall forecasting model includes 12 variables: temperature, wind speed, pressure, cloud percentage, humidity, and their derivatives such as temparature_lag1, windspeed_lag1, pressure_lag1, pressure_lag2, pressure_lag3, humidity_lag1, and cloud_lag1. There are two hidden layers with 13 and 10 hidden neurons in the first and second layer respectively. The transfer function of the Input hidden layer 1 as log-sigmoid, Hidden layer 1 to hidden layer 2 as tan-sigmoid and hidden layer 2 to output layer as pure linear function were finalized. The network was trained with Levenberg-Marquardt back-propagation algorithm with combination coefficient of 0.0001. Actual rainfall values and forecasted rainfall values were extracted and visualized in Figure 8.

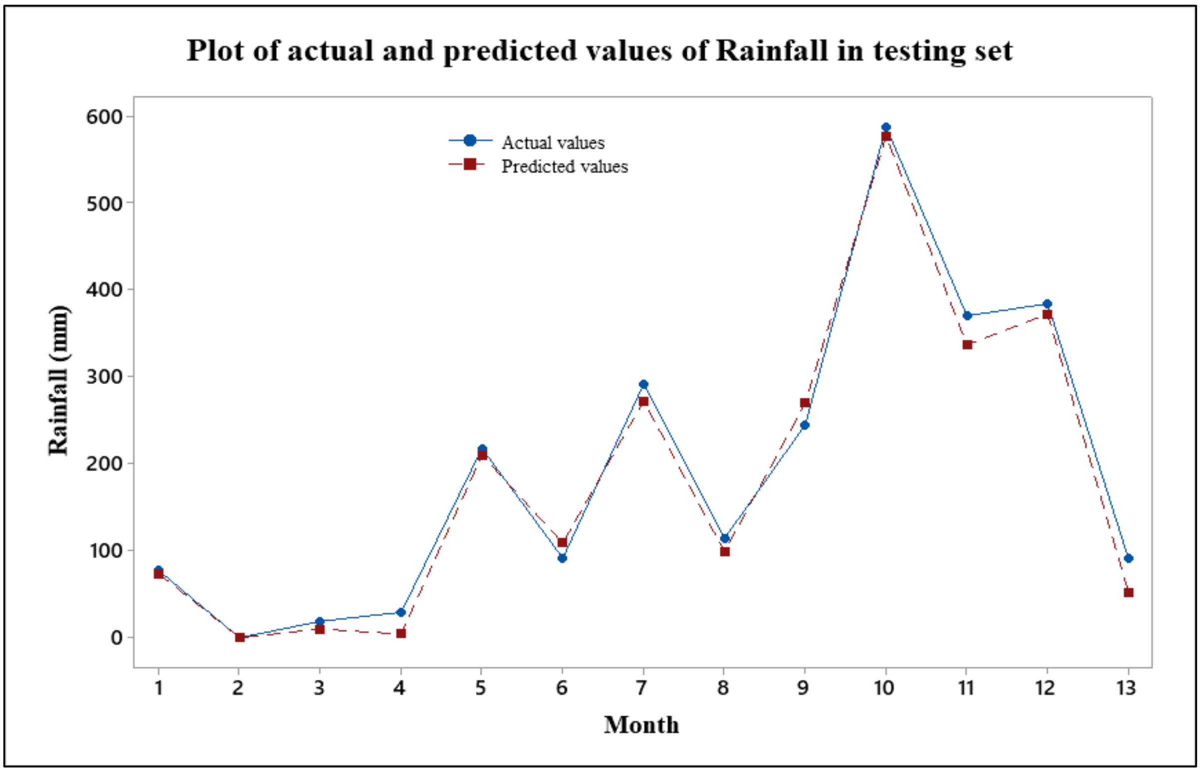

**Figure 8.** Plot of actual and predicted values of the rainfall for the test set

Precision agriculture's goal is to maximize growth efficiency at the seed and plant level. While farmers must make several daily decisions based on climatic conditions, there are four main aspects of farming that are fundamentally impacted by weather such as crop growth, fertilizer timing and delivery, disease control and field workability [14-16]. Therefore, the proposed multiple neural network model was generalized and it will be an effective approach for farmers in decision making and helping them to plan efficiently, minimize costs and maximize yields.

## Requirement of a cultivation plan to Sri Lanka

Sri Lanka, amidst facing one of its worst economic crisis, is currently experiencing rapidly rising inflation. Higher inflation causes adverse impacts on the economic performance of the country. Reduced imports of food grains due to foreign exchange constraints will exacerbate the crisis already facing by people from moderate to acute food insecurity. To overcome or minimize the issues faced by people, there should be a proper cultivation plan within the country [16-17]. A cultivation plan outlines the steps and practices needed to grow crops or raise livestock. It includes decisions about which crops to plant, when to plant them, what fertilizers or pesticides to use with cost, and how to manage irrigation and soil health. It considers factors like climate and soil type. Further, people should be encouraged to grow and maintain their foods as self-earners. The goal of Sri Lankan economy based agricultural is to generate a net profit in addition to food for human use. A comprehensive cultivation strategy should be in place that makes the best use of the available resources to maximize the net return from the crop [2], [18]. Statistical models can apply for rural agricultural regions in Sri Lanka to determine a proper cultivation plan and resource allocation under uncertainty to maximize profit, productivity, labor, water consumption, fertilizer costs, and land allocation [15]. In determining the best cultivation strategy, mathematical programming models are fundamental. The most common and straightforward approach for resource optimization with a single objective is linear programming. In practical sense, it is important to achieve desired goal instead of achieving few objectives in planning for a proper cultivation plan. In the procedure of cultivation planning, generally, involve multiple goals: maximization of the profit, maximization of the harvest, minimizing cost, minimization of the labour hours, optimize water requirement, utilization of the land resource and others. An objective function is a function that defines some quantity that should be minimized or maximized [15],[19]. Goal programming models are used to achieve several goals and constraints. Goal programming is a goal-oriented optimization method to solve multi objective decision problems in crisp decision environment. Multi-objective programming technique and lexico-graphic goal programming has been used by Sharma et al. in 2015 to solve agricultural land allocation problems and they proposed an annual agricultural plan [20]. In general, uncertainties are associated with the parameters related to the cultivation. A fuzzy approach for cultivation planning allows the vagueness that exists in the profit of the cultivation, production cost, resources and requirements like water, labour, machine power etc. into a modelling approach.

## Fuzzy approach

Picture Fuzzy sets (PFS) are a novel concept which is a direct extension of fuzzy sets and intuitionistic fuzzy sets. The picture fuzzy set is characterized by three membership functions incorporating a positive membership function, neutral membership function and negative membership function.

A picture fuzzy set $A$ on a universe $X \in R^{+}$ is an object in the form $A = \{(x, \mu_A(x), \eta_A(x), \nu_A(x)) | x \in X\}$ where $\mu_A(x) \in [0,1]$ is called the degree of positive membership of $x$ in $A$. $\eta_A(x) \in [0,1]$ is called the degree of neutral membership of $x$ in $A$ and $\nu_A(x) \in [0,1]$ is called the degree of negative membership of $x$ in $A$. Membership functions $\mu_A, \eta_A$ and $\nu_A$ should satisfy the condition $0 \leq \mu_A(x) + \eta_A(x) + \nu_A(x) \leq 1$, $\forall x \in X$. Furthermore, $\pi_A(x) = 1 - \mu_A(x) - \eta_A(x) - \nu_A(x)$ is the refusal membership function.

It is not always limited to these three opinions. There may be such opinions as abstain which is biased toward the positive opinion. Similarly, there may be an opinion such abstain which is biased toward the negative opinion. Thus, using the picture fuzzy sets, it is difficult to address such intermediate opinions. Hence, this study introduces the modified picture fuzzy sets to address the gap. To represent human opinions like yes, abstain with positive opinion, abstain with a negative opinion, no, neutral and refusal, a modified version of picture fuzzy numbers is introduced. The improved version of the Picture Fuzzy Sets is called Sceptical Picture Fuzzy Sets (SPFS). The philosophy of the word 'Sceptical' relates to the theory that certain knowledge is impossible due to vagueness.

Let X be a non-empty and finite set, a Sceptical Picture Fuzzy Set, N on X is defined as $N = \{x, \mu_A(x), \eta_A^{+}(x), \eta_A^{-}(x), \nu_A(x)) | x \in X\}$ where $\mu_A(x)$ is the positive membership function, $\eta_A^{+}(x)$ is the neutral plus membership function, $\eta_A^{-}(x)$ is the neutral minus membership function and $\nu_A(x)$ is the negative membership function with $\mu_A(x)$, $\eta_A^{+}(x)$, $\eta_A^{-}(x)$, $\nu_A(x) \in [0,1]$, $0 \leq \mu_A(x) + \eta_A^{+}(x) + \eta_A^{-}(x) + \nu_A(x) \leq 1$, $\forall x \in X$ and $\pi_A(x) = 1 - \mu_A(x) - \eta_A^{+}(x) - \eta_A^{-}(x) - \nu_A(x)$ is the refusal membership function. Using the newly defined two membership functions, researchers will be able to address numerical problems by introducing SPFS instead of limiting it to a measure of central tendency such as mean, median or mode.

## Modelling cultivation plans

Cultivation plans were developed based on data from farming village located in Dompe divisional secretariat in Gampaha district, Sri Lanka using selected crops such as Brinjals (*Solanum melongena*), chilies (*Capsicum annuum*), Luffa (*Luffa aegyptiaca*), wined beans (*Psophocarpus tetragonolobus*), tomatoes (*Lycopersican esculentum*), Bitter gourd (*Momordica charantia*), Bird chili (*Capsicum frutescens*), Lady's fingers (*Abelmoschus esculentus*), Snake gourd (*Trichosanthes cucumerina*), Manioc (*Manihot esculenta*), Taro (*Colocasia*) (*Colocasia esculenta*), Rambutan (*Nephelium lappaceum*), Banana (*Musa paradisicum*), Pineapple (*Ananus sativus*), Gadiguda

(*Baccaurea metleyana*), Durian fruit (*Durio*), lemon grass (*Cymbopogon*), Betel (*Piper betel*), Rice (*Oryza sativa*), Betel nut (*Areca catechu*), Coconut (*Cocos nucifera*), Tea (*Camellia sinensis*), Rubber (*Hevea brasiliensis*) and Pepper (*Piper nigrum*). These crops are categorized in to three categories as vegetables, fruits and other. The total area of land under cultivation is 474, 122.86 $m^2$. There are six cropping seasons for selected crops. The number of months required for the cultivation of a particular crop is known as seasons.

For each crop the season was recognized by the expertise knowledge and from the experience of the farmers. Model goals were listed and $x_{ijk}$ represents the area of cultivable land for $i^{th}$ variety of crop in $j^{th}$ season of $k^{th}$ crop in the study area ($i -$ Index of the variety of crop, $j -$ Index of the season, $k -$ Index of the crop name and $l -$ Index of the goal).

$$a_k = \begin{cases} 1; & \text{if } k^{th} \text{ crop will be cultivated} \\ 0; & \text{if } k^{th} \text{ crop will not be cultivated} \end{cases}$$

Five goals were considered under the study and each goal is described below in detail.

***Goal 1- Maximization of profit:*** The decision maker must allocate the total available land to the crops so that the total profit will be maximized. Profit is calculated by subtracting the production cost from the corresponding income of each crop. Thus, the first goal is $\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} (I_{ijk} - C_{ijk})\, a_k x_{ijk} \geq P$, where $I_{ijk}$ is the income gained per unit area of $k^{th}$ crop in season $j$ under the variety of crop $i$ in rupees, $C_{ijk}$ is the cultivation or maintenance cost per unit area of $k^{th}$crop in season $j$ under the variety of crop $i$ in rupees and $P$ is the expected net profit from all crops.

***Goal 2- Maximization of the production:*** The decision makers will be required to obtain maximum expected production from the crop cultivation. The production goal is $\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} Y_{ijk}\ a_k x_{ijk} \geq \sum_{k=1}^{K} Y_k$ where $Y_{ijk}$ is the average production per unit area of $k^{th}$crop in season $j$ under the variety of crop $i$ and $Y_k$ is the total production target of crop $k$.

***Goal 3- Labour requirement:*** The labour is required throughout the farming period of each crop in different levels. Labour hour were considered for each crop cultivation and the goal equation of the labour hour requirement is $\sum_{i=1}^{n} l_{ijk}\ a_k\ x_{ijk} \leq L \quad \forall\, j,\ k$ where $l_{ijk}$ is the labourrequired per unit area of $k^{th}$crop in season $j$ under the variety of crop $i$ and L is the expected total labour availability.

***Goal 4- Water requirement:*** Water is one of the most important inputs essential to growth of crops. To meet the target crop production, it is required to ensure the water requirement for the farming period of every crop. Equation of the water requirement goal is $\sum_{i=1}^{I}\sum_{j=1}^{J} w_{ijk}\ a_k\ x_{ijk} \leq W \ \ \forall\, k$ where $w_{ijk}$ is the water requirement per unit area of $k^{th}$crop in season $j$ under the variety of crops $i$ in rupees and W is the expected total water available for cultivation.

***Goal 5- Cost of fertilizer for cultivation:*** Regular doses of fertilizers are required to obtain maximum profit and yield from the crop cultivation. The amount of money per cultivation period should be reserved for fertilizers. Thus goal of cost of fertilizer is $\sum_{i=1}^{I}\sum_{k=1}^{K} f_{ijk}\ a_k\ x_{ijk} \leq F \ \ \forall\, j$ where $f_{ijk}$ is the cost for fertilizer required per unit area of $i^{th}$ crop in month $j$ under variety of crop $k$ in rupees and $F$ is the total cost of fertilizers in rupees.

There are some fixed resources regarding the cultivation. Among them this study focuses on land availability as a fixed resource as it is a fixed amount for a particular study area. Instead of considering it as a goal, it is required to consider land availability as an essential requirement. To satisfy this requirement, it is possible to use equality rather than inequality in the equation. Because the objective of the cultivation plan is to optimize the current agrarian lands instead of extending the arable areas. Land requirement can be expressed as $\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} a_k\, x_{ijk} = X$ where $X$ is the total land area for cultivation. As the factors that should be considered to develop a proper cultivation plan as not always crisps. Thus, it is important to consider the uncertainty often associated with them. For that reason, fuzzy numbers were considered to develop an Optimal cultivation plan.

According to the number of membership degrees in the fuzzy number, the range of the values must be introduced for each uncertain variable. Then, the Optimal Cultivation Plans were developed using several statistical models by considering the uncertainty of parameters and applied for selected study area, a farming village located in Gampaha district using 24 crops including Vegetables, Fruits, and Other crops. Statistical models used in this study with results are briefly summarized in Table 15. When comparing the maximum benefits obtained by the cultivation plans, it is very clear that newly introduced Sceptical picture fuzzy goal programming model with uncertainty condition provides the maximum benefits to the farmers.

**Table 15.** Summary of the proposed optimal plans

| Optimal Cultivation Plans | Used statistical models | Profit increment % |
|---|---|---|
| **Optimal Cultivation Plan 1** | Linear Programming model | 5.79 |
| **Optimal Cultivation Plan 2** | Fuzzy goal programming model | 11.00 |
| **Optimal Cultivation Plan 3** | Picture fuzzy goal programming model | 12.00 |
| **Optimal Cultivation Plan 4** | **Sceptical picture fuzzy goal programming model** | **14.00** |

The Optimal Cultivation Plan 1 suggested that there is a 5.79% increment of profit for the study area compared to the existing cultivation. Then this study was further extended to optimize the profit under uncertainty conditions. Thus, a fuzzy goal programming model called Optimal Cultivation Plan 2 was developed to achieve an optimal cultivation plan which increases 11% of the net return for same crops compared to the profit obtained from the existing cultivation. Optimal Cultivation Plan 3 suggested Rs. 2,713,109.00 profit from the cultivation and 37,033.39 kg of production from the cultivation. Profit obtained from the Optimal Cultivation Plan 3 and 4 are 12% and 14% compared to the existing cultivation. Thus, the maximum profit can be obtained from Optimal Cultivation Plan 4 developed using the newly introduced Spectical Picture Fuzzy Numbers from this study. According to the Optimal Cultivation Plan 4, profit is Rs. 2,789,423.247 while production is 39,457.40 kg. Maximum land area was allocated for rice while minimum land area was allocated for rubber. The results of Optimal Cultivation Plan 4 proposed large area allocation for Manioc, rambutan, Pineapple, Rice, coconut, and tea.

**Importance of the Smart Agro Planner**

Forecasting model and cultivation plans were developed based on statistical theories, techniques, and tools. Even though those results are important to the farming communities, handling of the theoretical and statistical tools and software are difficult to those communities. Therefore, rural communities are limited to their own experiences due to lack of transmission of the technology to the relevant parties. To overcome this issue, this study introduces a user-friendly technology transfer tool called 'Samrt Agro Planner' for agricultural officers to gather required details and prior knowledge on cultivation as well as weather forecasting which will be used in decision making. Because Smart Agro Planner will suggest which crop should be cultivated in which area which time to obtain maximum harvest and profit along with the cost of fertilizers, cost of seeds and cost of labour based on past data feed to the system (Figure 11). Moreover, it also interprets the rainfall and temperature forecasted value with a graphical representation of the past records as given in Figure 10. Farmers will get the benefits of the Smart Agro Planner through the agricultural officers. Interfaces of the Smart Agro Planner are given in Figure 9-11.

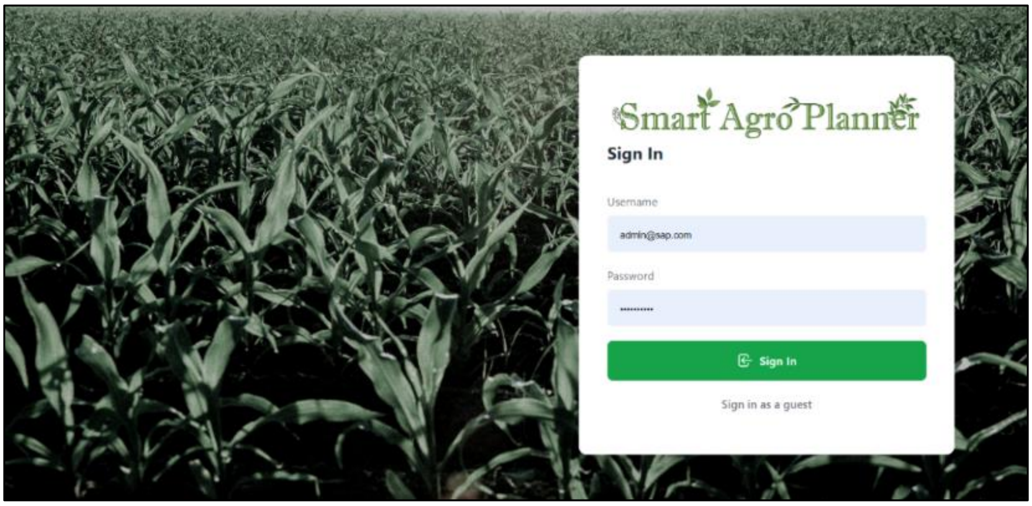


**Figure 9.** Logging Interface

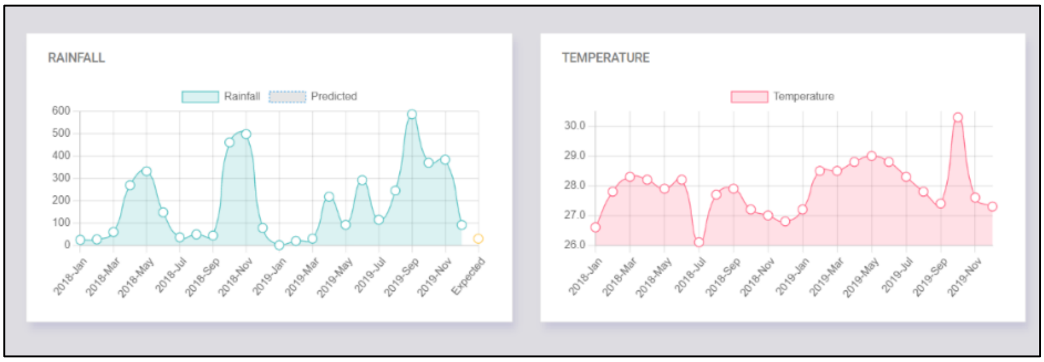


**Figure 10.** Climate forecasting Interfaces

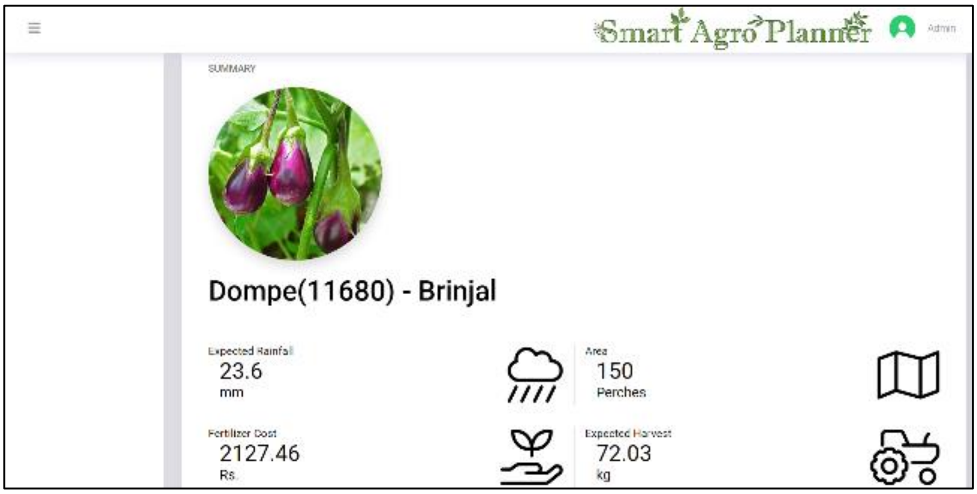


**Figure 11.** Output of the Optimal Cultivation Plan

## Conclusions and future prospects

The effects of climate changes on agricultural production are not limited to crop cultivation. Due to its significant impacts on agriculture, climate unpredictability puts local/ global economic and food security at risk. This implies the importance of the early recognition of climatic factors especially, rainfall. Rainfall forecasting is a complex task due to the dynamic and nonlinear nature of atmospheric processes. Among the forecasting techniques, ANNs are capable of forecasting rainfall with high accuracy, while Multiple ANNs are capable of forecasting rainfall by incorporating correlated climatic factors with the forecasted values. The multiple ANN rainfall forecasting model introduced in this study is capable of forecasting rainfall with higher accuracy which exhibits MSE of 0.0547 and NMSE of 0.378. Thus, it will be a benefit to the farming communities to access the rainfall variations early and make more effective decisions on cultivation. As the economic and food problems continue to have a significant impact on the populace in Sri Lanka, there should be a proper cultivation plan.

The application of linear programming model as a cultivation plan for selected 24 crops, suggested 5.79% increment of profit for the study area compared to the existing cultivation. Fuzzy goal programing model was developed to achieve optimal cultivation plan which increase 11% of the net return for same crops compared to the profit obtained from the existing cultivation. According to the fuzzy goal model it can be identified that the arable area of paddy cultivation should be double to obtain maximum profit than that of the linear programming model suggestions. Moreover, maximum profit (Rs. 2,745,327.00) can be obtained from the SPFN (Sceptical Picture Fuzzy Number) goal programming model compared to other models such as fuzzy goal programming model, linear programming model etc. Optimal land allocation for fruits, vegetables and other crop varieties was proposed using the SPFN goal programming model while achieving maximum profit from the cultivation.

Furthermore, the application of the fuzzy numbers and SPFNs in cultivation planning for high economic expectations successfully tackled the uncertainty and imprecision associated with estimating profits and production. Sceptical Fuzzy goal programing model (SPFGP) was able to maximize the net return from the cultivation up to 14% compared to the existing cultivation, which implies that this application will be a great reinforce to the food crisis in the country. Extension and application of the SPFGP model in rural farming sectors will lead to get more benefits such as higher income and achieve target food demand. Smart Agro Planner is a modest attempt to transfer the findings to the farming communities. There are several features which involve integrated planning, implementation, and control of agriculture related activities that can help farmers to produce the harvest efficiently. It is helpful for farmers as it can help them in getting better yields with proper planning. Smart Agro Planner is the tool that provides the optimal cultivation plan and the climate forecasts to the farming communities. Smart Agro planner will suggest which crop to grow in which area at which time for maximum yield and profit along with fertilizer, seed and labour costs based on historical data fed into the system. It also interprets the forecasted rainfall and temperature with a visual representation of historical data. Hence, maintenance and awareness sessions regarding the Smart Agro Planner will be continued.

## Acknowledgments

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## Conflict of interest

No conflict of interest.

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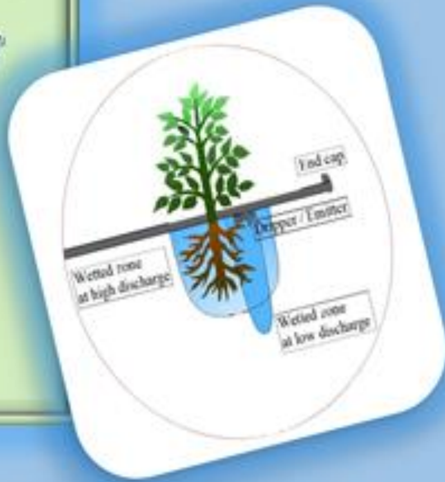
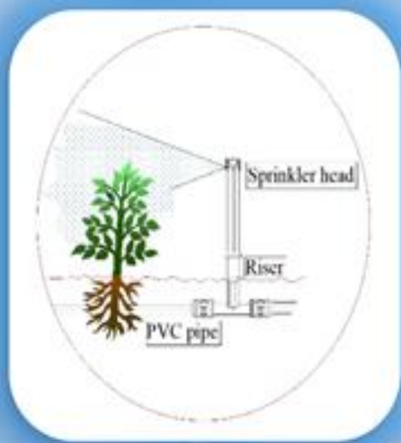
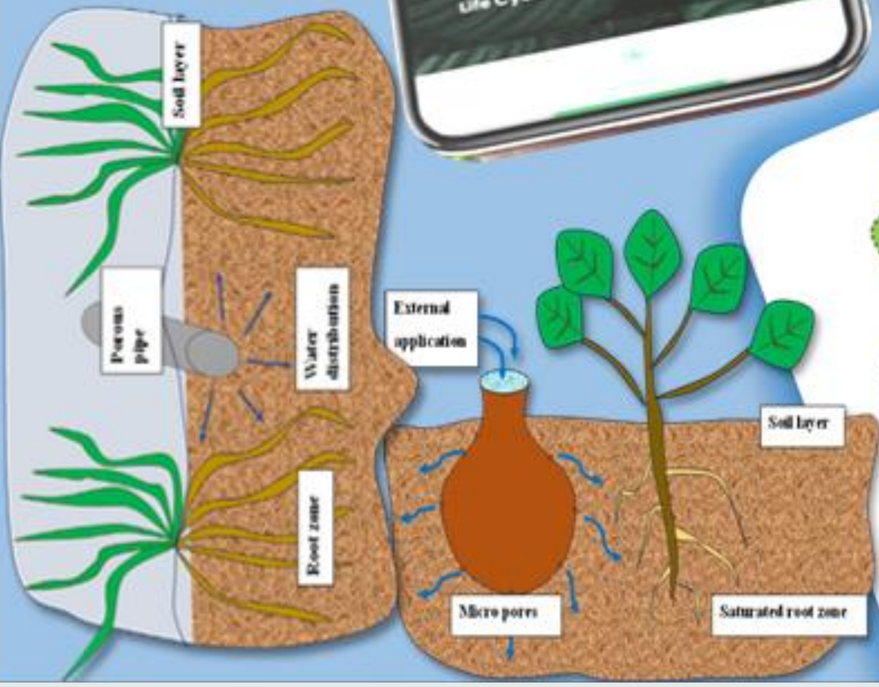
# **SECTION 2-** FISHERIES, COASTAL AND WATER RESOURCES

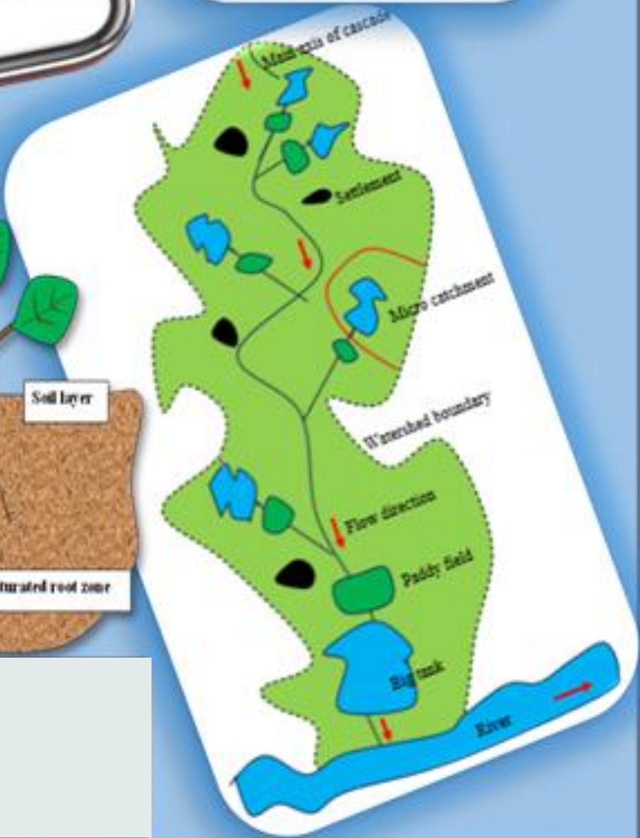
# Climate-smart water management strategies with special emphasize to micro-irrigation practices for sustainable use of water for irrigation in Sri Lanka: a conceptual framework







# Climate-smart water management strategies with special emphasize to micro-irrigation practices for sustainable use of water for irrigation in Sri Lanka: a conceptual framework

N. Kannan[1]*, S. Loveciya[1], A. Thusalini[1], T. Thiruvaran[2]

## Abstract

Shortage of irrigation water has been reported all over Sri Lanka due to many reasons: climate change, excessive pumping, deforestation and limited recharge of aquifer systems. Shortage of irrigation water significantly affects food production, which in turn negatively affects the Sri Lankan economy. Moreover, freshwater sources become polluted drastically due to excessive application of various agro-chemicals: fertilizer and pesticides. In addition, excessive pumping of groundwater leads to seawater intrusion into freshwater aquifer systems which impacts on irrigation water quality and quality. Therefore, the users of freshwater for irrigation must be trained properly for the effective use of irrigation water for the sustainability in terms of water use efficiency in irrigation with novel and innovative irrigation techniques. This chapter, therefore, attempts to elaborate core points related to good practices for the effective use of irrigation water. Furthermore, it describes novel sprinkler and drip irrigation systems, water usage in the precision agriculture, automated greenhouse, and key points related to paddy-water management. Moreover, it helps researches, policy makers, academics, farmers and other relevant agricultural experts to implement climate-smart irrigation practices in Sri Lanka.

**Keywords*:*** Climate change, water pollution, Effective irrigation, Sustainable water use

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## Introduction

Agriculture has been the backbone of Sri Lanka's economy and continues to play an important role in the national development. Around 42% of Sri Lanka's total land area is covered by agricultural coverage [1]. The role of irrigation in agricultural sector and food security is huge Agriculture sector uses around 70% of available freshwater globally, and this figure is significantly greater in Sri Lanka compared to many other countries [2]. The ineffectiveness of water use, poor adaptation in water conservation techniques, improper irrigation practices in farmer's field, water pollution and lack of management of water storage systems are the major reasons for increased water demand. In addition, anticipated climatic risk enhances the increased water demand to a higher extent.

Furthermore, the extent of paddy cultivation is projected to increase by 28% in 2025. Therefore, dry zone and some other regions in the country will experience an absolute water scarcity in future [3]. Therefore, adopting new technologies to increase irrigation efficiency, development of hybrid irrigation systems and use of saline-sodic water for irrigation will alleviate the existing water demand. Hence, the possibilities of adopting innovative techniques that can mitigate the water scarcity are of paramount importance to minimize water wastage. Therefore, this chapter leads to explore the climate-smart irrigation systems for the sustainable agriculture in terms of water usage in Sri Lanka.

## Water consumption pattern for irrigation in Sri Lanka

Shift in climatic pattern due to natural causes and anthropogenic activities is known as climate change [4]. The report of Intergovernmental Panel on Climate Change (IPCC) reveals that the global temperature has increased approximately by 1.1 ˚C since the pre-industrial era. If the current emission rates exist, global temperature increase is expected by 1.5 ˚C from 2030 to 2050 [5]. Climate change significantly increases the demand for water by temperature increase, extreme heat events, precipitation changes and sea levels rise. A report from National Oceanic and Atmospheric Administration (NDAA) says that the record-breaking heat events are three times faster than record- breaking cold events [6]. Furthermore, ecosystem, food, water, human health, welfare and infrastructure have been considered most vulnerable because of climate change [5]. Impact of climate change on agriculture anticipates significantly across different regions of the world due to variation in soil, land use pattern, demand of people and availability of infrastructures [2].

Irrigation has a significant importance in agriculture [3] as agricultural sector is the major consumer of water worldwide. Around 70% of withdrawal and 90% of consumption of freshwater are for agricultural activities, while it is 87.34% in Sri Lanka [3]. The significant expansion of irrigation practices has played a crucial role in supporting the substantial growth in agricultural production, which has been essential in feeding the rapidly increasing global population [7]. Irrigation has resulted in the expansion of many agricultural activities: cultivable land, crop yield on existing farmland and pattern of double cropping. Moreover, it has reduced the uncertainty associated with rainfall-dependent water supply [7]. However, the potential advantages of irrigation have not been evenly distributed across the globe. Additionally, cost for construction of irrigation structures, loss of natural habitat, environmental degradation, soil erosion, loss of water quality and spread of waterborne diseases are significant drawbacks due to irrigation. In addition, limited supply of freshwater is one of the major concerns of the future world [4].

Currently, different approaches are being implemented to adapt crop production to the changing climate and enhance the efficiency of water usage in order to increase food production per unit of water [3]. A report reveals that Sri Lanka had gained an excellent development in irrigation industry in the ancient time [8]. The Figure 1 indicates availability of total arable lands in Sri Lanka for 10 years of time period since 2010 [1]. It is clear from the Fig. 1 that the extent of arable land has been increased from 1 200 000 ha to 1 320 200 ha from 2010 to 2017. Therefore, it is highly important to think about efficient water management practices for managing increased water demand created by this increased extent in agricultural land. Surface, sub-surface and micro-irrigation systems are commonly used by Sri Lankan farmers [4]. Basin, border and furrow irrigation methods are good examples for surface irrigation systems, while drip, sprinkler and boom irrigation systems are falling under micro-irrigation systems. They promote efficient use of irrigation water. In addition to this, there were six irrigation systems followed in ancient Sri Lanka: tank method (*Wewa*), Anicut method *(Amuna)*, spring method *(Ulpath)*, animal method *(Sathwa)*, forest method *(Wananthara)* and earth method *(Bhoomi)* (Paranavithana et al., 2020). Low efficiency of water use, poor adaptation to water saving techniques, improper storage facilities, high losses of water during distribution, inefficient on-farm utilization of water and lack of conservation facilities of water are some notable reasons to increase the water demand for agricultural activities in Sri Lanka [3].

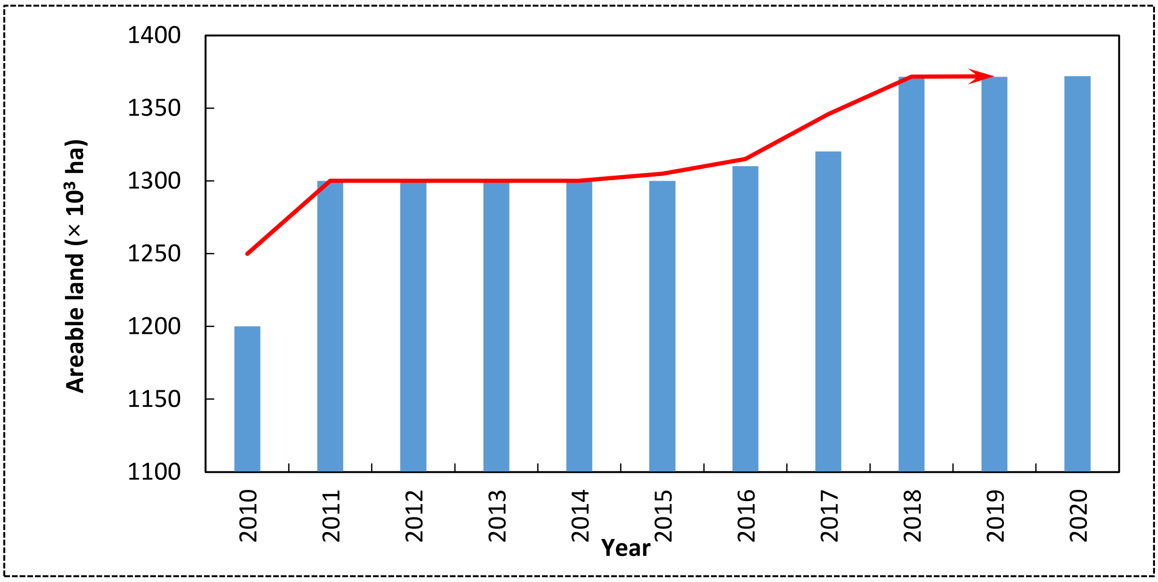


**Figure 1.** Land use in Sri Lanka for agriculture (Source: World Bank, 2022)

Agricultural activities of Sri Lanka mainly depend on rain fed and irrigation [9]. Normally, Sri Lanka has four distinct seasons of rainfall influenced by four major monsoons: first inter-monsoon (March - April), southwest monsoon (May - September), second inter-monsoon (October - November) and northeast monsoon (December - February) [10]. Based on this pattern, *Yala* (April - September) and *Maha* (October - March) are two major seasons of Sri Lanka, and Paddy is the dominant crop in this period of time [11].

Traditionally, farmers in dry zone of Sri Lanka depend on surface water for irrigation from tanks, lakes and ponds [11]. Especially, interlinked cascade system, as shown in the Figure. 2, plays a significant role in irrigation [11]. Over the years development of irrigation systems occurred. Bunds across the rivers to develop large irrigation channels are the major turning points in history of irrigation [11]. However, siltation due to runoff reduced the capacity of tanks. Therefore, there was a need to search for an alternative way of irrigation. At this point, agro-wells with small or large diameters with shallow depth were dug to access the groundwater [11]. A survey report, by Agrarian Research and Training Institute (ARTI), reveals that, in year 2000, the number of privately constructed agro-wells was higher than subsidy wells by the government, and the number kept on increasing [11]. Thereafter, consumption of groundwater for irrigation had been substituted by micro-irrigation practices. Hence, it is highly vital to go for sustainable methods of irrigation so as to keep environmental sustainability of water usage for agricultural production in Sri Lanka.

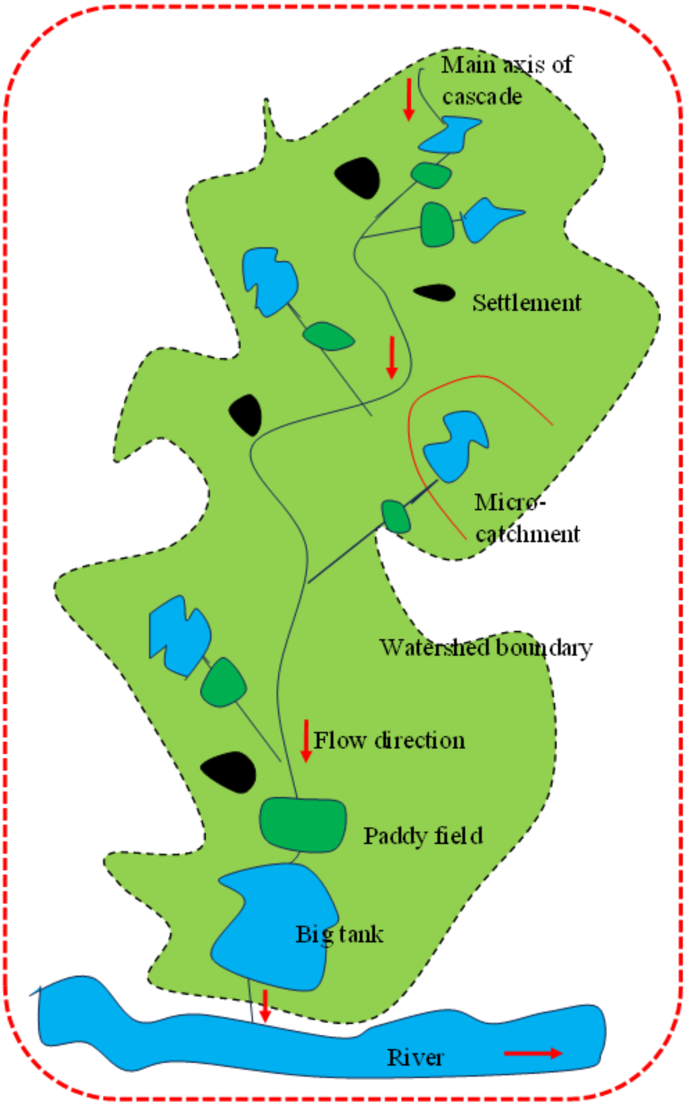


**Figure 2.** Ancient cascade system of tank (Source: Adopted from Department of Earth Science, Freie University Berlin, 2022)

## Climate smart irrigation practices for effective use of water

Water management in irrigated agriculture is becoming more complex to prevail over the expected stress of water scarcity (Patle et al., 2020). Ultimate goal of climate-smart irrigation practices is to optimize efficient use of water, enhance the sturdiness of agriculture with climate change and reduce emission of greenhouse gas [12]. Water-efficient irrigation techniques, irrigation scheduling, mulching, crop selection and rotation, rain water harvesting, soil management, integrated water management and use of climate information and decision support tools are some of the good examples for climate-smart irrigation practices [2]. These practices lead to improve water use efficiency, reduce energy consumption and enhance the resilience to climate change. Moreover, it enhances the sustainability of agriculture and mitigates economic and environmental risks related to climate change and water scarcity [4].

Climate change is a significant challenge for agriculture. Several research works had been done to study the impacts of climatic factors: rainfall, temperature, and evaporation, on agriculture (Patle et al., 2020). The followings are some of the techniques used by farmers to reduce water consumption: crop selection and rotation, water scheduling and rotation and reduction and recycling of water. Moreover, awareness regarding efficient water usage and policy regulations promotes sustainable water use. Further, the research and innovation related to efficient water usage will also lead to avoid issues in irrigation due to climate change. In this regard, overhead irrigation practices: pop-ups, impulse sprinklers, rotors, travelling guns, center-pivot system and, micro-irrigation techniques, (drip, soaker hoses and micro-sprinkler systems) have significant impact on minimizing water usage.

A research on adaptation to climate change by small holder farmers in Sri Lanka reveals that 94% of farmers in agro-ecological regions was vulnerable to climate change [13]. Increasing temperature and wind speed, decreasing rainfall and extreme climatic events: unexpected floods and prolonged drought, are the climate-related issues noted by farmers in Sri Lanka over 20 years [13]. Growing short -season crops, drought-resistant crops, delaying the planting date and changing the type of plant are some measures adapted by farmers to avoid yield reduction due to climate change [2]. Planning of irrigation and providing quality water are encouraged to minimize the water wastage.

Therefore, this sector is set to highlight some usable climate-smart irrigation structures that can be incorporated with new modifications for the sustainable use of water for irrigation in Sri Lanka. Micro-irrigation systems, precise irrigation, automated greenhouse and lined irrigation systems are highly considered in this section as important aspects for the development of conceptual framework that can lead to sustainable water usage in irrigation in future.

***Micro-irrigation practices***

Micro-irrigation is one of the most efficient methods of irrigating crops, which promotes water savings compared to conventional surface-irrigation methods [14]. It delivers water directly and precisely to the root zone of plants [15]. Particularly, it is suitable for areas with water scarcity or limitation. Even though lack of success in promoting professionally designed micro-irrigation systems within Sri Lanka, grassroot level innovations have given a promise [14]. Adaptations to micro-irrigation systems promote the extent of cultivatable area and yield. Moreover, micro-irrigation practices reduce soil erosion, loss of water due drainage, seepage and interception [16]. Hence, it should be promoted further in Sri Lanka to compete with the water scarcity especially in the dry areas of the country. On the other hand, fertigation is possible with micro-irrigation systems as well [17]. This process ensures the direct delivery of nutrient to the rhizosphere, which enhances the nutrient uptake and reduces wastage of fertilizer [17]. However, considerable cost for installation of micro-irrigation systems is one of the main drawbacks of its popularity. Moreover, regular maintenance and inspection for leaks, clogs and damaged parts are essential to ensure proper functioning of these systems [16]. Proper designing, installation and regular maintenance of micro-irrigation systems are crucial to maximize the effectiveness of the system to achieve sustainable irrigation towards the climate change mitigation. Hence, the research into this circle should be promoted to achieve water sustainability in Sri Lanka [14].

*Concept of drip-irrigation*

Drip-irrigation involves the use of tube or pipe network with small emitters that deliver water and nutrient directly to the rhizosphere of a plant at right amount at right time. It is one of the precise methods of water use with high initial cost [18]. Pump, water filters, backwash controller, pressure control valve, lines and emitters are the important components of a drip-irrigation system. A reported work on impacts of drip-irrigation in crop cultivation during drought reveals that tomato crops under drip-irrigation had shown 56.4% of water saving and 22% of yield increase with a water usage efficiency of 4.87%, whereas the saving was only 1.7% for furrow irrigation [19]. The conceptual and comprehensive model of this system is given in the Figure 3.

Subsurface drip-irrigation systems are developed for burying the drip lines underground. It helps to prevent weed growth by supplying water directly to the root zone. Development of new technologies with drip-irrigation systems is in use now: automated drip-irrigation systems with microprocessors coupled with sensors and valves. Several research works have also been reported on this hot topic: analyzing the water usage efficiency of an automated drip-irrigation systems in two different growing media [18]. Arduino incorporated smart-irrigation systems have already been introduced to small-scale home gardens [20]. IoT based smart-irrigation systems for Sri Lankan agriculture has also studied [21]. Field parameters: soil moisture, temperature and humidity, and water supply, can be remotely monitored by IoT based smart-irrigation systems. These innovative steps are still at the embryonic stage in Sri Lanka in comparison with other developed countries. However, these steps must be encouraged in irrigation systems of Sri Lanka to minimize the water footprint in crop production.

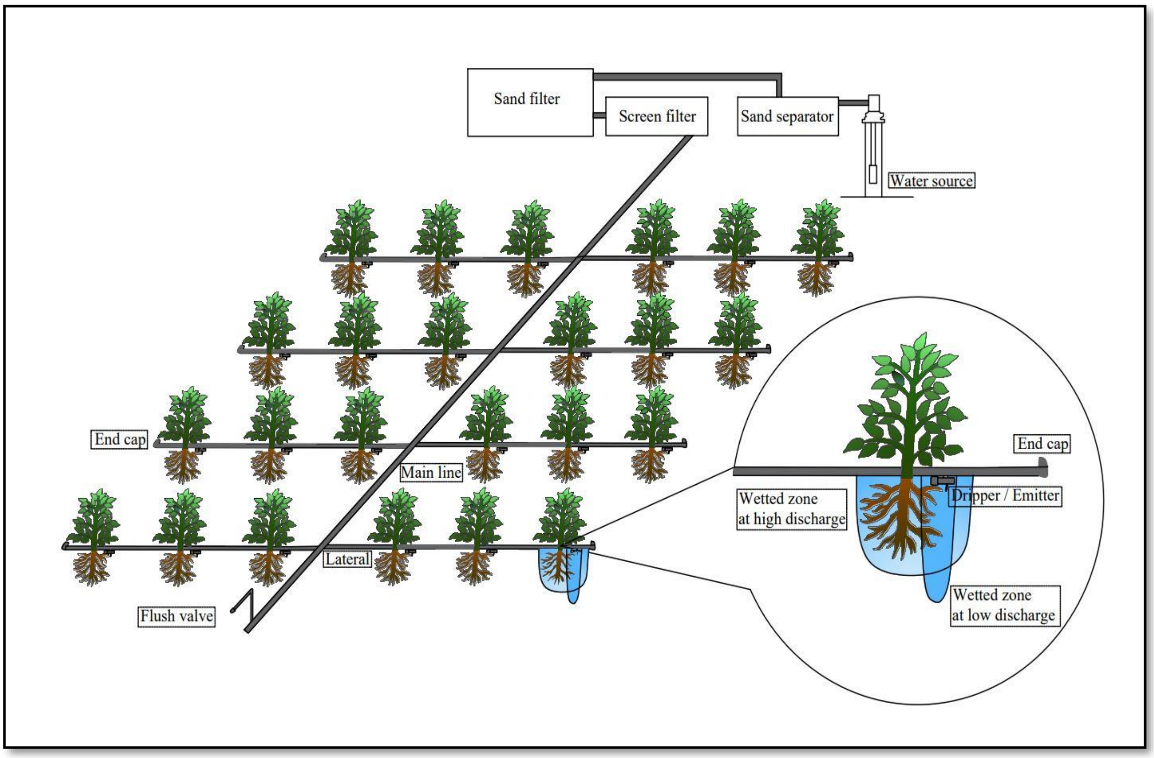


**Figure 3.** Components of a drip irrigation system

*Concept of sprinkler irrigation*

A Sprinkler irrigation system shown in the Figure 4 is a method of applying water similar to rainfall in a controlled manner. It is used to irrigate agricultural crops, home gardens, landscapes, golf courses and grass lands. Perpendicular pipes with horizontally moving nozzles are two major parts of sprinklers. In addition to this, water saving devices: pressure regulators, valves and flow controllers, are also available in sprinkler systems, which facilitate water distribution optimally without wastage [22]. They provide a fine and gentle spray. Low-cost sprinkler innovations are available for the use with recoverable input cost within a year or two [22]. These are user- friendly, easy to install, and have potential to irrigate cash crops. A research survey, conducted in Northern and Western parts of Sri Lanka, regarding irrigation, reveals that, among 100 farmers, 85% was adapted to use sprinklers [23]. Therefore, the innovative structures of sprinkler irrigation should be promoted in Sri Lanka for the sustainable use of water.

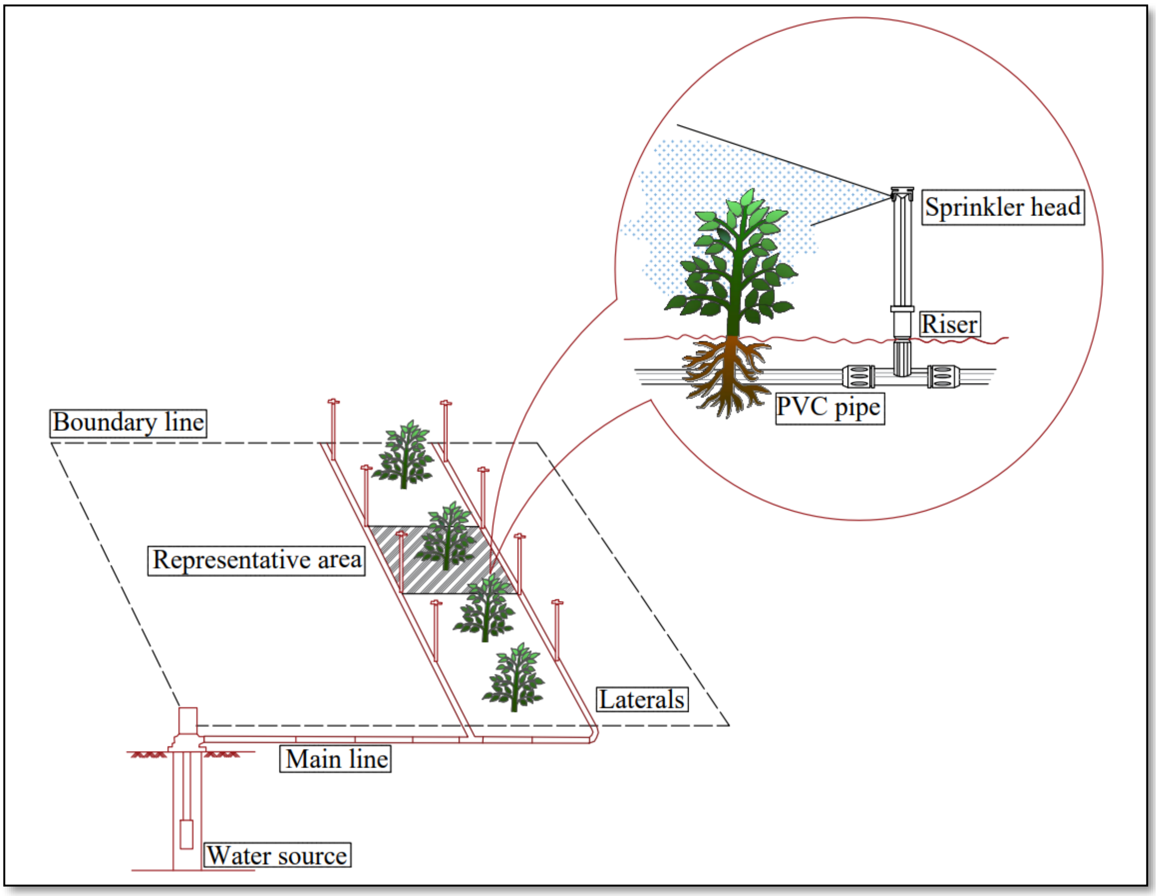


**Figure 4.** Layout of an effective sprinkler irrigation

***Automated greenhouse***

Around 50% of additional food supply is expected by the year 2050 compared to the year 2010 [24]. It is an additional burden to agriculture sector to assure the food security in future. Therefore, it is essential to increase the productivity of land. With this connection, protected agriculture plays a major role to assure high productivity under the controlled environmental conditions. The choice of irrigation systems for greenhouse operations depends on several factors: variety of plants, complexity of the operation, cost, water quality, and availability. Manual watering is possible for a small scale greenhouse, while large scale greenhouses are expected to have micro-irrigation systems [25]. Moreover, with the development of technology, most of the greenhouses are changed into automated or semi-automated irrigation structures with Arduino, micro-sprinklers, overhead booms and flood floor irrigation systems. This comprehensive concept is graphically illustrated in the Figure 5.

Overhead systems and closed systems are two major types of irrigation systems usually found in greenhouses. Greenhouse operators also have choices to select various sub-irrigation systems based on their needs and preferences [26]. European greenhouse industry has widely adopted the subsurface-irrigation structures [2]. However, initial cost for installation, proper maintenance and technical knowledge are key inputs needed to handle these types of modern irrigation structures in greenhouses. Under the closed irrigation systems, recirculation of nutrient solution is also taking place. Leaching of nutrients to soil is prevented by pumping water from tank to rhizosphere directly [14]. However, availability of equipment and initial cost are considerable factors. In addition, it may promote soil borne diseases. Hence, this new concept should be studied scientifically so as to strengthen its field applications.

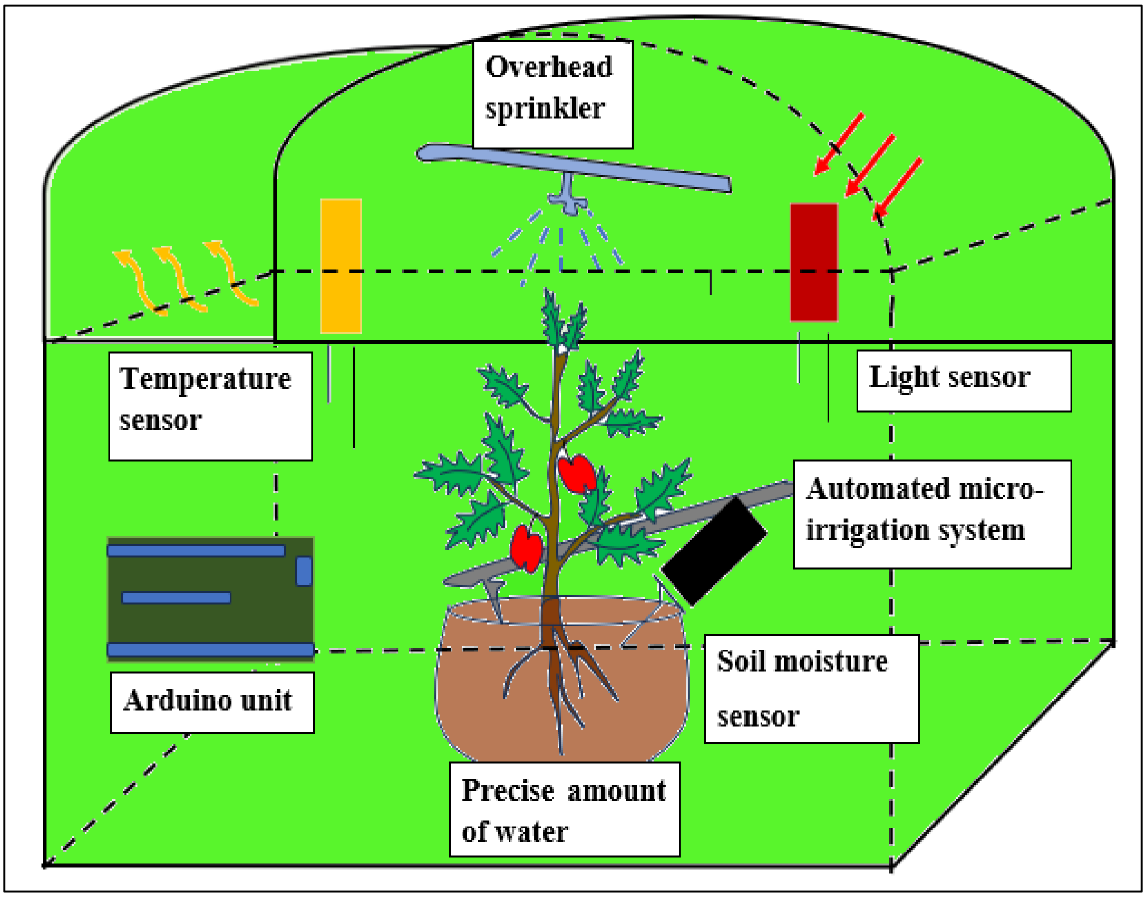


**Figure 5.** Components of an automated greenhouse system

***Conservation tillage and lined irrigation***

Soil tillage leads to loss of organic matter content in soil [27]. It effects on the water holding capacity (WHC) of soil [28]. Therefore, some techniques, followed by farmers to mitigate this effect, are zero tillage and conservation tillage, which enhance the availability of soil organic matter and promote the presence of soil microorganisms. In addition, fallen-crop residues are maintained on soil surface. Therefore, minimum soil disturbance is set to occur [27]. Conservation tillage practices reduce soil erosion and water loss from farm land [29]. Soil is compacted by conservation tillage. Therefore, the need of water for irrigation is also low compared to conventional soil tillage [30].

Line irrigation is another main concept in controlling water usage for irrigation [31]. Traditional farmers use mud channels to discharge water. However, the loss of water by pore filling, seepage and percolation is high. These losses lead to groundwater salinity [31]. An analysis of conveyance loss reveals that 70% of groundwater salinity was caused by irrigation water [31]. It was, then, replaced by concrete channels and the water loss was low compared to mud channels. Poly bags and PVC pipes are alternatives for above mentioned irrigation channels [32]. Expansion of research into this field is highly needed in Sri Lanka for reducing the conveyance losses in irrigation.

***Precision Irrigation***

Advanced technologies play a significant role in precision irrigation systems with the use of soil moisture sensors, weather data predictors and advanced electronic devices, which can estimate the required amount of water. Therefore, optimum amount of water application at right time is made possible. This helps to avoid over-irrigation. However, technical knowledge is needed to handle the electronic devices and connected parts. Precision agriculture provides the access to updated information regarding weather, pest and diseases, machinery and fertilizers. It leads to farmers to make correct decisions regarding their next move [33]. Data-oriented irrigation management, cloud-based irrigation control system, performance-proven water allocation are some of the advanced technologies, which have the potential to develop sustainable irrigation systems with high quality and increased efficiency [34]. Paying attention to these technologies and their suitability under Sri Lankan contest is very important for better use of irrigation water in Sri Lanka.

***Timely-irrigation and application of mulch***

Immediate, small-scale surrounding of an organism or system is known as micro-environment [35]. It contains the factors that have the direct influence on specific objects: temperature, humidity, air quality, presence of light and microorganisms. The quality of this micro-environment is one of the limiting factors of plant growth [36]. Pot and pitcher irrigation are customary methods of surface irrigation, which have been used in many countries [37]. It has a significant importance in micro-environment. It includes burying of a pot, pitcher, PVC pipe or porous plastic pipes near to the plant, and the refilling should be done manually or using a flexible hose. Therefore, moisture stress of plants and soil salinity will be reduced. The Figure. 6 is a graphical representation of different types of pitcher-irrigation methods for soil moisture conservation.

Clay pitches deliver water at a rate that closely matches with the water requirement for plants. It has been proved by an investigation of a pitcher irrigation conducted in India [37]. Pitcher irrigation exhibits a water distribution pattern that resembles a balloon shape with the potential for both horizontal and vertical water reaches. A research suggests that the distribution rate of water had been high for dry soil, and it had been at the low rate of distribution for wet soil [15]. Mulching is a process of application of organic materials or polythene in order to prevent the moisture loss from the field by reducing evaporation [38]. Furthermore, it also enhances the efficiency of micro-irrigation and helps to regulate soil temperature [38].

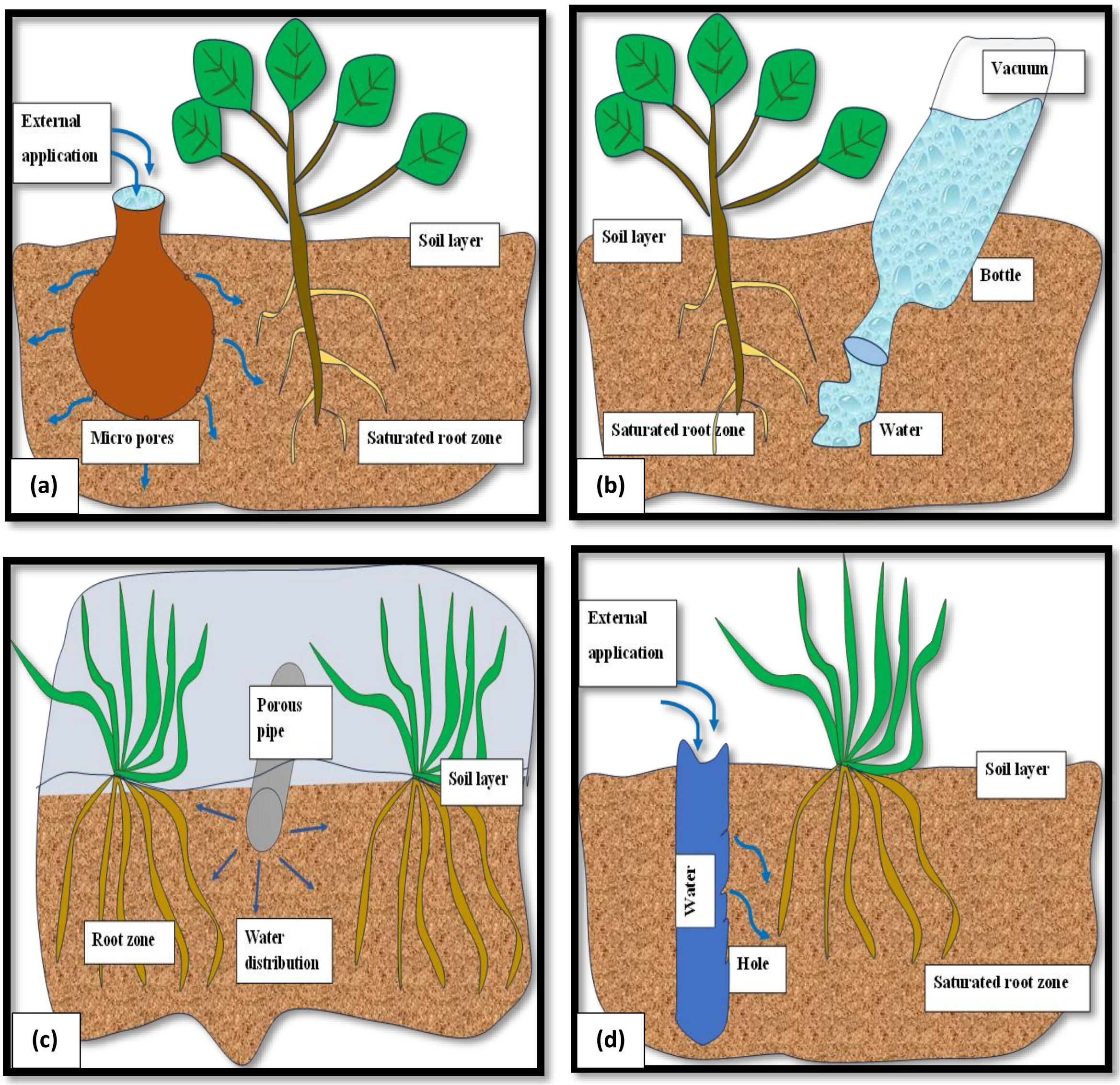


**Figure 6.** Different types of pitcher-irrigation systems **(a).** pot irrigation; **(b).** bottle irrigation; **(c).** porous irrigation; **(d).** perforated plastic sleeves

**Paddy cultivation and water management**

In context of Sri Lankan agriculture, paddy is the major crop cultivated to the extent around 10% of total available land (7080 km$^2$) [39]. Paddy cultivation is promoted through the irrigation and fertilizer application. The limitation in water resources and pollution by non-point sources, especially fertilizer application, cause the deterioration in water quality. The concept of water footprint is mainly used in water resource management in agriculture. Water footprint comprehensively summarizes the total direct or indirect water consumption in each step of a production and a tool used to analyze the impact on the quality and quantity of water during the production [40]. Since the economy of Sri Lanka is mainly based on agriculture, the understanding regarding the amount of water usage is curial to reduce the water scarcity. The conventional irrigation practice (Flooded irrigation) leads to the loss of water due to high seepage loss, evapotranspiration and percolation and causes environmental pollution due to the emission of methane gas. Alternate wetting and drying (AWD) generally practiced in low-land rice growing regions to improve the crop productivity by reducing the water usage by 30% and methane emission by 48% [41]. This irrigation strategy used in the paddy field to increase crop productivity is by regularizing the intervals and amount of water application without creating any detrimental moisture stress to the rice crop.

In Sri Lanka, paddy cultivation is mainly dependent upon the onset of rainfall and water available in reservoirs or tanks. Paddy cultivation in Sri Lanka is undertaken in two seasons based on the availability of water. *Maha* season mainly depends on rainfall along with alternate wetting and drying (AWD), which is supported with supplementary irrigation. The major paddy variety grown in this season is medium to long grain. Moreover, *Yala* season, which is provided with AWD condition, is set to have short duration variety [42]. Therefore, access to accurate forecasting will facilitate the farmer to make timely and appropriate decision on the varietal selection and time of cultivation. Furthermore ,the System of Rice Intensification (SRI) is another approach practiced globally in many countries, including China, India and Vietnam, to increase the productivity of irrigated rice by changing the management practices of water, soil, plant and nutrient [43]. The other possible water management strategies for paddy cultivation are listed in the Figure 7.

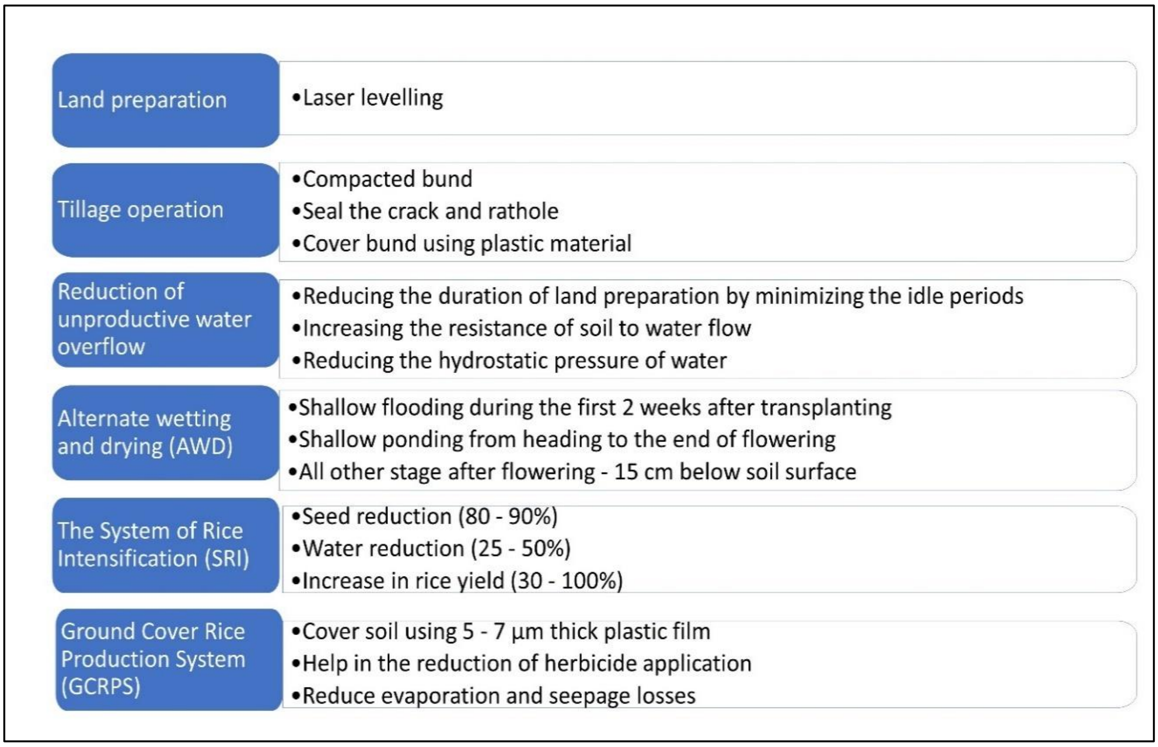


**Figure 7.** Possible water management strategies for paddy cultivation

## Conclusions

Sri Lanka is considered as an agriculture based country although its contribution to GDP is in the declining trend. Agriculture plays a crucial role in the economy of Sri Lanka as 26% of the employability is in this sector. However, shortage of good quality irrigation water significantly influences the agricultural production in Sri Lanka. Furthermore, climate change and its impact on crop production are to be taken into consideration so as to develop appropriate and compatible technologies for efficient use of irrigation water. The points discussed in this chapter are important for the development of conceptual framework to implement good water management strategies for irrigation applications in Sri Lanka. Moreover, well-structured research programs must be expanded in order to incorporate innovative technologies into irrigation systems in the country for the sustainable use of water. All in all, the points discussed in this chapter will help all professionals and policy makers, who are involved in Sri Lankan water sector, design efficient irrigation plans that lead to sustainable water usage for agriculture in the future.

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## Competing interest

Authors declare that they have no any competing interest to write this chapter.

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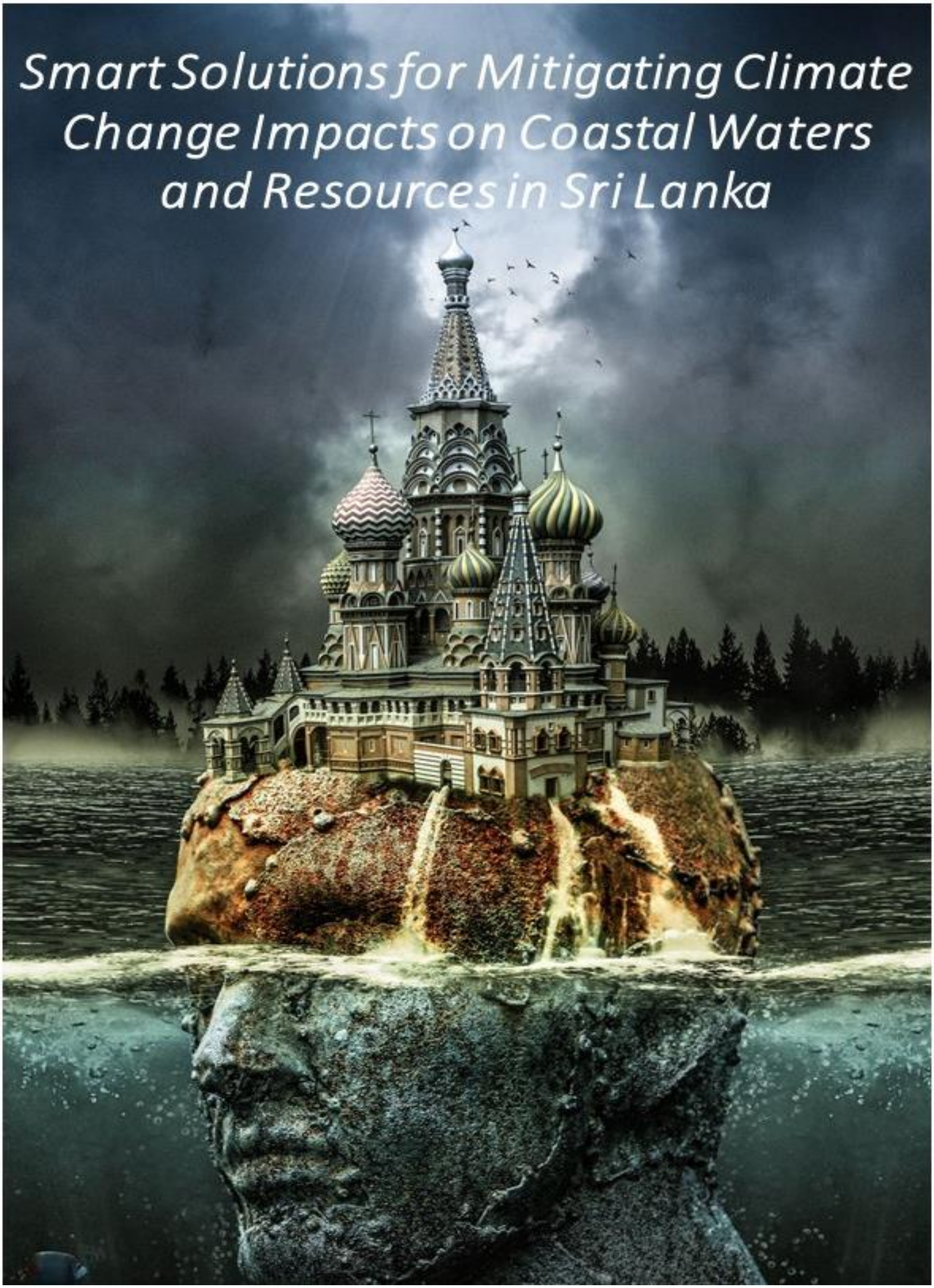
Smart Solutions for Mitigating Climate Change Impacts on Coastal Waters and Resources in Sri Lanka

# Smart Solutions for Mitigating Climate Change Impacts on Coastal Waters and Resources in Sri Lanka

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## Abstract

"Smart Solutions for Mitigating Climate Change Impacts on Coastal Waters and Resources in Sri Lanka" delves into the pressing issue of climate change's impact on coastal regions, focusing on Sri Lanka's unique coastal environment. It explores the science of climate change, highlighting the interconnectedness of rising sea levels, ocean acidification, and the importance of coastal fisheries and water resources. The book chapter emphasizes the role of advanced monitoring systems in early anomaly detection and decision-making through real-world case studies. Ecosystem restoration, specifically mangroves and coral reefs, is showcased for strengthening coastal resilience and marine biodiversity. Additionally, it discusses climate-resilient infrastructure, sustainable fisheries management, and responsible fishing practices, striking a balance between conservation and livelihoods. Empowering coastal communities is a recurrent theme, emphasizing the transformative potential of education and community involvement. Policy advocacy and collaboration are highlighted as crucial for advancing climate adaptation policies. The book chapter concludes with a call to action, urging individuals, communities, and policymakers to collaborate for a harmonious future where coastal ecosystems and human endeavors thrive together. This book chapter serves as a roadmap toward a sustainable and vibrant future for Sri Lanka's coastal regions, encapsulating the essence of collective action in the face of climate change's looming challenges.

**Keywords:** Climate Change Impacts, Coastal Resilience, Sri Lanka's Coastal Environment, Advanced Monitoring Systems, Ecosystem Restoration

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## Section 1: The coastal ecosystem of Sri Lanka - A precious resource at risk

The coastal ecosystem of Sri Lanka stands as a testament to the beauty and diversity of nature. Stretching along its shores are mangrove forests, coral reefs, sea grass beds, and pristine beaches, each contributing to a delicate balance that sustains marine life and human livelihoods [1]. However, this precious resource is now under threat due to the impacts of climate change.

### Coastal biodiversity hotspot

Sri Lanka's coastal waters are a biodiversity hotspot, teeming with a wide array of marine species. Coral reefs, often referred to as the "rainforests of the sea," harbor an astonishing variety of fish, mollusks, and other marine organisms. These reefs also provide habitat and shelter for countless species and offer a source of sustenance for local communities through fishing and tourism.
Mangrove forests, with their intertwining roots and unique adaptations, act as natural buffers against coastal erosion and storm surges [2]. They are also critical nurseries for juvenile fish and provide a haven for numerous bird species. The sea grass beds further enhance the coastal ecosystem by stabilizing sediments, serving as a food source, and acting as a breeding ground for marine creatures.

#### Climate change threats

Sri Lanka's coastal ecosystem faces an array of threats brought about by climate change. Rising sea temperatures are causing coral bleaching events, leading to the loss of vibrant and diverse coral reefs [3]. Ocean acidification, driven by the absorption of excess carbon dioxide, is affecting the ability of marine organisms to build and maintain their calcium carbonate structures, including corals and mollusks. Sea level rise, another consequence of climate change, directly threatens coastal communities and habitats. As sea levels rise, coastal erosion intensifies, endangering infrastructure, homes, and vital ecosystems. This is particularly concerning for low-lying areas and densely populated coastal cities.

### The way forward

In the face of these challenges, innovative and adaptive solutions are urgently needed to mitigate the impacts of climate change on Sri Lanka's coastal ecosystem. This book chapter will explore various strategies that researchers, policymakers, and local communities are exploring to protect and restore these vital habitats. From coral reef restoration and mangrove rehabilitation to the development of marine protected areas and sustainable fishing practices, the chapter will showcase the ongoing efforts aimed at preserving the rich biodiversity and ecological balance of Sri Lanka's coastal waters [4]. It will also highlight the importance of community engagement, education, and international collaboration in fostering resilience and sustainability.

As we navigate the complexities of climate change and its effects on coastal ecosystems, it becomes clear that safeguarding these environments is not only a matter of ecological conservation but also a means of securing the livelihoods and well-being of present and future generations. The journey toward smart solutions for mitigating climate change impacts on Sri Lanka's coastal waters is a shared endeavor that requires dedication, innovation, and a deep appreciation for the interconnectedness of all life forms on Earth.

## Section 2: The problems faced by the coastal areas of Sri Lanka

#### Rising tides - Sea level rise and its effects on Sri Lanka's coastline

Sea level rise is a stark reminder of the far-reaching impacts of climate change, and Sri Lanka's coastline is no stranger to its effects. As global temperatures rise, glaciers melt, and thermal expansion occurs, the world's oceans expand, causing sea levels to gradually increase. The phenomenon of sea-level rise and its associated challenges present significant threats to the low-lying coastal areas of Sri Lanka, making them vulnerable to inundation and erosion [5].

Among the notable low-lying coastal regions in Sri Lanka, Colombo stands out as the capital city located along the western coast. This area, along with its surrounding regions, is particularly susceptible to sea-level rise and flooding. Moving north, the Jaffna Peninsula, situated in the northern part of Sri Lanka, also contains low-lying coastal areas that face the risks associated with rising sea levels. On the eastern coast, Batticaloa is known for its low-lying terrain, making it prone to the impacts of sea-level rise. Similarly, the Trincomalee District in the east includes low-lying coastal regions that are at risk due to the changing sea levels. Heading to the southern part of the island, Galle and its surroundings have low-lying coastal areas, contributing to the overall vulnerability of Sri Lanka's coastal regions to the challenges posed by sea-level rise.

**The vulnerable coastal communities and impact on biodiversity and ecosystems**

Sri Lanka's coastal regions are home to a significant portion of the country's population, with bustling cities, fishing villages, and cultural heritage sites dotting the shoreline. Unfortunately, many of these communities are at risk due to sea level rise [6]. Coastal erosion, intensified by rising sea levels, threatens infrastructure, homes, and livelihoods, forcing communities to grapple with the difficult decision of whether to retreat inland or invest in costly protective measures [7]. The consequences of sea-level rise extend beyond human settlements to impact crucial coastal habitats such as mangrove forests, sea grass beds, coral reefs, sandy beaches, and estuaries and lagoons. Mangrove forests, found along Sri Lanka's coasts, face vulnerability as increased inundation can result in habitat loss and reduced sediment deposition [8]. Similarly, coral reefs in Sri Lanka's coastal waters are susceptible to bleaching and reduced calcification due to rising sea temperatures and ocean acidification [9]. Sea grass beds, vital for coastal ecosystem health, can be impacted by sea-level rise, leading to reduced light penetration and affecting their growth [10].

Sandy beaches, essential for tourism and nesting sea turtles, confront vulnerability as they experience erosion and loss due to rising sea levels and increased storm surges [11]. Furthermore, estuaries and lagoons in Sri Lanka are at risk of salinization and altered hydrodynamics due to sea-level rise, thereby affecting the biodiversity they support [12]. Mangroves, known for their unique ability to thrive in brackish water, act as natural buffers against storm surges and provide breeding grounds for marine life. However, as sea levels rise, these habitats are at risk of submergence, leading to the potential loss of biodiversity and disruptions to the intricate web of coastal ecosystems.

**Adaptation and mitigation strategies**

Efforts to address the challenges posed by sea level rise encompass a range of strategies, from immediate adaptation measures to long-term mitigation plans. Coastal engineering projects, such as seawalls and breakwaters, aim to protect vulnerable areas from erosion and inundation. While these measures can provide short-term relief, they often come with environmental trade-offs and may not be sustainable in the long run [13].

**Nature-based solutions, on the other hand, harness the power of natural ecosystems to mitigate the impacts of sea level rise.**

The restoration and conservation of mangrove forests, for instance, can provide coastal protection and marine life habitat. By carefully integrating these natural defenses with community needs, Sri Lanka can enhance its resilience to sea level rise while preserving the unique character of its coastal landscapes [14].

## A call for multifaceted action

Addressing the challenges posed by sea-level rise demands a multifaceted approach that intertwines scientific research, community engagement, and policy development. Combining local knowledge with global expertise is crucial for Sri Lanka to navigate the rising tides and secure a sustainable future for its coastal communities and ecosystems. Key strategies to mitigate sea-level rise include investing in the restoration and protection of mangrove forests along the coastline, as mangroves serve as natural buffers by trapping sediments and reducing wave energy [15]. Developing and upgrading climate-resilient infrastructure, such as elevated roads, flood barriers, and improved drainage systems, is essential [5]. Beach nourishment projects can be implemented to restore eroded shorelines, involving the addition of sand or sediment to replenish beaches and provide natural coastal protection [16]. The adoption of integrated coastal zone management plans is critical, balancing development with conservation and considering ecological, social, and economic aspects of coastal regions [17]. Community engagement plays a pivotal role, necessitating the involvement of local communities in decision-making processes and adaptation efforts, leveraging their traditional knowledge for sustainable coastal management [18].

Strengthening early warning systems for coastal communities, providing timely alerts about potential threats, is imperative [19]. Sustainable land use planning should be implemented to restrict construction in vulnerable coastal areas, thereby reducing exposure to sea-level rise and minimizing future risks [5]. Additionally, promoting livelihood diversification among coastal communities through alternative, less vulnerable income sources, such as sustainable aquaculture, is vital [20]. Launching education and awareness campaigns about the risks of sea-level rise and the importance of adaptation empowers communities with knowledge to take proactive measures [21]. International collaboration with neighboring countries and organizations facilitates the sharing of knowledge, resources, and best practices for sea-level rise adaptation [17]. Implementation of this multifaceted action plan necessitates collaboration among government agencies, NGOs, local communities, and international partners. By comprehensively addressing sea-level rise, Sri Lanka can enhance its resilience and protect its coastal areas.

## Ocean acidification - implications for marine life and fisheries

As the world grapples with the multifaceted challenges of climate change, another insidious threat looms beneath the surface: ocean acidification. This process, driven by the absorption of excess carbon dioxide by seawater, has far-reaching implications for marine ecosystems and the fisheries that depend on them. Sri Lanka's coastal waters, rich in marine biodiversity and resources, are not immune to the effects of this silent menace. Ocean acidification is a consequence of the increasing carbon dioxide levels in the atmosphere. As more carbon dioxide dissolves in seawater, it reacts with water molecules to form carbonic acid. This process leads to a decrease in the pH of the ocean, making it more acidic over time [22]. The impacts are particularly pronounced in cold-water regions and coastal areas, where upwelling brings carbon dioxide-rich water to the surface.

## Coral reefs and shellfish under threat

Marine calcifiers are one of the most vulnerable groups of organisms in the face of ocean acidification. These include coral reefs and shellfish, which rely on calcium carbonate to build their skeletons and shells [23]. As the ocean becomes more acidic, the availability of carbonate ions, essential for calcium carbonate formation, decreases. This strains coral reefs immensely, jeopardizing their growth and structural integrity. Similarly, shellfish like clams, oysters, and mussels find it increasingly challenging to form and maintain their protective shells [24].

## Impacts on fisheries and livelihoods

Ocean acidification reverberates through the marine food web, affecting species at all levels. Phytoplankton, the foundation of marine ecosystems, may experience shifts in growth and productivity, impacting the entire food chain. Commercially valuable species, such as fish and crustaceans, may exhibit altered behavior, reduced growth rates, and changes in distribution patterns. This, in turn, can disrupt fisheries and threaten the livelihoods of coastal communities that depend on marine resources for sustenance and income [25].

### Finding resilience through science and collaboration

The urgency of addressing ocean acidification cannot be overstated. To combat this threat, a multi-pronged approach is required. Scientific research plays a pivotal role in understanding the mechanisms and impacts of ocean acidification, guiding the development of mitigation and adaptation strategies [26]. For example, selectively breeding shellfish with increased tolerance to acidic conditions shows promise in ensuring the viability of aquaculture operations. Furthermore, international collaboration is essential, as ocean acidification knows no boundaries. By sharing knowledge, best practices, and innovative solutions, countries can collaborate to safeguard marine ecosystems and the resources they provide. As Sri Lanka navigates this uncharted territory, it can draw inspiration from global experiences and forge a path toward a more resilient and sustainable coastal future.

### Storm surges and extreme weather events - challenges and adaptation strategies

In an era of rapidly changing climate patterns, the coastal regions of Sri Lanka are increasingly vulnerable to the wrath of extreme weather events. Among these, storm surges stand out as formidable natural forces that can wreak havoc on coastal communities, infrastructure, and ecosystems [27]. This section delves into the dynamics of storm surges, their impacts, and the strategies being employed to enhance resilience in the face of these destructive events. Storm surges are characterized by a rapid rise in sea level, often triggered by tropical cyclones or intense storms. As strong winds push water toward the coast, it accumulates and surges inland, inundating low-lying areas. The combined effects of wind, low atmospheric pressure, and the Earth's rotation contribute to the formation and amplification of these surges [28].

#### Coastal vulnerabilities and human impact

Sri Lanka's densely populated coastal areas are particularly susceptible to the devastation caused by storm surges. Infrastructure, homes, and livelihoods are at risk, and the impacts can be felt far beyond the immediate event. Communities may experience prolonged displacement, loss of freshwater sources, and disruptions to essential services. In some cases, the ecological balance of coastal ecosystems can be severely disrupted, affecting the marine life and resources on which local communities depend [29].

#### Adaptation strategies and building resilience

The key to mitigating the impacts of storm surges lies in a combination of proactive measures and early warning systems. Coastal engineering projects, such as levees, seawalls, and breakwaters, provide physical protection against storm surges, preventing or minimizing the extent of flooding and erosion. However, these measures often require careful planning to ensure that they do not inadvertently exacerbate problems or harm local ecosystems [30].

Equally critical are early warning systems that provide timely and accurate information to communities at risk. These systems rely on meteorological data, satellite imagery, and modeling to predict the intensity and trajectory of storms and surges. When coupled with effective communication strategies and community engagement, early warning systems can significantly reduce the loss of life and property during extreme weather events. As climate change continues to influence the frequency and intensity of extreme weather events, the need for resilient coastal communities becomes paramount. By combining scientific research, technological innovation, and community empowerment, Sri Lanka can build a future where the impact of storm surges is minimized, and its coastal areas remain safe, thriving, and resilient.

## Section 3: Natural protestants

### Mangrove forests - Nature's shield against climate impacts

Mangrove forests, often referred to as "nature's nurseries," are unsung heroes in the battle against climate change and coastal degradation. These unique ecosystems, found along Sri Lanka's coastlines, provide a myriad of benefits that extend far beyond their aesthetic beauty [31]. This section delves into the vital role of mangrove forests in mitigating climate impacts, protecting coastal communities, and sustaining biodiversity.

### Biodiversity and ecological significance

Mangroves thrive in the intertidal zone, bridging the gap between land and sea. Their intricate root systems trap sediments and create natural barriers that absorb and dissipate wave energy during storms [32]. This makes mangroves invaluable in shielding coastal communities from erosion, storm surges, and rising sea levels. Their presence can mean the difference between devastation and safety during extreme weather events. Beyond their protective role, mangroves support a rich tapestry of biodiversity. These ecosystems provide critical habitats for various species, from juvenile fish seeking refuge to migratory birds en route to distant shores [33]. Mangroves also serve as spawning grounds for many marine organisms, contributing to the vitality of coastal fisheries. Their roots filter pollutants from the water, enhancing water quality and supporting healthier marine ecosystems.

### Carbon sequestration and climate mitigation

Mangroves are renowned for their impressive ability to sequester carbon dioxide from the atmosphere. The organic matter that accumulates in their soil and biomass can store carbon for centuries, playing a crucial role in mitigating climate change. This carbon sequestration not only helps reduce greenhouse gas concentrations but also provides a tangible incentive for conserving and restoring mangrove forests.

### Restoration and sustainable management

Despite their immense ecological and socio-economic value, mangrove forests are under threat from various factors, including deforestation, pollution, and aquaculture development. Efforts to restore and sustainably manage these ecosystems are crucial to their survival [34]. Successful mangrove restoration projects often involve local communities, empowering them to take an active role in safeguarding their natural resources.

#### Coral reefs in peril - bleaching and restoration efforts

Coral reefs, the vibrant and diverse underwater ecosystems that adorn the oceans, are facing a dire and existential threat: coral bleaching. These delicate and intricate habitats, including those found in Sri Lanka's coastal waters, are succumbing to the impacts of climate change [35]. This section delves into the phenomenon of coral bleaching, its implications, and the ongoing efforts to restore and protect these invaluable marine treasures. Coral reefs are often referred to as the "rainforests of the sea," due to the astonishing biodiversity they support. These underwater metropolises are home to an array of species, from colorful corals and mesmerizing fish to elusive crustaceans and majestic marine mammals [36]. Coral reefs also play an essential role in coastal protection, buffering against storm surges and erosion, and contributing to fisheries that sustain millions of livelihoods worldwide.

Coral bleaching occurs when coral polyps expel the symbiotic algae that provide them with essential nutrients and vibrant colors. This expulsion is often triggered by stressors, such as elevated sea temperatures and ocean acidification. Without their algae partners, corals lose their color, become more susceptible to disease, and may ultimately perish if the stressors persist.

**Climate change and coral resilience**

The main driver of coral bleaching is the increasing sea temperatures associated with climate change. As ocean temperatures rise, corals are exposed to prolonged and intense heat waves, pushing them beyond their temperature tolerance limits [37]. While some corals exhibit a degree of thermal tolerance, the frequency and severity of bleaching events are outpacing their capacity to recover, leaving reefs in a state of chronic stress.

**Restoration and resilience strategies**

Efforts to combat coral bleaching are twofold: immediate restoration measures and long-term resilience-building strategies. Coral nurseries, where fragments of healthy corals are grown and transplanted onto degraded reefs, offer hope for rapid recovery [38]. Additionally, reducing local stressors, such as overfishing and pollution, can enhance coral resilience to climate-induced stress. Building coral reef resilience requires a holistic approach that involves science, policy, and community engagement. By nurturing the recovery of coral reefs, we can protect the intricate web of life they support and secure a future where these underwater wonders continue to thrive and inspire generations to come.

## Section 4: Management strategies to overcome the problems Sri Lanka faces

### Sustainable fisheries management in a changing climate

The coastal waters of Sri Lanka have long been a vital source of sustenance and livelihoods for its communities, heavily reliant on fisheries. However, the dual pressures of overfishing and climate change are putting these resources at risk. This section explores the complex interplay between sustainable fisheries management and the challenges posed by a changing climate, offering insights into innovative strategies for safeguarding both marine life and human well-being. Climate change impacts ripple through marine ecosystems, affecting fish populations, migration patterns, and reproductive cycles. Warmer waters can lead to shifts in fish distribution, potentially altering the abundance and availability of species that coastal communities depend on. Changes in ocean chemistry, such as ocean acidification, may further disrupt the marine food web and the delicate balance of aquatic life.

### Overfishing - A dual threat

While climate change poses significant challenges, the threat of overfishing remains equally pressing. Unsustainable fishing practices, such as trawling and overexploitation of certain species, can deplete fish stocks and harm the overall health of marine ecosystems. This not only jeopardizes livelihoods but also diminishes the resilience of fisheries to climate-related stressors.

### Sustainable fisheries management: Balancing act

Sustainable fisheries management requires a delicate balancing act that considers ecological, economic, and social factors. Ecosystem-based approaches, such as implementing marine protected areas and enforcing catch limits, promote the recovery of fish populations and maintain the integrity of marine habitats. These measures, when tailored to the unique context of Sri Lanka's coastal waters, can foster the long-term viability of fisheries.

### Enhancing resilience and adaptation

Adaptation strategies are essential to address the challenges that climate change poses to fisheries. Integrating traditional knowledge and scientific insights can help identify resilient fish species and sustainable fishing practices. Strengthening post-harvest processing and market linkages can enhance the economic viability of fishing communities, reducing their vulnerability to climate-induced disruptions. As Sri Lanka navigates the complexities of a changing climate and its impact on fisheries, the integration of conservation, responsible governance, and community engagement will play a pivotal role in ensuring a future where both marine ecosystems and coastal communities thrive in harmony.

### Integrated coastal zone management - balancing development and conservation

The coastal zones of Sri Lanka are dynamic and diverse landscapes, serving as hotspots of human activity, economic development, and ecological richness. However, the intricate balance between development and conservation is increasingly challenged by the impacts of climate change. This section delves into the concept of Integrated Coastal Zone Management (ICZM), exploring how it can provide a framework for harmonizing development goals with the imperative of protecting fragile coastal ecosystems. Coastal zones encompass a wide range of environments, from bustling urban centers to remote fishing villages and pristine natural habitats. The interactions between human activities, land use, and marine resources create intricate webs of social, economic, and environmental dynamics. Balancing the demands of various stakeholders while preserving the integrity of these ecosystems is a complex and nuanced endeavor. ICZM is a holistic and adaptive approach that seeks to coordinate and integrate policies, activities, and stakeholders across coastal areas. By promoting sustainable development and ecosystem conservation, ICZM aims to minimize conflicts, enhance resilience, and safeguard the long-term well-being of both human communities and natural habitats.

### Climate change adaptation through ICZM

As climate change accelerates, the principles of ICZM become even more relevant. The rising sea levels, increased storm intensity, and changing precipitation patterns associated with climate change demand proactive and flexible approaches to coastal management. ICZM provides a framework for identifying vulnerable areas, implementing adaptive strategies, and engaging local communities in the decision-making process.

### Case studies

From multi-stakeholder engagement and participatory planning to innovative coastal engineering projects and sustainable tourism initiatives, the case studies offer valuable insights into the practical implementation of ICZM principles.

### Charting a sustainable course

Sri Lanka's coastal zones are at a crossroads, with the dual challenges of development and climate change demanding a cohesive and forward-looking strategy. ICZM underscores the importance of an integrated, sustainable, and community-driven approach to coastal management. By embracing these principles and working together, we can safeguard our coastal ecosystems, enhance resilience in the face of climate change, and promote the well-being of coastal communities for generations to come.

### Harnessing renewable energy - wind, solar, and tidal power along the coast

In the quest for sustainable and resilient coastal development, the exploration of renewable energy sources emerges as a promising avenue. Sri Lanka's coastal regions, abundant in natural resources and subjected to the impacts of climate change, stand to benefit from harnessing clean energy from wind, solar, and tidal sources. This section delves into the potential of renewable energy to mitigate climate impacts while fostering economic growth. Renewable energy sources such as wind, solar, and tidal power capitalize on the Earth's natural processes to generate electricity. Wind turbines harness the kinetic energy of moving air, while solar panels convert sunlight into electrical energy. Tidal power taps into the gravitational pull of the moon, producing electricity through the ebb and flow of ocean tides. These sources offer a sustainable alternative to fossil fuels, reducing greenhouse gas emissions and the reliance on non-renewable resources.

### Advantages for renewable energy

Sri Lanka's coastal areas possess unique characteristics that make them well-suited for renewable energy development. The consistent coastal winds, ample sunlight, and predictable tidal patterns create a favorable environment for the installation of wind turbines, solar panels, and tidal energy systems. These installations not only produce clean electricity but can also stimulate local economies through job creation and technological innovation.

Offshore wind farms have gained traction as a viable means of generating large amounts of electricity. By harnessing the strong and consistent winds that sweep across the ocean, these farms can contribute significantly to a country's energy mix. Tidal energy, on the other hand, utilizes the reliable ebb and flow of tides to turn turbines and produce power [39]. Both of these technologies offer a unique opportunity for Sri Lanka to tap into its coastal energy potential.

### Community engagement and environmental considerations

As with any development endeavor, community engagement and environmental considerations are paramount. Proper site selection, environmental impact assessments, and stakeholder consultations are critical to ensure that renewable energy projects do not inadvertently harm coastal ecosystems or disrupt local communities. By involving local residents in the decision-making process, projects can be tailored to suit the needs and priorities of the people they will affect.

### Blue economy opportunities - Sustainable tourism and coastal economic development

The concept of the "blue economy" holds the promise of balancing economic growth with environmental sustainability in coastal regions. Sri Lanka's coastal waters, brimming with natural beauty and marine resources, present a wealth of opportunities for sustainable tourism and economic development. This section explores the potential of the blue economy to drive prosperity while safeguarding the delicate balance of coastal ecosystems. The blue economy encompasses a wide range of economic activities that revolve around oceans, seas, and coastal areas. From fisheries and aquaculture to tourism and renewable energy, these activities contribute to economic growth and job creation. The key challenge is to ensure that these activities are carried out in a manner that conserves marine resources, maintains ecosystem health, and benefits local communities.

### Sustainable tourism - balancing exploration and preservation

Tourism is a cornerstone of the blue economy, offering opportunities for economic growth and cultural exchange. Sri Lanka's coastal areas, with their stunning beaches, diverse marine life, and cultural heritage, are prime destinations for tourists. Sustainable tourism practices prioritize environmental conservation, respect for local cultures, and equitable distribution of economic benefits. By engaging in responsible tourism, Sri Lanka can create memorable experiences for visitors while safeguarding the very assets that attract them.

### Aquaculture and mari-culture - nurturing marine life responsibly

Aquaculture, the cultivation of aquatic organisms, and mari-culture, the cultivation of marine organisms, provide avenues for sustainable food production and economic diversification. By adopting responsible and environmentally conscious practices, such as reducing pollution and ensuring proper waste management, Sri Lanka can enhance its seafood production without compromising the health of coastal ecosystems.

## Challenges and opportunities

While the blue economy offers immense promise, it also presents challenges that must be addressed. Overfishing, habitat destruction, and pollution can undermine the sustainability of economic activities. By adopting sound policies, investing in research and innovation, and involving local communities in decision-making, Sri Lanka can overcome these challenges and unlock the full potential of its coastal resources.

## Community engagement and empowerment - The role of local knowledge

In the intricate tapestry of coastal resilience and climate adaptation, the active participation of local communities is pivotal. The wisdom and knowledge held by those who inhabit coastal areas for generations are invaluable assets in crafting effective solutions. This section delves into the power of community engagement and empowerment, highlighting the role of local knowledge in shaping strategies for mitigating climate change impacts.

### A source of wisdom

Local communities possess a deep understanding of their natural surroundings, acquired through generations of interaction with coastal ecosystems. This traditional knowledge encompasses insights into weather patterns, marine life behavior, and sustainable resource management practices. This accumulated wisdom is a valuable resource for crafting climate adaptation strategies that are tailored to the unique needs and challenges of specific coastal areas.

### Building resilience through collaboration

Engaging local communities in decision-making processes fosters a sense of ownership and responsibility. Collaborative efforts that bring together scientists, policymakers, and community members can generate holistic and effective solutions. By combining scientific expertise with traditional knowledge, communities can co-create strategies that not only enhance resilience but also respect cultural values and promote social equity.

### Community-based adaptation

Community-based adaptation involves empowering residents to take the lead in identifying and implementing climate resilience measures. This approach recognizes that those who intimately interact with the environment are best positioned to devise contextually relevant strategies. From restoring mangrove forests to establishing early warning systems, community-based initiatives can yield long-lasting and sustainable benefits. While community engagement offers great potential, it also comes with challenges, including social inequalities, limited resources, and the need for capacity building. Effective community engagement requires inclusive and participatory processes that ensure marginalized voices are heard and integrated into decision-making. Through targeted interventions and support, these challenges can transform into opportunities for empowerment and positive change.

### Policy frameworks for coastal resilience - Navigating the path forward

Effective policy frameworks are the cornerstone of coastal resilience and climate adaptation. Sri Lanka's efforts to mitigate the impacts of climate change on its coastal areas require well-defined strategies, regulations, and incentives. This section delves into the importance of robust policy frameworks, exploring the challenges of implementation and the potential for creating an enabling environment for sustainable coastal development.

**The role of policy in resilience**

Policies provide the necessary guidelines and incentives to steer development in a direction that ensures resilience to climate impacts. Integrated coastal management plans, zoning regulations, and environmental impact assessments are tools that help balance economic growth with environmental protection. By aligning policy objectives with sustainable development goals, Sri Lanka can create a roadmap for safeguarding coastal ecosystems and communities.

**Multilevel governance and collaboration**

The complex challenges of coastal resilience necessitate collaboration across multiple levels of governance. Effective policies require coordination between national, regional, and local authorities, as well as engagement with stakeholders from various sectors. Creating mechanisms for dialogue, information sharing, and joint decision-making can facilitate the development and implementation of policies that address the interconnected issues of climate change and coastal development.

**Incentives for sustainable practices**

Policy frameworks can incentivize sustainable practices by offering rewards for conservation efforts and penalties for harmful activities. Subsidies for renewable energy projects, tax incentives for eco-friendly businesses, and grants for community-based adaptation initiatives are examples of policy tools that can drive positive change. By aligning economic incentives with environmental goals, Sri Lanka can encourage a shift towards more sustainable coastal development. The implementation of effective policy frameworks can encounter challenges such as resource limitations, lack of enforcement capacity, and conflicting interests. Overcoming these challenges requires investment in institutional capacity building, public awareness campaigns, and innovative financing mechanisms. Leveraging international partnerships and knowledge exchange can also provide valuable support in developing and implementing robust policies.

**Education and awareness - Empowering coastal communities for change**

Empowering coastal communities to actively participate in climate adaptation and resilience efforts requires more than just policies and infrastructure. Education and awareness play a crucial role in fostering a sense of ownership and responsibility among community members. This section delves into the power of education and awareness campaigns in driving positive change, building capacity, and nurturing a culture of resilience.

**Knowledge as a catalyst**

Education is a catalyst for change, equipping individuals with the information and skills needed to make informed decisions. By raising awareness about the impacts of climate change, the importance of ecosystem conservation, and sustainable resource management practices, communities can better understand the challenges they face and take proactive measures to address them.

**Community engagement and empowering the youth**

Effective education and awareness campaigns engage communities in meaningful ways, allowing them to contribute their knowledge and insights. Workshops, training programs, and participatory activities empower community members to identify local vulnerabilities, develop adaptation strategies, and monitor environmental changes. This bottom-up approach fosters a sense of ownership and investment in the resilience-building process. Involving young people in education and awareness initiatives is particularly impactful, as they are not only the future stewards of coastal ecosystems but also catalysts for change within their communities. By equipping young minds with knowledge about climate change, sustainable practices, and the value of coastal resources, Sri Lanka can nurture a generation of informed and engaged leaders.

**Creative communication**
Effectively conveying complex concepts requires creative and culturally sensitive communication methods. Storytelling, art, music, and traditional knowledge sharing can bridge language and literacy barriers, making information accessible to diverse audiences. Utilizing these creative approaches can facilitate meaningful engagement and resonate with community members on a personal level.

**A resilient future through education**
Sri Lanka can cultivate a culture of resilience, where communities are equipped with the knowledge, skills, and motivation needed to adapt to climate impacts and secure a more sustainable future for generations to come. Education empowers coastal communities to understand the dynamics of their local ecosystems, helping them make informed decisions about resource management, disaster preparedness, and sustainable livelihoods. It fosters a deeper appreciation for the delicate balance between human activities and the environment, emphasizing the importance of responsible stewardship. Additionally, education forms the foundation for effective coastal zone management policies. Policymakers and planners armed with insights gained through education can develop strategies that not only protect the environment but also enhance the resilience of coastal communities. These strategies encompass a wide range of topics, including habitat conservation, disaster risk reduction, and sustainable economic development.

**Technology and innovation for coastal resilience**
In the age of rapid technological advancement, innovation holds immense potential for enhancing coastal resilience and climate adaptation. Sri Lanka's coastal areas can benefit from cutting-edge technologies that provide real-time data, predictive modeling, and early warning systems. This section explores the role of technology and innovation in bolstering coastal defenses, monitoring changes, and facilitating effective decision-making.

**Remote sensing and data analytics**
Satellite imagery, drones, and remote sensing technologies enable researchers and policymakers to monitor coastal changes with unprecedented accuracy [40]. These tools can track shoreline erosion, sea level rise, and changes in vegetation cover, providing valuable insights for informed decision-making. Advanced data analytics can analyze large datasets to identify trends, assess risks, and develop targeted strategies.

**Early warning systems**
In the face of climate-induced disasters, timely information can mean the difference between safety and destruction. Early warning systems, powered by real-time data and predictive modeling, can alert communities to impending storms, flooding, and other hazards. By providing timely and accurate information, these systems enable communities to take proactive measures, reduce vulnerabilities, and save lives.

**Climate-resilient infrastructure**
Innovative engineering and design approaches play a pivotal role in enhancing the resilience of coastal infrastructure, offering solutions to the challenges posed by rising sea levels, storm surges, and erosion. Examples of climate-resilient infrastructure include floating buildings, seawalls with recreational spaces, sustainable drainage systems, elevated roads and bridges, tidal energy systems, and smart infrastructure with sensor networks.

Floating architecture, exemplified by structures like floating homes, schools, and hospitals, represents a cutting-edge innovation capable of adapting to rising sea levels and storm surges.

The "Floating Pavilion" in the Netherlands, designed by Delta Sync and Public Domain Architects, serves as an illustrative example. Integrating recreational spaces with traditional seawalls presents a dual-purpose solution, offering coastal protection alongside areas for leisure and tourism. The "BIG U" project in New York City, featuring a protective system of berms and parks, exemplifies this innovative approach. Sustainable drainage systems (SuDS), employing techniques like permeable pavements, green roofs, and rain gardens, manage stormwater and prevent flooding. The "Rain Ready" program in Chicago, USA, incorporates SuDS into urban planning for effective water infiltration and runoff reduction. Elevated roads and bridges constructed above expected flood levels ensure connectivity during extreme weather events. The "Venice Flood Barrier" in Italy, known as MOSE, employs a system of movable barriers to protect the city from high tides and storm surges. Tidal energy systems harness the power of ocean tides for electricity generation, providing a sustainable alternative to fossil fuels. The MeyGen tidal energy project in Scotland stands out as a notable example. Smart infrastructure, equipped with sensor networks and real-time data analytics, aids in monitoring and managing coastal conditions. The "Smart Bay" project in Galway, Ireland, deploys sensor networks to predict storm surges and monitor coastal conditions. While not traditional infrastructure, the restoration and conservation of mangrove forests contribute significantly as natural buffers against coastal erosion and storm surges. The "Coastal Greenbelt Project" in the Philippines focuses on mangrove reforestation. Collectively, these examples showcase the diverse and innovative approaches that can fortify coastal regions against the impacts of climate change.

**Citizen science and crowd-sourcing**

Engaging citizens in data collection and monitoring can amplify the effectiveness of climate resilience efforts. Crowd-sourced data, collected by community members using smart phones and other devices, can provide valuable insights into local conditions and trends. This approach not only enhances the accuracy of data but also fosters a sense of ownership and responsibility within communities.

**Collaboration and partnerships**

Collaboration between governments, research institutions, private sectors, and local communities is crucial for harnessing the potential of technology and innovation. Open data platforms, knowledge sharing, and public-private partnerships can facilitate the exchange of ideas, resources, and expertise, accelerating the development and adoption of innovative solutions.

**Embracing a technological future**

By leveraging the power of technology and fostering a culture of innovation, Sri Lanka can pave the way for a more resilient and adaptive coastal future, where cutting-edge solutions work hand in hand with traditional wisdom to protect communities and ecosystems.

## Section 5: Collaboration on a global scale - Towards a resilient coastal future

In an increasingly interconnected world, the challenges of coastal resilience and climate adaptation transcend national boundaries. Collaborative efforts on a global scale are essential to effectively address the multifaceted impacts of climate change on coastal areas. This final section explores the significance of international cooperation, knowledge sharing, and collective action in building a resilient coastal future for Sri Lanka and beyond.

**The urgency of global collaboration**

Climate change knows no borders, and its impacts are felt across continents. Rising sea levels, extreme weather events, and ocean acidification are shared challenges that demand united responses. By joining forces with other nations, Sri Lanka can tap into a wealth of knowledge, expertise, and resources to strengthen its coastal resilience strategies.

**Knowledge exchange and capacity building**

International collaboration facilitates the exchange of best practices, lessons learned, and scientific research. Partnering with countries that have successfully implemented coastal resilience initiatives can provide valuable insights and guidance. Capacity-building programs, workshops, and joint research projects can equip Sri Lanka with the tools needed to navigate the complexities of climate adaptation.

**Funding and investment**

Global partnerships can unlock financial resources that support ambitious climate resilience projects. International organizations, development banks, and donor countries often provide funding for initiatives that promote sustainable development and environmental conservation. By engaging in collaborative efforts, Sri Lanka can access the financial support needed to implement innovative and impactful projects.

**Trans-boundary ecosystem management**

Coastal ecosystems often span multiple countries, necessitating trans-boundary cooperation for effective management. Shared marine resources, migratory species, and pollution can only be effectively addressed through collaborative agreements and coordinated management efforts. By working with neighboring nations, Sri Lanka can ensure the health and resilience of shared coastal ecosystems.

**A unified vision**

As Sri Lanka embarks on a journey to strengthen its coastal resilience, embracing international collaboration is not just an option—it is a necessity. By uniting with other nations, learning from their experiences, and contributing its unique insights, Sri Lanka can contribute to a global movement towards a more resilient, adaptive, and sustainable coastal future. Through collaboration, knowledge sharing, and collective action, the world can collectively build a world where coastal communities and ecosystems thrive despite the challenges of a changing climate.

## Conclusion: Forging a resilient coastal legacy

The path to resilience in Sri Lanka's coastal regions, amidst the challenges posed by climate change, embodies unity, innovation, and unwavering commitment. This exploration highlights the immense promise in forging a sustainable coastal future. Sri Lanka's coastal areas, known for their beauty and vibrant communities, face undeniable climate impacts. However, armed with knowledge, innovation, and collective resolve, Sri Lanka can script a story of resilience, transformation, and legacy.

This journey begins by recognizing coastal ecosystems' value and their role in community well-being. It weaves science, policy, and local wisdom into holistic solutions. Empowering communities, harnessing technology, and fostering local-global collaboration are pivotal. The legacy of resilient coastal resources is not just for the future; it's a present responsibility to protect what sustains us. As we navigate a changing climate, unity in crafting a legacy of resilience, where human progress harmonizes with the natural world, is vital. This journey is a collective endeavor, transcending boundaries, generations, and ideologies. Together, we can shape a legacy that defies challenges and bears witness to the unwavering dedication of Sri Lanka's coastal communities to a thriving and resilient future.

**Epilogue: A glimpse of tomorrow's coastline**

As we peer into the horizon of tomorrow, the coastal landscape of Sri Lanka undergoes a remarkable transformation. The vision of a resilient and adaptive future begins to materialize, shaped by the collective efforts, innovation, and determination of communities, policymakers, scientists, and advocates. Mangrove forests stand tall along the shores, their intricate root systems serving as natural shields against storm surges and erosion. These vibrant ecosystems not only provide critical habitats for marine life but also contribute to carbon sequestration, playing a vital role in mitigating climate change. Offshore wind turbines sway gracefully in the breeze, generating clean energy that powers homes, businesses, and industries. The once-vulnerable coastal infrastructure is now fortified, resilient to the challenges posed by rising sea levels and extreme weather events.

Local fishermen, armed with knowledge from generations past and innovative tools of the present, navigate the waters with purpose. Sustainable fishing practices, guided by science and tradition, ensure the health of marine resources and secure livelihoods for coastal communities. Schools and community centers buzz with activity as education and awareness initiatives thrive. Young minds, equipped with insights into climate change, environmental stewardship, and sustainable practices, are leading the charge towards a more resilient and sustainable future. International collaborations, fueled by a shared commitment to coastal resilience, bridge gaps and break barriers. Nations unite, sharing experiences, expertise, and resources, propelling the global movement towards a world where coastal ecosystems and communities flourish despite the challenges of a changing climate. The vision of tomorrow's coastline is one of harmony, where the delicate dance between human progress and ecological preservation is perfectly choreographed. It is a testament to the power of collective action, the fusion of tradition and innovation, and the unwavering spirit of a nation dedicated to safeguarding its coastal treasures. As we bid farewell to this journey of exploration and discovery, we carry with us the profound understanding that the legacy of a resilient coastal future is not a distant dream—it is a reality within our grasp. Through united efforts, shared knowledge, and an unyielding commitment to a thriving and sustainable tomorrow, we embark on a new chapter, where the coastal waters and resources of Sri Lanka shine brightly as beacons of resilience and hope.

**Author's note: Navigating the tides of change**

As the author of this comprehensive exploration into mitigating climate change impacts on Sri Lanka's coastal waters and resources, I am humbled by the depth of knowledge, innovation, and dedication that have been uncovered on this journey. The tapestry of resilience and adaptation that we have woven together reflects the intricate interplay of science, policy, culture, and community.

Throughout these pages, we have delved into the intricate ecosystems of mangrove forests, the delicate balance of coral reefs, the potential of renewable energy, the power of community engagement, and the promise of technology and collaboration. Each chapter serves as a testament to the challenges we face and the opportunities that lie ahead. The future of Sri Lanka's coastal regions is not set in stone; it is a canvas upon which we, as stewards of the environment and architects of change, can paint a masterpiece of resilience. It is a reminder that our actions today shape the legacy we leave for generations to come—a legacy of vibrant ecosystems, thriving communities, and a harmonious coexistence with nature.

I am grateful for the insights shared by experts, the stories of communities, and the passion of individuals who have contributed to the richness of this exploration. Together, we stand at the crossroads of possibility, ready to navigate the tides of change with courage, wisdom, and unity.

**How you can make a difference**

The journey towards a resilient coastal future is not limited to the pages of this exploration—it is a call to action that extends to each individual, community, and organization. Here are some ways you can contribute to the effort of mitigating climate change impacts on Sri Lanka's coastal waters and resources:

1. Raise Awareness: Spread the word about the importance of coastal resilience, climate adaptation, and sustainable development. Engage in conversations with friends, family, and colleagues to promote understanding and action.

2. Support Local Initiatives: Get involved with community-based organizations and initiatives focused on coastal conservation and resilience. Volunteer your time, skills, or resources to contribute to positive change at the grassroots level.

3. Advocate for Policies: Engage with policymakers and advocate for the development and implementation of policies that prioritize coastal resilience, sustainable development, and climate adaptation.

4. Adopt Sustainable Practices: Make conscious choices in your daily life that reduce your carbon footprint and promote environmental sustainability. Reduce waste, conserve energy, and support eco-friendly products and practices.

5. Educate and Empower: Share your knowledge and insights about climate change and coastal resilience with others. Empower communities with information and resources to make informed decisions.

6. Promote Collaboration: Encourage collaboration and knowledge sharing among different sectors, organizations, and communities. Building partnerships and working together can amplify the impact of resilience efforts.

7. Support Research and Innovation: Contribute to research initiatives, funding campaigns, and projects that focus on developing innovative solutions for coastal resilience and climate adaptation.

8. Stay Informed: Stay updated on the latest developments, research findings, and best practices in the field of coastal resilience. Being informed allows you to make more informed decisions and take effective action.

9. Engage in Advocacy: Use your voice to advocate for increased attention and resources for coastal resilience in national and international discussions on climate change and sustainable development.

10. Be a Role Model: Lead by example and inspire others to take action. Your commitment to coastal resilience can inspire positive change in your community and beyond.

Every small action contributes to the collective effort of building a resilient coastal future. By coming together, sharing knowledge, and taking meaningful steps, we can make a lasting impact and ensure that the beauty and vitality of Sri Lanka's coastal waters and resources endure for generations to come.

**Frequently asked questions (FAQs)**

To provide further clarity and address common queries, here are some frequently asked questions about mitigating climate change impacts on Sri Lanka's coastal waters and resources:

Q1: Why is coastal resilience important for Sri Lanka?

A1: Coastal resilience is crucial for Sri Lanka because its coastal regions are highly vulnerable to the impacts of climate change, including sea level rise, extreme weather events, and coastal erosion. Building resilience ensures the protection of communities, ecosystems, and vital resources.

Q2: What are some key strategies for coastal resilience?

A2: Key strategies include mangrove restoration, sustainable fishing practices, coastal infrastructure improvement, early warning systems, community engagement, policy development, and international collaboration.

Q3: How can communities contribute to coastal resilience?

A3: Communities can contribute by participating in local conservation efforts, adopting sustainable practices, engaging in early warning systems, and collaborating with policymakers and experts to develop resilience strategies.

Q4: What is the role of technology in coastal resilience?

A4: Technology plays a significant role in coastal resilience by providing real-time data for monitoring changes, predictive modeling for risk assessment, and early warning systems for disaster preparedness.

Q5: How can I get involved in coastal resilience efforts?

A5: You can get involved by volunteering with community organizations, supporting policy initiatives, participating in education and awareness campaigns, advocating for sustainable practices, and contributing to research and innovation.

Q6: How can international collaboration benefit Sri Lanka's coastal resilience?

A6: International collaboration brings together expertise, resources, and best practices from around the world. It enables knowledge sharing, capacity building, funding opportunities, and the exchange of innovative solutions.

Q7: What are the long-term benefits of coastal resilience?

A7: Coastal resilience leads to safer communities, preserved ecosystems, sustained livelihoods, enhanced biodiversity, reduced vulnerability to climate impacts, and a more sustainable and adaptive future for Sri Lanka's coastal regions.

**Glossary of key terms**

To aid in understanding the terminology associated with mitigating climate change impacts on Sri Lanka's coastal waters and resources, here is a glossary of key terms:

Coastal Resilience: The ability of coastal communities and ecosystems to absorb, adapt to, and recover from the impacts of climate change, including sea level rise, storms, and erosion.

Climate Adaptation: The process of adjusting systems, practices, and behaviors in response to the changing climate to reduce vulnerability and increase resilience.

Mangrove Forests: Coastal ecosystems characterized by salt-tolerant trees and shrubs that provide vital habitats, protect shorelines from erosion, and contribute to carbon sequestration.

Coral Reefs: Marine ecosystems formed by the accumulation of calcium carbonate by corals, which provide habitats for marine species, protect coastlines, and support local economies.

Sea Level Rise: The gradual increase in the average global sea level due to melting glaciers and thermal expansion of seawater, leading to coastal inundation and erosion.

Sustainable Fishing Practices: Harvesting of fish and other aquatic resources that maintains ecological balance, prevents overfishing, and ensures long-term resource availability.

Ecosystem Services: The benefits that humans obtain from ecosystems, including provisioning services (e.g., food, water), regulating services (e.g., climate control, flood prevention), cultural services (e.g., recreation, tourism), and supporting services (e.g., nutrient cycling, habitat provision).

Early Warning Systems: Tools and processes that provide timely information and alerts about impending natural hazards, enabling communities to take preventive measures and evacuate if necessary.

Adaptive Governance: Flexible and collaborative decision-making processes that facilitate adjustments to changing conditions and promote sustainable management of coastal resources.

Renewable Energy: Energy derived from sources that are naturally replenished, such as solar, wind, and hydroelectric power, reducing dependence on fossil fuels and mitigating climate change.

Community Engagement: Involving local communities in decision-making, planning, and implementation of projects to ensure their needs, knowledge, and concerns are considered.

Policy Frameworks: Sets of regulations, guidelines, and incentives established by governments to guide development and promote sustainability in various sectors.

Transboundary Cooperation: Collaborative efforts between countries to address shared challenges and manage resources that cross national boundaries.

This glossary provides a foundation for understanding key concepts related to coastal resilience and climate adaptation. By familiarizing yourself with these terms, you can better engage in discussions, make informed decisions, and contribute to the ongoing efforts towards a resilient and sustainable coastal future.

## Acknowledgments

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## Conflict of interest

The information presented in this book is provided objectively, free from any conflict of interest, to ensure the utmost integrity in our exploration of this critical subject.

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# Impacts of Anthropogenic Pressures in the Surface Water Quality of Major Lagoons in Sri Lanka

# Impacts of anthropogenic pressures in the surface water quality of major lagoons in Sri Lanka

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## Abstract

Lagoons are an environmentally and economically important ecosystem in Sri Lanka. They support a range of natural services that are highly valued by society including fishing, storm protection, provide habitat for fauna and flora, tourism, and others. However, it is often subjected to natural and man-made changes. Contamination of surface water of lagoons has become a common phenomenon worldwide due to the rapid industrialization, urbanization and development in agriculture and mining. Excess nutrients, sea water intrusion, and heavy metal discharge from agricultural and industrial wastage together with land reclamation are found to be the most serious problems confronting the sustainability of Sri Lankan lagoons. Several toxic elements finally end up in lagoons from various sources deteriorating the quality of water and threatening the lives of organisms living in. Despite increasing public sensitization, water pollution continues to generate unpleasant implications for health and community development. Therefore, the protection of water quality and the aquatic ecosystem is of utmost importance to prevent water pollution and degradation of brackish water resources in Sri Lanka. It is important to continually investigate the quality of surface and groundwater of lagoons to check the influence of growing population, urbanization and industrialization on it.

**Keywords:** Contamination, Lagoons, Pollutants, Urbanization, Water quality

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## Lagoons: A valuable ecosystem

Lagoons, are distinct and dynamic ecosystems that connect land and sea. Sandbars, barrier islands, or spits often separate these shallow, semi-enclosed bodies of water from the open ocean [1]. They lie at the interface of land-ocean ecotone and harbor diverse habitat systems. The lagoon ecosystem consists of several components including a catchment area, ocean side and lagoon mouth [2] and these components affect the mixing processes of the lagoon influencing the social and economic activities surrounding it [3]. Lagoons are located along coastlines throughout the world, and they play a crucial role in environmental and human contexts.

Lagoons have a strong impact on uplifting the living standards of people, especially the fishing community. Shrimp fishing is one of the direct benefits obtained from lagoons [4]. They are good places for rearing not only shrimps but also fish, prawns and crabs [5]. Other than shrimp fishing, lagoons have indirect values of anchorage, fodder, fuel wood, ecotourism, bird watching, coastal photography, aqua-scenic beauty, film shooting, scholarly values, education spots and cultural stimulus [6]. In some lagoons, salt is also produced during the dry season [7]. People living surrounding the lagoon area use the water for domestic activities such as drinking, watering plants, washing cars and other home utilities. Lagoons support a variety of habitats, such as benthic seagrass, extensive mudflats, salt marsh, and fringe mangroves, allowing a variety of organisms to thrive [8]. For migratory birds, some of the lagoons provide ideal habitats too [6] (Figure 1).

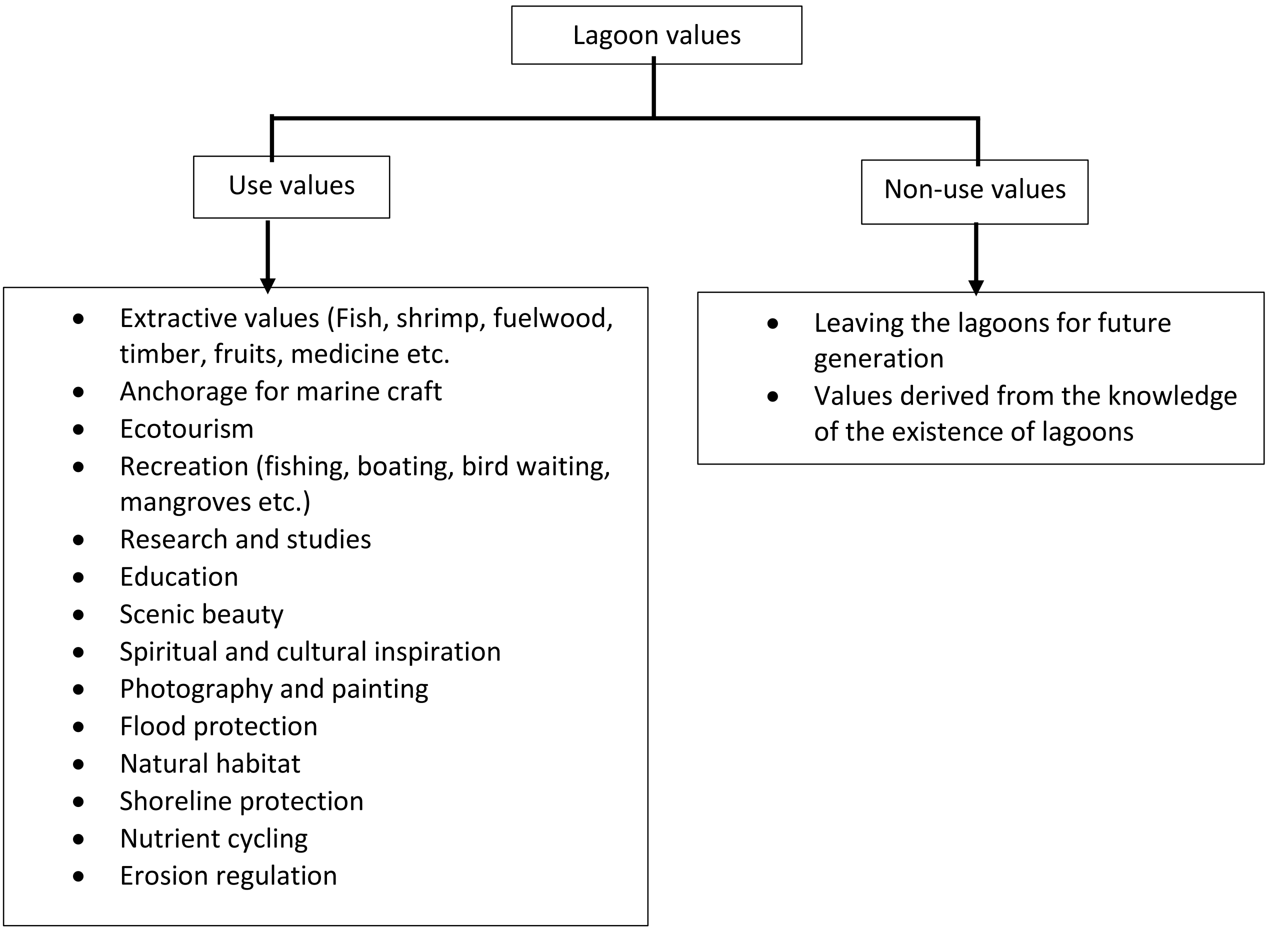


**Figure 1.** Social and economic values of lagoons (Source: Silva *et al.*, 2013 [6])

Lagoons, however, confront a variety of difficulties, primarily brought on by human activity and alterations in the environment. The delicate balance of these ecosystems can be thrown off by pollution, habitat destruction, overfishing, and climate change, which will have detrimental effects on both their ecological and socioeconomic roles [9]. Lagoon dynamics may be impacted by rising sea levels and shifting weather patterns, which could change their biological and physical makeup [10]. The value of protecting and managing these vulnerable resources is highlighted by their natural diversity, cultural relevance, and economic contributions. Hence, lagoon conservation and sustainable use are crucial aspects of our attempts to protect our planet's biodiversity and natural resources as we go through a period of rising environmental awareness.

## Sources of lagoon water contamination

### *Anthropogenic activities*

Water pollution has a significant impact on aquatic ecosystems whereas contamination of lagoons has become a threatening menace to the natural ecosystem and humans [11]. Several organic and inorganic toxicants released from multiple sources notably pollute the water resources changing their chemical, biological and physical characteristics and harmfully affecting the quality of human life and lagoon habitants.

Water contamination arises from a variety of human activities. Intensive usage of agrochemicals in agriculture has been the key source of lagoon pollution depleting the aquatic biota and water quality [12]. Rapid industrialization has introduced many synthetic materials including agrochemicals and pharmaceutical products into our environment. These chemicals are rich sources of nutrients such as nitrogen and phosphate that can lead to nutrient load in lagoons [13]. Lagoons can be easily contaminated by the effluents of industries located near them. Runoff, toilet waste, effluent discharges from markets, bus stand, hospitals and small industries are the main reasons for raised total dissolved solid levels in lagoon water [14]. Cleaning compounds (soap and detergent) used for bathing and washing clothes and phosphate-containing rocks are some point sources of increased phosphate levels in lagoon water [15]. Urban and solid dumping are another sources of lagoon pollution in Sri Lanka [16].

Moreover, dam construction, irrigation channels, factory farming, as well as forest and wetland destruction can also significantly lead to lagoon water pollution [17]. Disturbances of the soil mantle by ploughing, road construction, stream irrigation and mining break the protective vegetation cover and encourage soil washout by storm water during rainfall [18]. These activities result in organic, and inorganic salts, nutrients, heavy metals, pesticides and pathogens being washed into lagoons. Air pollutants like oxides of nitrogen and Sulphur become acidic contaminants during rainfall [19].

### *Climate change*

Lagoon water quality is being significantly impacted by climate change, which is also having an enormous adverse effect on human health and the environment. The lagoons' water quality has undergone several interrelated changes as a result of the increased global temperatures and altered precipitation patterns brought on by climate change [20]. The increase in water temperature is one of the most noticeable effects of climate change. An increase of few degrees (0.5$^{o}$C) in atmospheric temperature can affect the physical and chemical properties of lagoon water leading to a drastic reduction in fish population and the loss of numerous flora and fauna [21]. Many native species are temperature-sensitive, and they may struggle to survive or reproduce in warmer waters [22]. At the same time, invasive species that flourish in warmer climates may establish themselves, altering the natural balance of the ecosystem and potentially causing a reduction in water quality [23]. According to Fatoki and Awofolu [24], temperature increases by 0.5 – 4 $^{o}$C can enhance the toxicity of many elements specially heavy metals in water. A rise in temperature accelerates the nitrification and ammonia oxidation into nitrates leading to an oxygen deficit in water [25].

Moreover, changes in rainfall patterns cause shifts in freshwater intake to lagoons. Variations in rainfall intensity and distribution can cause changes in freshwater input, which alters the salinity of the lagoon water [26]. Changing salinity levels can be stressful to aquatic creatures, particularly those accustomed to specific salinity ranges. Furthermore, decreased freshwater inflow might impede the dilution of pollutants entering lagoons, resulting in increased concentrations of contaminants that deteriorate water quality [27].

Another significant effect of climate change on lagoon water quality is sea-level rise. Rising sea levels can cause saltwater intrusion, which occurs when saltwater infiltrates freshwater supplies [28]. This influx can cause increased salinity in lagoons, making them less welcoming to freshwater species and affecting the overall ecosystem composition. Saltwater intrusion can also cause soil salinization in nearby locations, harming vegetation and agricultural output [29]. The increased intensity of extreme weather events is another pressing concern. More frequent and severe storms might cause pollutants from neighbouring land regions to run off into lagoons. The influx of sediment, fertilizers, and other contaminants can cause eutrophication, which is a process in which excess nutrients stimulate algal blooms and oxygen depletion, worsening water quality and endangering aquatic life.

Furthermore, the combination of higher temperatures changed salinity, and nutrient loading can impair the lagoons' natural ability to self-purify [30]. This exacerbates water pollution issues and can result in the accumulation of toxic compounds in the aquatic environment, impacting not just aquatic organisms but also the communities that rely on these lagoons for livelihood, food, and leisure activities.

***Water quality parameters***

Scientists study various physio-chemical parameters including, temperature, , turbidity, pH, hardness, total dissolved solids (TDS), total suspended solid (TSS), salinity, alkalinity, nutrient (nitrite, nitrate, ammonia, phosphate) content, heavy metal content, electrical conductivity (EC), , dissolved oxygen (DO), biochemical oxygen demand (BOD) and chemical oxygen demand (COD) to assess the quality of water, especially to human consumption, to maintain the aquatic habitat favourable for the existence of living organisms and for its sustainability [31]. The range of these parameters determines the species abundance, diversity and composition of the lagoon [32]. Hence, frequent analysis of these quality parameters in water resources is important to maintain them within the optimal level.

The temperature of lagoon water depends on water origin, climatic zone, season and inflow of industrial and municipal sewage of cooling and power plants [33]. It affects metabolic activities, growth, feeding, reproduction, distribution and migratory behaviours of aquatic organisms [34]. The pH represents the activity of $H^+$ ions in water whereas low pH values negatively affect aquatic life, impair recreational uses of water and reduce the solubility of certain essential elements such as Al, B Cu, Hg, Mn and Fe and higher values could alter the toxicity of water pollutants [35]. Changes in pH could cause some of the solutes to precipitate [15]. The recommended pH value for drinking and fish production ranges from 6.5 to 8.5 [36]. The potential of neutralizing strong acid by bicarbonate, carbonate and hydroxide ions is denoted by the total alkalinity of water and the recommended limit for drinking purposes is 200 – 600 mg/l [37]. The total hardness of water is the ion concentration that reacts with sodium soap and precipitates an insoluble residue. It is imparted mainly by calcium and magnesium ions [38]. Hardness of more than 500 mg/l is considered to be unsafe from a health point of view [39].

Total Dissolved Solid (TDS) is mainly comprised of inorganic salts principally carbonates, bicarbonates, chlorides, sulfates, phosphates, calcium, magnesium, sodium, potassium, iron and a small amount of organic matter and dissolved gases and the acceptable limit is 500-2000 mg/l [40]. TDS is also related to the Electrical Conductivity (EC) of water which is a measurement of the total concentration of ionized substances or salt content in the water [41] and the allowable range for aquatic water is 5-150 mS/m [42]. Total suspended solids (TSS) are the suspended particles in the water body and they influence turbidity and transparency of lagoons. It is claimed that the main reasons for turbidity are the presence of suspended particles, such as clay, silts, fragmented organic and inorganic matter, plankton, and other microscopic organisms [43].

The DO is the dissolved gaseous form of oxygen and it is an important functional water quality parameter that decides the natural self-purification potential of the lagoon [44]. The higher the concentration of DO, the better the water quality. DO value of lower than 3.9 mg/l create stress condition for the organisms, and if it drops lower than 2.0 mg/l, it will cause a risk of death [45]. DO enters water through diffusion from the atmosphere and is produced as a byproduct of photosynthesis in algae and plants. Fish and other aquatic animals must breathe [46]. BOD and COD are both a function of DO. BOD is an indirect indicator of the amount of biodegradable organic compounds in water and it is the amount of oxygen absorbed by microbes during the decomposition of organic materials whereas, the amount of oxygen required for the chemical oxidation of both organic and inorganic materials is known as COD. The BOD and COD readings will rise when DO values drop and that is an indication of poor water quality [47]. DO increases during high wind incidence which can increase the wave action and reduce the surface water temperature [48]. The levels of nitrates in aquatic water that are considered unsafe for aquatic water and animals are set at 1 mg/l and 5 mg/l respectively [49]. Further, the threshold value of phosphates for aquatic species is 0.4 mg/l while the maximum level of phosphate to avoid eutrophication is 0.1 mg/l [45].

## Lagoons in Sri Lanka: an overview

The coastline of Sri Lanka, a tropical island in the Indian Ocean is about 1770 km long and composed of diverse resources of marine ecosystems including coral reefs, beaches, lagoons, mangroves, estuaries, bays, lakes, wetlands and peat land [50]. These ecosystems are vital in the global biogeochemical processes. Among these ecosystems, lagoons are ecologically and economically important to humans and their habitant. There are a totally 82 lagoons occupied in a 1520 $km^2$ area diversified in size, shape, configuration, eco-hydrology and ecosystem values and services in Sri Lanka [6]. Some of the lagoons in Sri Lanka have been classified as Ramsar sites or Wetlands of International Importance because of their significant habitat variety and significance of endemicity. Both inland and inshore fisheries place a high priority on their protection due to the interconnectedness of their ecosystems [51].

According to the report of Silva *et al*. [6], some of the lagoons located on South Eastern coast of the country experience insufficient input of fresh water and high evaporation, hence they are considered to be biologically less productive with inhibited ecosystem values. Nevertheless, the ecological significance and characteristics of the several lagoons in the area differ. Some are important migrating bird habitats, while others along the southern coast receive plenty of freshwater, supporting a high biodiversity and acting as important resource units. The fish populations in the lagoons on the southwest coast are less diverse but have little isles and abundant mangrove swamps. Complex lagoons provide a remarkable environmental diversity in the Jaffna Peninsula. Wider lagoons which are in fewer numbers along the east coast, are extremely productive and have a variety of habitats.

Lagoons are more exploited for industrial, commercial, residential, and agricultural development as well as for the disposal of home, agricultural, and industrial waste. In Sri Lanka, the conversion of coastal wetlands into agricultural, aqua-cultural, urban, and other uses has significant negative ecological, social, and economic effects on lagoon ecosystems [52]. Moreover, changes in climatic conditions have worsened the lagoon pollution.

Though in developed countries stringent laws are followed to control water pollution, in most developing countries including Sri Lanka the situation is different. Wastewater treatment is not prioritized and lagoons are used as sinks for untreated wastages released from industrial and agricultural activities. Poverty, population pressure, urbanization, development activities and multi-stakeholder issues are some of the other sources of lagoon pollution [6]. The consequences are increased water pollution, loss of aquatic life and uptake of pollutants by plant and animals which eventually get into the human body resulting in several health-related problems. Ensuring their preservation and sustainable management is crucial for maintaining the ecological balance and socioeconomic well-being of the nation.

**Table 2.** Demographic characteristics of major lagoons in Sri Lanka

| **Lagoon** | **Latitude** | **Longitude** | **District** | **Agro-ecological zone** | **Area** | **References** |
|---|---|---|---|---|---|---|
| Batticaloa | 7° 24′ - 7° 46′N | 81° 35′ - 81° E | Batticaloa | DL2b | 168 $km^2$ | Sugirtharan *et al*. [45] |
| Negombo | 7° 12′ 31.38″N | 79° 49′ 39.10″E | Gampaha | WL3-4 | 35 $km^2$ | Wijesinghe *et al*. [50] |
| Jaffna | 9° 26′N to 9° 46′N | 79° 52′E to 80° 38′E | Jaffna | DL3 | 412 $km^2$ | Sivakumar, [7] |
| Valaichchenai | 7° 55′N | 81° 54′E to 81° 55′E | Batticaloa | DL2b | 0.13 $km^2$ | Naganathan and Wickramaratne, [53] |
| Chilaw | 7° 36' 24"N | 79° 47' 13"E | Puttalam | IL1a | 18 $km^2$ | Joseph, [54] |
| Bundala | 6° 10′N | 81° 14′E | Hambanthota | DL5 | 62 $km^2$ | Piyankarage *et al*. [55] |
| Rekawa | 6º 03′N | 80° 50′E | Hambanthota | I(L1-L3) | 2.4 $km^2$ | Gunaratne *et al*. [56] |
| Puttalam | 8° 23' 01"N | 79° 48' 3"E | Puttalam | DL3 | 357.7 $km^2$ | Pathirana *et al*. [57] |

### ***Anthropogenic pressures in the surface water quality of major lagoons in Sri Lanka***

Only few lagoons were selected to be described in this chapter based on their economic importance and the abundance of researches done in those lagoons.

*Batticaloa lagoon:*

The Batticaloa lagoon, the third-largest brackish water system in Sri Lanka, is of critical ecological and economic significance as it shelters an extensive population that engages in fishing as well as the growing of rice, coconuts, and shrimp [58]. The Batticaloa Lagoon is a chocked lagoon of primary concern for its biodiversity, habitats and resource supply [59]. It has extensive mangrove swamps and some seagrass beds. This lagoon plays a vital role in the life of the fishing community providing employment opportunities in this district [45]. Unfortunately, it is one of the key lagoons in Sri Lanka which have been severely impacted by human activities. During the past few decades, specifically since 2009 after the end of the civil war in Sri Lanka, large-scale rapid development and poor agricultural methods, as well as fish and shrimp farming, have all contributed to the degradation of the lagoon's natural ecology [60]. Most of the marshes and waterways have currently been transformed into paddy fields, which are grown throughout two seasons of the year. Additionally, in areas with a high population density, domestic effluents and municipal trash disposals are widespread and are untreated before being thrown directly into the lagoon.

According to Harris and Vinobaba [61], shrimp aquaculture, has had a significant impact on water quality, fish distribution, and communities, especially during the dry season through nutrient loading, salinity changes, sedimentation and decreased DO levels. Though the Batticaloa lagoon is suitable for producing brackish water fish and prawns, because of the high amounts of salt and suspended particles, it is not safe to drink. Metals like Zr, Cu, Ni, and Zn found in sediment above expectations point to contamination may have been impacted by naturally occurring ocean flows [62]. Sugirtharan *et al*. [45] stated that severe drought and flood conditions, rise in sea level and seawater intrusion can aggravate the diminishing water quality of the Batticaloa lagoon. During the rainy season, sand, silt and clay particles are rapidly discharged from elevated terrains to the lagoon increasing the turbidity of water and harming the aquatic life [41].

Starting from 2013, the EC values of Batticaloa lagoon has been increasing and exceeded (>150 mS/m) the allowable range of 5-150 mS/m for aquatic water (Table 3). Scientists believe that the accumulation of high amount of industrial and urban discharges has resulted this situation. Saline water from the ocean is mostly responsible for the salinity of Batticaloa lagoon. The maximum level of salinity was higher than 5 ppt which is not suitable for consumption. However, a fluctuation in salinity level is observed whereas the level of 4 to 25 ppt is considered to be favourable for most of the prawn species [63]. Hence, it can be said that high salinity level of Batticaloa lagoon favours the prawn growth but not human consumption. The maximum DO values of Batticaloa lagoon has been fluctuating between 5.9 mg/l to 19.9 mg/l making the lagoon water is favourable for aquatic species (Table 3). However, a minimum DO level of 2.1 mg/l was recorded in 2017 which was not suitable for drinking and other purposes. The main reason for low DO is considered to be the higher organic content along with increased microbial activity.

**Table 3.** Summary of water quality parameters of Batticaloa lagoon from previous studies

| Year | EC (mS/m) | Salinity (ppt) | DO (mg/l) | Nitrate(mg/l) | Phosphate (mg/l) | Reference |
|---|---|---|---|---|---|---|
| 2004 | -NA- | 35 | 4.55 - 5.9 | 0.01-4.00 | 0.11-1.68 | Vinobaba, [64] |
| 2008-2010 | -NA- | 8.10 to 30.16 | 4.15-15.66 | 2.07-3.71 | 0.31 -0.52 | Harris and Vinobaba, [61] |
| 2013-2014 | 60 – 170 | -NA- | 4.6 - 7.1 | 0.97- 2.60 | 0.19 - 0.76 | Thivyatharsan *et al*., [41] |
| 2012-2013 | 2.4 – 366 | 1.6-34 | 5.9 - 7.6 | 0.8-8.3 | 0.04-1.56 | Sugirtharan *et al*., [45] |
| 2015 | -NA- | -NA- | -NA- | 0.016 | 0.07 | Ariyasinghe *et al*., [65] |
| 2017 | -NA- | -NA- | 2.1 - 15.3 | -NA- | NA- | Delina *et al*., [66] |
| 2019 | 543 – 590 | -NA- | 12.5 - 19.93 | -NA- | -NA- | Azaam and Sugirtharan, [67] |

**NA-** Not available

Though the nitrate content in the Batticaloa lagoon has been lower than 5 mg/l, it has always been higher than 1 mg/l. Mixing of effluents from paddy field and prawn farm during rainy periods is considered to be the main reason for the increased nitrate content in Batticaloa lagoon. The threshold value of phosphates for aquatic species is 0.4 mg/l while the maximum level of phosphate to avoid eutrophication is 0.1 mg/l [47]. Though the phosphate content has been fluctuating from 2004 to 2019, the range exceeds the maximum permissible level, causing threats to aquatic life and enhanced eutrophication. The release of fertilizers from nearby farm lands, discharge of effluents from residents, toilets, market, hospital and small industries and most importantly mixing of soap and detergents used by people could be the possible causes for the increased phosphate level in Batticaloa lagoon (Table 3).

*Negombo lagoon:*

Negombo lagoon is a shore parallel beach lagoon situated along the west coast of the country. It can also be identified as a shallow basin estuary [68]. It has a shoreline that extends for 24 km and ranges in width from 0.6 to 3.6 km. Its mean depth is 0.65 m [69]. It is a portion of the 6,232 ha Muthurajawela Marsh-Negombo Estuary Coastal Wetland, which has been designated by the Wildlife Act of 1989 as a protected area for the conservation of biodiversity [70]. According to Dahanayaka *et al*. [71] and Rathnayake and Dissanayake [72], Negombo Lagoon is one of Sri Lanka's most productive lagoons in terms of mangrove vegetation, fauna, and inland fisheries. It also serves as a sink for several anthropogenic effluents and industrial discharges from the areas near urban area [68].

According to Katupotha *et al*. [73], anchorages are being established and several fishing boats, including multi-day boats, are being landed in the Negombo lagoon. They further stated that the edge mangroves are fully destroyed for house constructions, firewood, and poles owing to anthropogenic water pollution. Further, mangroves are being cut down for building construction and resource extraction, while mudflats, marshes, and seagrass beds are being lost. Gammanpila

[68] revealed that the lagoon was with organic pollution due to dumping of household wastes and or detergents by the surrounding houses and the oxidation of organic matter. This was indicated with higher concentrations of phosphate (1.18 mg/l) and nitrate (1.23 mg/l), and BOD (3 mg/l) . Also it might be attributed to the raw human sewage, animal fecal matter, fertilizer runoff and industrial discharges and Dungalpitiya site being discharged into the canal water. Rathnayake and Dissanayake [72] observed a low abundance of finfish and shellfish due to very low DO (3.14 mg/l - low compared to the level required for fish and aquatic life) and high orthophosphate (1.02 mg/l). Moreover, salinity and Nitrate-N also had a significant effect on the density of fish and shellfish in Negombo lagoon. However, in a recent study Wijesinghe *et al*. [50] concluded that Negambo lagoon is less susceptible to aquatic deterioration and still act as a healthy ecosystem under the minor influence of sewage or agricultural nutrient contamination.

Previous studies have assessed the status of the Negombo lagoon through accumulation of heavy metals in selected constituents. According to Indrajith and Pathiratne [74] and Indrajith *et al.* [75], the concentrations for Cd and Pb, in Negombo lagoon were as high as 5.70 and 2.10 µg/L while Asanthi *et al*. [76] recorded, 2.16 µg/L for arsenic. Sivanantha *et al*. [77] evaluated the presence of five toxic heavy metals *viz*: Cr, Cd, As, Hg and Pb in different biotic and abiotic components of Negombo lagoon such as water, sediment, soil, bark and leaves of mangrove and selected fauna. And all the five heavy metals were present in relatively large amounts in one or more of the other tested constituents, clearly confirming the lagoon pollution. The overall trend of heavy metal content was water < leaves < bark < snails < fish < crab < sediment < soil.

*Jaffna lagoon:*

Jaffna lagoon is the largest lagoon in Sri Lanka and it is a shallow water body comprising 3 lagoons named Thondamanaru, Upparu and Valukiaru lagoon. The Indian Ocean is near these lagoons' sea outlets. As a result, it is extremely vulnerable to the entrance of saline water into the lagoon area [78]. The lagoon is surrounded by the densely populated Jaffna peninsula. Mangroves and bird sanctuary is also available in this area. There are numerous fishing villages and some saltpans. The lagoon has extensive mudflats, seagrass beds and some mangroves. It also attracts a wide variety of aquatic birds [79].

A variety of anthropogenic have a substantial impact on the water quality of Jaffna Lagoon in northern Sri Lanka [80]. Negligence, poor maintenance of Salt Water Exclusion (SWE) bunds, inadequate care of existing barrages, pollution from trash and soakage pits, and increased pesticide usage have all contributed to both surface and subsurface water contamination in the Jaffna Peninsula. The faulty operation of barrages has resulted in saltwater intrusion, lowering the quality of subsurface water sources even further [7]. Inadequate water exchange inside the lagoon and between the lagoon and the sea has resulted in wide salinity swings. Pollutants such as fishing-related activities, garbage dumping, animal waste, decomposition, metal waste, and household goods have all contributed to the deterioration of surface water quality along the lagoon's coastline. As a result, residents experience difficulties in accessing clean water for their daily requirements [79].

*Valaichchenai lagoon:*

Valaichchenai lagoon is located close to Passikudah Bay in the Batticaloa District. This estuary lagoon serves as a nursery for a variety of marine animals. At least 3,000 fisher families from the 26 villages that surround the lagoon depend on its fisheries for their major source of income, and about 5,000 people go fishing there, providing a supply of protein-rich food as well as a means of subsistence for fishers [53].

The quality of water in Valaichchenai lagoon has received serious concerns as numerous enterprises surround it, including a fishing harbor, a paper mill, a rice mill, and shrimp farms. Selvadurai and Senthilmohan [81] found that except turbidity, most of the water quality parameters including pH, salinity, BOD, DO and the content of trace elements to be within the tolerance threshold.. High turbidity in the lagoon sample (>500 mg/l) may be detrimental to the survival of prawns and other living things. Additionally, they claimed that the seasonal rainfall enabled a certain amount of pollution dilution to a level that assisted in preventing the death of living organisms.

In another study, Santharooban *et al*. [82] observed high levels of nitrates and nitrites in paper mill discharging area and phosphates at fishing harbor. In addition, very low pH level (4.5), low salinity and high turbidity level that are harmful to aquatic organisms were recorded at paper mill discharging area and high level of electrical conductivity was detected at fishing harbor. According to the above findings, it was obvious that pollutants discharged from paper mill, fishing harbor and rice contributed considerably to pollution in this lagoon. In a recent study, Udagedara *et al*. [83] also mentioned Valachchenai lagoon has been polluted by anthropogenic activities; this may lead to the degradation of aquatic resources in the lagoon.

*Chilaw lagoon:*

The Chilaw lagoon is located on the west coast in the Puttalam district of the North Western Province. It is about 29.5 km in length and 2 km wide at its broadest end and has a depth range of 0.9-3.0 m. It is considered one of the less productive lagoons of the country due to lower fishing activities compared to Negombo or Puttalam Lagoons [84].

The Chilaw lagoon is dominated by brackish water marshes and mangrove forests, however these have been converted into shrimp farms to a large extent [54]. According to Jayawickrema and Sideek, [84] more than 50 % of the lagoon area was dominated by mangroves in 1980 and it has been recorded that 09 species of true mangroves were destroyed in order to facilitate space for shrimp farms. There is a strong belief that Chilaw lagoon has been polluted due to excessive shrimp farming because those farms use the lagoon water and discharge the effluents to the same lagoon. Based on the research of Corea *et al*. [85], eutrophication of neighboring waterways and groundwater pollution near to Chilaw Lagoon were the results of high concentrations of nitrates and phosphates emitted from shrimp ponds into the coastal waters. Their results revealed that total suspended solids from shrimp farms that enter the canal were high (200–600 mg/l), and BOD levels were also high (60–180 mg/l). These effluents heavily silt up the canal, which raises the turbidity. Shrimp farm effluents are also responsible for these waterways' high sulfide and ammonia levels.

Jayawickrema and Sideek [84] observed higher inorganic phosphate concentration (270 g/l) during rainy period. This may be due to the intrusion of fresh water carrying washed off phosphate manure from the vegetation areas and coir fibre mill in the vicinity. Chilaw is famous for its fish market and beach. Joseph [54] mentionedthat the Chilaw Lagoon is contaminated by widespread residential liquid and solid wastages dumping from heavily populated town areas and suburbs. The Chilaw market releases organic trash, including dead fish, directly into the estuary and act as a significant source of pollution there. Due to its popularity, to meet the demands of tourists, a number of hotel developments have emerged. Rapid urbanization on both sides of the Chilaw Lagoon, the creation of anchorages, the arrival of numerous fishing boats, and the building of fish markets are all directly tied to lagoon pollution and have an impact on the lagoon's water, fish population, avifauna, and natural beauty.

Maddumage *et al*. [86] studied the water quality parameters of Chilaw lagoon seasonally and spatially from March to August in 2016. They found that pH levels in the lagoon's water varied between 6.7 and 9.3. The lagoon DO levels ranged from 1.25 to 6.79 mg/L while he salinity variance was 2 to 35 ppt and the EC values varied from 2.8 to 55.1 mS/cm. The maximum nitrite nitrogen, nitrate nitrogen and orthophosphate value were 0.04 mg/L, 0.32 mg/L and 0.29 mg/L respectively. The abovementioned spatiotemporally varied water quality parameters indicates their effects on the aquatic life in the lagoon.

*Rekawa lagoon:*
Rekawa lagoon is a comparatively small coastal lagoon connected to the sea with a narrow inland waterway. It is shallow with an average depth of 1.4 meters and the widest point is approximately 2.5 km [87]. A good supply of water is bought into the lagoon *via* the channels running through agricultural lands carrying a fair amount of sediments and perhaps agrochemicals [88]. Mangroves can be found along the shoreline of both the channel and the main basin of the lagoon [89]. The Rekawa Lagoon is one of the most important aquatic environments in southern Sri Lanka and is regarded as a rare natural resource.

Singappuli [88] was able to carry out a detailed work on Rekawa Lagoon. According to their findings, due to the unusual hydrodynamics of the lagoon, which is resolved by the position of freshwater intake, the open water salinity never dropped below 15 ppt and rarely reached zero. Madarasinghe *et al*. [90] looked into land-use changes and found that human activities, such as hotel development, private property encroachment, trash disposal, and mangrove clearance for a variety of reasons, were the main causes of ecological changes in the lagoon. The natural vegetation was further challenged by the invasion of non-native species, which over the years has resulted in a decrease in mangrove cover.

*Bundala lagoon:*
Bundala lagoon is situated inside the Bundala National Park wetlands which is the only RAMSAR site in southern Sri Lanka with three other lagoons; Koholankala, Malala and Embilikala [91]. These wetlands are very important waterflow habitats for migratory shore birds in South Asia. Though Bundala Lagoon remains largely intact, Malala and Embilikala are impacted by drainage from upstream agricultural lands and human settlements [55].

Agricultural activities, human settlements in the upstream area are perceived to be connected with the reduced fish and shrimp population due to significant decline in salinity levels of this lagoon [92]. Enrichment and accumulation of nutrients such as nitrogen and phosphorus in the lagoon has led to rapid aquatic plant growth and eutrophication. Species extinction, changes in habitat diversity and economic and social impacts due to issues in eco-tourism and fisheries are the main concern of lagoon pollution here [93].

According to the study of Piyankarage *et al*. [55], Bundala Lagoon, which was not affected by agriculture, recorded the highest ammonia and total nitrogen concentrations and the lowest phosphorus levels. The major reason for the highest ammonia level was the accumulation of cow dung and urine with surface runoff after heavy rainfall. Bundala wetland parks are often used to feed cattle and buffaloes due to the insufficient grass lands in the upstream rice fields [94]. In addition to this, mineralization of organic nitrogen is another possible reason for the elevated ammonia content in the lagoon. The Bundala Lagoon's salinity level was higher than the others because of its proximity to the sea, salt farms in its western region, and less salt dilution from comparatively low surface runoff and rainfall. Agricultural drainage, the addition of livestock, and the breaching of the sand bar separating Malala Lagoon from the ocean were among the processes that had an impact on the water quality of the Embilikala-Malala lagoon system. The pH levels in all three lagoons were favorable for the majority of aquatic species [55].

*Puttalam lagoon:*
Puttalam lagoon, the second-largest lagoon in Sri Lanka, is an estuary with a productive basin on the country's northwest coast [6]. It has an abundance of natural resources, including salt marshes, beaches, sand dunes, mangroves, sea grass beds, fish, shellfish, and coral reefs. A landscape with coconut trees, vegetables, open woodlands, meadows, and scrublands surrounds the lagoon. Shrimp farming, salt production, and rice farming are all done on marginal soils [95]. This valuable lagoon has also degraded as a result of human activity both inside and outside the system.

Rapid and uncontrolled development of shrimp farming by converting mangrove forests and salt marshes has resulted in severe degradation of Puttalam Lagoon [57]. Mangroves have been converted to 45 shrimp farms, making up 75.5% of the total carbon loss [96]. Use of harmful and unsustainable fishing methods has led to the reduction of fish varieties in the lagoon and the degradation of the sea grass beds [57]. According to Katupotha [73], anchorage establishments, landing of large number of fishing crafts and the removal of oil and garbages from those fishing crafts are the major causes of Puttalam Lagoon pollution. In addition to those, dumping of domestic wastages and refusal of townships especially during rainy season pollute lagoon coast. As a result, sewage water is injected into the lagoon, polluting the water and endangering the mammals, reptiles, fish, and avifauna that live there and in the area around it. All of these, especially shrimp ponds, can raise the concentrations of Ld, Cr, and Cd. Stagnant water patches serve as breeding grounds for mosquitoes that spread diseases like dengue and others [75]. Furthermore, in a recent study Gunathilaka [97] has stated that the major causes of lagoon degradation are overutilization of natural resources, destructive fishing methods, discharge of sewage, aquaculture, constructions and reclamations, marine debris, landing sites and shoreline trash and the root causes of the drivers of degradation are lower education, harsh sandy – salty-dry environment, scarcity of pure water, less income, weak legal framework and ethnic and religious diversity. The environment indicates that the lagoon's carrying capacity has already been achieved its maximum level and that it is unable to guarantee the lagoon's future viability based on the identified underlying causes of deterioration.

## Major pollutants and associated problems

The industrial, domestic and agricultural wastes that are discharged into lagoons contain harmful substances such as heavy metals, oil, settle able solids, nitrogen, phosphorus, polycyclic aromatic hydrocarbons (PAH's) and other pollutants that can result in a range of short and long term effects to the environment and human health [98]. Agrochemicals are rich in nutrients such as nitrogen and phosphate. Nitrates are naturally present in water owing to the results of organic matter decomposition [99]. Though nitrogen and phosphorus are important elements in regulating biological productivity in aquatic ecosystems, increase in these nutrient loads in lagoons leading to eutrophication and creating conducive environment to undesirable organisms with unpleasant side effects [41] [100]. Studies have revealed a relationship between nitrites' presence in water and gastric cancer and methemoglobinemia [101].

Heavy metals such as Cd, Pb, As, Cr and Hg are non-essential elements that can be toxic in biota even at trace levels [102]. Dallinger, [103] stated that by measuring the concentration, these heavy metals can be used as bio-indicators of environmental pollution. The presence of high heavy metal content in lagoons can negatively impact humans and other organisms because of their bio-accumulative and non-biodegradable nature [104] causing potential risks to a vast range of flora and fauna species, as well as humans [105]. When heavy metals enter into an aquatic environment, they get dispersed in different levels into their biotic and abiotic components depending on the condition of the water such as temperature, DO and organic matter at a given time [106]. According to Goodwin *et al*. [107], toxic chemicals can accumulate in fish from water, diet and contaminant and reach thousand times higher concentration measured in water, sediment and food.

The major source of heavy metal contamination of lagoons is anthropogenic activities including the release of untreated industrial effluent and intense use of agrochemicals in surrounding lands [108]. In addition to that, industrial effluents contain sulphate, chloride, starch, waxes, carboxymethyl cellulose (CMC) and polyvinyl alcohol that can lead to lagoon water contamination. Sulphates are considered as least toxic anions whereas, large quantities of them can cause health disorders like diarrhea [109]. High level of chlorides in lagoon inhibits the growth of plants, bacteria and fish breaking down the cell structure and may develop kidney stones and cardiovascular diseases in human [110]. Since human health and water quality are closely related, many epidemic diseases like cholera, tuberculosis, typhoid, and diarrhea can be easily spread through contaminated water [111].

Once the lagoon is polluted from the normal function and population dynamics of plants and animals inhabiting it will be affected. Release of various pollutants can induce reversible or irreversible ecological changes in lagoons. Hence, a proper understanding of water quality parameters (and their potential impacts) of lagoons is crucial. Policies, legislations and proper management systems should be implemented for the sustainable use of lagoons while preserving natural habitats and biodiversity [57], [112].

## Conclusions and adaptation strategies

Pollution has already brought major changes in the water quality parameters in most of the lagoons in Sri Lanka and these changes are increasingly harmful to aquatic resources, especially fisheries and biodiversity, if water quality regulations are not implemented. Of the various anthropogenic activities and shrimp farming played main role in contaminating the lagoons. Further accumulation of untreated waste disposals also has a negative impact on the lagoon's natural ecology. In this context, it is vital to better understand the variations in water quality parameters of lagoons associated to these anthropogenic activities. Therefore, detailed and continuous surveillance through regular monitoring and assessment is needed to conserve these valuable resources. Hence, strict rules and regulations should be enforced among fishing societies to stop illegal and restricted fishing. Proper legal licensing of all types of fishing gear should be followed to stop illegal trespassing. Construction that is harmful to the lagoon ecosystem should be restricted and protected ecosystem areas can be established to control the human disturbances. Besides, aquaculture effluents can be treated and or recycled with the novel techniques such as bioremediation, algal bioreactors, aquaponics, sensor technologies and data analytics prior to discharging into the lagoon to minimize the pollution. Furthermore, to implement appropriate strategic management plans and utilize this priceless inland water resource sustainably, support from the public and private sectors as well as community involvement are crucial. Most importantly, vocational training, outreach and awareness programs can be conducted for the fishing society to have a sustainable fishery industry without lagoon pollution. Such a program should be conducted targeting not only the fishing community but also a wide range of stakeholders including government and non-government officials, provincial councils, local authorities, police officers and students. More research should be carried out in each and every lagoon all over the country and with that a strong interaction between scientists and policymakers to enhance decision-making associated with lagoon pollution.

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## Conflict of interest
Authors declare no conflict of interest

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# Current Status and Future Prospects of Ornamental Fish Industry in Sri Lanka

# Current status and future prospect of the ornamental fish: A case of Colombo District, Sri Lanka

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**Abstract**

Ornamental fish production is one of the main sectors in the aquaculture industry. Sri Lanka has shown a great improvement in the trade of ornamental fish exports in the last three years, amidst the pandemic. This book chapter discusses the importance of the ornamental fish industry, the present situation, and the future prospects to develop it further as a sustainable industry in Sri Lanka. Information present in this chapter is based on the rigorous literature review and also a recent case study on ornamental fish production in the Colombo district covering the main ornamental fish production Divisional Secretariate divisions namely; Padukka, Kaduwela, Kesbewa, and Seethawaka. As per the findings of the literature review, Sri Lanka has lots of opportunities to produce a vast array of ornamental fishes. Meanwhile, there is a good demand for ornamental fish in the world market. Currently, Sri Lanka exports a considerable level of fish to the world market and earns a substantial amount of foreign exchange annually. The common challenges identified can be categorized into four: production-related issues, market/economy-related issues, technology adoption, and other problems. The economic complexity and comparative advantage indicators suggest that there is a huge potential in Sri Lanka for ornamental fish products. Prospects heavily rely on the market conditions, incentivizing the farmers to engage and to maintain a balance with environmental sustainability and proper governance of resources. We propose that, more incentives and the popularization of fish culture in selected localities to overcome the resource issues and supply chain barriers.

**Keywords:** Aquaculture industry, foreign exchange earner, future prospects, ornamental fish, Sri Lanka.

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## Introduction to the global ornamental fish industry

Among the different types of fish industry, ornamental fish trade has a significant importance for a country. Mainly because they are live fish and plants which generate export income for many countries. Ornamental fish are reared for aesthetic purposes in home and or in other places in aquaria and ponds. Ornamental fish are preferred by millions of people due to their brilliant colors, attractive shapes and behaviors. Thus, ornamental fish are called "*Living Jewels*". The global ornamental fish industry represents a captivating and important sector within the broader aquaculture and pet trade. In parallel to this, the aquatic plant and fish feed industries also have gained momentum [1]. Due to these reasons, the multifaceted dimensions of the global ornamental fish industry have economic, environmental, and social implications [2-3]. As they have implications to the greater people, this trade is also governed and regulated by different stakeholders and international agreements play an important role in ensuring the sustainability of the industry and the protection of endangered species [4].

The global ornamental fish industry has evolved from ancient civilizations into a thriving sector with economic, environmental, social, and cultural dimensions [5, 6], The history of ornamental fish dates back to ancient cultures of Egypt, China, Greece and Rome [7-9]. For a long time, developed countries have been the major ornamental fish keepers and also the main buyers. As the demand increased, an economic opportunity was created for developing countries to become the major producers of ornamental fish [10-11]. The mass production and trade of ornamental fish became feasible with the development of efficient breeding and rearing techniques and the expansion of fast transportation including air-cargo facilities for live fish. It is believed that the growing interest from the millennials and generation Z was partly responsible for the growing demand in the ornamental fish industry [12]. There were also challenges, especially after the COVID-19, ornamental fish industry was affected by lower demand.

This has been a trend even in the global pet animal trade. As in the pandemic situation, money was mostly spent on necessities. Some link this to the long-term impacts like climate change as well. Contrary to the general belief, authors have found that this pandemic has also hugely helped the ornamental fish industry. According to Weerasinghe and Malkanthi [13], the COVID-19 pandemic had a huge positive impact on the ornamental fish industry. As the pandemic progressed, a significant increase in adoption for raring new pets was observed including ornamental fish which had a positive influence on market growth [14]. It was suggested that mental wellbeing was one of the major reasons for this.

Another strand of literature links the dynamics in the ornamental fish industry to the climate change phenomenon. Climate change-induced alterations in natural habitats, regulations, and consumer attitudes are influencing how ornamental fish are collected, bred, and traded [15]. To ensure the industry's longevity and the conservation of these beautiful species, stakeholders must continue to adopt sustainable practices and recognize their role in mitigating the impacts of climate change on the aquatic world [16]. Embracing responsible and environmentally conscious approaches in the ornamental fish industry helps to expand the industry amidst these threats. Despite, all these challenges, this industry still remains to be an important force in the economy.

## Importance of the ornamental fish industry

Currently, the global ornamental fish industry is a billion-dollar market. The economic significance of this industry mainly encompasses the sales of a wide array of products and services which include fish, equipment, fish feed, and related products [17]. This also includes various players at different nodes of the production chain, like breeders, wholesalers, retailers, consumers/hobbyists exporters etc [18-19]. Furthermore, the industry provides employment opportunities for a wide range of individuals, from fish breeders and farmers to retailers and exporters. As a result, the job market created through the ornamental fish industry continues to support countless families and communities, especially in developing countries as a significant source of income [6, 10, 20].

The global ornamental fish trade was valued at over $5.97 billion in 2022 and is predicted to grow up to $13.26 billion by 2032 [21-22]. As a result, many countries heavily rely on increasing ornamental fish exports to boost their economies. Countries like Japan, Spain, Thailand, Singapore, and Indonesia are the major exporters in this industry [23]. By the end of 2022, Sri Lanka and the Netherlands also became the highest exporter of ornamental fish along with Japan, Singapore and Indonesia [24]. Over the years, the ornamental fish industry has evolved into a major industry with a strong presence in the international market. Statistics on export and import market values indicate the significance of ornamental fish trade in the global economy. Figure 1 presents the average wholesale value of freshwater and marine ornamental fishes in the global export market. Figure 1 below, depicts the value of ornamental fish exporters from different continents. It can be seen that Asia and Europe are leading the world in ornamental fish exports. The graph also clearly shows that there is a significant rise in exports post-pandemic.

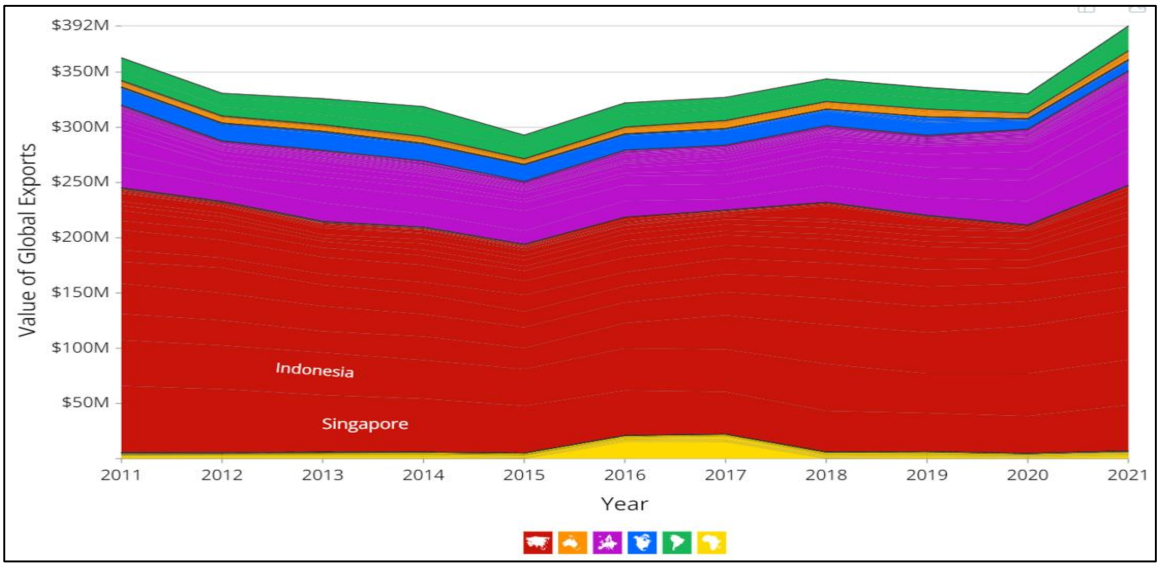


**Figure 1.** Value of exports of ornamental fish between 2011 to 2021: A regional outlook [selected countries] (Source: "Ornamental fish," Observatory Economic Complexity, 2023. Available: https://oec.world/en/profile/hs/ornamental-fish?filterSelector=valueFilter0.

***Note:*** *Red - Asia; Orange-Oceania; Purple - Europe; Blue-North America; Green- South America; Yellow - Africa*

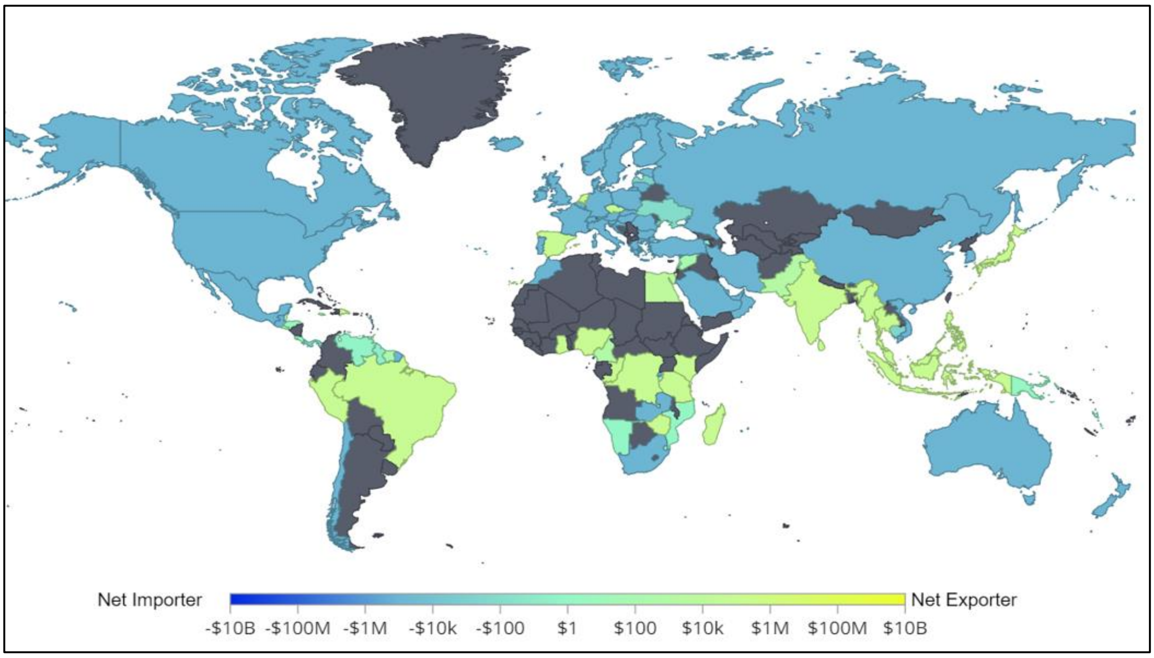


**Figure 2.** Net ornamental fish trade in 2021. (Source: "Ornamental fish," Observatory Economic Complexity, 2023. Available: https://oec.world/en/profile/hs/ornamental-fish?filterSelector=valueFilter0.

***Top exporters**: Indonesia ($34.1M), Singapore ($30.8M), Japan ($26.8M), Sri Lanka ($22.3M), and the Netherlands ($19.4M).* ***Top Importers**: United States ($67.1M), France ($22.9M), Germany ($22.3M), United Kingdom ($16.9M), and China ($14M).*

Figure 2 above, presents the net ornamental fish trade on a world map, with different colors indicating who is a net importer and who is a net exporter of fish. This clearly shows that the global North is a netimporter and the global South will be the net exporter of ornamental fish in 2021.

As per the statistics of Figures 1 and 2, Asia is the major regional exporter of fish and among them, Indonesia, Japan, Singapore, and Sri Lanka were the main exporters of ornamental fish in 2021. Thus, in addition to direct sales and exports, as major exporters they received the ability to generate income through public and private aquariums by attracting tourists and conducting local and international exhibitions which further supports in expanding the market share of local producers [26-27]. Their international trade creates economic ties between nations to stimulate their national economies and it is further amplified by related tourism activities [13]. Apart from business purposes and tourist attraction, the presence of ornamental fish in schools, museums, and public places serves an educational purpose, i.e. teaching children about aquatic ecosystems, biodiversity, and the importance of conserving natural resources, and research purposes, i.e. as a model organism for studying various aspects of fish biology, behavior, and genetics [28].

In addition to that, the preservation of the environment and biodiversity is important for the sustainability of industry. The trade-in ornamental fish has raised concerns about the sustainability of sourcing species from the wild. Overfishing and habitat destruction create threats to some species, leading to calls for more sustainable and responsible practices, such as captive breeding and trade regulations [29, 15]. The ornamental fish industry plays a role in conservation efforts by promoting the breeding and protection of endangered or threatened species.

The ornamental fish industry encourages community involvement in local and global initiatives related to fish conservation, responsible breeding, and sustainable trade [30]. Further, programs like the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) regulate and monitor the international trade of endangered species, including ornamental fish, to ensure their conservation [15]. The ornamental fish industry helps to reduce the pressure on wild populations by captive breeding of these species. Also, it supports expanding the awareness about the role of fish species ecosystem especially through maintaining aquariums and caring for ornamental fish, hobbyists, and enthusiasts providing a better understanding of aquatic ecosystems and their importance in the broader environmental context. This awareness can lead to more responsible environmental behavior. Moreover, research opportunities can be created by making facilities to study ornamental fish species often leads to scientific discoveries and insights into fish behavior, genetics, physiology, and health. This research contributes towards a border understanding of aquatic life and can have wider applications in ecology and biology [31-33]. Thus, in turn, the industry helps to protect the delicate balance of aquatic ecosystems [34] and provides evidence of the power held by the industry to promote sustainability and protection of aquatic ecosystems at the global scale [35].

Apart from these facts, ornamental fish are culturally significant in many societies and provide recreational and therapeutic benefits to aquarium enthusiasts [36]. They are also believed to have mood-calming effects and are good for people with high blood pressure. Moreover, in many cultures, ornamental fish are considered symbols of good luck, prosperity, and well-being. They are often featured in art, literature, and religious rituals, contributing to the cultural richness of societies [37]. Over the years, the advancements in technology and its application in this particular industry have risen dramatically. Needless to say, the breeding techniques, but also other applications, disease prevention, nutrition, water quality management, and logistics have improved a lot, facilitating higher production of live specimens and facilitating trade [38-39]. This is an industry where the multifaceted benefits support a diverse range of communities worldwide without any cultural taboos [35, 40].

## Present status of the ornamental fish industry in Sri Lanka

### *Background*

Sri Lanka has a good potential to have a vibrant ornamental fish industry, though the population is comparatively small. Sri Lanka due to its resource endowments it’s much easier to establish fishing ponds and water is freely available in most of the places across the country. Also, Sri Lanka is known to be one of the higher biodiversity hotspots with rich species diversity. From the trade point of view, Sri Lanka’s geographical location is beneficial as it is located in one of the busiest trade routes and has access to both the East and the West. Prominently, due to its fish species and vibrant aquatic biodiversity, Sri Lanka's ornamental fish industry has garnered international recognition and demand [10], [40-41]. Sri Lanka becoming one of the top exporters in 2022 is proof that even amidst the pandemic. Sri Lanka provides a home to a total of 111 ornamental fish species living in fresh, brackish, and marine water habitats, which makes the country one of the most sought-after aquarium fish exporter destinations in the world [42-43]. Sri Lanka, exports wild-caught and farm-bred aquarium fish species to more than 70 countries [44].

In Sri Lanka, the ornamental fish industry dates nearly 100 years back when interested collectors started exploring and discovering indigenous fish varieties in rivers, lagoons, and marine habitats around the country [40], [45-46]. The trade of marine water ornamental fish commenced in the 1930s, with Sri Lanka being one of the first countries to collect and export coral reef fishes for aquariums [34]. Initially, the industry was small-scale and primarily focused on the collection and export of native fish species found in the country's rivers and streams. These early exports consisted mainly of barbs, and other locally available species [41].

Sri Lanka has become one of the leading exporters of ornamental fish in Asia, exporting to countries across the globe. Sri Lankan exports amounted to 2.7% of the world market in 2021 and we earned a revenue of USD 22.3 million [25], [46].

Sri Lankan ornamental fish exports consist of freshwater ornamental fish (70%) and marine water ornamental fish (30%). Out of the freshwater fish exported, nearly 60-70% of them are fancy guppy species. Notably, Sri Lanka can broaden its marine ornamental fish exports by breeding high-value marine ornamental fish including exciting new varieties and rare species endemic to the tropical island [45]. However, it is also believed that Sri Lanka has a competitive advantage in exporting guppy breeds, which are well adapted to Sri Lankan conditions. There are about 50 regular export companies in the country. Major buyers of Sri Lankan ornamental fish are the USA, Japan, and the European Union. The export of ornamental fish contributes significantly to the country's foreign exchange earnings, creating employment opportunities for a large number of people in the country.

The industry has experienced steady growth, specifically in the years of 2019, 2020, 2021, and the export volume almost doubled every year [47]. The export of ornamental fish contributes significantly to the country's foreign exchange earnings, creating employment opportunities along the supply chain. Sri Lanka primarily exports the following fish types of *inter alia* are Guppies, Platy, Swordtail, Molly, Goldfish, Barbs, Danios, Tetras, Gouramis, Catfish and Cychlids (Angels, discus). Other than this a considerable number of other fish species are also exported, *viz*, Bannerfish, Clowns, Jacks, Groupers, Eels, Grunts, Pipefish, Toadfish, Anemones, Starfish and Urchins. The diversity of species allows Sri Lanka to cater to different markets and customer preferences. Application of market diversification via exploring new markets and niche segments can help to reduce reliance on a few major markets [47]. Sri Lanka can diversify its ornamental fish species to cater to specific niche markets. Developing unique strains and varieties can set Sri Lankan exports apart [48].

### *Ornamental fish production in Colombo district in Sri Lanka*

In 2019, ornamental fish production contributed about 2% to the total export value of the country [45]. The industry consists of fish breeders, fish growers, outgrowers, middlemen, collectors, and exporters. However, in the Sri Lankan context, it is difficult to find out fish breeders and growers separately, because they conduct both activities together. Therefore, those parties are commonly known as ornamental fish farmers [48, 49]. Currently, there are about 8,000 ornamental fish farmers around the country and they are a major part of the ornamental fish value chain, supplying fish either directly or indirectly to the market [46-47].

In 2021, Weerasinghe and Malkanthi [13] conducted a study on “Export Performance of the Ornamental Fish Industry in Colombo district in Sri Lanka: Especially during the Covid-19 Pandemic Situation”. According to this study, there is a very good export market for ornamental fish in Sri Lanka. Nevertheless, the production capacity of the country is not sufficient to fulfill the market requirement. Many are engaged in ornamental fish production as a self-employment opportunity. It contributes to increasing employment opportunities, especially for youngsters, women, etc., providing a living by collecting marine and inland water fish, and invertebrates from the wild for the local as well as export markets [50].

- ✓ It acts as an additional income-generating activity.
- ✓ It enhances people’s land usage efficiency.
- ✓ It is a good opportunity for foreign income generation.
- ✓ It can be practiced with a minimum space.

### ***General characteristics of the ornamental fish farms in Colombo district***

It is important to understand the main characteristics of the ornamental fish farms in the country. According to the case study by Weerasinghe and Malkanthi [13], general characteristics of Sri Lankan ornamental fish farms in the Colombo district such as cultural activities, size of the farms, nature of production facility, water source, type of labor used in ornamental fish farming, and production capacity are shown in Table 1. As per the information given in Table 1, the main cultural activities in the farms are both breeding and rearing activities. The reason behind this result is that farmers can obtain more financial benefits when conducting both activities together on the farm. However, it can be varied based on the varieties of ornamental fish. Also, results revealed that the size of the majority of the farms is less than 20 perches. Moreover, a considerable number of farms belong to the 20-119 perches category. They are very small in size. A few farms have more than 320 perches (2 acres) of land. Most of the ornamental fish farms are mainly located away from the urban areas. Also, most farms (30%) have cement and glass tanks as their production facilities and 27% have only cement tanks. The rest of the farms (18%) use all kinds of tanks. The ornamental fish farms dominantly (43%) use wells as the water source and 27% of farms use tap water. 6% of farms use other water sources such as natural water channels. However, some farmers use tap water under special management practices. Also, 24% of farms use river water as a water source mainly for the mud ponds. According to the findings, while 65% of farms use family laborers, 32% of farms use hired laborers. Only 3% of farms use both types of labor for farming activities. Most of the farmers don't use hired labor due to the very high costs associated with it.

**Table 1.** General characteristics of the ornamental fish farms in Colombo District (Source: Weerasinghe and Malkanthi, 2021).

| Characteristic | | Percentage (%) |
|---|---|---|
| Cultural activities on the farms | Breeding | 6.7 |
| | Rearing | 8.3 |
| | Outgrowing | 3.3 |
| | Breeding and rearing both | 78.3 |
| Size of ornamental fish farms | < 20 perches | 40.0 |
| | 20-119 perches | 28.3 |
| | 120-219 perches | 16.7 |
| | 220-319 perches | 6.7 |
| | >320 perches | 8.3 |
| Nature of production facility on ornamental fish farms | Cement tank | 27.0 |
| | Mud ponds | 3.0 |
| | Glass tanks | 5.0 |
| | Cement tanks and Mud ponds | 15.0 |
| | Cement tanks and Glass tanks | 30.0 |
| | Mud ponds and Glass tanks | 2.0 |
| | Use all types of tanks | 18.0 |
| Water sources for ornamental fish farms | Well | 43.0 |
| | Tap water | 27.0 |
| | River water | 24.0 |
| | Other | 6.0 |
| Type of labor of farms | Family labor | 65.0 |
| | Hired | 32.0 |
| | Both | 3.0 |
| Production capacity on the farm (number of fish/month) | <833 | 6.6 |
| | 833-8333 | 46.7 |
| | >8333-83333 | 30.0 |

***Impacts of the COVID-19 pandemic on the ornamental fish industry case of Colombo district, Sri Lanka***

The COVID-19 pandemic had negative impacts on most of the industries in all the countries. One of the main parts of the case study of Weerasinghe and Malkanthi [13] was to find out the impact of the COVID-19 pandemic on the ornamental fish industry in the Colombo district Comparison of median value was used to analyze the difference between the level of production, selling amount and cost of production of ornamental fish farmers before and during Covid-19 pandemic. As per their findings, farmers' production, cost of production, and selling amount were significantly different before and during the COVID-19 period (Table 2).

**Table 2.** Impacts of the COVID-19 pandemic on the ornamental fish industry
(Source: Weerasinghe and Malkanthi, 2021).

| Factors | Rank | Sum of Ranks | Remark |
|---|---|---|---|
| Production level of ornamental fish before and during the Covid-19 pandemic | Negative Ranks | 950.00 | *High negative rank* During Production capacity per month < Before Production capacity per month |
| | Positive Ranks | 131.00 | |
| Selling amount of ornamental fish before and during Covid-19 pandemic | Negative Ranks | 269.00 | *High positive rank* During Selling amount per month > Before Selling amount per month |
| | Positive Ranks | 1501.00 | |
| Cost of production before and during Covid-19 pandemic | Negative Ranks | 147.50 | *High positive rank* During Cost of production per month > Before Cost of Production pre month |
| | Positive Ranks | 842.50 | |

While Ornamental fish production had reduced, the cost of production had considerably increased (Figure 3). However, the selling amount has unexpectedly increased during this period. Thus, it emphasizes that there was a higher market demand for ornamental fish during the pandemic period than before. However, the main problem faced by the farmers during this period was the low production capacity due to difficulties in finding inputs for the production. Nanayakkara, et al., [51] mentioned in their study that during the COVID-19 pandemic, 30% of exporters received an unexpected increase number of export orders from their buyers.

Moreover, based on the findings of the case study of Weerasinghe and Malkanthi [13] ornamental fish farmers have been using several marketing alternatives as four different market actors within their two different markets. They are the local market, supply exporters, local and supply exporters, and direct exporters. Out of the four markets, selling to supply exporters is the main market opportunity for the farmers to sell their products (31.7%), followed by supplying to exporters (35%), to both local market and exporters (21.7%) and direct export (6.7%) [13]. The Figure 3 shows the total quantity of ornamental fish supplied to the global market during the year 2020. During this period the world faced the problem of the COVID-19 pandemic, especially in April and May indicating the full lockdown period in the world. It was highly affected by the exportation of ornamental fish during this period. However, after the lockdown period, demand for ornamental fish produced in Sri Lanka at the world market unexpectedly rose due to the other ornamental fish exporting countries had introduced some restrictions on exporting their ornamental fish. Therefore, most of the farmers were able to sell their products to the supply exporters and receive higher prices than sending them to the local market.

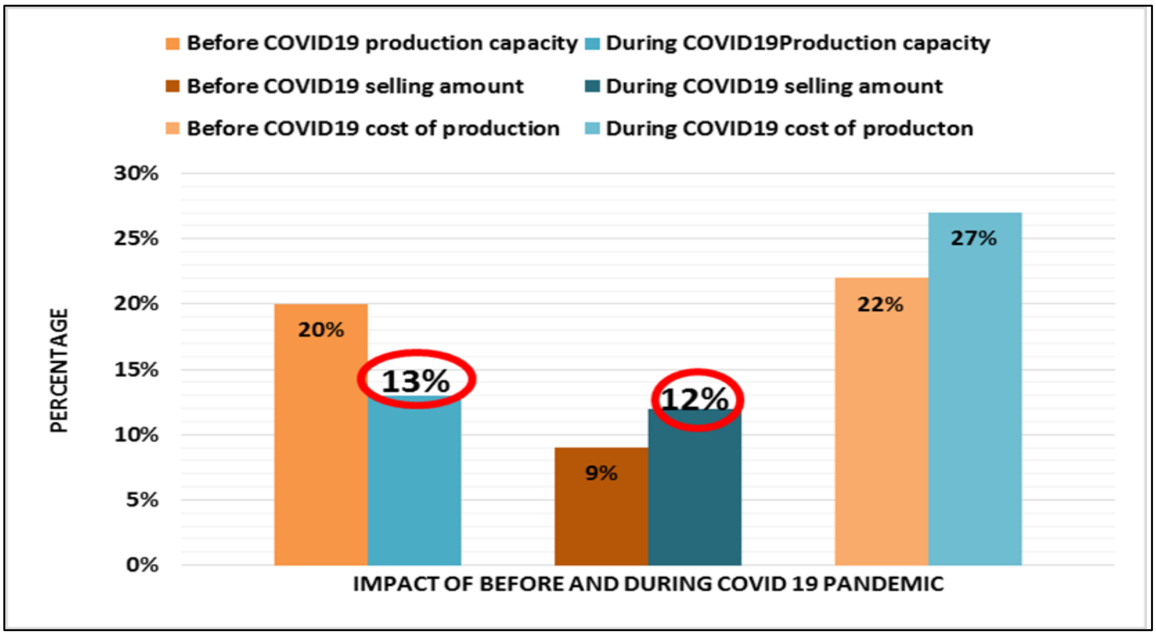


**Figure 3.** Comparison of production capacity, selling (production) amount, and cost of production before and during COVID-19 pandemic (Source: Weerasinghe and Malkanthi, 2021).

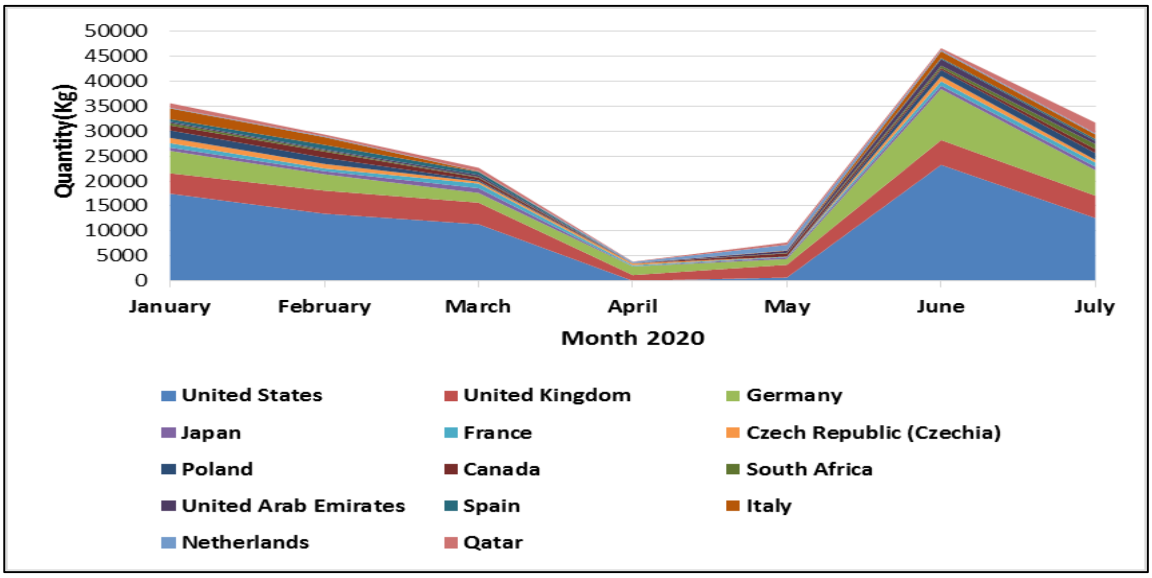


**Figure 4.** Total quantity of ornamental fish supplied to the global market during the year 2020 (Source: EDB, "Export Oriented Ornamental Fish Farming in Sri Lanka," 28 September 2020)

Problems of ornamental fish farmers can be categorized into three parts as production problems, market problems, and other problems [13, 10]. The current status of them is presented in Table 4. There are eight problems related to the production of ornamental fish. From them, number one is the receiving fish feed and additives. Most of the fish feed is imported to Sri Lanka. However, due to the economic crisis, some issues have been arising in importing them. Therefore, farmers faced difficulty in accessing the feed during this period. It is directly affected for maintaining the fish quality. The other main problems are the mortality of fish, maintenance of quality, difficulty in functioning natural and artificial breeding activity properly, difficulty in finding quality breeding fish, receiving fish medicine, and disease infections. Among market-related problems, four main ones are there. Finding transport facilities is very difficult. Since fish are live creatures, they need proper facilities during transport. Other than that, unavailability of stable prices, rejection of the stocks due to unavailability of the correct weight of fish, and lack of intermediate collectors. Other main problems are the lack of involvement of government and other responsible organizations, dearth of loan facilities, lack of insurance facilities, labor problems, and difficulty in recovering received loans. Based on the findings of the case study of Weerasinghe and Malkanthi [13], in Sri Lanka, fish production has been categorized according to the NAQDA production capacity levels.

III group: small-scale farms (monthly production< 833 fish),
V group: (monthly production 833-8333 fish),
IX group: (monthly production 8333-83333 fish),
VI group: (monthly production> 83333 fish).

**Table 4.** Problems of ornamental fish farmers during the COVID-19 pandemic (Source: Weerasinghe and Malkanthi, 2021)

| Problems of ornamental fish farmers | | Percentage (%) |
|---|---|---|
| **Production problems** | Receiving feed and additives | 87.7 |
| | Fish mortality | 80.7 |
| | Maintain fish quality | 78.9 |
| | Difficult to function natural and artificial breeding activities properly | 77.2 |
| | Difficult to find quality brood fish | 61.4 |
| | Non availability of medicine/chemical for disease treatment | 35.1 |
| | Disease infections | 31.6 |
| | Farm maintain problems (ex: Shortage of Labor, cleaning tank, water exchange etc) | 22.8 |
| **Market problems** | Transport facility | 98.2 |
| | Unavailability of stable price | 34.5 |
| | Rejection of the export stock due to the weight problem | 32.7 |
| | Buyers collect fewer fish for selling | 27.3 |
| **Other problems** | Lack of involvement of government and other responsible organizations | 96.6 |
| | Lack of loan facilities | 86.2 |
| | Lack of insurance facilities | 72.4 |
| | Labor problem | 25.9 |
| | Difficult to recover loans | 25.9 |

The study emphasized that the majority (46.7%) of farms belong to the production capacity of 833-8333 per month (named as V group). Another 30% of farms belong to the capacity of 8333-83333 per month (IX group). Of the sample, 6.6% of farms exist with less than 833 production capacity per month. The results indicated that most of them are not able to reach the high production capacity due to a lack of facilities.

**Table 5.** Production and Market problems against the Production capacity of ornamental fish farms in Colombo district (Source: Weerasinghe and Malkanthi, 2021)

| Problem | Amount | Production levels | | | |
|---|---|---|---|---|---|
| | | <833 | 833-8333 | 8333-83333 | >83333 |
| Production problems | Frequency | 4.0 | 25.0 | 18.0 | 6.0 |
| | Percentage (%) | 7.5 | 47.2 | 34.0 | 11.3 |
| Market problems | Frequency | 4.0 | 22.0 | 18.0 | 6.0 |
| | Percentage (%) | 8.0 | 44.0 | 36.0 | 12.0 |

Table 5 reveals the production and market problems against the production capacity of the farms. Due to small farm sizes and limited land areas, ornamental fish farmers can't reach high production levels. This is a main critical issue in the country. Also, the lack of government attention and support for the ornamental fish farmers and the dearth of loan facilities for this industry are other dilemmas of ornamental fish sector.

***Improving the ornamental fish industry in the Colombo district***

Since our market potential for ornamental fish is not fully reached, there should be improvements and strategies to streamline the process and capitalize on the competitive advantage we have over other countries. Number of suggestions have been posed by growers as well as other stakeholders [10, [13]. The identified suggestions are as follows. Responsible organizations should provide proper training and knowledge about modern technology to increase the production capacity of the farmers. The government needs to contribute by providing loan facilities based on the farmers' capabilities to enhance their production capacity and also provide quality brooders. Moreover, it is essential to establish places where farmers can easily access ornamental fish quality brooders for their production process to improve the quality of fish and to reduce genetic deterioration. Responsible authorities should focus on taking the decisions to facilitate the necessary inputs for the farmers without disturbance and should monitor the farming processes at least once in every six months. The government should promote the production of fish feed in Sri Lanka, instead of importing them. Also, it is important to provide knowledge and skills through conducting awareness programs and training programs for the farmers to produce fish feed at the domestic level as an alternative feed for using "*Artemia*". Introducing alternative strategies to produce low-cost nutritious fish feed formulation techniques/recopies to farmers will help to reduce the feed costs. Necessary technological knowledge should be transferred to improve the "*Artemia"* production in potential salt pans in the country. Moreover, the farmers have to bear more cost of buying feed. Then, the government can be concerned with reducing the import tax of feed and that benefits should also be given to the farmers.

The establishment of research and development centers regarding ornamental fish is crucial to developing new varieties. Furthermore, providing laboratory facilities for them is essential. Fish grades should be based on quality and standards to prevent the refusal of their products. Hence the government has to focus on establishing a fish quality checking team in the country. There are a number of entrepreneurial opportunities in the local ornamental fish industry such as the production of fish feed, breeding substrate, etc. Hence, there should be more awareness about the available opportunities among entrepreneurs to attract and encourage their investments. Weerasinghe and Malkanthi [10] have identified "Ideal "ORNAFISBIZ" Model in their study to overcome the major constraint of the ornamental fish farmers while introducing strategies for enhancing the quality of ornamental fish production. It has also emphasized the suggestions for building the connection between th farmers and the exporters to create a better flow of information regarding the market demand dynamics (Figure 3).

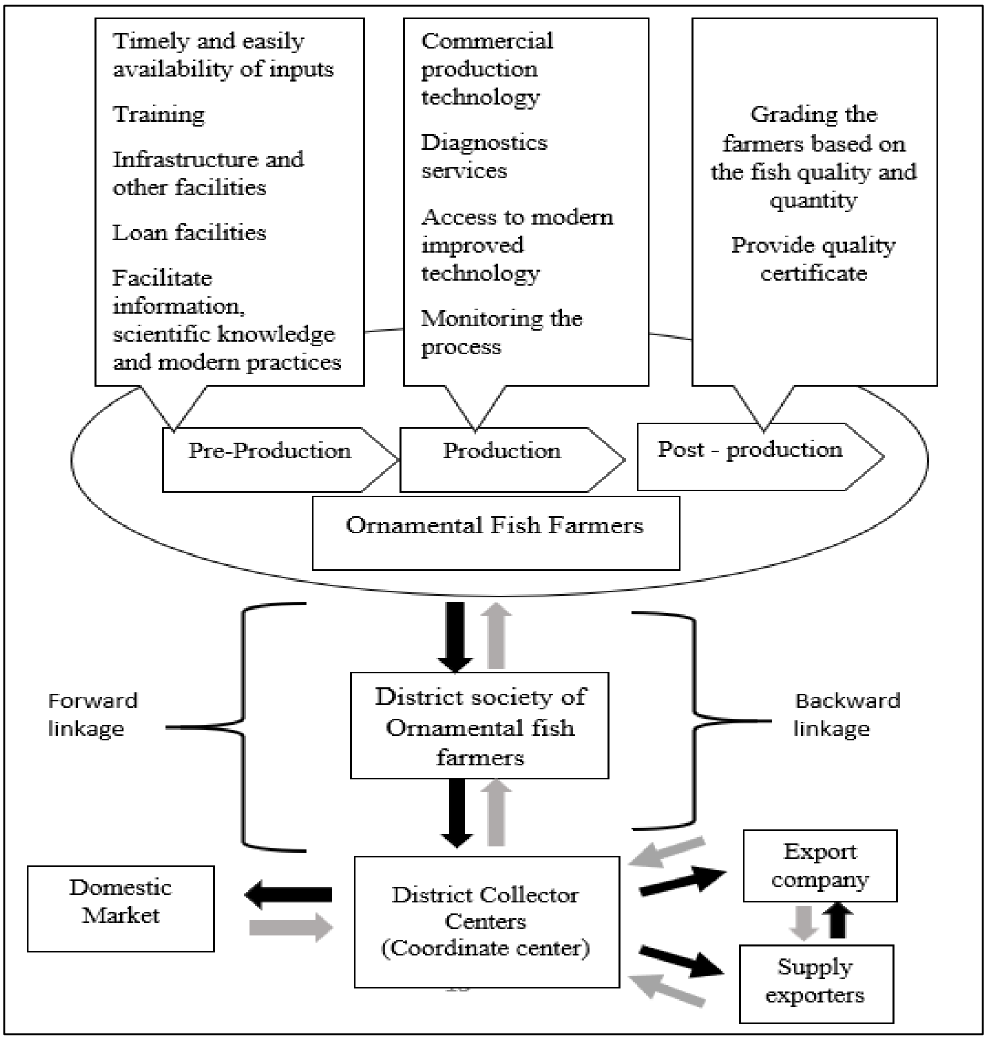


**Figure 5.** Ideal "ORNAFISBIZ" Model for Sri Lanka to link information between the farmers and exporters

## Impacts of climate change on the ornamental fish industry

This industry is not resistant to the broad effects of climate change. Climate change is altering environmental conditions, posing challenges for aquatic ecosystems and the ornamental fish trade. The climate change effects can be different for marine ornamental fisheries and freshwater ornamental fisheries.

*Temperature variations:*

Rising temperatures associated with climate change have direct consequences for ornamental fish species. Many ornamental fish are adapted to specific temperature ranges, and even small deviations can lead to stress, altered behavior, and increased susceptibility to diseases. A study by Mora et al. [52] highlights the vulnerability of marine species to temperature changes, with potential implications for tropical ornamental fish residing in coral reef ecosystems.

*Marine acidification:*

Increased carbon dioxide ($CO_2$) levels, a result of human activities, are leading to ocean acidification. This phenomenon has been shown to impact the development and survival of marine organisms, including ornamental fish larvae. A study by Hamilton et al. [53] emphasizes the sensitivity of fish otoliths to changes in pH, potentially affecting their sensory capabilities and overall fitness.

*Habitat Loss and Destruction*:
Climate change contributes to habitat loss and fragmentation through events such as coral bleaching, extreme weather events, and altered precipitation patterns. These changes can disrupt the natural habitats of ornamental fish, affecting their breeding and feeding grounds. A study by Hughes et al. [54] underscores the widespread and severe impacts of climate change on coral reefs, which are vital ecosystems for many ornamental fish species.

*Disease spread*:
Climate change can influence the distribution and prevalence of diseases affecting ornamental fish. Changes in water temperature and altered ecological conditions may create favorable environments for the proliferation of pathogens. A study by Harvell et al. [55] discusses the links between climate change, disease dynamics, and the health of marine organisms, including ornamental fish.

*Difficulties in inducing fish for captive breeding*:
Fish breeding is an issue that most of the growers are facing across the freshwater fisheries. Especially for some fish species, it is hard to breed at captive conditions. This has to be on time happening in a tandem to maintain the fish stock. Different new techniques have been tried in other countries, but still not been introduced or not widely practiced in Sri Lanka [56].

*Water scarcity:*
Water source is the most important resource for aquaculture. And the water demand is huge for tanks/ponds and cleaning purposes. Unless otherwise, a good waterbody is available, the water has to be taken from other human purposes or agricultural purposes or else from ground water. This would deplete the water resources quickly in that area unless the aquifers are replenished on time [57]. On the other hand, Adverse *climate influences like floods, droughts etc*. can also have an impact on ornamental fish production [58-59]. They can affect the access to clean water. Floods can change the clarity of the water, hardness, and pH at times. Thus, these have to be monitored regularly. Otherwise, the fish stock will be lost or can be vulnerable to diseases.

*Interferences to supply of feed ingredients and price fluctuations*- Fish feed is a crucial element of the aquaculture industry. Especially for the ornamental fish, feed is important to maintain the colors in the body. Thus, fish feeds include microbial additives, yeast types, algae and other additives. The pigments in the feeds are vital for pigmentation in the fish. Thus, proper nutritious feed should be always available
[35, 60, 61]. And the macroeconomic indicators like trade and inflation can have a say in the price of the fish feed, that in turn affect fish production.

The ornamental fish industry is intricately connected to the health of aquatic ecosystems, which are increasingly under threat from climate change. As temperatures rise, oceans acidify, habitats degrade, and diseases spread, the ornamental fish trade faces significant challenges. Sustainable practices, habitat conservation, and global efforts to mitigate climate change are crucial for preserving the diversity and economic viability of the ornamental fish industry.

## Coping strategies for ornamental fish production amidst climate change

Climate change poses a difficult challenge to ornamental fish production, requiring a comprehensive set of coping strategies. These strategies encompass temperature management, water quality assurance, genetic selection for resilience, aquaculture system innovation, and community engagement. By adopting these measures, the ornamental fish industry can navigate the complexities of a changing climate and carry out fish production.

*Temperature management:*
Rising temperatures due to climate change can disrupt the breeding patterns and overall health of ornamental fish. Effective temperature management strategies are essential to mitigate these impacts. Employing advanced temperature control systems in production facilities and incorporating shade structures are proven methods [62]. Such interventions help maintain optimal conditions for fish growth and reproduction.

*Water quality assurance*:
Climate change can influence water quality, affecting the well-being of ornamental fish. Implementing healthy water quality management practices is crucial. Regular monitoring of parameters such as pH levels, dissolved oxygen, and nutrient concentrations, along with the use of efficient filtration systems, ensures a stable aquatic environment [63]. Maintaining pristine water quality is vital for the health and marketability of ornamental fish.

*Genetic selection for resilience:*
Genetic diversity plays a critical role in conferring resilience to environmental stressors. Selective breeding programs that prioritize traits associated with climate resilience can enhance the adaptive capacity of ornamental fish populations. Research by Abisha *et al*., [64] highlights the importance of incorporating genetic diversity in breeding programs to develop strains that are better equipped to cope with changing environmental conditions.

*Aquaculture system innovation:*
Innovative aquaculture systems that integrate sustainable practices can enhance the resilience of ornamental fish production. Recirculating aquaculture systems (RAS), and integrated multitrophic aquaculture (IMTA) are examples of eco-friendly approaches [65]. These systems minimize environmental impact, reduce resource usage, and contribute to the overall sustainability of ornamental fish production.

*Community engagement and education*:
Engaging local communities and educating stakeholders about the impacts of climate change on ornamental fish production is essential. Encouraging sustainable practices, responsible consumption of resources associated with ornamental fish, and conservation efforts can contribute to the preservation of natural habitats and the long-term viability of the ornamental fish industry [66].

## Challenges faced by the ornamental fish industry in Sri Lanka

Despite its growth and potential, the ornamental fish industry in Sri Lanka faces several challenges which include site-specific local issues as well as macro challenges pose by the changes in the economy which leads to risks and uncertainties.

*Disease management*:
Disease outbreaks can lead to significant losses in fish farms. Effective disease management and quarantine measures are essential to maintain the health of ornamental fish. Management and hygienic practices also must be properly followed to reduce the incidence of disease outbreaks.

*Culture environment*:
The degradation of the quality of aquatic culture environments and their surrounding ecosystems is a significant threat to the ornamental fish industry. Ornamental fish, prized for their vibrant colors and unique features, are highly dependent on clean and well-maintained aquatic environments for their health and survival. The pollution and degradation of these culture

environments, driven by various human activities, pose a direct risk to the well-being of ornamental fish populations. This may also lead to disease spreading.

*Biodiversity conservation*:
One of the primary concerns in the ornamental fish industry is the sustainability and ethical sourcing of fish species. Overexploitation of certain species can lead to population degradation. On the other hand, habitat destruction by human activities can reduce the quality of the habitat or even can lead to loss of habitat for fish species. These aspects can endanger the species and can cause sustainability issues.

*Introduction of invasive species*:
In any ecosystem, the introduction of invasive species can cause potential threats to endanger the local species. This may also cause competition for available resources in that habitat. Further, improper release of invasive species into wastewater can lead to many other issues and cross-breeding, etc. Which might cause imbalances in the genetic pool of the ecosystem.

*Market competition*:
Competition from other ornamental fish-exporting countries like Thailand, Singapore, and Malaysia has intensified. Sri Lanka needs to maintain quality and competitiveness in pricing.

*Export standards and regulations:*
Stringent export regulations and quality standards imposed by importing countries can hinder market access for Sri Lankan exporters or at least may cost a heavy charge during exportation.

*Market demand and macroeconomic conditions*:
The demand for ornamental fish can fluctuate due to shifts in consumer preferences, economic conditions, and cultural factors. Thus, there is a price risk involved in exporting fish. Along with this, the macroeconomic conditions may also can cause severe pressure on the exporters and producers. Thus, having a portfolio of fish and fish product exports is advisable. Further, any political disagreements can also lead to loss of markets in this industry between countries. So, capitalizing on the existing economic conditions is a skill that needs to be in the ornamental fish market.

## Important features of the ornamental fish industry in Sri Lanka

The ornamental fish industry in Sri Lanka has a rich history as well as a significant potential for expanding in the future. Followings are the important legislation, which helps to govern the Sri Lankan ornamental fish industry. Local regulations in Sri Lanka governing the ornamental fish industry are established through various policies and acts to ensure sustainability, protect natural ecosystems, and promote responsible trade.

1. Fisheries and Aquatic Resources Act (No. 2 of 1996): forms the foundational legal framework for managing the ornamental fish industry on licensing, conservation, and resource management, regulating licensing for ornamental fish breeding, collection, and export (Fisheries and Aquatic Resources Act, 1996).

2. National Aquatic Resources Authority (NARA): plays a crucial role in implementing and enforcing regulations related to the ornamental fish trade in Sri Lanka. It issues licenses and permits, monitors the industry, and ensures compliance with quality and health standards for exported fish (National Aquatic Resources Authority, Sri Lanka).

3. Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) Regulations: state the protection of endangered and protected species of ornamental fish in international trade.

4. Department of Animal Production and Health (DAPH): enforces export controls to guarantee the quality and health of ornamental fish intended for export to prevent the spread of diseases and parasites (Department of Animal Production and Health, Sri Lanka).

5. Conservation and Environmental Regulations: to protect natural habitats and ecosystems that support ornamental fish species and aim to prevent habitat destruction and over-exploitation in areas where ornamental fish are collected.

6. Inspection and Quarantine: Measures related to inspection and quarantine are in place to prevent the spread of diseases and parasites through the trade of ornamental fish.

7. Certification and Labeling: to ensure accurate information is provided to consumers and regulatory authorities, promoting transparency and responsible practices within the industry.

Currently, local laws and regulations are already placed under several policies and acts to have better ornamental fish production and marketing in the country. However, it is essential to control the destruction of habitats and breeding populations of rare and exotic fish species for the proper implementation of laws and regulations associated with this industry [45]. The future of the local ornamental fish industry should be shaped by evolving consumer preferences, sustainability initiatives, and advancements in breeding technology. The global demand for ornamental fish is on the rise, driven by the increasing popularity of home aquariums and decorative fish tanks. As the ornamental fish industry in the country has a promising future, under effective management, it is crucial to ensure sustainable growth and success.

The Figure 6, denotes where Sri Lanka stands in terms of relatedness vs complexity for ornamental products in trade for the year 2021. The graph clearly shows that compared to other major ornamental fish exporters like Japan, Indonesia, Malaysia, Spain and the Netherlands, Sri Lanka performs slightly lower compared to the other countries. Notably, in the country complexity (y axis) Sri Lanka performs less than zero, whereas other major exporters are ranked above zero. Corresponding to this, we observe the indicators for the selected major ornamental fish exporting countries in (Table 6). The revealed comparative advantage (RCA) score for ornamental fish for Sri Lanka is 88, the highest among the selected nations and it is almost more than 10 times higher than that of other countries. This indicates that Sri Lanka has a greater advantage over others in ornamental fish trade. Strikingly, the only index Sri Lanka underperforms is the ECI or economic complexity index for trade. This of course corresponds with the income of the countries, yet the Sri Lankan index is negative. This is one important aspect that needs attention, as the facilitation of business and trade is needed to smoothen the exporting process. This also measures the country's relative knowledge intensity towards the product. Thus, we can infer that this denotes that most of our ornamental trade is less value added and less technologically advanced products. This demands more research and technology applications in this field.

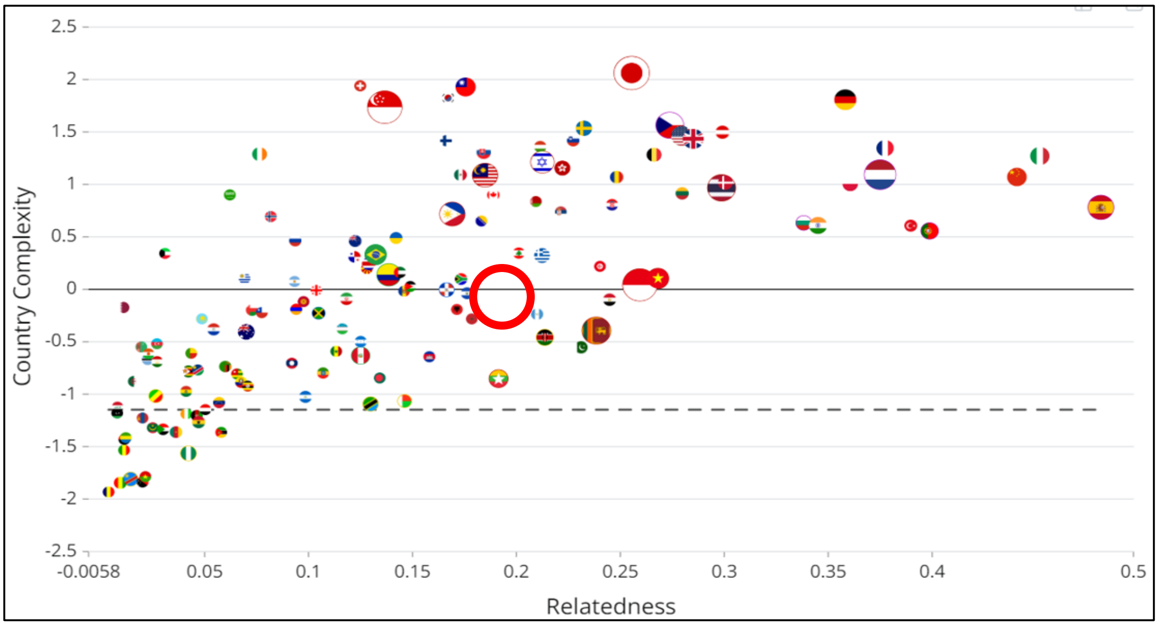


**Figure 6.** Relatedness vs Country complexity for aquaculture products 2021 (Source: OEC, "Ornamental fish," Observatory Economic Complexity, 2023. https://oec.world/en/profile/hs/ornamental-fish?filterSelector=valueFilter0.)

***Note****: The Complexity-Relatedness diagram compares the risk and the strategic value of a product's potential export opportunities. Relatedness is predictive of the probability that a country increases its exports in a product. Complexity is associated with higher levels of income, economic growth potential, lower income inequality, and lower emissions.*

**Table 6.** Comparative indicators on Complexity-Relatedness indicators for selected ornamental fish exporting countries (Source: OEC, "Ornamental fish," Observatory Economic Complexity, 2023. https://oec.world/en/profile/hs/ornamental-fish?filterSelector=valueFilter0.)

| **Country** | **RCA** | **ECI** | **Relatedness** |
|---|---|---|---|
| Indonesia | 8.82 | 0.042 | 0.259 |
| **Sri Lanka** | **88.1*** | **-0.39** | **0.238** |
| The Netherlands | 2.63 | 1.09 | 0.374 |
| Spain | 2.26 | 0.78 | 0.481* |
| Singapore | 6.38 | 1.74 | 0.136 |
| Japan | 3.3 | 2.06* | 0.255 |
| Malaysia | 2.35 | 1.09 | 0.184 |
| Thailand | 4 | 0.97 | 0.298 |
| Vietnam | 1.12 | 0.1 | 0.268 |
| India | 0.45 | 0.61 | 0.345 |

***Note:*** *RCA: Revealed comparative advantage (range o to infinity) and higher RCA indicates the country has a higher revealed comparative advantage in trade for that particular product, ECI: Economic complexity index. Trade ECI estimates a country's ability to produce and export complex products that require a high level of knowledge and skills. Relatedness is predictive of the probability that a country increases its exports of a product*

Receiving government support and enhancing collaboration between the government and industry stakeholders can lead to policies and initiatives that support the growth and development of the ornamental fish industry. Continued government support in terms of, capacity building, internationally recognized certifications, better pathways to access local and international markets, and access to agricultural loans at concession rates can boost the industry's growth.

Application of research and innovation can play a significant role in the development of the industry, overcoming emerging challenges. Continued research into breeding techniques, disease management, and sustainable practices can enhance the industry's competitiveness. To fully harness these benefits, it is essential for Sri Lankan stakeholders to invest in research, development, and training to integrate all the suitable technologies into their ornamental fish farming practices. Collaborative efforts with universities, research institutions, and international partners can accelerate the adoption of new technological solutions. Capitalizing on emerging opportunities, the industry can contribute to economic development, poverty alleviation, gender equality, and environmental conservation in the country while providing livelihoods to many rural communities including women and young people [67-68].

## Conclusions and future prospects

The ornamental fish industry in Sri Lanka has shown great potential as a lucrative sector with a global reach. Known for its diverse aquatic biodiversity, the country has been a source of unique and beautiful ornamental fish species. To ensure the sustainable growth of this industry, embracing new technology is crucial. Sri Lanka's rich aquatic ecosystems are vital for the success of the ornamental fish industry as some of the species found in Sri Lanka can be bred on at large scale and can be exported. This also applies to aquatic plants. As the trade indices suggest that, Sri Lanka needs to make a great leap in the use of technology and knowledge-intensive activities in this industry. One way this could be done is through improving the breeding techniques and application of novel breeding techniques and come up with marketable breeds with royalty. Also, intensive research in this field also can have better marketable ornamental fish varieties etc.

New technologies in aquaculture are expected to revolutionize the breeding processes in Sri Lanka's ornamental fish industry. With the adoption of automated feeding systems, and water monitoring systems fish growers can expand into smart aquaculture systems. Maintaining proper water quality parameters is very crucial and through smart aquaculture systems this can be easily performed. Similarly, an automated feeding system can also be very useful for large aquariums or farms. Systems. These systems can regulate temperature, lighting, and water quality to optimize breeding success. This will lead to increased production and a wider variety of locally bred ornamental fish. We should also look into the application of technology in to hatchery and fish larvae management (image acquisition of larvae, underwater data acquisition, feeding larvae). Some technologies might take time to adopt, but some technologies and management practices can be imparted through proper training programs.

The next aspect of prospects is towards enterprise facilitation and providing the logistics/resources. Based on the surveys, what we infer is that compared to agriculture, aquaculture and ornamental fisheries require some more initial capital to establish the unit. Thus, the promotion of this industry with some government assistance to initiate the business is needed. Sri Lanka still ranks somewhat lower in doing business rankings and trade facilitation indicators. This is one reason for us to get the needed foreign investments in this industry. Comparatively, southeast Asian nations perform well and facilitate investments in ornamental fisheries, especially from foreign investors. Our bureaucracy has kept these investments far away from Sri Lanka. Most of these aspects cater to the production problems highlighted in the study. Production of ornamental fish should be incentivized with proper programs and strategies as happened with the government home garden program and propaganda.

The third aspect is marketing and economics-related problems. Most of the potential fish farmers are quite skeptical about how and where to sell their produce. This indicates that they are not aware of the potential avenues to sell their fish and plants.  Transportation is an important factor for ornamental fish. Standardization of fish, identification of diseases, and price determination are vital factors. On top of this, the country's trading climate and macroeconomics also can play a huge role in the production uncertainties of ornamental fish. Promotion of certain localities for ornamental fish production would ease some of the concerns of individuals. Industry promotion among the locals is something the authorities have to focus on. Sri Lankan consumer base is still largely untapped.

The future development of Sri Lanka's ornamental fish industry through new technology holds great promise. By embracing advanced breeding techniques, genetic improvement, online marketplaces, sustainable practices, and education, the industry can continue to grow and thrive in a competitive global market. Moreover, these developments can contribute to the preservation of Sri Lanka's unique aquatic biodiversity while boosting the country's economy through increased exports and creating employment opportunities for local communities. With the right balance of technological advancement and environmental stewardship, Sri Lanka can secure a prosperous future for its ornamental fish industry.

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## Conflict of interest

The authors have declared that no competing interests exist.

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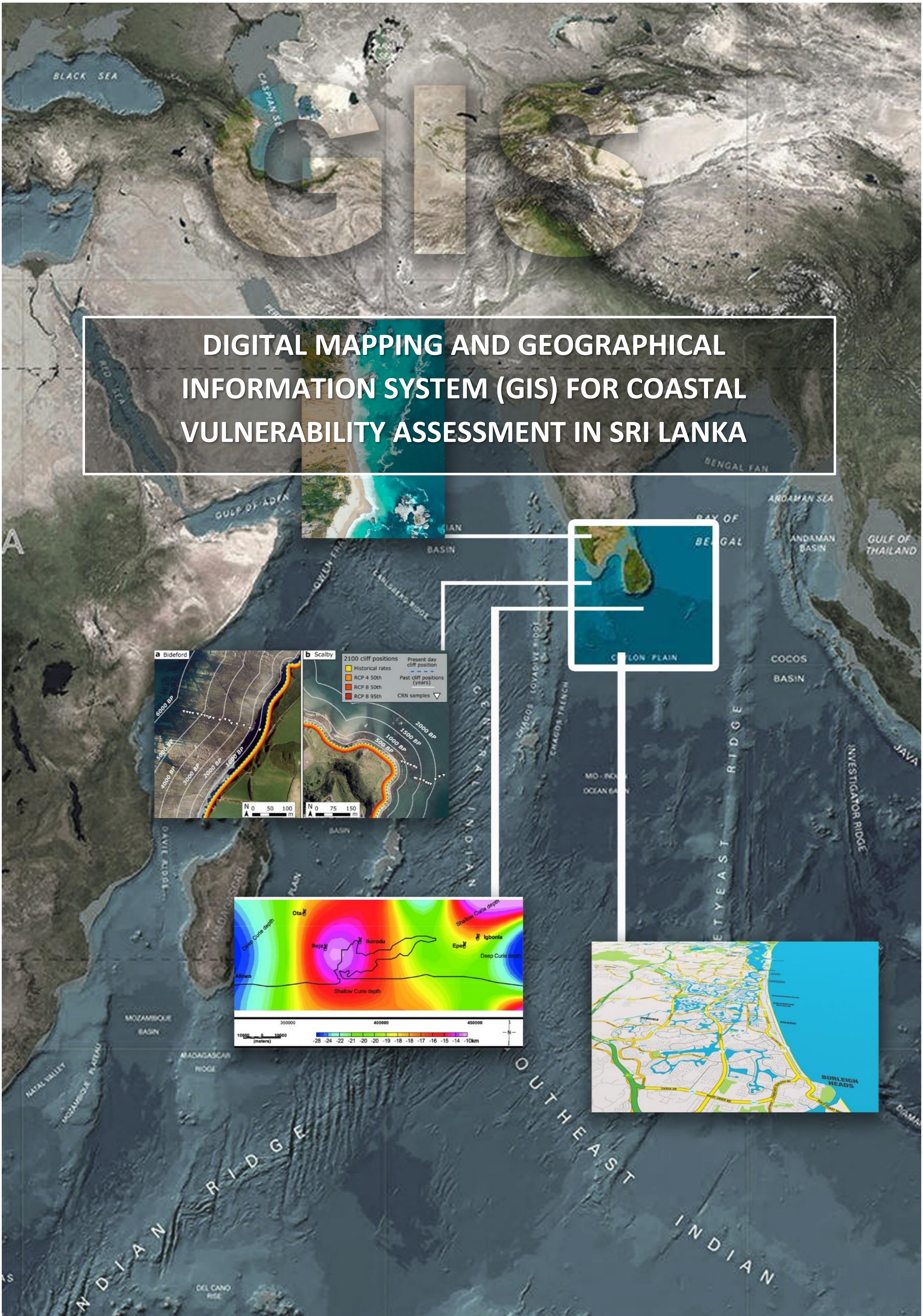
# **SECTION 3-** INFRASTRUCTURE AND TECHNOLOGICAL DEVELOPMENT


GIS
DIGITAL MAPPING AND GEOGRAPHICAL INFORMATION SYSTEM (GIS) FOR COASTAL VULNERABILITY ASSESSMENT IN SRI LANKA
BLACK SEA
CASPIAN SEA
GULF OF ADEN
BENGAL FAN
ANDAMAN SEA
BAY OF BENGAL
ANDAMAN BASIN
GULF OF THAILAND
CEYLON PLAIN
COCOS BASIN
INVESTIGATOR RIDGE
CENTRAL INDIAN
SOUTHEAST INDIAN
INDIAN RIDGE
MOZAMBIQUE BASIN
MADAGASCAR RIDGE
NATAL VALLEY
MOZAMBIQUE PLATEAU
DAVIE RIDGE
DEL CANO RISE
a Bideford
b Scalby
2100 cliff positions
Historical rates
RCP 4 50th
RCP 8 50th
RCP 8 95th
Present day cliff position
Past cliff positions (years)
CRN samples
6000 BP
5000 BP
4000 BP
3000 BP
2000 BP
1000 BP
1500 BP
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BURLEIGH HEADS

# Digital mapping and Geographical Information System (GIS) for coastal vulnerability assessment in Sri Lanka

H.M.A.J. Herath[1*], D.M.H.M. Dissanayaka[1]

## Abstract

Climate change is one of the most pressing issues facing our planet today, and its impact on coastal areas is particularly concerning. As global temperatures continue to rise, the consequences for coastal regions are becoming increasingly apparent. Coastal vulnerability due to climate change encompasses a wide range of impacts, including sea level rise, changes in storm wave climate, extreme weather events, and human activities. These factors contribute to the deterioration of coastal socio-economic and physical conditions, ultimately leading to heightened vulnerability in coastal communities. As a result of Sri Lanka is being an island, a significant threat is ahead to and the assessment of coastal vulnerability to climate-related impacts is essential for understanding the risks associated with climate change and developing effective adaptation and mitigation strategies in the country. In the Global context Geographical Information Systems play a crucial role in assessing and understanding coastal vulnerability to climate change. By integrating data from various sources such as satellite imagery, topographical maps, and climate models, GIS allows for a comprehensive analysis of the potential impacts of climate change on coastal areas. In Sri Lanka also using GIS in vulnerability assessments provides researchers and decision-makers with valuable information on the spatial distribution of vulnerability hotspots, the exposure of critical infrastructure, and the identification of at-risk populations. But there are critical limitations in country level access to the high resolution and in-depth information in Sri Lanka. Taking steps to get funding sources and investing on GIS is essential to conservation of biodiversity, ecosystem services, and coastal resilience, yet are undervalued and imperiled by population growth, development, habitat destruction, and climate change.

**Keywords:** Coastal vulnerability, GIS, Satellite imagery, Topography

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## Introduction

### Climate change and coastal vulnerability

The climate of the world is changing. Carbon dioxide levels in the atmosphere have increased as a result of human activities like land clearing and the burning of fossil fuels. This results in worldwide worming and has an impact on the coast. As a result, unlike other settings, the coastal systems are going through significant transformation. Where the sea and the land converge is along the shoreline. Sri Lanka, the twenty-fifth largest island in the world by landmass, has a 1,620-kilometer-long coastline. Sri Lanka's coastline is made up of estuaries, lagoons, beaches, rocky shorelines, sand dunes, salt marshes, and mangroves, with the rare hill or cliff directly on the oceanfront [1]. Less than one-third of Sri Lanka's coastline might be protected by current bio shields like mangroves, whereas more than 90% of it is susceptible to water-related hazards [2]. Currently, natural occurrences including sea erosion, sea water intrusion, a decrease in the amount of river silt, an increase in wave energy, and sea level rise pose a serious threat to coastlines [3-4].

One of the most obvious and pervasive effects of climate change is sea-level rise, which is caused by the thermal expansion of ocean waters and the increasing melting of glaciers and ice caps. There is broad scientific consensus that the rise in the global sea level will continue well into the next century. In the period from 1990 to 2100, the Intergovernmental Panel on Climate Change (IPCC) predicts that the average worldwide sea level will rise by 9 to 88 millimeters [5]. Sea levels are rising at an average pace of nearly 3 mm per year, which is much faster than the norm over the past 50 years, according to recent satellite data paired with tide gauge data [5]. As long as temperatures continue to rise, this pace is anticipated to exponentially increase in the twenty-first century [6]. According to the Copenhagen International Scientific Congress on Climate Change, the maximum sea level rise by 2100 may be around one meter or even more. Since recent estimates of ocean surface temperature and heat content show that ocean warming is around 50% more than had been previously reported by the IPCC in 2007, this rise is mostly caused by the thermal expansion of saltwater [7]. Accelerated sea level rise will transform the ecological structure and functions of the coasts by affecting their physical, biological, and biogeochemical properties at various time and spatial scales. 33% of Sri Lanka's population lives in coastal regions or the adjacent coastal zone [8]. Additionally, some of the most productive and intricate biological systems may be found in coastal regions, which also sustain a variety of plant, fish, and animal species. The coastal population would be in danger on all fronts if sea levels rise more quickly.

Following are the biophysical impacts of sea-level rise on coastal areas [9].

- Inundation and displacement of lowlands and wetlands
- Coastal erosion
- Intensification of coastal storm flooding
- Salt-water intrusion into freshwater aquifers, and degradation of water quality
- Change of tide in rivers and bays
- Change of sediment deposition patterns
- Loss of coastal habitat

Socio-economic impacts of sea-level rise is including the following [10].

- Damage to coastal infrastructure, including that used for transportation and recreation
- Increased property loss
- Increased risk of disease
- Increased flood risks and potential loss of life
- Changes in renewable and subsistence resources
- Loss of cultural resources and values

- Reduction in the functioning of drainage and sewage systems
- Increased susceptibility to liquefaction due to the rise in ground water levels.
- Damage to coastal tourism activities

Studies have shown that when simply the coastal geomorphological slope is taken into account, 81% of Sri Lanka's coastline will be vulnerable to sea level rise by the year 2020. About 34% of Sri Lanka's coastline is still very susceptible to sea level rise. The majority of Sri Lanka's beaches, several lagoons, estuaries, coastal cities, and industrial areas have all been shown to be extremely vulnerable to the sea-level rise scenario [8]. According to the vulnerability index (Figure 1), the majority of Sri Lanka's coastline lies within a 2 km zone between "flooded" and "run-up" areas, and most localities, particularly those near water bodies or lakes, are vulnerable to the effects of ocean surges. The erosion of Sri Lankan beaches will get worse as the sea level rises, and severe weather can bring deadly floods to low lying coastal areas. With the expected sea level rise, which will mostly be caused by the extra water from the glaciers that are already melting quickly, large portions of the coastal regions of Puttalam, Galle, Hambantota, and Jaffna run the risk of being flooded by the end of the century.

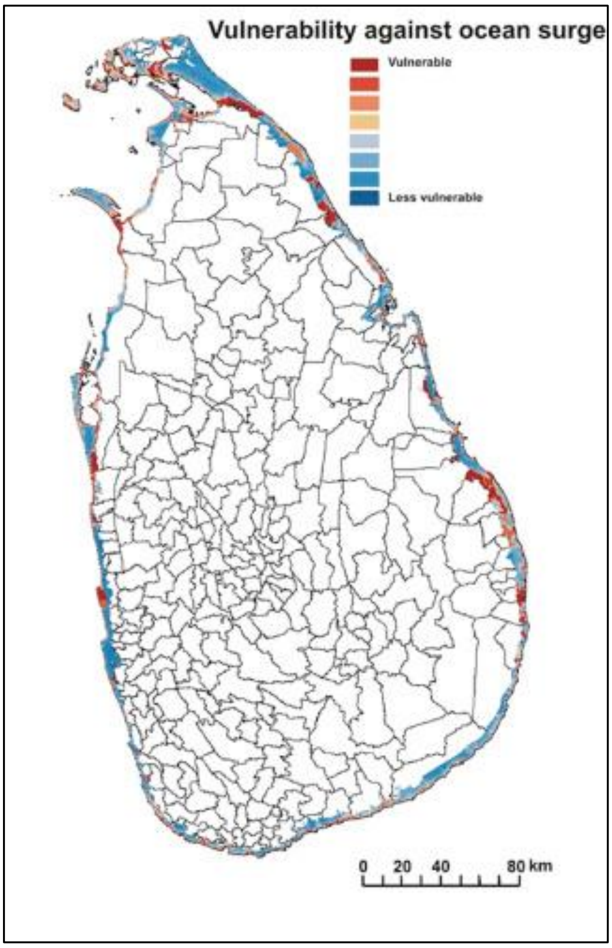


**Figure 1.** Vulnerability index, up to 2 km inland from the Sri Lankan shore. Local administrative boundaries are depicted by polygons on the country map (Source: Behara and Tom, 2017, Available at; *https://www.researchgate.net/publication/320841738)*

To effectively manage the coastal zone over the coming decades, it is crucial to establish a quick technique for evaluating vulnerability and risk that enables coastal managers and planners to identify high-risk regions in the coastal zone. Geographic Information Systems (GIS) are the perfect assessment tool to support such management efforts in the coastal zone and to deal with the significant uncertainty surrounding forecast of climate-change consequences and near-future morphological changes.

## Fundamentals of GIS and digital mapping

Since technological advancements in computer hardware and mapping software have already prompted many statistics and census offices to switch from conventional cartographic approaches to digital mapping and geographic information systems. The use of Geographic Information Systems (GIS), a disruptive technology, has completely changed how we gather, handle, analyze, and interpret spatial data. These systems combine geographic data, attribute information, and cutting-edge software to produce potent tools for comprehending and resolving challenging real-world issues. Urban planning, environmental science, disaster management, and public health are just a few of the disciplines that have adopted GIS widely. GIS refers to three integrated parts;

1. Geographic - Of the real world; the spatial realities, the geography
2. Information - Data and information; their meaning and use
3. Systems - The computer technology and support infrastructure

A geographic information system (GIS) is a tool for gathering, managing, storing, manipulating, and displaying spatial or geographic data. Users can create interactive queries (user-created searches), analyze geographical data, change data on maps, and present the outcomes of all these actions using GIS apps. Geographic information science (GIScience), the science behind geographic concepts, applications, and systems. GIS is a general term that covers a wide range of technologies, procedures, techniques, and methodologies. It is incorporated into numerous processes and has numerous uses in engineering, planning, management, transportation and logistics, insurance, telecommunications, and business. Maps have always supported enumeration and been used to convey aggregate census findings in a cartographic format. This position has been substantially extended by cartographic automation. GIS currently plays a significant role in the transmission of census data as well as in the analysis of population and household data, in addition to making it possible to produce enumerator maps and thematic maps of census findings more effectively.

The fundamental idea behind GIS is the use of spatial data, which includes details on the position, characteristics, and qualities of geographical phenomena. Global positioning system (GPS) devices, remote sensing technologies, surveys, and digitalized maps are just a few of the sources from which spatial data can be produced [11]. The ability of GIS to merge spatial and attribute data, allowing for a richer understanding of spatial phenomena, is one of its core components. Additional details regarding geographic features, such as demographics of the populace, patterns of land use, climate factors, or any other information that may be connected to specific areas, are provided by attribute data. GIS can respond to queries like "Where are specific types of land cover found, and how does this relate to patterns of urban development?" by combining these two forms of data [12]. Streets, buildings, and other types of data, as well as flora, can all be displayed on a single map using GIS (Figure 2). This makes it simpler for people to see, evaluate, and comprehend patterns and correlations.

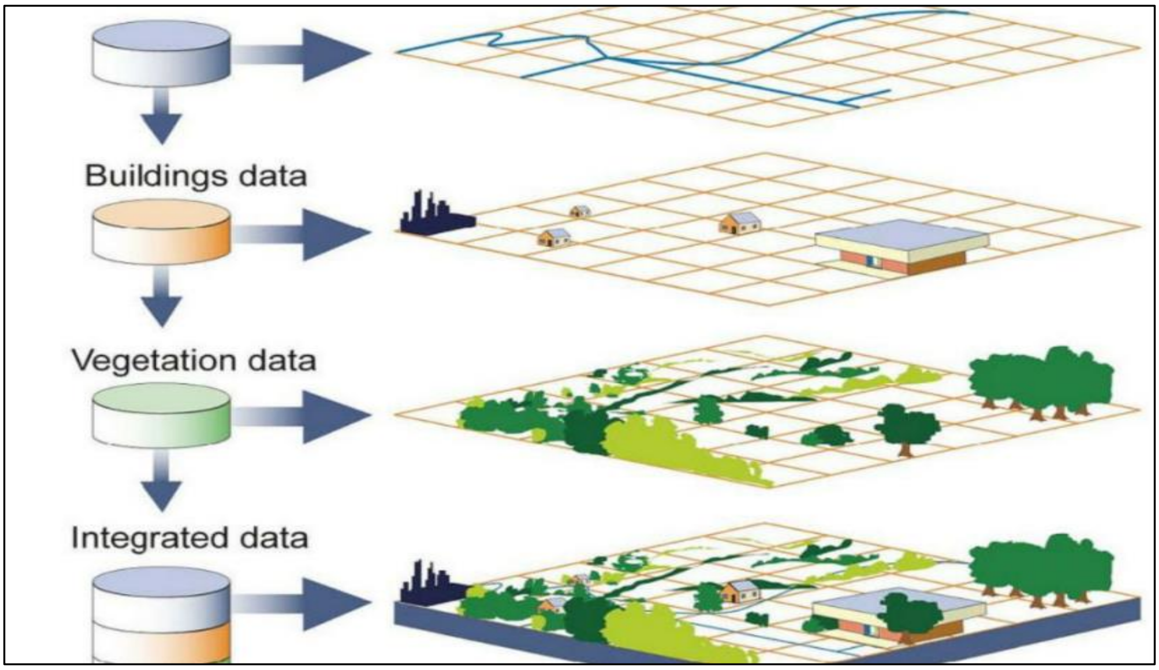

**Figure 2.** Digital Mapping of GIS Showing different kind of data in one map (source: National Geographic Public Domain, Available at; https://education.nationalgeographic.org/resource/geographic-information-system-gis/)

The functionality of GIS depends on its software component. The necessary tools for data editing, analysis, and visualization are provided by many GIS software programs, including ArcGIS and QGIS. With the use of these tools, users can run geographic statistics, create themed maps, run buffer analysis, and perform spatial queries [13]. Applications for GIS can be found in many different industries. GIS is used by environmental scientists to manage natural resources, track deforestation, and model habitats [14]. GIS is used by urban planners to model urban expansion, plan optimal land use, and assess transportation networks. GIS is used in disaster management to map catastrophe-affected areas in real time and to help identify susceptible populations. GIS is used by public health experts for epidemiological investigations, illness mapping, and resource allocation for healthcare services [15].

***Components of GIS System***

*Spatial data*:
Spatial data, which represents details about the position and form of geographic elements such points, lines, and polygons, provides the basis of GIS [11]. For the purpose of making maps and doing spatial analyses, this data is necessary.

*Attribute data*:
Attribute data adds further details about the geographic dataset's properties [11]. Any information related to geographic factors, such as population, land use, temperature, or other qualities, can be included in these attributes.

*GIS software*:
The digital workspace where users interact with spatial and attribute data is provided by GIS software [11]. There are numerous GIS software programs available, ranging from open-source alternatives like QGIS to proprietary programs like Esri's ArcGIS. GIS software offers a variety of

features, such as: Data Input and Editing, Data Management, Analysis and Processing, Visualization and Geo-processing.

*Hardware*:
To process and store data, GIS depends on hardware elements such as computers and servers [11]. Large-scale GIS projects involving intensive data processing or real-time applications like web mapping, high-performance workstations or servers can be required.

*People*:
A crucial element of GIS is people. Designing, implementing, and sustaining GIS projects are the responsibilities of qualified experts, frequently referred to as GIS analysts or GIS specialists [11].

### Applications of GIS and digital mapping in coastal disasters

Accurately measuring the coastline is crucial for coastal zone management applications like shoreline classification, erosion monitoring, biological resource mapping, habitat assessment, and planning and responding to natural disasters like storm surges and man-made ones like oil spills. By definition, managing the coastal zone involves managing space. Digital map data that is geo referenced contains a unique geographic reference, such as latitude and longitude, for each feature of the earth that is saved as spatial data. In order to address the planning and management concerns in the coastal zone, organizations and researchers are increasingly using spatial data and GIS [16].

Since the coastlines throughout the world are rapidly developing, it is necessary to implement strict control policies. However, the policies must be founded on reasoned judgment in order for any management of the beach to be effective [16]. This calls for quick access to pertinent data and information that is timely, accurate, and in the right shape for the job at hand. There are many possible applications for coastal GIS technology given the variety of tasks that coastal managers must complete and the variety of data processing capabilities that may be found in a conventional GIS.

The survey and management of coastal resources: As the human population continues to grow, there is more demand for dwelling space, leisure time, and a variety of other reasons on the coast. In addition, the world's oceans and coastal waters serve as significant hunting grounds for a variety of valuable commercial resources [16]. The necessity to investigate conservation strategies for remaining sticks grows in direct proportion to the steady depletion of these resources. GIS has a lot of promise to help with these chores.

Monitoring and analysis of coastal change: The coastal zone is very dynamic, and scientists and managers increasingly need access to tools that can capture these dynamics, particularly to assess and respond correctly to changes in the shore's geometry [17]. It is possible to distinguish between two basic categories in coastal change study, namely monitoring and simulation modeling.

GIS has been used near the coast to monitor a variety of natural and human-caused changes [18], such as:

- Wetlands' size and ecosystem are changing.
- Analysis of coastline alterations and erosion
- Evaluation of flood damage and risk, both real and anticipated.
- the sanding down of harbors, as well as the success and results of mitigation measures like dredging.

- Monitoring the behavior of oil spills in coastal environments; Monitoring the changes in land use in the coastal hinterlands, particularly the expanding urbanization of the coastal fringe.

Modeling coastal processes: Monitoring can aid in spotting and assessing changes occurring along the shore, but effective management of the coastal zone occasionally necessitates intervention and manipulation of the processes, checks, feedback, and interrelationships operating along, within, and across the shore in order to achieve more desirable outcomes. The effectiveness and potential effects of such action can be evaluated through modeling and simulation of coastal phenomena.

## GIS data collection and management

### *Coastal data collection methods*

Because of its dynamic character, the coast is a physical area with seasonal, short-term, and long-term trends that is exceedingly challenging to map or represent [3]. The analysis of data obtained from satellite imagery, aerial photography, digital maps, LiDAR data, remote sensing, and tabular data allows GIS to simulate vulnerability to sea-level rise, coastal erosion, and other disasters.

### *Satellite imagery*

Images of the Earth captured by satellites orbiting the planet are referred to as satellite imagery. In order to create high-resolution photographs, these satellites are outfitted with a variety of sensors for detecting visible light, infrared light, microwave radiation, and more. By providing comprehensive images of coastlines, satellite imagery is a useful tool for studying and tracking the dynamics of coastal erosion.

There are a few basic categories of satellite imagery, each of which may record a particular range of data (Figure 3). Following are the top three most typical types of satellite imagery [11]:

- Visible imagery - uses the visible light spectrum to capture a representation of the coastal surface.
- Infrared imagery - captures images of the using infrared light. infrared imagery can detect energy in the infrared spectrum, specifically the temperature
- Water vapor imagery - uses sensors to detect and measure the amount of water vapor in the Earth's atmosphere. This detects the microwave energy emitted by water molecules and use for climate studies.

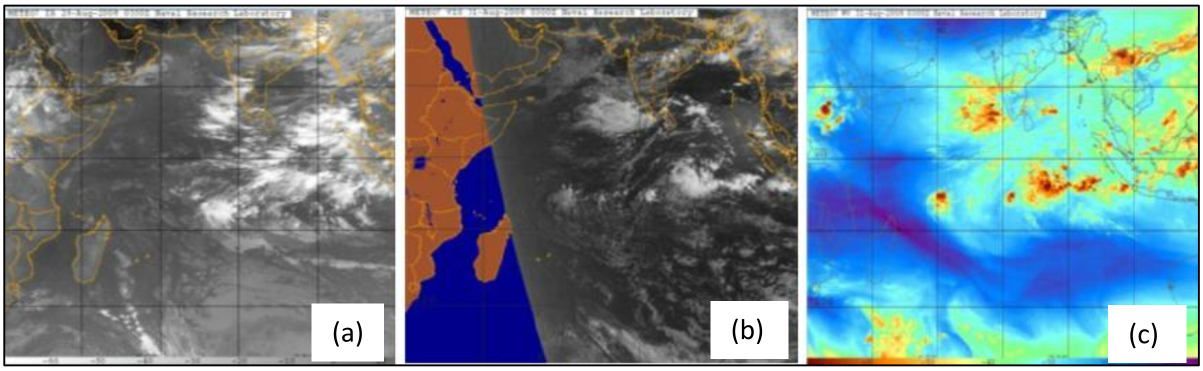


**Figure 3.** Satellite image types. (a). visible image of clouds; (b). infrared image of clouds; (c). water vapor image of clouds (Source: Conference: Institute of Physics - Sri Lanka-IPSL, Available at; https://www.researchgate.net/figure/Satellite-image-types-Images-from-left-to-right-are-visible-image-of-clouds-infrared_fig1_237054454

High resolution satellite photos offer comprehensive information about a coastline's physical features, including its topography and sediment make-up. With the aid of this information, it is possible to pinpoint regions that are most susceptible to erosion, flooding, and storm surges. Monitoring variations in water temperature and salinity can also be done using satellite pictures. Areas that are more likely to be impacted by sea level rise can be identified using this data. Researchers can better understand the possible effects of climate change on coastal areas by keeping an eye on these changes, which will help them decide how best to safeguard them. Due to access issues, high quality satellite imagery is very expensive, and in places like Sri Lanka, it is challenging to evaluate those images for the purposes of assessing coastal vulnerability. Therefore, research highly reliant on Google Earth imagery to assess and analyze imagery and develop data analysis like change detection [19].

***Aerial photographs***

Aerial photography is the practice of using cameras mounted on aircraft, rockets, Earth-orbiting satellites, and other spacecraft to take pictures of the Earth's surface or specific elements of its atmosphere or hydrosphere. Aerial images are typically shot in overlapping series from an airplane flying in a predetermined pattern at a given altitude for the mapping of terrestrial characteristics. Each image shows a region with a number of control points, the positions of which were established using ground-surveying methods (Figure 4). The creation of contour (connects sites with the same height (elevation) above a certain level, like the average sea level) maps or three-dimensional models of the photographed terrestrial surface is made possible by the photogrammetry (Techniques of capturing, measuring, and interpreting photographic images and patterns of observed radiant electromagnetic radiation and other phenomena which is used to get accurate information about real-world objects and the environment) technology, which involves the simultaneous projection of the overlapping images [20].

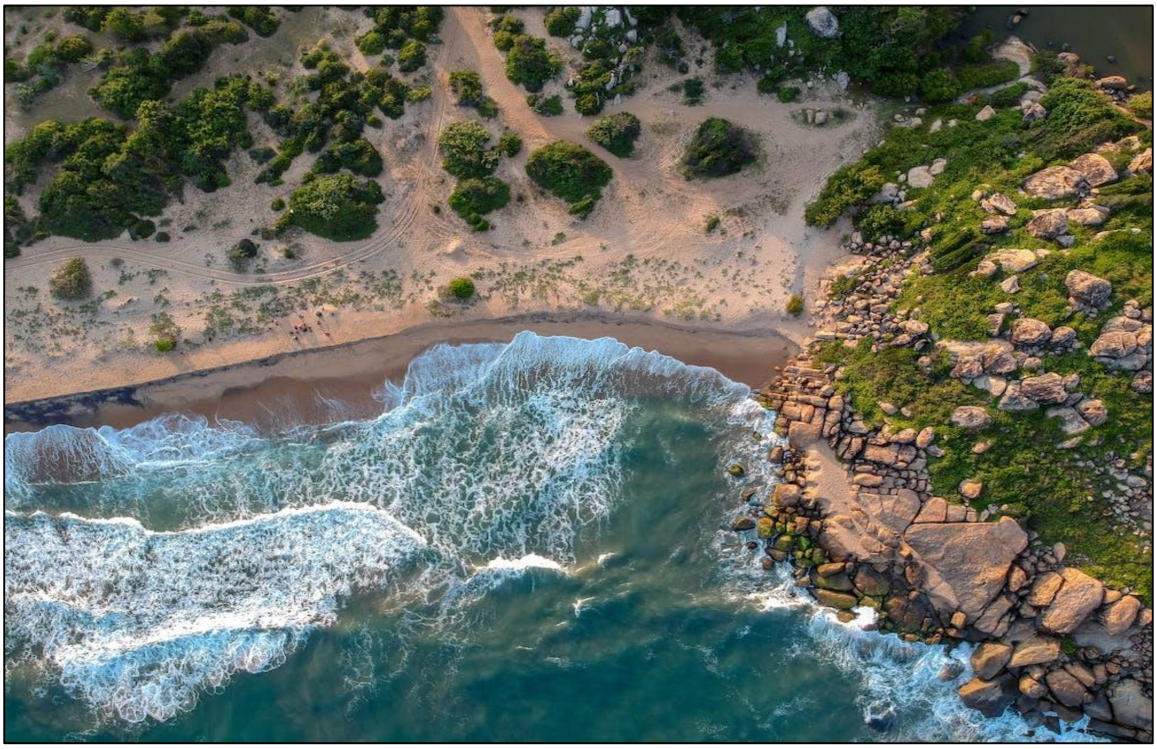

**Figure 4.** Aerial Photograph of the coast (Source: Internet Public Domain, Available at; https://depositphotos.com/photo/aerial-view-of-the-south-coast-of-the-island-of-sri-lanka 247550660.html

In order to investigate coastal vulnerabilities such coastal erosion and the effects of sea level rise on land-uses, high spatial-temporal data must be used. Drone aerial photography is frequently employed to produce Digital Elevation Models and high resolution ortho-imagery, which are crucial for accurately simulating sea level rise and developing maps for coastal habitats. However, using multi-spectral agricultural drones to gather the data is expensive and requires a license to use in Sri Lanka [21].

***LiDAR data***

A pulsed laser is used in the distant sensing technique known as Lidar, which stands for Light Detection and Ranging, to measure ranges (varying distances) to the Earth. These light pulses produce precise, three-dimensional information on the shape of the Earth and its surface features when paired with other data captured by the aerial system. A lidar device's main components are a laser, a scanner, and an advanced GPS receiver (Figure 5). The most popular platforms for gathering lidar data over large areas are aircraft and helicopters. Topographic and bathymetric lidar are two different types. While bathymetric lidar also measures seafloor and riverbed elevations using water-penetrating green light, topographic lidar typically maps the terrain using a near-infrared laser [22].

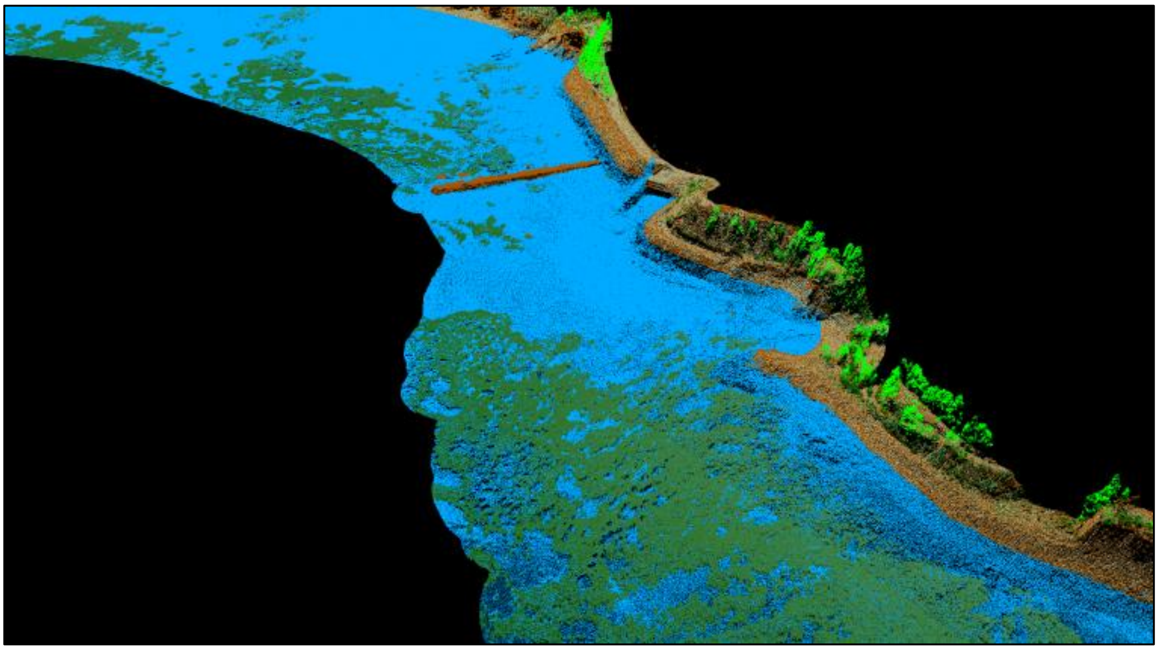

**Figure 5.** Mapping the Catalan coast using airborne Lidar bathymetry (Source: Hydro International Public Doman, Available at; https://www.hydro-international.com/content/article/mapping-the-catalan-coast-using-airborne-lidar-bathymetry)

### *Remote sensing*

A key method for examining the dynamics of ocean and coastal systems is remote sensing. Due to its capability to offer synoptic information over vast areas with high collection frequencies, a range of satellites and sensors are supplying spatio-temporal data (which used in data analysis when data is collected across both space and time) for monitoring and assessing daily changes in the ocean and coastal habitats [22]. Resource development, coastal zone planning and management, shoreline change monitoring, and the comprehension of physical processes in the coastal environment have all benefited from the use of remote sensing and geographic information systems [23]. Through the use of remote sensing technology, data is gathered and stored without physical touch with an object. As the science and technology of Earth observation, including space to Earth observation, aircraft observation, and field monitoring, remote sensing has been redefined [24]. Remote sensing technologies are becoming more useful and appealing for use in research and management of coastal ecosystems, such as wetlands, estuaries, and coral reefs, because to improvements in sensor design and data analysis techniques. For imaging coastal land cover, concentrations of organic/inorganic suspended particles, and dissolved compounds in coastal waters, multispectral and hyperspectral imagers are available. Microwave radiometers can detect ocean salinity, soil moisture, and other hydrologic factors, while thermal infrared scanners can precisely map sea surface temperatures and trace coastal currents. Information on ocean waves, ocean winds, sea surface height, and coastal currents—which have a significant impact on coastal ecosystems—is provided via radar imagers, scatter meters, and altimeters. Even in coastal seas that are only moderately murky, bathymetric maps can be created using aircraft light detecting and ranging equipment. Due to the great spatial complexity and temporal variability of coastal ecosystems, it is frequently necessary to examine them from both satellite and airplane to achieve the necessary spatial, spectral, and temporal resolutions [23].

## GIS data types

GIS data comes in two different varieties. These are raster and vector data, respectively. Because it is the format used by mapping portals like Open Street Maps and Google Maps, vector data is the type of spatial data that most people are familiar with. Additionally, it is heavily utilized in CAD and computer graphics. It is made up of polygons, lines, and points [25].

- Point Data – Point Data often represents unique data points or nonadjacent features (Figure 6). Because points are zero-dimensional, it is impossible to calculate their length or area. Cities, tourist attractions, and schools are examples of point data.

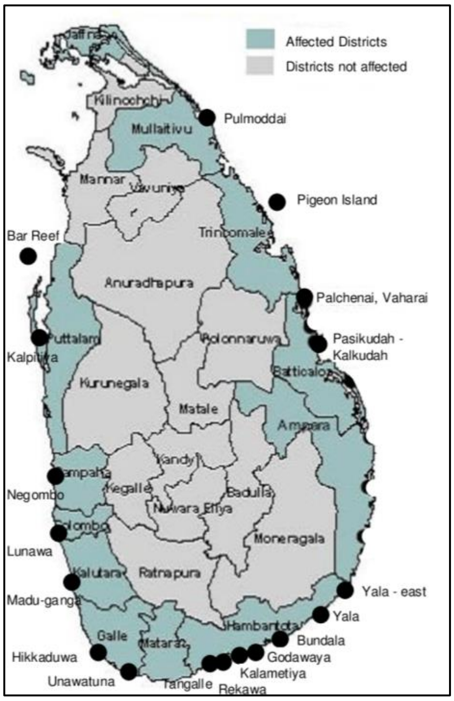


**Figure 6.** Sample image for Point Data - A map of Sri Lanka cost sites affected by the Indian Ocean Tsunami 2004. (Source: ResearchGate Public Domain [26] , Available at: https://www.researchgate.net/publication/260217066_Some_Aspects_of_Coastal_Zone_Management_in_Sri_Lanka_Including_Impact_of_Tsunami_A_Review)

- Line Data – Arc data is another name for line data. Linear features like rivers, streets, and pathways are represented by it. Since line data only has one dimension and can only be used to measure length, it has a beginning and an end. Different colors or line thicknesses, as well as solid or dashed lines, can be used to separate arc characteristics from one another (Figure 7). For instance, a river might be a dashed blue line, whereas a road might be a solid black line [25].

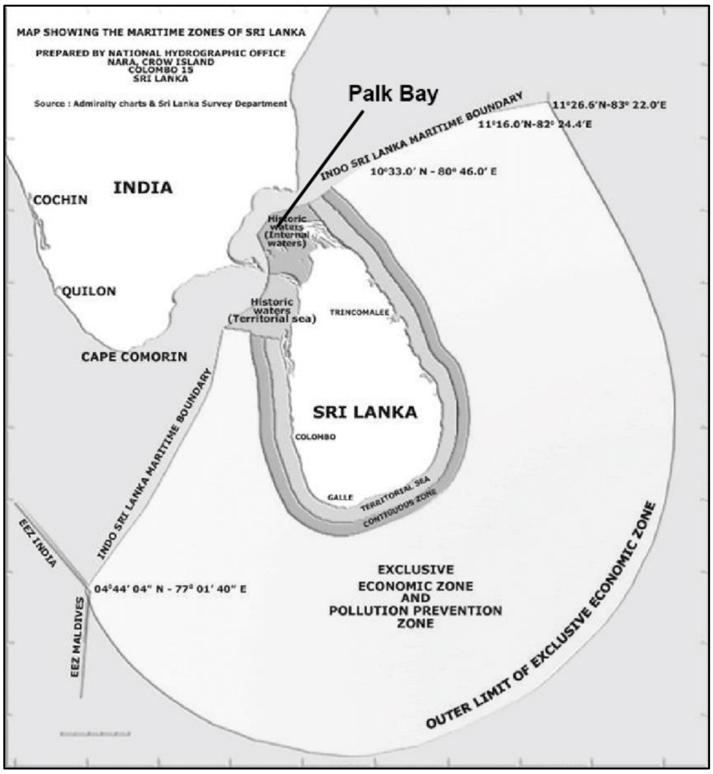


**Figure 7.** Sample image for Line Data - Sri Lanka's maritime zones (Source: PhD Thesis work by, Joeri Scholtens, University of Amsterdam, 2016, Available at: https://www.researchgate.net/publication/310590098_Fishing_in_the_Margins_North_Sri_Lankan_fishers'_struggle_for_access_in_transboundary_waters)

- Polygon Data – Typically, polygons symbolize places like towns, lakes, or woods. Polygons, which are two-dimensional and may measure the area or perimeter of a geographic feature, differ from point and line data (Figure 8). To distinguish polygon features, color schemes, patterns, or gradation color schemes could be employed [25].

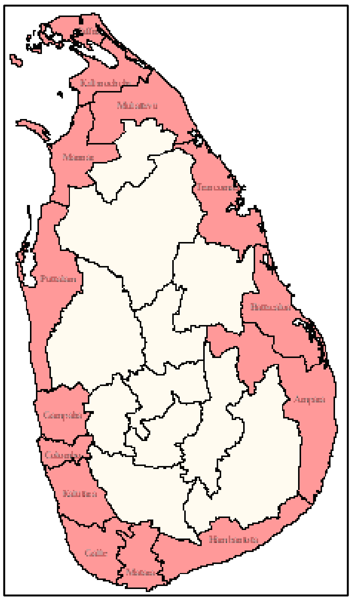

**Figure 8.** Sample image for Polygon Data – Coastal Zone of Sri Lanka (Source: ResearchGate Public Domain, Available at: https://communitylegal.lk/projects.php)

Pixels make up raster data, sometimes referred to as grid data, and each pixel has a value. Topographic maps, satellite photos, and aerial surveys all contain raster data. For the assessment of coastal risk and catastrophe management, raster data is essential. Continuous and discrete raster data are the two different forms [25].

- Continuous Data – Continuous rasters are grid cells that alter over time. An aerial photograph, height, and temperature are a few examples. A constant registration point is the source of continuous raster surfaces (Figure 9). For instance, the sea level is utilized as a registration point in digital elevation models. Every cell displays a value above or below sea level [25].

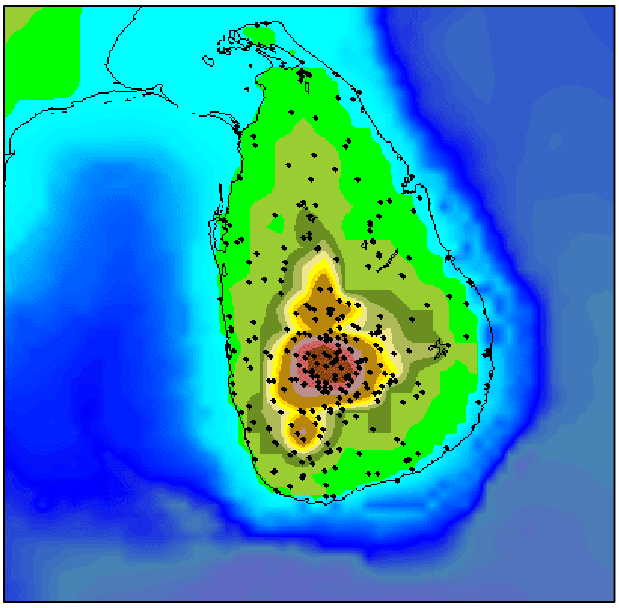

**Figure 9.** Sample image for Continuous Data - Topography map of Sri Lanka (Source: Available at: https://www.researchgate.net/figure/Elevation-map-of-Sri-Lanka-showing-the-location-of-the-187-stations-used-in-this-study-in_fig1_248289944)

- Discrete Data – Each pixel in a discrete raster data set is allocated to a particular class or theme. Discrete data, as contrast to continuous data, can only accept specified values, not values from a range (Figure 10).

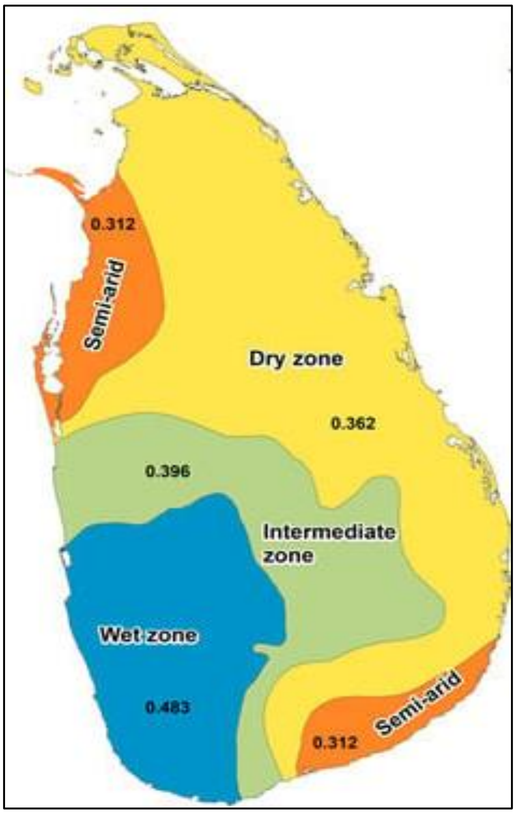


**Figure 10.** Sample image for Continuous Data Discrete Data - Representation of changes in annual rainfall at district and climatic zone level in Sri Lanka. (Source: Available at: https://www.mdpi.com/1003644)

## Freely available GIS applications in coastal vulnerability assessment

Google Earth Pro (https://earth.google.com)

Google offers Google world Pro software that integrates a large amount of satellite data into one system to display the world and analyze numerous geographic features. It has been overseen by Google since the mid-2000s and is based on projects that have been conducted over many years with groups like Keyhole. It is a sophisticated version of Google Maps that places a greater emphasis on science than on navigation. It is also referred to as a "geobrowser." A large portion of the studies on Sri Lanka's coastal vulnerability were based on Google Earth (Figure 11).

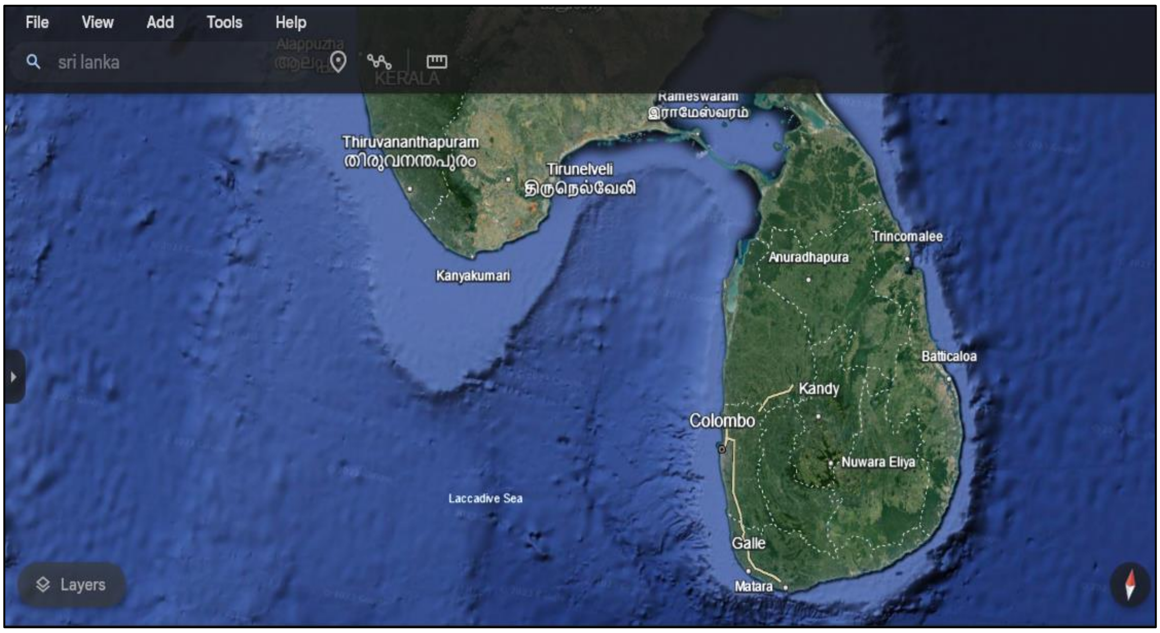


**Figure 11.** Interface from "GeoBrowser" (Source: Natural Earth Data. Available at: https://www.naturalearthdata.com)

For cartographers, Natural Earth Data (NED) is a particularly valuable resource that consistently ranks at the top of lists of the finest open-source GIS databases. NED provides a mix of raster and vector data sets, the majority of which are offered in three different size scales. NED hosts data on a worldwide scale and is supported by the North American Cartographic Information Society (Figure 12).

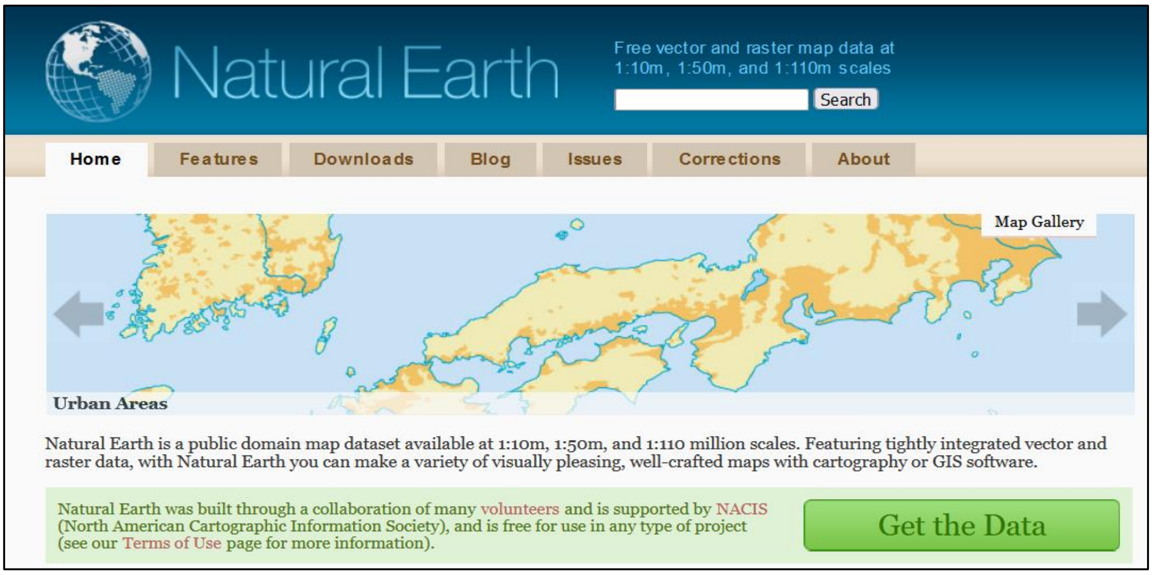


**Figure 12.** Interface of Natural Earth Data (Source: OpenStreetMap Data. Available at https://www.openstreetmap.org)

High spatial resolution vector data is available through OpenStreetMap (OSM). All of the data on OSM is gathered from cartographers and other GIS map creators, which sets it apart from other GIS data sources (Figure 13). This indicates that there is an enormous amount of specific information available.

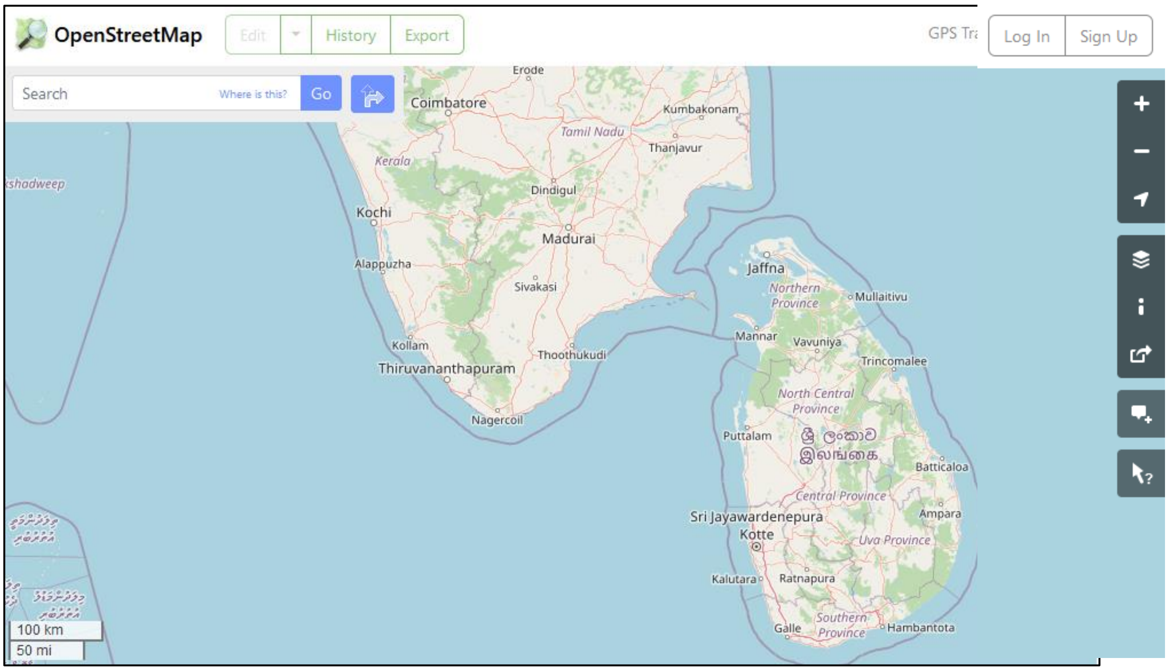


**Figure 13.** Interface of Open Street Map (Source: USGS Earth Explorer. Available at: https://www.usgs.gov)

One of the most complete sources of remote sensing data, or information from satellites or other high-flying aircraft, is without a doubt USGS Earth Explorer (Figure 14). For cartographers in need of satellite or aerial data, USGS is a valuable resource with one of the more user-friendly search features and bulk download capabilities.

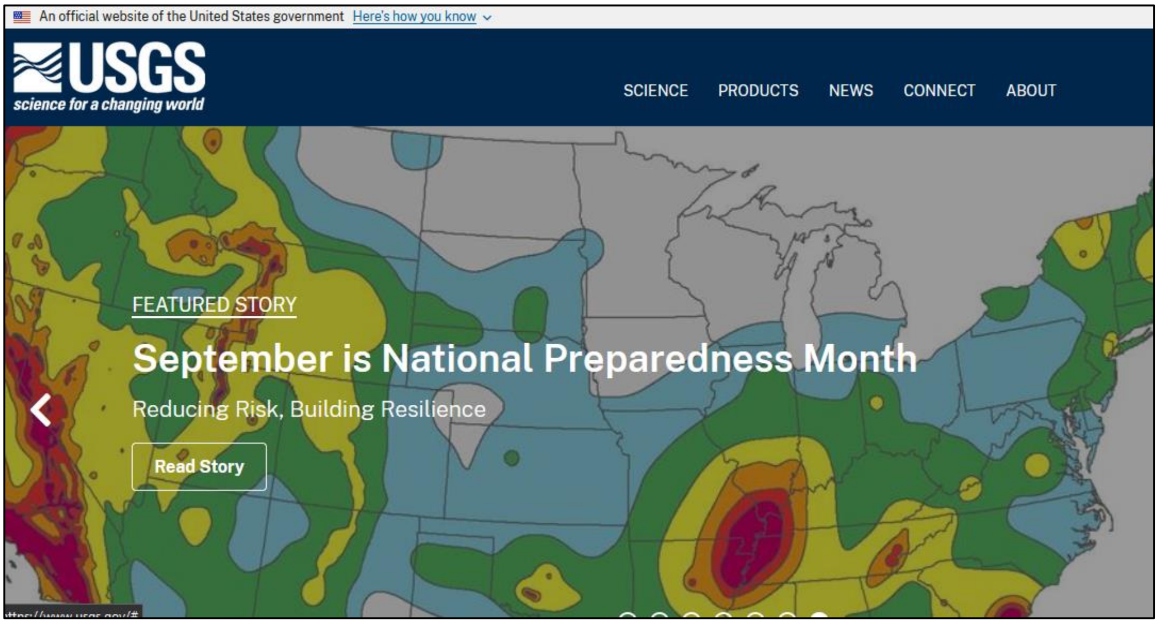


**Figure 14.** Interface of NASA Earth Observations (Source: Available at; https://neo.gsfc.nasa.gov)

Another source that concentrates on data from remote sensing is NASA Earth Observations (NEO) (Figure 15). Because the data are focused on climate and the environment, it is easier to get information on the atmosphere, land, oceans, energy, and human existence. Additionally, these resources come in a variety of forms and are regularly updated (ensuring higher accuracy): GeoTIFF, JPEG, PNG, and KML.

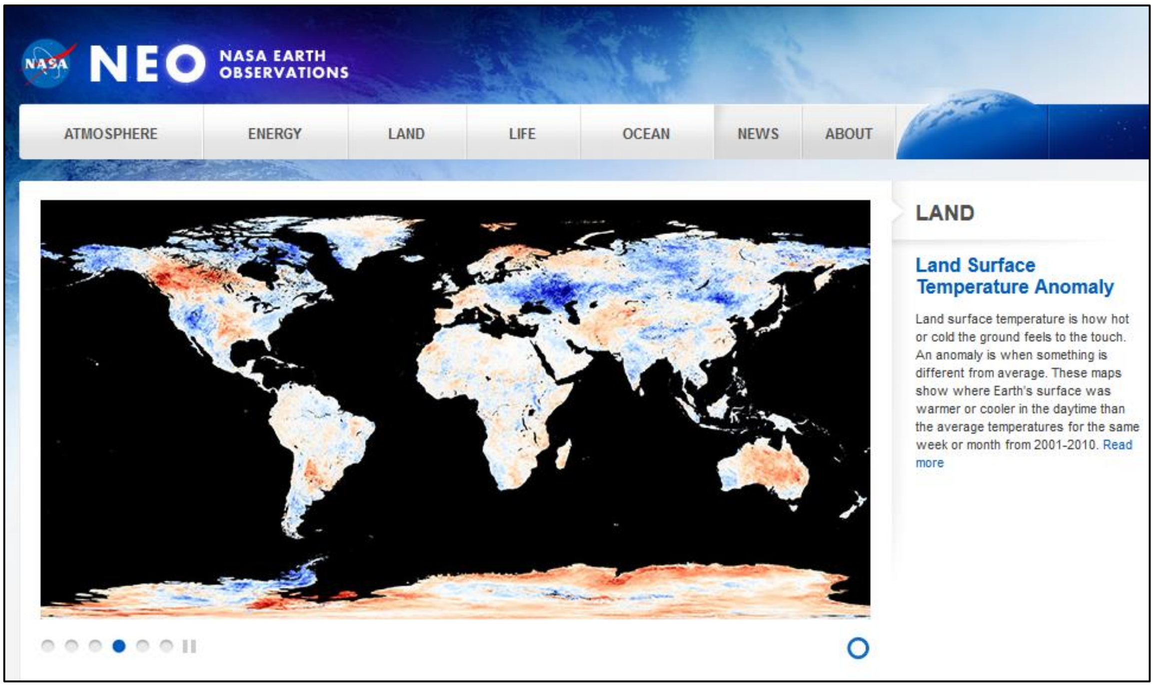


**Figure 15.** Interface of NASA Earth Observations (NEO) (Source: Available at; https://neo.gsfc.nasa.gov/)

## Conclusion and recommendation

By the end of the century, Sri Lanka's temperatures could increase by up to 3°C. The wide and diverse coastal region of the nation, which occupies about a quarter of the island, is projected to suffer severe harm from more frequent storms and a probable 1-meter sea level rise, which will negatively impact Jaffna and Gampaha 18. Sea level rise has accelerated coastal erosion, estuary siltation, saltwater intrusion into rivers, and salinization of the country's coastal plains.

The coastal region of Sri Lanka is divided into 74 administrative regions. A lot of the high priority archeological, historical, religious, cultural, and scenic and recreational sites are located there, along with 23% of the islands' 65 610 km2 of land, 33% of the population, including 65% of the total urban population, 70% of the tourist hotels, and 62% of the industrial units. Therefore, it is crucial to safeguard the country's coastal interests, and coastal vulnerability assessment is essential for coastal conservation. A vulnerability assessment must take into account a number of factors since vulnerability may be linked to natural hazards as a result of climate change. For managing the coasts, a variety of coastal vulnerability assessment techniques, such as inundation maps and computer-aided models, have been created. One of the recognized and most widely used indicators for determining sensitivity to coastal erosion and sea level rise is the coastal vulnerability index (CVI), which was created by Thieler and Hammar-Klose [27]. Authorities in research are using GIS and remote sensing technology to compile, evaluate, and show data on numerous vulnerability characteristics and to calculate CVI [28]. By tying a location's information to its attribute information, the Geographic Information System (GIS) manages spatial data. GIS has the features and resources necessary to effectively collect, store, analyze, and present data about places and things. GIS must be used for data compilation and mapping of the spatial linkages between natural hazard phenomena and the elements in danger. It has been demonstrated that the methods of remote sensing, GIS, and GPS may provide incredibly significant information for scenario analysis and the creation of management action plans. Studies have shown that compared to using conventional methods, satellite remote sensing provides great temporal resolution for tracking land-use change [29].

Numerous authorities in Sri Lanka are involved in coastline protection and conservation. The Ministry of Environment, Environmental Authority, Sri Lanka Ports Authority, Coast Guard Department, Disaster Management Center, and Sri Lanka Navy are among the major government entities in addition to the Coastal Conservation Department, which is the principal agency. In order to coordinate development efforts and safeguard the coastal environment and resources, Sri Lanka implemented a Coastal Zone Management Plan in 1997. The Plan has mostly concentrated on how susceptible the coast is to erosion. For reliable investigations, high-resolution spatiotemporal data is necessary, but access restrictions make it difficult for Sri Lankan researchers to analyze GIS data [30] Even though, empirical studies and scale experiments are highly needed, but as yet largely inexistent [2].

There are a large number of islands in Sri Lanka, and studies about the vulnerability of the coastal areas have been done using GIS data. While some researchers have created their own methods for gathering aerial imaging data of the shore, most studies have used Google Earth data. The Sri Lankan coastline contains various places with elevated CVI values, according to studies. It implies that the coastal conservation department must give these regions its immediate attention. Following the construction of artificial barriers composed of hard stones, some field investigations have shown that the rate of erosion has sharply risen in some locations. Therefore, before beginning any form of mitigation process, a thorough investigation of the coastline's profile utilizing digital mapping technologies and GIS data is a requirement [2] [4] [26].

In order to improve understanding of coastal ecosystems, facilitate informed decision-making, and contribute to the sustainable management and protection of these priceless coastal resources, it is advised that advanced GIS be incorporated into coastal conservation efforts in Sri Lanka. To access and share GIS data, the government should further cooperate with international government organizations, academic centers, and NGOs. The following tips will help you use GIS in coastal conservation initiatives in Sri Lanka efficiently.

- Produce in-depth digital atlases of coastal regions that show shoreline shifts, wetlands, coral reefs, and mangrove forests. For local research, these maps should be readily available.
- Evaluate the condition and health of coastal habitats like mangroves and coral reefs using GIS.
- Using GIS, create and oversee MPAs (marine protected areas). Using information on fisheries, biodiversity, and other ecological aspects, choose appropriate places for MPAs.
- To better understand how these processes impact the shoreline, monitor and predict coastal erosion and sediment movement. Plan and implement erosion control strategies using GIS.
- Involve regional communities in the processes used to gather data and make decisions. The creation of interactive maps and tools using GIS can assist communities in understanding the value of coastal conservation.
- Plan sustainable tourism operations in coastal areas using GIS to ensure less influence on delicate ecosystems and to advance economic potential.
- Create GIS-based disaster management strategies for coastal regions, including tsunami, storm, and other natural disaster early warning systems.
- Give decision-makers GIS-based data to help the creation and application of policies pertaining to coastal management and conservation.
- Provide GIS training to local professionals and conservationists, enabling them to use GIS effectively for continuing monitoring and management.

- Create data-sharing systems to promote stakeholder cooperation and guarantee accountability for conservation activities.
- Put in place a long-term monitoring program that uses GIS to monitor changes in coastal habitats and assess the efficacy of conservation efforts.
- Seek funding for GIS-based coastal conservation projects in the nation from international organizations, grants, and partnerships.

In conclusion, Sri Lanka must examine its coastal vulnerability in order to proactively address the problems caused by climate change, natural catastrophes, and inland human activity. It is anticipated that Sri Lanka will be fortunate to have more investments in incorporating technology into the country's coastal conservation since the country lags behind in the use of GIS and digital mapping technologies for coastal vulnerability assessment.

## Acknowledgement

We would like to acknowledge the contributions of all the authors of the references and all who enriched us with knowledge. Their words, writings, comments were instrumental in shaping this chapter and bringing it to its final form.

## Competing interest

Authors declare that they have no any competing interest.

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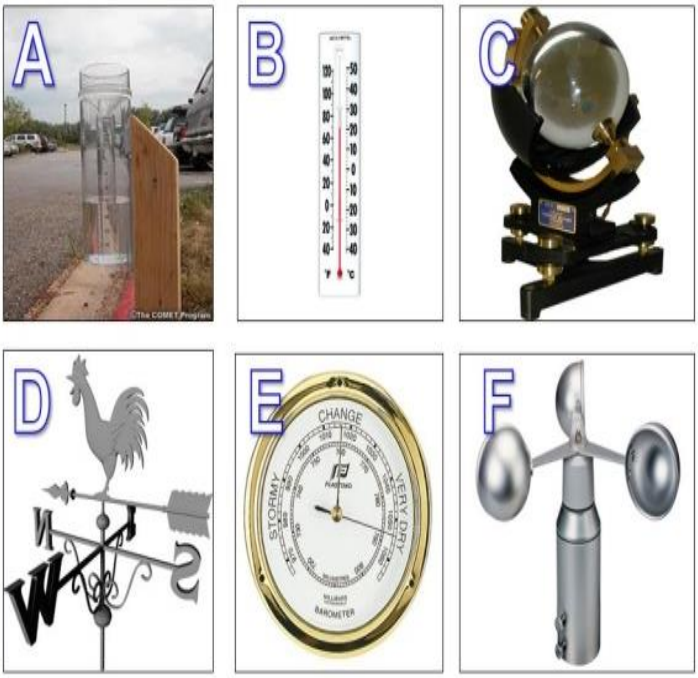
# Metrological Impact on Climate Change Measures in Sri Lanka




# Metrological impact on climate change measures

G.D.T.A. Pathiragoda

**Abstract**
Climate change, Long term shift in weather conditions decide from measurement values of temperature, rainfall, humidity, wind speed, etc. Therefore, to take reliable measurements to compare throughout the world, strengthening quality Infrastructure with digitalization is crucial. Developing and validating new measurement techniques in digital era utilizing mobile devices and artificial intelligence. 'Thingspeak.com' IOT platform used with digital thermometer for data acquisition to IOT to view from remote location, it contributes to increase productivity, sustainability and resilience across the environment sector. Temperature, pressure sensor and anemometer used in climate data collection calibrated according to international standards. Importance of using correction factors in calibration certificates in measurement process highlighted by comparing series of previous calibration reports and confirm with metrological requirement specified in procedures are critically important to improve monitoring climatic data quality and take actions on climate changes.

Considering the importance of metrology infrastructure and use of climatic data for mitigation actions, It is recommend that the policy makers shall focus on following technical and policy suggestions

1) High level metrology infrastructure through establishment of scientific metrology facilities with university academics and international collaboration.
2) Strengthen National Quality Infrastructure (NQI) in digital environment to deliver quality data to take measures for protecting environment to improve existing systems and implement collaborative strategies in global framework.
3) Provide training in measuring equipment metrological characteristics (MEMC) to satisfy their metrological requirement to get internationally competitive measurement results. In addition, It is necessary to establish the regulatory process, which is needed for single, coherent measurement system with traceability to SI units through providing facility to calibrate measuring equipment used in measurement processes by reducing uncertainties and improving accuracy. This pave the way to achieve reliable, globally comparable measurement results in support of evidence based climatic decisions and actions to achieve sustainable development goals.

**Keywords:** Metrology, Calibration, Climate measurements, Uncertainty

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## Introduction

Climate change is long-term shifts in the measures of climate over a long period of time including temperature, Humidity, and wind patterns. Key factors for climate change are changes in the solar activity, change in earth due to its natural activities large volcanic eruptions or man-made activity like burning fossil fuel, industrialization etc. which change the nature of earth. Global warming is the rise in global temperatures mainly due to the increasing concentrations of greenhouse gases in the atmosphere. Global warming caused long lasting changes, which threatens irreversible consequences like more droughts, heat waves and increased intensity of storms. More heat in the atmosphere and warmer ocean surface temperatures can increase evaporation causing powerful storms and lead to increased wind speeds in tropical storms. Long-term effects of climate change will include a decrease in sea ice and an increase in permafrost thawing, an increase in heat waves and heavy precipitation. Emerging technologies like satellite imagery, Digital Elevation Models (DEMs) provide data on the elevation of glacier ice. Rising sea levels expose new locations not usually subjected to the power of the sea and to the erosive forces of waves and currents.

**Figure 1.**Climate effects faced by Sri Lanka [https://climatefactchecks.org/global-climate-change-and-weather-pattern-changes-in-sri-lanka/]

In modern world, every one experiencing the drastic effects of climate change due to various man made activities. Resulted **climate impacts** are harming health, air pollution, disease, extreme weather events, forced relocation, pressures on mental health, and increased hunger and poor nutrition due to insufficient food cultivations. Living and coping with uncertain impacts of climate change is an imperative, not a choice now**. Climate change mitigation** include reduce emissions of heat-trapping greenhouse gases into the atmosphere, reduce burning of fossil fuel, sustainable bio mass energy production, bio diversity conservation and increase disaster risk reduction and management to prevent the planet from warming to more extreme temperatures.

The objective is to focus on Metrology; science of measurement and it's application concerned with application of measurement to environmental processes, their use in society, ensuring the suitability of measurement instruments, their calibration and quality control. Calibration establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding unknown device with associated measurement uncertainties under specified conditions. In the process of calibration of an instrument or material measure, the test item either adjusted or correction factors are determined against reference value of a measurement standard with uncertainties under specified conditions. Metrological Traceability is the value of a measurement standard or measuring instrument can be determined by an unbroken chain of comparisons with a series of higher-level standards with stated uncertainties. Metrological Traceability guarantees international consistency and comparability.

Metrological perspective help to understand the way earth's climate changing extend from earth observation via space based satellites from land based measurement of emissions and the measurement of changes in ocean environments. Confidence in the data gathered from these different systems is anchored in traceability to SI units, the main requirement of the National Quality Infrastructure (NQI). An effective quality and standards ecosystem as the National Quality Infrastructure (NQI)is an essential ingredient for competitiveness, access to new markets, productivity improvement, innovation of new products, environmental protection as well as health and safety of populations, and consumer protection. The measurement management system manages the risk of measuring equipment and measurement processes [1], produce incorrect results affecting the quality of an organization's product providing the assurance and confidence that measurements are accurate, helping to prepare for the challenges of tomorrow. Accredited calibration certificates ensure the reliability of measurement results, and international competitiveness and serve as the metrological basis for the measurement and test equipment quality assurance to support climatologist. It underpins scientific innovation and the protection of the global environment providing confidence in the accuracy and global comparability of measurements needed for protection of the environment, global climate studies and scientific research. It requires the creation and adoption of a full digital representation of the SI, including robust, unambiguous, and machine-actionable digital representations of units of measurement and of measurement results and uncertainties [7].

Climate measurement management system monitor and control interrelated or interacting elements necessary to achieve metrological confirmation and continual control of measurement processes. Metrological confirmation is achieved when the fitness of the measuring equipment for the intended use has been demonstrated and documented. When conducting climatology research, measuring equipment metrological characteristic(MEMC) should satisfy customer metrological requirement(CMR) to get internationally competitive measurement results. This pave the way to achieve reliable, globally comparable measurement results in a climatic observation which is the basis for taking climatic actions according to the theme of the book.

This international metrology system provides the necessary assurance and confidence that measurements are accurate and helping us to prepare for the challenges of tomorrow. Reliable, comparable measurements and observations are critically important to take decisions on climate changes and climate actions. Metrologist support climatologist by reducing uncertainties and improving accuracy of their data. Therefore, reviewed the perspective of metrology to climate change measures in Sri Lanka. Even though it is internationally recognized and founded MeteoMet in 2011 to support climatologists, by European union involving 21 nations, It's not seen any applications in Sri Lanka. Therefore, this chapter focused on unites world of metrology and meteorology realizing the joint role to play in advancing climate change.

## Methodology

Long-term accuracy and reliability of measuring instruments for identifying trends in climatic parameters are important. In Sri Lanka, Number of equipment used in measurements are often not calibrated so it's not traceable to SI units, It does not give idea about errors due to frequency of usage of equipment or wear and tear, etc. The big challenge is the propagation of a metrological measurement perspective to meteorological observations. Across the world NMI's continually advance measurement science by developing and validating new measurement techniques in digital world. Therefore, in Sri Lanka, needed to establish traceability of measuring equipment to understand, monitor and mitigate climate-related risks through comprehensive analysis of climatic parameters reducing uncertainties and improving accuracy.

Common instruments used to measure climatic conditions

Temperature – Thermometer    Rainfall - Rain gauge

Humidity – Hygrometer    Solar radiation – Pyranometer

Wind speed and direction with time - Anemometer and wind vane

Atmospheric pressure - Barometer, Pressure sensor or gauge

Temperature, pressure and wind speed selected as a key observable for this study, and calibrated several temperature sensors/thermometers, pressure sensor, anemometer used for measurement process defining minimum requirements for the calibration procedure and for determination of measurement uncertainty with traceability according to international guidelines. Figure 3 shows how the traceability chain maintains upwards to SI units and uncertainty dissemination downward in different applications.

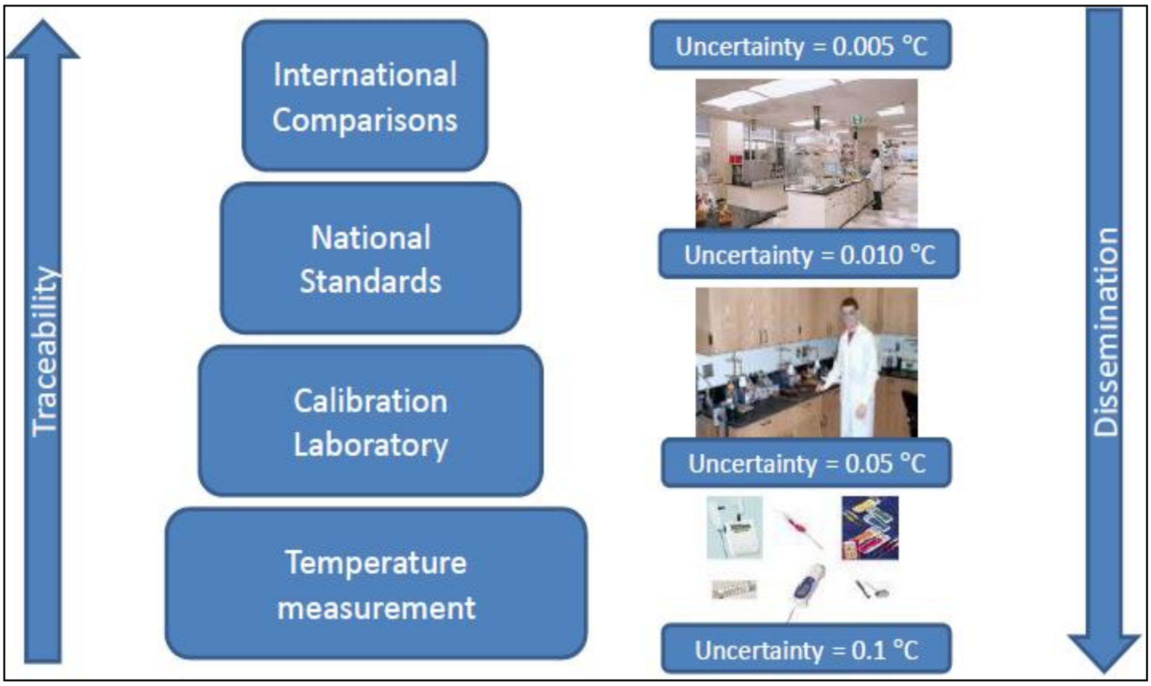


**Figure 3.** Traceability dissemination of temperature measurement in Sri Lanka

Temperature calibration done with direct comparison of reference thermometer and test device inserted to dry well as given in Figure 4.

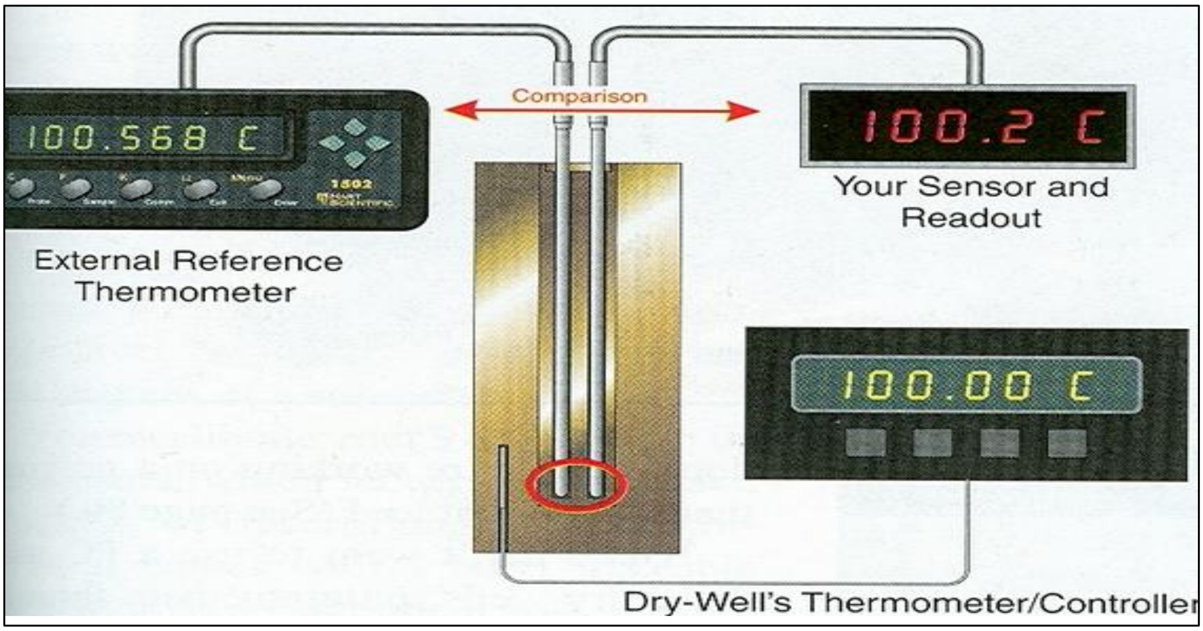


**Figure 4.** Comparison calibration of digital thermometer

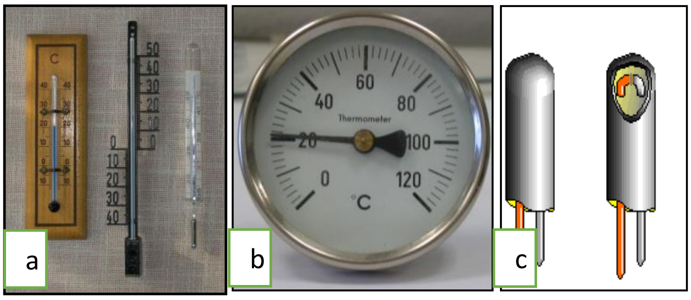


**Figure 5.** Temperature Measuring equipment for different applications **(a)** Liquid in glass Thermometer **(b)** Dial Thermometer **(c)** Thermocouple

Internationally traceable metrology facilities provided through accredited and non-accredited calibration certificates according to ISO 17025:2017 General requirements for the competence of testing and calibration laboratories [3] to the local and foreign customers. Accredited calibration certificate has third party attestation for technical competency and traceability to ISO 17025: 2017 standard. Non-accredited calibration reports given without ILAC MRA logo and accreditation body logo, with traceability to reference standard by direct comparison or with international guidelines. Reference standards used for calibration with uncertainty fulfilling the ISO 17025:2017 standard requirement, ensure the standardized process of operation from receiving customer request to issuing final calibration report.

## Results and Discussion

Calibration correction for temperature indicators/controllers given by the following equation,

$$\mathbf{C = (T_0 - T) + (Z_f - Z_i),} \qquad (1)$$

Where, **$T_0$=** Temperature indicated in the Reference Standard
**T =** Temperature of the test controller/indicator,
**$Z_f$=** Final zero point, **$Z_i$=** Initial zero point

## Measurement uncertainty calculation

The process oriented estimation of the measurement uncertainty associated with the measured data and the influences on the measuring process used according to international standards "Guide to the expression of uncertainty in measurement [4]. Contributions from the complete measurement process in an environment separated into contributions from the measurement system.

Type A evaluation (statistical) through uncertainty component $U_7$,

Type B evaluation (calibration certificates, Instrument specifications, manuals) through uncertainty components from $U_1$to$U_6$

$U_1$ - Reference thermometer Calibration uncertainty. Calibration certificate and divide it by the appropriate factor (if k=2 is given, then divide by 2).
$U_2$ - Resolution of the Reference thermometer display value divided by 2 $\sqrt{3}$
$U_3$- Accuracy of the reference thermometer (selected from values given in simulator 741B as the reference) divided by $\sqrt{3}$
$U_4$-Probe calibration uncertainty as given in the calibration certificate divided by the factor (if k=2 is given, then divide by 2).
$U_5$ - Drift of the thermocouple divided by $\sqrt{3}$
$U_6$ - Resolution of the test temperature controller. Consider it as a rectangular distribution
$U_7$ - Scatter of results(type A): Take the highest standard deviation of the mean divided by $\sqrt{n}$

Combined uncertainty $U_C = \sqrt{\sum_{i=1}^{7} U_i^2}$ -------------------------------------- 2

Selection of Coverage factor k on the basis of desired level of confidence to be associated with the interval defined by U = k *$U_c$.

Expanded uncertainty, $U_{95}$ = 2*$U_c$, for Coverage factor k = 2 -------------- 3

Coverage factor selected from the confidence level required for application from student's t distribution. For 95% confidence interval, k=1.96 and for 99% confidence interval, k=2.58. In metrology, we use k=2 then actually we estimate uncertainty to 95.45% confidence. The focus was on ensuring reliability and trust in results by consistently incorporating measurement uncertainties and data quality. Calculated correction factors and uncertainty of calibrated equipment given in Table 1, Table 2, Table 3.

**Table 1.** Calibration results of temperature indicator

| Nominal value (°C) | Reference value (°C) | Test value (°C) | Correction (°C) | Uncertainty, k=2 (°C) |
|---|---|---|---|---|
| -30 | -30.01 | -30 | 0 | 0.1 |
| -15 | -15.02 | -15 | 0 | 0.1 |
| 0 | 0.02 | 0 | 0 | 0.1 |
| 15 | 15.01 | 15.1 | -1 | 0.1 |
| 30 | 30.02 | 30.1 | -1 | 0.1 |
| 45 | 45.07 | 45.1 | 0 | 0.1 |

**Table 2.** Calibration results of barometer

| Reference value (mbar) | Test value (mbar) | Correction (mbar) | Uncertainty, k=2 (mbar) |
|---|---|---|---|
| 900.0 | 901 | -1 | 0.1 |
| 1000.0 | 1000 | 0 | 0.1 |
| 1100.0 | 1100 | 0 | 0.1 |
| 1200.0 | 1201 | -1 | 0.1 |
| 1400.0 | 1401 | -1 | 0.1 |

**Table 3.** Calibration results of anemometer

| Reference value ($ms^{-1}$) | Test value ($ms^{-1}$) | Correction ($ms^{-1}$) | Uncertainty, k=2 ($ms^{-1}$) |
|---|---|---|---|
| 0.10 | 0.1 | 0 | 0.1 |
| 0.50 | 0.5 | 0 | 0.1 |
| 1.00 | 1.0 | 0 | 0.1 |
| 5.00 | 5.0 | 0 | 0.1 |
| 10.00 | 10.1 | 0.1 | 0.1 |
| 20.00 | 20.1 | 0.1 | 0.1 |
| 30.00 | 30.1 | 0.1 | 0.1 |

Calibration measurement capability or the realizable best measurement uncertainty get from those expanded uncertainty values. The reported expanded uncertainty of measurement is based as the standard uncertainty of measurement multiplied by a coverage factor k=2, corresponding to a coverage probability of approximately 95%. The standard uncertainty of measurement has been determined in accordance with Guide to the expression of uncertainty in measurement (GUM-JCGM 100: 2008).

## Climate change trend in Sri Lanka during past few years

Sri Lanka's 100-year warming trend from 1896 to 1996 is 0.003 °C per year indicating a faster warming trend in more recent years. Over the period 1961-1990, there was a general increasing temperature trend by 0.16˚C per decade, with the highest increase of minimum temperature around 2.0˚C at Nuwara Eliya[9]. Historical records from 1974- 2004 indicate that droughts are increasing. In the country as a whole, the number of consecutive dry days increased while the number of consecutive wet days reduced. Recent analysis of the spatial pattern of rainfall also indicates an expansion of the dry zone. The current rate of sea level rise in coastal areas of Asia is reported to be 1-3 mm/year which is marginally higher than the global average. However, the specific rate of rise in seas surrounding Sri Lanka is not known [9]. Temperature variation plot in different countries given in figure 6. It shows the importance of applying correction factors to measurement results since those variations are small like 2°C or 3°C over fifty years in many countries around the world.

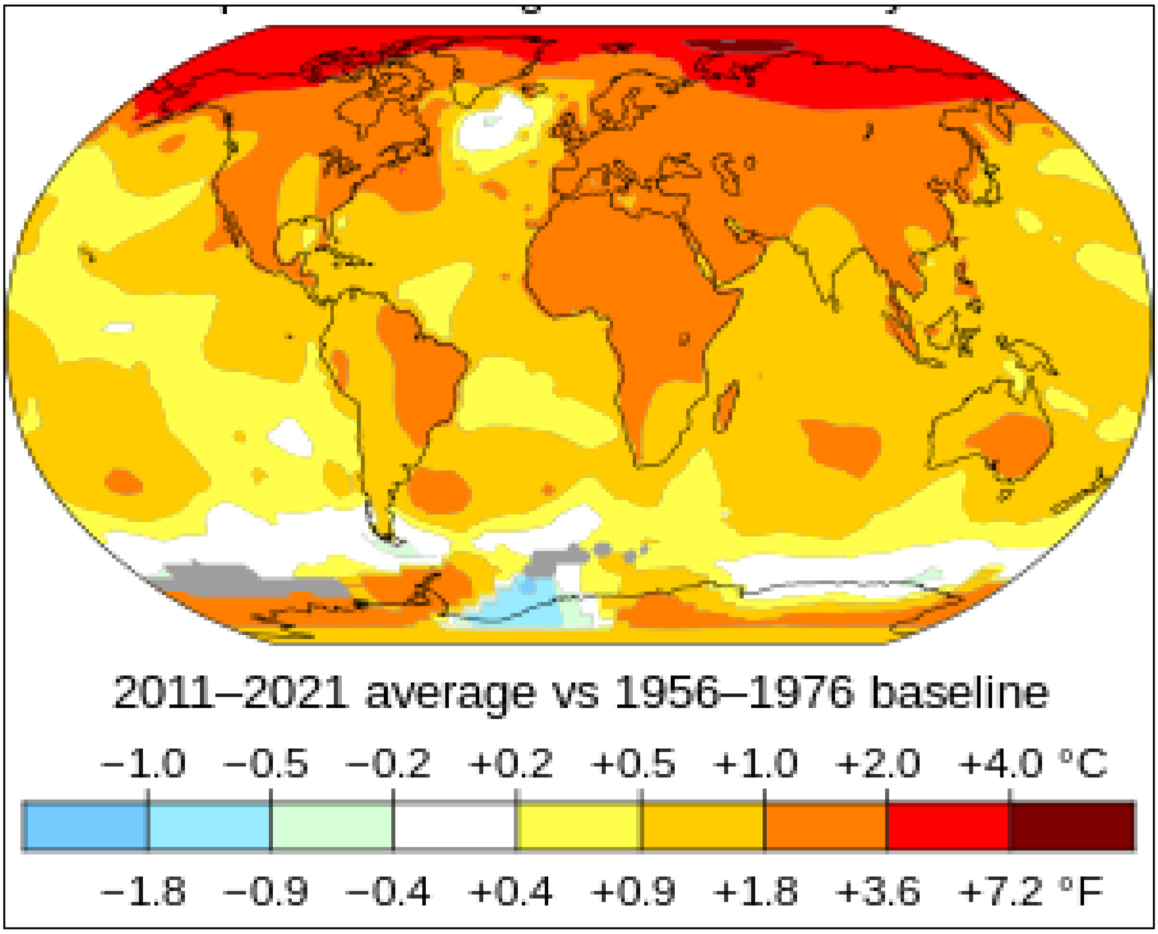


**Figure 6.** Temperature change in last 50 years [8]

Difficulties faced due to calibration devices need to be taken to calibration laboratory or onsite calibration arranged which will not be feasible in next decade with industry 4.0 environment. So developing remote calibration applications are crucial using remote interfaces and data communication methods. Recalibration of instruments need standard guidelines, using RS232 remote interface, wireless sensor networks and software application separately purchased from manufacture or calibration provider. Internet of things (IOT) platform or additional software can be developed using remote panels in Lab view. 'Thingspeak.com' IOT platform used with digital thermometer for data acquisition to IOT to view from remote location. Remote calibration model for direct comparison is universal can be implemented successfully since transducers are developing for conversion of physical quantities and electrical signal and vice versa in wireless sensor networks. More over developing digital reference system for digital SI units is to be done. Digital development is a decision not a choice for a comprehensive and sustainable development for generations.

## Conclusion and future prospects

The metrological impact on climate data helps to study long term climate data which lead to climate modeling which is required for predictions important in agriculture, industry, constructions and transport sectors etc and It is also needed to collaborate globally as the climate change is a global activity with local impacts with future concerns. Metrological confirmation of measuring equipment achieved through calibration and use of correction factors to meet requirements for measurement processes and measuring equipment metrological characteristic (MEMC) satisfy customer metrological requirement (CMR) for the measuring process satisfying tolerances required for scientific research otherwise they have to take corrective actions to facilitate the meteorologists and climatologists to rely on measurement data. If there is deviation customer should correct/ replace their equipment to ensure the quality of their climate data to compete in internationally and achieve sustainable development goals. Many scientists not heard of metrology and Labs having trouble reproducing their measurements. Therefore, metrology should be included into scientific and technical training at all levels to foster the dedication to precision measurement throughout science. It is challenging and cannot be tackled by the metrology community alone.

Metrology play a key role in developing research on measurement systems, early warning systems, assuring their accuracy and reliability with long term use, establish traceability and proper measurement techniques in subject of climate change. Monitoring of parameters with reliability, long term accuracy and acquisition capabilities require sophisticated equipment, data storage and analyzing facilities. Also, additional to local measurements, it requires remote sensing including monitoring climatic data using satellites application of GIS etc. Climate change is a global activity and it require global climatic data to model the local climatic change. Different measurement set ups and strategies add challenges to ensuring the traceability of the measuring process. New concepts and innovative technologies integrate to the measurement processes since some equipment usually too large to fit into conventional measuring devices or to be transported to a calibration laboratory, which have to be measured in process or in situ. It's very important to come together and discussthe quality infrastructure in digital environment. Finally, for implementation of digital transformation and traceability the backbone in metrology, in industrial internet of things(IIOT) and sensor networks. This needs an international effort and coordination to achieve sustainable development goals. The metrology community steps up to the challenge of quantifying uncertainty in complex problems, in particular by engaging more statisticians, data experts and researchers from problematic areas.

Finally, the policy makers shall focus on following recommendation

1) Establishment of high level metrology infrastructure through scientific metrology facilities *with the help of university academics in physics and engineering international collaboration*.

2) Support of the Government to strengthen National Quality Infrastructure (NQI) with digitalization to Metrology, Standards, conformity assessment and accreditation to deliver quality data in technical and research services to take measures for protecting environment, to improving existing systems and use of international framework for climatic data.

3) Provide training for climatologist in measuring equipment metrological characteristic (MEMC) to satisfy their metrological requirement to get internationally competitive measurement results.

In addition, It is necessary to establish the regulatory process, which is needed for single, coherent measurement system with traceability to SI units through providing facility to calibrate measuring equipment used in measurement processes by reducing uncertainties and improving accuracy.

This pave the way to achieve reliable, globally comparable measurement results in support of evidence based climatic decisions and actions to achieve sustainable development goals.

## Acknowledgments

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## Conflict of interest

There is no conflict of interest.

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# Advancing Public Safety Management in Sri Lanka Through Computer Vision Enhancement

# Advancing Public Safety Management in Sri Lanka through Computer Vision Enhancement

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## Abstract

This study investigates the transformative potential of computer vision technology in advancing public safety management on a global scale, with a specific emphasis on Sri Lanka. Computer vision, a subdivision of artificial intelligence, empowers machines to interpret and analyze visual data, imitating human visual capabilities. Incorporating computer vision technology into initiatives for public safety exhibits promise in revolutionizing surveillance, traffic management, disaster response, and security of critical infrastructure. Through a comprehensive examination of case studies from cities such as Singapore, Barcelona, and New York City, this chapter highlights the successful integration of computer vision, resulting in decreased crime rates, improved traffic flow, and heightened safety. Anticipated future trends underscore elevated automation, integration with the Internet of Things (IoT) and big data, as well as solutions that uphold privacy. Recommendations entail establishing clear regulations, infrastructure investment, collaborations between the public and private sectors, research promotion, and community engagement, which are all important considerations. By responsibly adopting computer vision technology, cities have the potential to establish urban environments that are both safer and more efficient. As a result, this can contribute to the economy's growth and enhance residents' quality of life.

**Keywords:** Computer vision, Deep learning, Smart city initiatives, IoT (Internet of Things), Object detection

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## Introduction

Public safety represents a matter of utmost importance for any given society, as it aims to protect its citizens and ensure the overall well-being and order within communities. In the present-day world, the advent of technological advancements has emerged as a transformative tool for enhancing public safety measures. In the case of Sri Lanka, a nation renowned for its cultural heritage and rapidly growing urban areas, ensuring public safety poses an evolving challenge that calls for innovative solutions [1-2]. The subsequent section of this study delves into the incorporation of computer vision, which falls under the realm of artificial intelligence, as a powerful tool to drive the management of public safety in Sri Lanka towards a new era. By utilizing machine learning algorithms and image processing, computer vision enables the automated analysis and interpretation of visual data, thereby opening an opportunity to revolutionize conventional safety approaches. By harnessing the potential of computer vision technology, Sri Lanka can fortify its public safety initiatives, optimize the allocation of resources, and respond to emergencies with enhanced precision [3].

### Background on public safety in Sri Lanka

Sri Lanka, a nation on an island in the Indian Ocean, is distinguished by its rich culture, stunning natural scenery, and resilient population. Like numerous countries, Sri Lanka confronts many public safety obstacles encompassing traffic control, crime deterrence, disaster reaction, and security for public gatherings. These obstacles demand inventive and effective resolutions capable of adjusting to the changing requirements of a dynamic society [4].

### Importance of public safety

The foundation of societal welfare is deeply rooted in the preservation of public safety, which profoundly influences the day-to-day existence of individuals, communities, and the entirety of the nation. A secure atmosphere not only guarantees the flourishing of citizens but also nurtures the expansion of the economy, the advancement of education, and the establishment of social concord. Being dedicated to progress and prosperity Sri Lanka duly acknowledges the pivotal significance of augmented public safety measures in shaping a more promising future [2].

#### *Role of technology in public safety*

Advancements in technology, especially in artificial intelligence and computer vision, offer unprecedented opportunities to bolster public safety efforts. The potential applications of computer vision extend beyond just regulating traffic, encompassing diverse areas such as facial recognition systems at airports, license plate recognition in car parks, and even facial mask detection systems for COVID-19 prevention. Implementing these capabilities effectively in Sri Lanka's public safety framework can confront challenges and create a more secure environment for its citizens.

#### *Understanding computer vision for advancing public safety management*

In the contemporary age of expeditious technological progress, computer vision has surfaced as a pivotal instrument in diverse public safety management spheres. This section aims to clarify the rudimentary principles of computer vision and how this innovation harbours the capacity to augment the measures undertaken to ensure public safety in Sri Lanka. Beyond the basics, this innovative technology encompasses an array of ground-breaking applications crucial for safeguarding communities. Facial recognition systems aid law enforcement in locating missing persons and identifying suspects while managing crowd movements in crowded areas or events.

License plate recognition enhances traffic management and assists in identifying vehicles linked to criminal activities. Moreover, with the emergence of health concerns like COVID-19, mask detection systems become integral in enforcing safety protocols in public spaces. Beyond these established applications, specific regional safety measures, such as elephant detection systems proposed in Sri Lanka to avert human-elephant conflicts and global initiatives like shark identification systems for public warning, stand as remarkable instances of innovative uses of computer vision for public safety. These systems showcase the technology's adaptability, ranging from wildlife safety concerns to beach safety, emphasizing its pivotal role in addressing diverse safety challenges. As the technological landscape evolves, these applications underline the immense potential of computer vision in revolutionizing public safety measures worldwide.

## Definition and principles of computer vision

Computer vision is a discipline within artificial intelligence that grants machines the capacity to interpret, scrutinize, and comprehend visual data from the external world. It aims to replicate the human visual system, thereby facilitating computers in perceiving and comprehending their surrounding environment through images, videos, or other forms of visual data. The underlying principles of computer vision comprise the domains of image manipulation, object detection, identification of patterns, machine learning, and deep learning algorithms. In its essence, computer vision bestows upon machines the faculty of extracting meaningful information from visual inputs, consequently enabling a broad spectrum of applications such as identifying objects, recognizing facial features, tracking activities, and comprehending scenes.

### Applications of computer vision in public safety

#### *Digital surveillance*

Computer vision technology possesses the capability to greatly enhance surveillance systems through the automatic identification of unconventional activities or potential risks. This proactive methodology has the potential to bolster public safety by facilitating the continuous monitoring of public areas and a swift response to emerging circumstances [5]. Digital surveillance has expanded far beyond its traditional role, now encompassing a diverse range of unconventional activities. It involves detecting unusual behaviour in emergencies, managing crowds at events or in public spaces, and swiftly aiding the elderly in case of falls. Additionally, it tracks environmental aspects like air quality and fires while also delving into retail analytics to decode shopper behaviour and enhance retail experiences. It optimizes traffic flow, ensures workplace safety protocols are adhered to, and plays a vital role in wildlife conservation by monitoring animal movements and preventing poaching. Furthermore, these systems can interpret gestures and emotions in various contexts and are equipped to safeguard sensitive information and identities through advanced privacy protection measures. Digital surveillance has evolved into a multifaceted tool, contributing significantly to safety, efficiency, and decision-making across a wide spectrum of applications [6-7].

#### *Anomaly detection*

Through the utilization of sophisticated algorithms, computer vision possesses the ability to detect irregularities in communal environments, such as unattended bags or dubious conduct, thereby initiating prompt notifications to law enforcement. This capacity serves to fortify security measures and assists in thwarting potential risks [8-9].

***Traffic management and analysis***
Efficient traffic management plays a vital role in ensuring the general public's safety. The utilization of computer vision technology has the potential to contribute significantly towards the analysis of traffic flow, identification of congestion, and prevention of accidents. Moreover, it enables the enhancement of traffic signal optimization and the anticipation of traffic patterns, ultimately leading to a reduction in traffic-related incidents [10-11].

***Disaster response and relief***
In the realm of disaster response, computer vision stands as a valuable asset aiding response teams. Its analysis capabilities extend to assessing the extent of devastation, identifying critical areas needing urgent aid, and facilitating search and rescue missions. Practical examples, such as fire, tsunami, and flood detection systems, demonstrate the breadth of its application. These systems might rely solely on visual data or integrate information from other sensor types to offer comprehensive disaster warnings and management strategies. Integrating computer vision into Sri Lanka's public safety strategies can foster a data-centric approach, ensuring a more secure environment for its citizens [12].

## Current Public Safety Management Initiatives in Sri Lanka
In this section, we shall delve into the prevailing endeavours undertaken by the Sri Lankan government regarding public safety management. Our objective is to shed illumination on the various approaches, technologies, and initiatives that have been put in motion to safeguard the well-being and protection of the nation's populace [2], [13].

### Overview of Sri Lanka's public safety management
Sri Lanka has made noteworthy advancements in augmenting public safety administration throughout the years, propelled by a dedication to protecting its populace and upholding legal regulations. The nation implements a diversified methodology encompassing diverse tactics, including law enforcement, disaster readiness, public health initiatives, traffic control, and community involvement.

***Law enforcement and crime Prevention***
The maintenance of public safety is the responsibility of the Sri Lanka Police, which is assisted by a range of specialized units. The police force fulfils this duty through various initiatives such as community policing, programs designed to prevent crime, and endeavours to combat drug trafficking and organized crime. The implementation of community engagement programs serves the purpose of fostering trust between the police force and the community, thereby contributing to the creation of safer neighbourhoods.

***Disaster preparedness and response***
Given Sri Lanka's susceptibility to natural calamities, the essence of public safety lies in the preparedness and reaction to such disasters. The Disaster Management Centre (DMC) spearheads these endeavours, with a particular emphasis on implementing timely cautionary measures, diminishing the risks associated with catastrophes, and effectively organizing relief operations during critical situations like deluges, mudslides, and tsunamis.

***Traffic management and road safety***

Addressing the issue of road safety represents a pivotal facet of public safety. In the context of Sri Lanka, various strategies, including traffic regulations, awareness campaigns, and law enforcement, are implemented to handle traffic and diminish the occurrence of road accidents effectively. The Sri Lanka Traffic Police assumes an active role in the enforcement of traffic laws and regulations, thereby guaranteeing enhanced safety on the roads.

## Challenges and limitations

In the pursuit of advancing public safety in Sri Lanka, technological integration poses a significant challenge. Varying levels of technological infrastructure across regions, compatibility issues between different systems, and the considerable cost of implementing and maintaining sophisticated technologies present hurdles. Additionally, concerns about data privacy, skill gaps in technology handling, and the establishment of robust regulatory frameworks add complexity to the integration process. Overcoming these challenges demands substantial efforts in infrastructure development, resource allocation, skill enhancement, and regulatory formulation to ensure the seamless integration of advanced technologies for bolstering public safety across the country. Implementing comprehensive public safety initiatives nationwide encounters difficulties due to inadequate infrastructure and limited resources. Compared to urban hubs, rural regions frequently encounter resource discrepancies, which consequently affect the extent and effectiveness of safety programs.

***Technological integration***

The incorporation of sophisticated technologies such as artificial intelligence, data analysis, and computerized visual perception in the domain of public safety administration is presently in its nascent phase. The adoption of these technologies has the potential to substantially augment the efficacy and productivity of preventive measures [8].

**Public awareness and education**

Raising awareness among the public regarding safety measures and stimulating active involvement in safety initiatives continues to present a formidable obstacle. Educational endeavours and outreach campaigns guarantee that individuals are well-informed and actively involved in advancing a more secure society. In the following sections, we will explore how the integration of computer vision technology can address some of these challenges and contribute to the advancement of public safety management in Sri Lanka.

## Integration of computer vision for enhanced public safety in Sri Lanka

In the present section, we shall discuss the plausible amalgamation of computer vision technology to augment the management of public safety in Sri Lanka. We shall examine applications and the advantages of incorporating computer vision into safety protocols.

### Potential applications of computer vision in Sri Lanka

The utilization of computer vision technology holds the potential to propel the progress of public safety management in Sri Lanka through multiple avenues. Implementing it can yield significant benefits by tackling individual challenges and augmenting the overall security measures.

***Digital surveillance systems***

The integration of intelligent surveillance systems equipped with computer vision technology has the potential to augment the supervision of public spaces. These systems can promptly detect and notify authorities of any unusual activities or objects in real-time. This forward-thinking strategy can fortify public security by facilitating rapid responses to potential dangers [13-16].

***Traffic monitoring and control***

Computer vision algorithms can be utilized to monitor real-time traffic, manage traffic congestion, detect traffic violations, and optimize traffic flow. These measures have the potential to decrease the occurrence of road accidents and improve the overall level of road safety nationwide [17].

***Disaster response and management***

Integrating computer vision into the context of disaster response can be advantageous in the evaluation of harm, distribution of resources, and execution of search-and-rescue operations in times of emergency. The automated scrutiny of areas affected by disasters, accomplished through aerial images, can expedite and enhance the efficiency of endeavours to alleviate the consequences of such calamities [12].

***Security of critical infrastructure***

The application of computer vision in the surveillance of important infrastructure, such as airports, ports, and power stations, can bolster security measures by effectively detecting potential security breaches or unauthorized activities. This proactive security strategy plays a pivotal role in protecting critical facilities.

## Benefits of integrating computer vision

***Real-time monitoring and response***

The field of computer vision permits the continuous monitoring of diverse scenarios, offering prompt notifications and expediting timely reactions to occurrences. This amplifies the effectiveness of governmental security endeavours and reduces the duration of response.

***Data-driven decision making***

Analyzing data obtained via computer vision technology yields valuable insights that can inform decision-making driven by data. Authorities can use this data to formulate proactive strategies, efficiently allocate resources, and optimize safety measures [18].

***Enhanced efficiency and accuracy***

The implementation of computer vision in the automation of surveillance and monitoring processes leads to an improvement in productivity and precision, ultimately alleviating the workload on human resources. Consequently, this enables personnel to dedicate their attention to crucial responsibilities while technology adeptly manages mundane monitoring tasks [19].

***Improved public safety outcomes***

By preventing potential threats, enhancing traffic management, and enabling faster disaster response, the integration of computer vision ultimately leads to improved public safety outcomes and a safer environment for all citizens. The incorporation of computer vision into the management of public safety in Sri Lanka signifies a progressive and forward-looking strategy to tackle current obstacles and actively improve safety measures. By embracing this technological advancement and harnessing its prospective applications, Sri Lanka can progress towards a future that is safer and more secure for its population [20].

## Case studies and success stories

In this section, we shall provide a compilation of case studies and success stories from various parts of the globe. The main objective is to illustrate how the incorporation of computer vision technology has significantly improved the management of public safety. These instances serve as highly valuable perspectives that shed light on the potential influence and efficacy of utilizing computer vision in the context of public safety.

***Case Study 1: Implementation of computer vision for public safety in Singapore city, Singapore***

Singapore, a forward-thinking metropolitan hub, effectively deployed computer vision technology to enhance public safety. The city seamlessly incorporated computer vision into its surveillance systems, facilitating automated surveillance of heavily frequented zones and communal areas. Computer vision algorithms promptly identified dubious activities, atypical crowd conduct, and potential security jeopardy [21].

**<u>Key outcomes</u>:**

*<u>Crime prevention</u>:* Implementing proactive monitoring resulted in a discernible decrease in illicit behaviour, thereby augmenting the overall perception of security within the local populace and tourists.

*<u>Faster response times</u>***:** Authorities could respond swiftly to incidents, minimizing potential damage and ensuring the public's safety.

*<u>Efficient resource allocation</u>***:** The data generated by computer vision helped authorities to adopt modern technological resources effectively, optimizing policing efforts and improving overall operational efficiency.

***Case Study 2: Experience with computer vision in disaster management in Barcelona, Spain***

Spain, a country susceptible to natural calamities, incorporated computer vision into its disaster management strategies. Aerial drones, able to perceive visual information, were dispatched to evaluate areas affected by disasters, detect impaired infrastructure, and pinpoint individuals who have survived amidst emergency situations [22].

**<u>Key outcomes</u>:**

*<u>Rapid damage assessment</u>***:** Computer vision enabled a swift and accurate assessment of the extent of damage, allowing for immediate prioritization of relief efforts.

*<u>Enhanced search and rescue</u>***:** By automating the search process, authorities could locate and rescue survivors more efficiently, saving crucial time and lives.

*<u>Data-driven disaster response</u>***:** The data collected through computer vision analysis informed disaster response strategies, ensuring a well-coordinated and effective relief operation.

These case studies exemplify the capacity for incorporating computer vision into public safety administration, showcasing substantial advancements in the deterrence of criminal activities, prompt handling of calamities, and the overall enhancement of safety conditions. Sri Lanka can acquire invaluable insights from these achievements as it contemplates integrating computer vision technology to ensure public safety.

Recently, metropolises worldwide have taken the lead in utilizing advanced technologies to enhance urban living and streamline different aspects of city administration. One of the pivotal technologies that has gained prominence in this endeavour is computer vision. [23].

## Applying computer vision to cities

Many prominent cities have adopted computer vision as an essential tool in their smart city initiatives. Singapore, Barcelona, London, New York City, Dubai, and Tokyo are among these cities, each utilizing computer vision in unique and innovative ways to tackle their distinct challenges. In this discourse, we delve into how these cities have effectively integrated computer vision technology to enhance urban life, ranging from traffic and waste management to security and public safety [24]–[26].

In the quickly advancing realm of urban development, cities are increasingly adopting state-of-the-art technologies to enhance efficiency, safety, and sustainability. Among these advancements, computer vision technology stands out as a notable innovation, empowering cities to utilize visual data for well-informed decision-making. Table 1 demonstrates how prominent cities like Singapore, Barcelona, London, New York City, Dubai, and Tokyo are implementing computer vision technology across a wide range of domains to revolutionize urban living. From optimizing the flow of traffic to fortifying public safety, these cities serve as exemplary instances of how the utilization of computer vision has the potential to redefine the future of intelligent urban environments [27].

**Table 5.** City innovations: Transforming urban living with computer vision technology

| **Country and City Name** | **Usage of Computer Vision** | **Key Outcomes** | **How This Technology Impacts the Development of that Country** |
|---|---|---|---|
| Singapore, Singapore | Urban planning, traffic management, public safety | Crime reduction, Traffic optimization, and Enhanced public safety through surveillance. | The use of computer vision technology in Singapore is pivotal for its vision of a Smart Nation. It contributes to efficient urban planning, better traffic management, and safer public spaces. By reducing crime rates and optimizing traffic flow, Singapore can sustain its reputation as a global business hub and an attractive place to live, work, and visit [28]. |
| Spain, Barcelona | Traffic management, waste management, public safety | Reduced traffic congestion, Efficient waste collection, Enhanced safety and security. | Barcelona's integration of computer vision in urban management leads to reduced traffic congestion and optimized waste management. This enhances safety and security for its residents and visitors, promoting sustainable urban development and making Barcelona an attractive city for both residents and tourists [29]. |

| | | | |
|---|---|---|---|
| United Kingdom, London | Surveillance, public safety, traffic management | Improved public safety, Enhanced traffic flow and safety, and Crime prevention through monitoring. | London's implementation of computer vision technology in surveillance and traffic management enhances public safety. It aids in crime prevention and allows for quicker responses to incidents, contributing to an overall safer environment. This, in turn, promotes economic development and fosters a sense of security among the city's residents and visitors [30]. |
| USA, New York City | Public safety, surveillance, traffic optimization | Enhanced public safety, Real-time incident response, and Improved traffic management. | New York City's use of computer vision in public safety and traffic optimization significantly enhances safety levels. Rapid incident response and efficient traffic management positively impact the city's development by attracting businesses and investments. The technology contributes to the city's reputation as a global economic hub and a technologically advanced metropolis [31]. |
| United Arab Emirates, Dubai | Traffic control, public safety, urban development | Reduced traffic accidents, Enhanced public safety, and Smart urban development. | Dubai's integration of computer vision technology in traffic control and public safety reduces traffic accidents and enhances safety. It also contributes to smart urban development, positioning Dubai as a technologically advanced and safe city. This technology plays a crucial role in attracting businesses, tourists, and talent, boosting the city's economy and overall development [32]. |
| Japan, Tokyo | Transportation, crowd management, security | Efficient transportation systems, Enhanced security during events, Traffic optimization. | Tokyo's use of computer vision in transportation and security leads to efficient transportation systems and enhanced security during crowded events. The optimized traffic flow positively impacts the city's development by making it more accessible and attractive to both residents and visitors. This technology plays a crucial role in enhancing urban mobility and ensuring a safe environment, contributing to |

| | | | |
|---|---|---|---|
| | | | Tokyo's continued growth and development [33]. |
| China, Beijing | Traffic monitoring, public safety, surveillance | Improved traffic management, Enhanced public safety, and Efficient surveillance. | Beijing's integration of computer vision technology in traffic monitoring and public safety contributes to improved traffic management and enhanced public safety. The efficient surveillance provided by this technology supports law enforcement efforts, making the city safer for its residents and visitors. By improving traffic flow and ensuring safety, Beijing fosters a conducive environment for economic growth and development [31]. |
| France, Paris | Traffic management, public safety | Traffic flow optimization and enhanced public safety. | Paris' use of computer vision in traffic management and public safety optimizes traffic flow and enhances public safety. This technology enables smoother traffic operations and a safer urban environment, contributing to the city's appeal for both residents and tourists. It positively impacts the city's development by creating a more efficient and safer urban landscape, supporting economic activities and improving the quality of life for its inhabitants. |
| South Korea, Seoul | Smart traffic systems, surveillance, urban planning | Efficient traffic management, Enhanced security, and Improved urban planning. | Seoul's incorporation of computer vision technology in smart traffic systems and urban planning leads to efficient traffic management and enhanced security. This technology plays a significant role in supporting Seoul's development by creating a safer and more organized urban environment. It contributes to the city's economic growth and sustainability, making Seoul an attractive destination for residents and businesses alike. |
| San Francisco, USA | Autonomous vehicles, surveillance, public safety | Advancements in autonomous vehicles, Enhanced public safety, | San Francisco's integration of computer vision in autonomous vehicles and public safety enhances transportation through |

| | | | |
|---|---|---|---|
| | | and Real-time incident monitoring. | advancements in autonomous technology. Additionally, real-time incident monitoring contributes to improved public safety. These developments position San Francisco as a hub for technological innovation, attracting talent and investments and furthering the city's reputation as a leader in cutting-edge technology, positively impacting the city's economic growth and development [31]. |

The featured table offers a glimpse into how major cities worldwide are harnessing the potential of computer vision to instigate transformative alterations in their urban environments. These pioneering methods highlight the significance of utilizing technology to establish more astute, secure, and sustainable cities for the future. Figure 1 presents a timeline illustrating the evolution of computer vision technology and its influence on public safety. As adoption rates have risen steadily, so too has the observed impact on public safety. The progression showcased here emphasizes the vital contributions of computer vision towards creating safer and more secure urban environments.

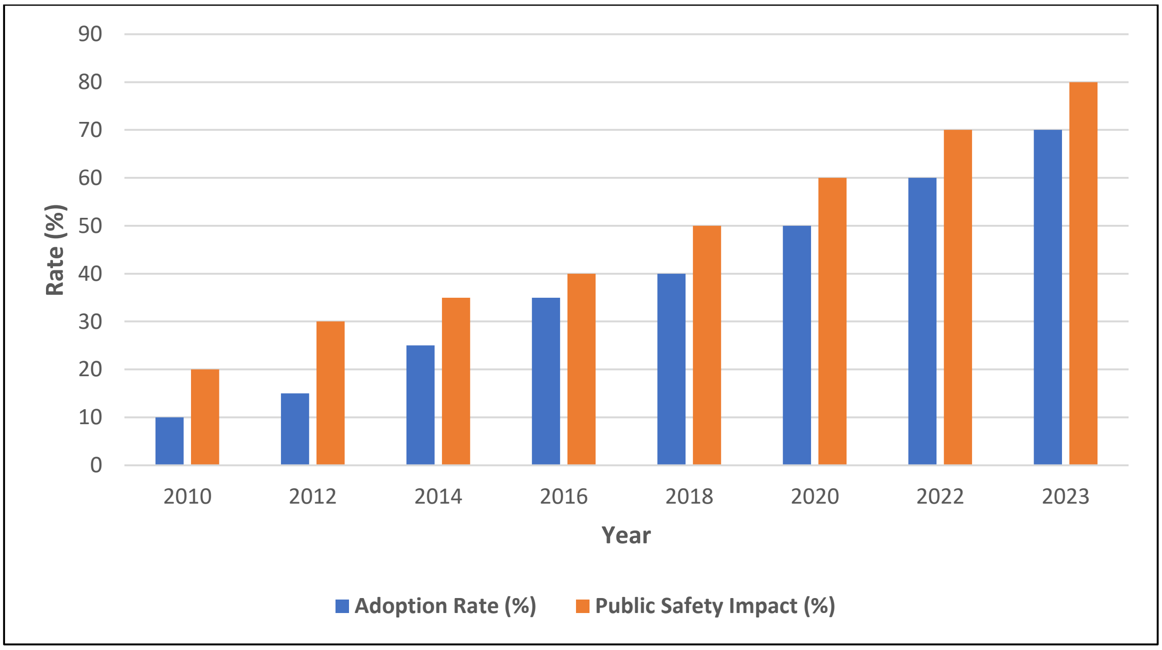


**Figure 1.** Evolution of Computer Vision Technology Impact on Public Safety (Source: Abdel-Aty *et al.,* 2023)

## Prospects and recommendations

In this section, we shall present the forthcoming possibilities of incorporating computer vision technology to propel public safety management in Sri Lanka. Furthermore, we shall furnish recommendations to policymakers and stakeholders to guarantee a triumphant and efficient execution of this technology, yielding advantageous outcomes for society.

## Future trends in computer vision and public safety

***Enhanced automation and intelligence***

Future advancements in the field of computer vision will result in the development of highly intelligent systems that possess the capacity to comprehend and interpret intricate scenarios. By incorporating enhanced automation, these systems will be capable of swiftly and accurately identifying anomalies, potential threats, and critical incidents [35-36].

***Integration with Internet of Things (IoT) and big data***

Integrating computer vision with the Internet of Things (IoT) and Big Data analytics will provide a comprehensive approach towards ensuring public safety. Real-time data analysis from diverse sources such as cameras, sensors, and social media will enable a comprehensive understanding of the environment, thereby facilitating proactive decision-making [7].

***Privacy-preserving solutions***

In response to the growing concerns surrounding privacy, future trends in computer vision will concentrate on creating privacy-preserving solutions. Also, by utilizing technologies like federated learning and edge computing, data processing will be conducted locally, minimizing privacy risks while leveraging computer vision's capabilities.

## Recommendations for policy and implementation

***Formulate clear regulations and policies***

It is imperative for Sri Lanka to formulate unambiguous regulations and policies that govern the utilization of computer vision technology in matters of public safety. These regulations must encompass concerns regarding privacy, storage of data, control of access, and restrictions on usage so as to ensure the ethical and responsible implementation of this technology.

***Invest in infrastructure and training***

Adequate allocation of resources towards infrastructure development is crucial, encompassing upgrading existing surveillance systems and integrating computer vision capabilities. Furthermore, it is essential to devise training programs to impart knowledge to law enforcement authorities and other relevant personnel, enabling them to effectively employ and manage computer vision technology.

***Foster public-private partnerships***

Promoting collaboration between the government, private sector, and research institutions holds great potential for driving innovation in the field of computer vision technology. Public-private partnerships can facilitate the creation of customized solutions tailored to Sri Lanka's specific requirements in terms of public safety while simultaneously benefiting from the expertise offered by multiple stakeholders.

***Promote research and innovation***

Facilitate and endorse research and development endeavours that are specifically aimed at enhancing computer vision technology for public safety applications. By providing financial support to research projects and encouraging innovative ideas, the progress of technology can be expedited to address the distinct challenges Sri Lanka faces effectively.

***Engage with the community***

Encourage and foster active involvement of the community in relation to the utilization of computer vision technology for public safety. Implement outreach programs within the community to educate individuals about the advantages, potential risks, and ethical considerations associated with incorporating this technology. By embracing these recommendations and remaining well-informed about future trends, Sri Lanka can effectively navigate the integration of computer vision into public safety management, consequently establishing a more secure and safer environment for its citizens.

## Conclusions

In this chapter, we have explored the transformative potential of computer vision technology in enhancing public safety management. By examining its fundamental principles, versatile applications, and ongoing initiatives in Sri Lanka, we have revealed its capability to completely change safety measures. From intelligent surveillance systems to optimized traffic management and robust security for critical infrastructure, computer vision provides a wide range of possibilities. Using this technology, cities can actively identify and respond to potential threats, streamline traffic flow, and ensure their residents' overall safety and security. Future trends indicate an increase in automation, integration with the Internet of Things (IoT) and Big Data, and a strong emphasis on privacy-preserving solutions, all of which will play a significant role in shaping the future of public safety measures. Through the responsible integration and ethical application of computer vision, urban areas have the potential to establish a pathway towards safer and more efficient environments, thereby augmenting the overall well-being of their residents, not solely limited to Sri Lanka but on a worldwide level.

## Acknowledgement

Not applicable

## Competing interest

Authors declare that they have no any competing interests.

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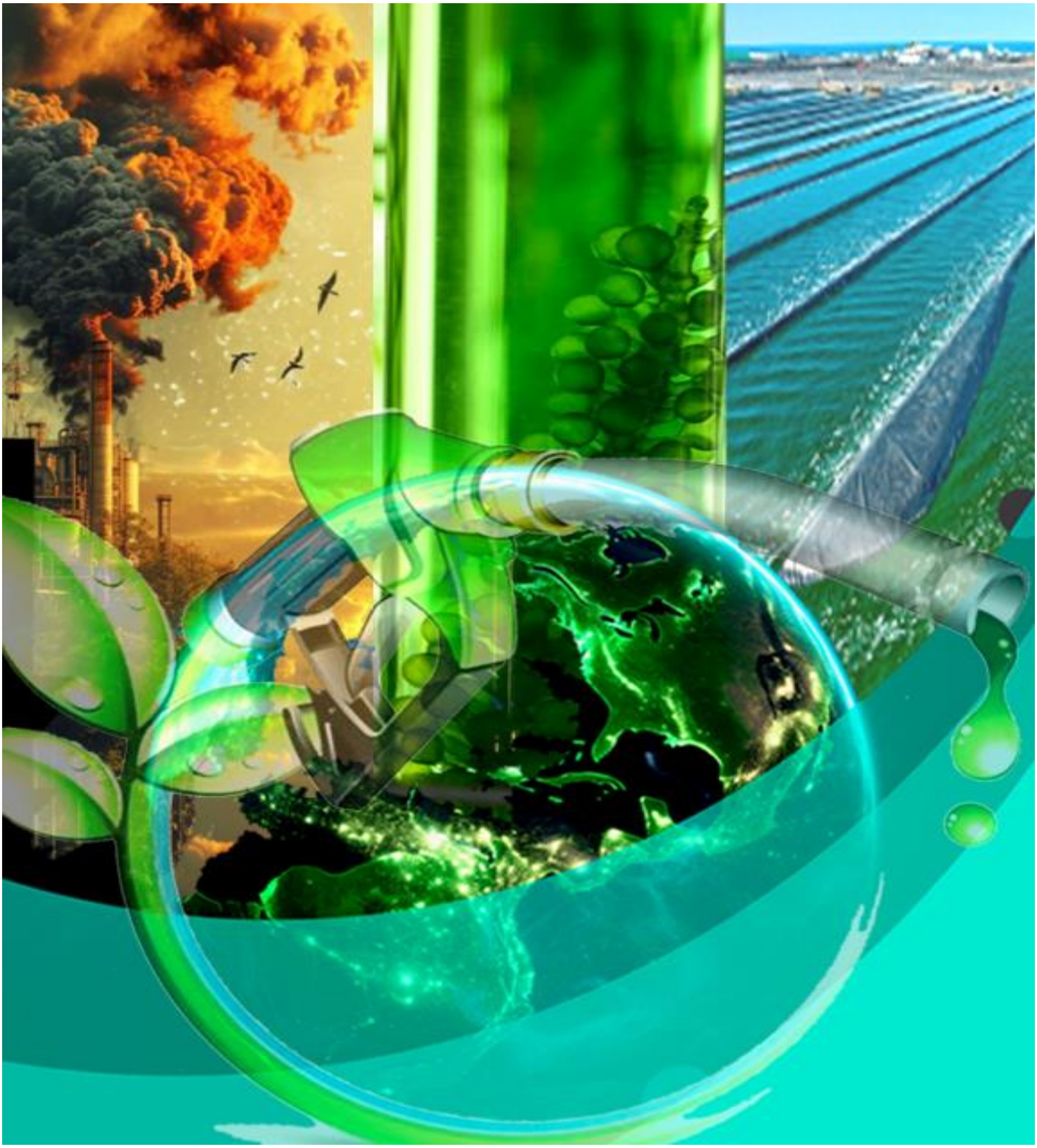
# **SECTION 4-** RENEWABLE AND GREEN ENERGY

# Biofuels: Potential Sources for Mitigating the Effects of Climate Change in Sri Lanka



# Biofuels: Potential sources for mitigating the effects of climate change in Sri Lanka

R. Rathiverni*, S.A.C.N. Perera

## Abstract

Climate change continues to be the most pressing global issue of the century. Fossil fuel combustion is the major contributor to the ever-increasing atmospheric temperature resulting in global climate change. In view of mitigating the problem, several technological developments are being made to invent alternative energy sources and biofuels are identified as potential future fuels. Of the different generations of biofuels, the first-generation, which uses edible crops as feedstock, has several drawbacks as it poses a threat to food security and biodiversity. The production of biofuels is still in its infancy in Sri Lanka, and the utilization of food resources in energy production is controversial. The second-generation of biofuels are generated from non-edible plants and waste oils, and it is highly possible in Sri Lanka to use cooking oil with proper policies and monitoring of the waste-energy chain. Further, *Gliricidia sepium* would be an ideal feedstock for power generation and a potential source to produce biodiesel and $CO_2$ sequestration. Third-generation biofuels are largely produced from algae species. Several algae species, including *Sargassum sp. and Turbinaria ornate,* are ideal for biofuel production due to their high concentrations of lipid and higher abundance in the country. With the country's current policies regarding genetically modified organisms, advanced-level, fourth- and fifth-generation biofuels production are not yet applicable. But it's also feasible to produce carbon- and nitrogen-negative biofuels if GMO regulations are re-evaluated and biosafety laboratories are established. This chapter focuses on various biofuel generations, the strategies currently employed in Sri Lanka, the challenges and the opportunities for climate change mitigation.

**Keywords:** Algae, Biofuel production, Policies, Sri Lanka

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## Introduction

Climate change is the burning global concern of the century. United Nations defines the climate change as a long-term alteration in regional or global climate patterns [1]. Rise in global temperature, severe storms, increased drought, a warming rising ocean, extinction of species, food insecurity, poverty and displacement are some of the direct effects of climate change. In less than 30 years, 28 million tons of polar ice have melted, endangering the lives of arctic species such as seashells and polar bears [2]. NASA reported 2023's summer as the Earth's hottest summer ever with 0.23 °C warmer than in past [3]. If the Earth's atmospheric temperature increases in 1.5 °C above the pre-industrial period, the globe will face detrimental effects of climate change including loss of 70-99 % coral reefs, half of the insects and global pollinators would lose their habitats and the Arctic Ocean would experience ice less summers and one meter rise in ocean level. Alarmingly, the average atmospheric temperature has already been increased by 1.2 ˚C above the pre-industrial period [4].

The accumulation of greenhouse gases (GHGs) in the atmosphere is the primary cause of this concerning shift. The balance between solar and infra-red radiation that the Earth absorbs and emits is what keeps the atmosphere at a constant temperature in nature. But, GHGs absorb infra-red radiation emitted from the earth's surface and are almost transparent to solar radiation, hence lead to increase in atmospheric temperature [5]. Emission of GHGs has been prompted on by anthropogenic activities, such as burning of fossil fuels and changes in land use, which are resulting in a steadily rising concentration of $CO_2$, $CH_4$, and $NO_2$. Moreover, $CO_2$ accounts for about two-third of GHGs [6]. Furthermore, combustion of fossil fuel and cement production together caused the highest $CO_2$ emission of the decade accounting to 36.1 billion metric tons in the year 2022 which was 92 % of global $CO_2$ emission [7]. Nevertheless, 80 % of global energy needs are supplied by fossil fuels in 2022 [8]. Despite being a trace gas, $CO_2$ emissions in the atmosphere have increased eight times between 1950 and 2020, as shown in Figure 1. This rapid increase initiated with the industrial revolution which paved the way to release $CO_2$ to the atmosphere which was stored underground previously [9]. Therefore, it is essential to shift to an environmental-friendly alternative fuel sources to mitigate the effects of climate change.

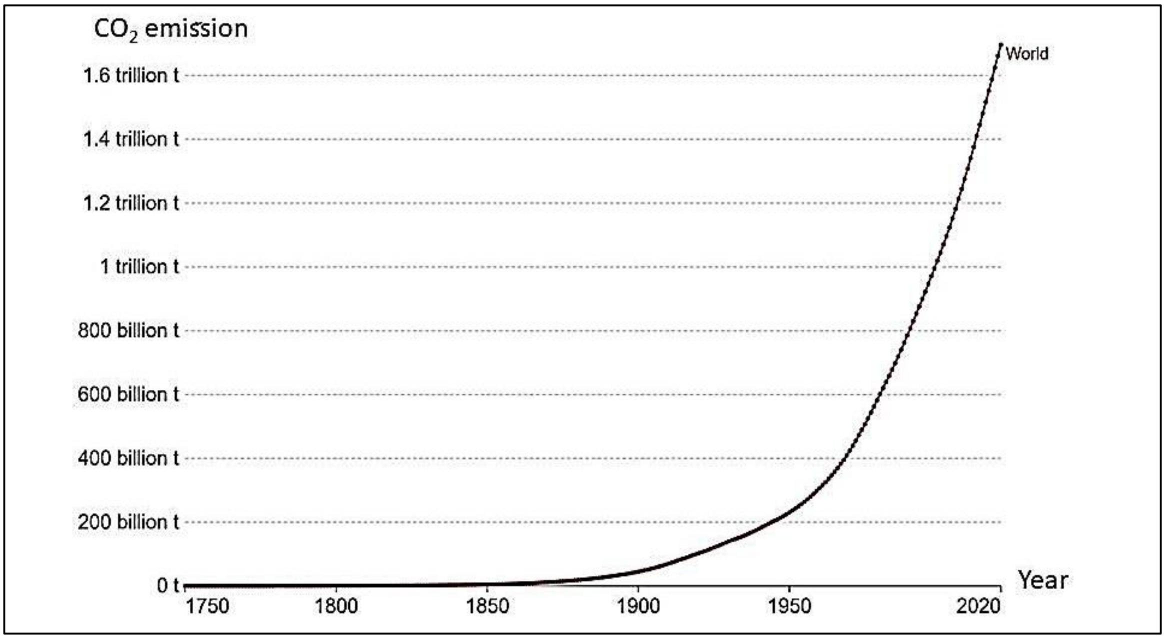


**Figure 1.** Cumulative emission of $CO_2$ from 1750 to 2022 (Source: World Economic Forum, 2022)

## Renewable energy as an alternative to fossil fuels

As a substitute for energy derived from fossil fuels, the world is currently concentrating on producing renewable energy sources. Renewable energy comes from naturally replenishing and nearly endless sources over an extended period of time. Because they don't deplete finite resources and have a smaller environmental impact than fossil fuels, these energy sources are regarded as sustainable [10-11]. Biomass, geothermal, wind, solar, wave energy are some of the energy sources that are currently identified. Bio-based fuels, also known as biofuels, are one of the highly promising future sources of fuel energy [12].

## Role of biofuel in climate change mitigation

The term biofuel refers to energy sources such as bioethanol and biodiesel derived from biomass feedstock including plant materials, including wastes from forestry and agriculture, municipal wastes, and crops [13]. The process of converting biomass feedstock into biofuels is environmentally-friendly. Therefore, it can be used in transportation sector which generates the largest share of GHGs emission [14]. There are three ways that using biofuel instead of fossil fuel contributes to lowering atmospheric $CO_2$. Firstly, it eliminates the emissions that are emitted in the combustion of fossil fuel. Secondly, cultivating new biomass for fuels, provide a mechanism for $CO_2$ absorption and permit the $CO_2$ content of fossil fuels to remain stored in Earth. Thirdly, biofuels present the most advantageous substitute for mitigating greenhouse gas emissions from the transportation sector because of their compatibility with the natural carbon cycle [15]. Biofuels and the cycle of carbon are naturally cycled through the atmosphere, plants, animals, oceans, soil, and rocks by means of the Earth's carbon cycle. Carbon is stored, released, and recycled in a way that preserves a delicate and life-sustaining natural balance. Therefore, the utilization of biofuels such as bioethanol and biodiesel in transportation sector, would contribute to the restoration of the atmospheric $CO_2$ balance [16]. There exists compatibility between Carbon cycle and biofuel production and utilization as depicted in Figure 2.

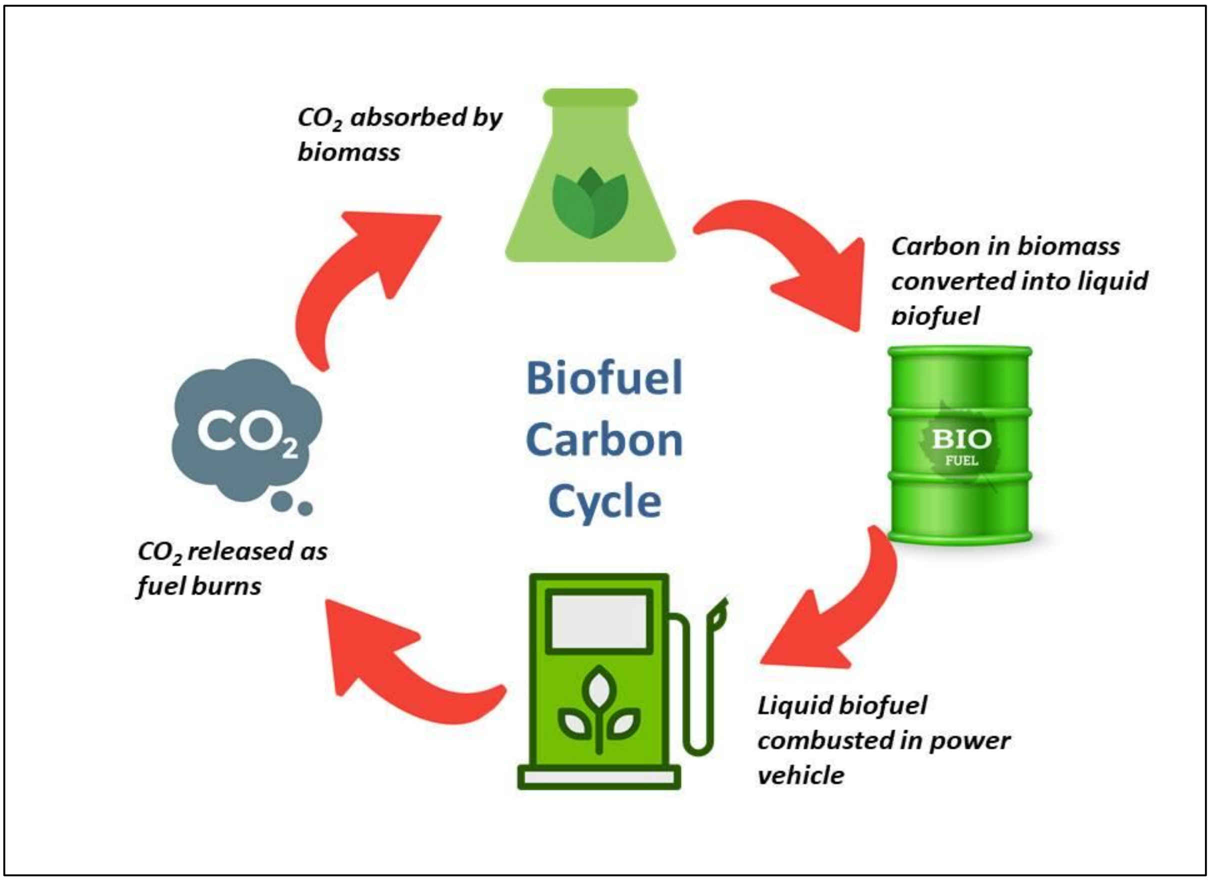


**Figure 4.** Compatibility between carbon cycle and biofuel production to help mitigate climate change.

In addition to reducing GHGs emissions, biofuels also have the potential to mitigate emissions of significant toxic substances generally associated with conventional fuels. Engines running on biofuels or combining conventional fuels and biofuels tend to have lower particulate matter and CO emissions as well as lower sulfate emissions. Bioethanol also shows a decrease in volatile organic compounds [17] and therefore, fostering the use of biomass would hasten the fossil fuel transition and lower GHGs emissions from transportation.

## Major types of biofuels

### a. Biodiesel

Biodiesel is typically produced from vegetable oil/ animal fat by an alkali-, acid-, or enzyme-based trans-esterification process. It is meant to be used in diesel engines alone or blended with petroleum diesel. Further, micro-emulsification is an alternative method for biodiesel fuel production that reduces the by-products resulting from the trans-esterification process. Moreover, Pyrolysis technology has been identified as an advanced technique in the production of biodiesel which has a low cost of production and less time consumption compared with the other two methods while resulting in low pollutants [18]. Therefore, biodiesel can favorably reduce particulate matter by nearly 88 % relative to petro-diesel. Using 100 % biodiesel in heavy-duty highway engines produces on average almost 70 % less hydrocarbons, 50% less particulates and carbon monoxide, and 10 % more NOx emissions. Biodiesel has negligible sulfur oxide emissions and half the ozone-forming potential of that of petro-diesel [19].

### b. Bioethanol

Bioethanol is produced from microbial fermentation of carbohydrates. Corn and sugarcane are the largely used feedstock in bioethanol production [20]. Bioethanol has a wide range of applications. It can be blended with gasoline in 10 % (E10) and possibly up to 22 % (E20 and E22). Additionally, it can be used to make ethyl tertiary butyl ether (ETBE), a fuel additive that increases octane and makes fuel more efficient and relatively clean-burning without the need for engine modifications. Flexible-fuel vehicles can use higher-level blends, such as E85, which is 85 % [21]. Therefore, blending biofuels with traditional transport allows for a gradual integration of renewable energy source into existing infrastructure, while it is commonly practiced in USA and some other developed countries [22].

### c. Biogas

Waste organic biomass is converted into biogas through the anaerobic digestion of microorganisms. Biogas typically contains 30 % $CO_2$ and 70 % methane. Once captured, biogas can be used to power fuel cells, microturbines, and engines by producing heat and electricity. Additionally, biogas can be processed to produce biomethane, also known as renewable natural gas (RNG), which can then be utilized as fuel for automobiles [23-24].

### d. Syngas or Synthetic gas

Syngas is created by a thermochemical process known as gasification, which transforms carbonaceous materials like biomass, waste from cities, coal, petroleum, and tires into syngas inside a gasifier with regulated amounts of oxidants like oxygen, air, and $CO_2$. The primary components of synthesis gas, or syngas, are CO, $H_2$, and $CO_2$. It might also contain other gases like methane and nitrogen which can be used as a primary source to produce diesel [25-26].

## Classification of biofuels

In general, biofuels are classified into five generations based on their feedstock.

#### First-generation biofuels

First-generation biofuels are those derived directly from food sources, such as biomass containing sugar, starch, and vegetable fats and oils. First-generation based bioethanol and biodiesel are the largely produced biofuels to date and their production is based on wheat, corn and sugarcane [27]. The United States of America is currently leading the way as the world's largest corn-based ethanol producer accounting to be 58.29 billion litters in 2022 [28]. Meanwhile, the largest sugarcane based ethanol production is made in Brazil which accounted to be 31.66 billion liters in 2022 [29]. However, the production of biofuel may encounter a number of difficulties in Asian nations that may render them less viable or sustainable than in other regions of the world [30]. There is a competition between the production of food crops and the development of biofuel crops, particularly in areas with limited arable land. It is not advised to forgo food security for the cultivation of biofuel crops because water supply is a crucial aspect of agriculture that may mitigate the simultaneous cultivation of both types of crops [31-32]. Further, there is a high challenge for the sustainable maintenance of biodiversity of a country when a large area of land is utilized for biofuel production and this can even lead to deforestation and land exploitation [33]. Accordingly, to overcome the drawbacks of first-generation biofuel production, the second-generation of biofuels were invented.

#### Second-generation Biofuels

Plant biomass, which is mostly made up of lignocellulosic materials, is used to produce second-generation biofuels. Second-generation biofuels are typically produced from non-food chemicals obtained from plants, such as animal fats, wheat bran, or leftover cooking and frying oil. Other non-food plants such as drought-resistant shrub or tree *Jatropha curcas*, which can also be grown in wastelands, might yet be a different promising source for second-generation biofuels [34]. In the process of biofuel production, the feedstock used as raw materials is treated prior to fuel production to reduce their complex nature. Organic compounds such as cellulose, hemicellulose and lignin are then converted to their respective sugar monomers by enzymatic hydrolysis process, and bioethanol is produced subsequently by microbial fermentation. Accordingly, second-generation biofuels must be combined with other technologies to ensure sufficient levels of fuel production [35]. Even though the second-generation biofuel production systems engage in circular market for reuse of waste agricultural residues, their limitations in feedstock and pre-treatment costs have seeded the pathway for third-generation biofuel.

**Third-generation biofuels**

Third-generation biofuels, also known as advanced biofuels, are more developed and involve environmentally friendly methods of production than the first and second-generations of biofuels. These advanced types of biofuels do have the potential to solve some of the drawbacks associated with the prior generations of biofuels. They are often generated from non-food feed stocks, such as algae, cellulosic biomass, or waste materials by deploying microorganisms [36].

**a. Biofuel from algae**

Algae are aquatic photosynthetic species rich in oil content which can be extracted by breaking their cell structure. Algae can be classified into major two groups as macroalgae which are commonly known as seaweed and microalgae [37]. Approximately, about 60 % of the dry weight of the composition of macro algae is carbohydrates. Cell wall accounts for the larger source of carbohydrates including Mannan, ulvan, carrageenan, agar, laminarin, mannitol, alginate, fucoidin, fucose and uronic acid and little amount of lignin [38]. Rich carbohydrate content is suitable for bioethanol production through hydrolysis process. However, in this method, the yield of bioethanol could vary depending on the species type of algae used in the biofuel production. Still, macroalgae itself is not the most suitable source for biodiesel production as they lack in triglycerides which is the primary substrate in biodiesel production [39].

In comparison to the potential alternative plant sources, microalgae is considered to be the best source for biodiesel production [40]. Microalgae are prokaryotic or eukaryotic cellular organisms that can generate around 50 % of the total $O_2$ content on earth through photosynthesis. Microalgae generally contain a lipid content of 20-50% of their dry weight, while this proportion can exceed 80 % under certain conditions. Microalgal lipids are classified into two groups based on their carbon number. Fatty acids containing 14-20 carbon in its carbon chain are used in the manufacture of biodiesel [41]. However, starch is the main source of energy stored in microalgae. Yet, when microalgae are exposed to a stressful environment such as high salinity or nutritional deprivation, lipid synthesis, in particular, triglyceride formation takes place [42]. A recent study revealed that nitrogen stimulation is more successful at producing lipid than phosphorous stimulation [43] for the effective production of biofuel using algae. For the purpose of biofuel production, microalgae cultivation can be conducted via two methods as open system and closed system which are illustrated in Figures 3 and 4 respectively.

**b. Open-pond algae cultivation**

Open ponds are divided into shallow big ponds, tanks, circular ponds and raceway ponds based on mixing and cultivation. When compared to closed systems, they often have cheaper starting expenditures and can be developed in a variety of designs made of concrete or compacted soil. They are also typically able to meet such fundamental requirements such as sufficient levels of sunlight, an ideal hydrodynamic force, and a closed loop channel to maintain uniformity of cells. However, they need plenty of water instead of arable land, which is still a disadvantage [44].

**Figure 3.** *Euglena* algae cultivation in raceway ponds for biodiesel production in Japan 2019.
Image source: https://www.japan.go.jp/technology/innovation/fuelingjet.html

**c. Bioreactor cultivation/ Closed pond algae cultivation**
When the land is the limiting factor to establish open pond systems, the photo bio reactor would be the viable alternative option for cultivation of microalgae. However, appropriate conditions such as light, air and nutrients should be supplied additionally into this system. Thus, it needs technically advanced operation systems to overcome $CO_2$ mitigation, photo inhibition and waste water treatment for a successful cultivation [46].

**Figure 4.** World's largest microalgae production plant in Malaysia initiated in 2023. It is a tubular system expected to produce 350 tons dry microalgae biomass per year fixing 700 tons $CO_2$ per year.
Image source: https://chitose-bio.com/news/

**Fourth-generation biofuels**

This is an extended version of third-generation biofuels and is carried out by deploying of genetically modified algae with desired traits. Fourth-generation biofuel production is still under research level with the aim of rapidly enhancing the quality and productivity of biofuel system while reducing the cost of production. Microalgae and cyanobacteria are widely used as model organisms for the biofuel production. The genetic modification of organisms used for biofuel production is done in two ways. One is to alter the cellular pathways to enhance photosynthesis, lipid production for organisms which can be utilized for biofuel production naturally [48]. Another way is to genetically engineer the organisms (micro-organism) which are not naturally biofuel producers but with high growth rate. *Chlamydomonas reinhardtii sp., Phaeodactylum tricornutum sp., and Thalassiosira pseudonana sp* are genetically modified algae strains to increase growth rate and adaptability to grow in poor nutrient environments [49].

**Fifth-generation biofuels**

The fifth-generation of biofuels refers to the most advanced category of biofuels derived from non-food sources and often associated with the use of algae, microbial biomass, or waste materials. The main aim of this biofuel is to produce carbon and nitrogen negative biofuel production with the aid of genetic engineering tools. In general, *in-vitro* technique is deployed in fifth-generation of biofuel production to cultivate the genetically modified feed stocks avoiding the competition for arable land and the food and feed industry [50-51].

However, research and development is still ongoing for fifth-generation biofuels. It will also need to address issues like scalability, cost-effectiveness, and large-scale production techniques for these biofuels to become globally commercially viable. Table 1 summarizes the generation of biofuels and their major characteristics.

**Table 6.** Generations of biofuels and their major characteristics.

| **Generation of biofuel** | **Feedstock** | **Characteristics** |
|---|---|---|
| First-generation | Sugarcane, Beet, Wheat, Maize | Edible biomass |
| Second-generation | Wheat barn, Straw, Grass, Used culinary oil | Non-edible biomass |
| Third-generation | Microalgae, Macroalgae | Algal biomass |
| Fourth-generation | Genetically modified organisms | Genetically modified carbon negative biomass |
| Fifth-generation | Genetically engineered algae | Genetically modified carbon and nitrogen negative biomass |

## Status of biofuel production in Sri Lanka in the past decades and at present

Biofuel production in Sri Lanka has gained some attention as a potential avenue for energy diversification, reducing dependence on fossil fuels, and addressing environmental concerns. In 2005, biodiesel and bioethanol productions in Sri Lanka were at its initial stage. With increasing rate in Sri Lanka sugarcane yield of 58.6 metric tons/ hectare, sugarcane was used for first-generation bioethanol production in 2005. Also, paddy, maize, cassava and soy beans were cultivated for bioethanol production. Meanwhile, 5,800 liters oil extracted from oil palm, have been used for biodiesel production. Moreover, soy bean oil, mustard and castor oil have also been used in the past few decades in the production of biofuel [52].

However, the production declined due to scarcity in water supply, fractionalized arable land, and the crops being considered as food crops [53]. On the other hand, coconut, oil palm, castor, and soybean are also considered as potential candidates for biodiesel production. Yet again, the ongoing dilemma is whether to use these crops for consumption purposes or to be utilized for the production of bioenergy.

The possibility of producing bioethanol from sugarcane is still being debated in Sri Lanka. The extent of cultivation and the produce of sugarcane is not sufficient to produce bioethanol, and worrisomely; the nation's annual sugarcane production has declined significantly in the past decade from 66.9 tons to 44.1 tons, which is lower than the average sugarcane production in Asian countries. Prolonged drought conditions, land fractionation, underdeveloped technologies and machinery, and the change of land management from public sector to the private sector are considered as the major reasons contributing to the low sugarcane yield [54]. Thus, the first-generation biofuel is not a feasible practicality under the current status in Sri Lanka.

Despite this debate, currently, small-scale second-generation biofuel producing private industries are evolving using waste vegetable oil as feedstock. Also, there is a high potential of biodiesel production in Sri Lanka using waste cooking oil instead of re-selling the used oil which leads to tremendous negative health effects [55]. Currently, authorities that are mandated for research and development in Sri Lanka are paying much attention on algae to gear up the third-generation biofuel production. Identification of potential species is one of the key objectives of biofuel related research in the country. Sea weed species such as *Sargassum sp*, *Ulva fasiata*, *Turbinaria ornata*, *Gellidium sp*, *Thallasia sp* which are grown in Jaffna peninsula are identified as promising third-generation feedstock for biodiesel production [56]. Among them, *Sargassum sp* showed a higher biodiesel yield at optimal growth conditions. Further, small scale production of biodiesel from *Sargassum sp* reached the international standard as 863.3 $kgm^{-3}$ density and thus could be recommended as satisfactory feedstock for large scale biodiesel production [57]. Apart from the macroalgal species, microalgae species are now being studied in terms of their ability to produce biofuel. There are 64 culturable Cyanocbacteria species so far identified all over the country. Meanwhile, a study conducted in South east coast of Sri Lanka revealed that sea weed *Sargussum wightii* contains 18.35 % monounsaturated fatty acid which is a positive property to produce biofuel. Among them, *Oscillatoria* sp, *Microcoleus* sp. and *Microcystis* sp. are found abundantly in over 16 reservoirs in Sri Lanka [58].

Further, research conducted at the National Institute of Fundamental Studies, Sri Lanka, showed, cyanobacteria species such as *Oscillatoria* sp, *Synechococcus* sp. *Croococcidiopsis* sp, *Leptolyngbya* sp. *Limnothrix* sp. *Calothrix* sp. *Nostoc* sp. *Cephalothrix* sp. *Cephalothrix Komarekiana* and *Westiellopsisprolifica* isolated from Sri Lanka are potential sources for biodiesel industry due to their high fatty acid content. Among them *Oscillatoria* sp. contained the highest lipid content as 31.9 ± 2.01% of dry biomass [59]. Additionally, Sri Lanka has also taken several initiatives to produce and consume biogas in national level. By 2026, it is anticipated that Sri Lanka will consume 35.09 million metric tons of bioenergy. It increased by 0.7% annually to 34.2 million metric tons in 2021 [60]. Further, a recent research conducted in 2019 indicates that biogas energy potential from organic waste recycling is 29–42 PJ which accounts for 16–23% of the household energy demand of the country, and can cut down 3.9–4.8 million tons of $CO_2$ equivalent gases (or 8.6− 10.8% of nationwide GHG emissions). However, biogas adoptions in Sri Lanka are mainly occurring through administrative enforcement rather than market-based incentives [61].

Agroforestry plays a major role in mitigating climate change through carbon sequestration. Especially Gliricidia sepium has been identified as a potential source of mitigating climate change. According to recent findings, one hectare of Gliricidia has the ability to sequester 146.8 tons of

$CO_2$ [62]. In addition to trapping $CO_2$ from the atmosphere, Gliricidia can be used as bioenergy feedstock due to their higher wood biomass density and higher calorific energy [63]. Considering the Sri Lankan context, Gliricidia is widely used as boundary fences in rural areas and has a variety of uses, including providing shade, a soil moisture retention source, and nitrogen fixation in tea and coconut plantations in Sri Lanka. Moreover, an experiment conducted at Rathmalagara Research Center proved that a Gliricidia species named Gualan (OFI Indent No. 15/84) has the highest dry weight (88.2% higher than the local land race), highest oven dried density (20.3% higher than the local land race), low ash content (26% lower than the local land race), low moisture content (57.9%), and a good calorific value (3,750 kcal/kg), which was found to be a promising source for dendro thermal power generation in Sri Lanka [64]. Apart from leaves and stems, Gliricidia seed oil has potential for producing biodiesel. Higher content of saturated fattyacids, palmitic acid, and stearic acid in seed are promising sources to produce methyl esters for the ultimate production of biodiesel [65]. Therefore, much attention is needed on current discoveries and findings.

The government has implemented policies and programs to support biomass energy projects, encouraging investment in this sector. However, the scale of biomass production and its utilization for energy is subject to various factors such as technological advancements, economic viability, and environmental considerations. Accordingly, Sri Lanka has a high potential to shift fossil fuel to biofuel by using second and third-generation feedstock. However, national level policies have to be aligned in terms of encouraging the national level biofuel production.

## Climate Change risk in Sri Lanka and National level policies

In a world of climate risk, Sri Lanka also facing detrimental impacts of climate change. As a tropical country ranked 124 as vulnerable to climate change, the nation is currently dealing with issues such as temperature increases, altered rainfall patterns, rising sea levels, and extreme weather. According to the World Bank's Climate change risk country profile, temperature increases under the highest emissions pathway (RCP8.5) are expected to occur by the 2090s, with an increase of 2.9°C to 3.5°Cover the baseline of 1986–2005. Rising temperatures will probably result in lower agricultural yields, especially in important staples like rice. Food security in the country and in households may suffer as a result. Also, the extreme heat poses a threat to people's health and quality of life, especially for outdoor workers in cities without proper cooling systems. Communities in Sri Lanka's northern region will be especially affected. Negative effects could also strike Sri Lanka's significant tourism industry. Further, flooding can pose potential disease transmission [66]. Also, the county is projected to face a loss of 1.2% of its gross domestic income due to climate-related issues by 2050 [67]. Therefore, adaptive actions need to be taken at the earliest possibility to save the lives, livelihoods and unique biodiversity in Sri Lanka.

Climate change is the largest and most pervasive threat to the environment and lives on Earth. A single nation cannot tackle the issue alone. Therefore, to suppress the global warming, Paris agreement was signed by more than 100 countries including Sri Lanka at the United Nations Framework Convention on Climate Change's (UNFCCC) 22$^{nd}$ Conference in 2015. The agreement is a legally binding international treaty on climate change, stating increasing average global temperature should be limited well below 1.5˚C by 2030 in order to protect the earth from detrimental effects of climate change. Also, UNFCCC initiated another goal of reaching a state where the amount of carbon release from human activities and removal of GHGs are in a balance by 2050 [68]. Meanwhile, Sri Lanka shares 0.08 % global GHGs emission and currently has introduced several other policies as discussed below.

**National Adaptation Plan for Climate Change (NAP)**

Being a signatory to the Paris Agreement, the nation has initiated National Adaptation Plan for climate change (NAP) with a forecasting period of 2016-2025. The key plan includes, increase the ability of people to adapt to the effects of climate change on an individual, community, and societal level, reduce vulnerability to climate risks by strengthening ecosystems' and communities' resilience, and seize any opportunities that arise from changes for the benefit of society as a whole [69].

**Nationally Determined Contributions (NDC)**

Sri Lanka has constructed a Nationally Determined Contributions (NDC) in 2021 to mitigate climate change and launched in 2023 to achieve the goal of Paris Agreement. According to the report, the nation pledges to cut GHGs emission from electricity generation, transportation, industry, waste, forestry, and agriculture by 14.5% between 2021 and 2030 and to increase forest cover by 32% simultaneously. Moreover, by implementing above policies, it is expected that in GHGs emissions reduction by 4.0% in the transport sector equivalent to an estimated total mitigation level of 5,348,000 MT of $CO_2$ equivalent during the period of 2021-2030 [70]. Moreover, the country has announced plans to increase user efficiency in a few industrial subsectors including tea, rubber, apparel, tourism, rice processing and to keep switching fuels to sustainable biomass energy from 2021 to 2030. In addition, by raising feedstock quality, operating and maintenance procedures, system design, and automation, it will be possible to increase biomass user efficiency between 2021 and 2030. Additionally, adaptation plans are introduced to transition the government institutions from fossil fuels to biomass energy for thermal energy requirements and to introduce biomass "co-generation" in industries between 2021 and 2030 [71].

**Founder member of Global Biofuel Alliance (GBA)**

Positively, Sri Lanka has taken a significant step toward boosting the production of biofuels by joining the Global Biofuel Alliance as a founding member. The alliance was established during the G20 summit in 2023 with the goal of increasing the supply and demand for biofuels. Through the participation of a wide range of stakeholders, the alliance aims to shape robust standard setting and certification, increase the use of sustainable biofuels, and facilitate technological advancements [72-73]. As a result, Sri Lanka has a significant advantage and strong foundations to increase the country's production and consumption of biofuels.

## Challenges and opportunities for biofuel production in Sri Lanka

The effective generation of biofuels might be hampered by inadequate technological infrastructure and outdated processing facilities. More investment in research and development is required to create better processing and conversion technologies. It can be expensive to produce biofuel, including the expense of feedstock cultivation, harvesting, and processing. A major problem for the biofuel production is ensuring that the biofuel initiatives are economically viable. The stability and consistency of government policies and incentives can significantly impact the growth of the biofuel industry. Frequent policy changes can deter investment, and supportive policies, such as tax incentives and mandates for blending biofuels with fossil fuels, are crucial for stimulating production. Further, public awareness and acceptance of biofuels can influence the demand. Educating consumers about the benefits of biofuels and addressing misconceptions is vitally important. Especially, continuations of research and development efforts are needed to identify suitable feedstock, improve crop yield and enhance conversion technologies. It will need a concerted effort from the government, private sector research and development programs, and community involvement to overcome these obstacles in biofuel production.

First-generation of biofuel production is practically impossible in Sri Lanka, since the nation is struggling to ensure food security. Therefore, food resources cannot be utilized in biofuel production as of nation’s current status. However, with proper policies to avoid re-selling of waste cooking oil and to invest them on second-generation biofuel production, especially biodiesel would pave way to gear up biofuel production. Also the biodiesel can be utilized in railway sector which is the largest fossil fuel consuming industry in the nation. Moreover, paying much attention on third-generation biofuel production and facilitating sophisticated and environmental safety labs in research stations and universities would enhance algae based biofuel production. However, fourth and fifth-generation biofuels productions are doubtful in Sri Lanka due to prevailing biosafety act on genetically modified organisms. Thus, with the appropriate technology and financial provision for proper research and development, large scale of biofuel production is possible in Sri Lanka in future and that would contribute to reducing the burning of fossil fuels leading to positive effects in mitigating climate change.

Considering the biogas production, there are persisting gaps in knowledge about the role of administrative (regulatory) and market-based policy instruments in the waste-to-energy value chain for facilitating biogas adoption. However, carbon net-zero plans include the promotion of biogas and other renewable energy such as solar and wind power. Nevertheless, there is no such particular plan to promote biofuel including biodiesel and bioethanol in the country. Despite, recent study on policy instruments in Sri Lanka has proved, that several policies initiatives including fuel switching, increase share of public transport, enhancing renewable energy, tax implementation on $CO_2$ emission as between 32US\$/t$CO_2$ to 562 US\$/t$CO_2$, would assist the progress of reducing net energy import dependency in 13 % while reaching net-zero in 2050 [74]. As of today biodiesel has been used in more than 60 countries worldwide [75]. Thus, Sri Lanka can also be one of them in future with implementation of proper policies and adaptation measures. There is no "silver bullet" to overcome the burning issue; all the nations should play their own role. The time has arrived for the country to adopt new technologies and disseminate knowledge from other countries to play a significant role in mitigating climate change. Encouraging foreign investment on national level biofuels production could be one of the future initiative steps. This scenario would provide new job opportunities, earn foreign revenues, and develops Sri Lanka's economy while mitigating climate change. While the sands of time are running out, it is not too late to save our planet.

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## Conflict of interest
The authors declare no conflict of interest.

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# Nexus of Sustainable Development Goals and Environmental Sustainability in Achieving Climate Resilient Sustainable Development: Perspectives from Sri Lanka

# Nexus of sustainable development goals and environmental sustainability in achieving climate resilient sustainable development: Perspectives from the developing world

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## Abstract

Sustainable development goals are the new approach of global governance to ensure sustainable development and environmental sustainability. They include 17 goals with 169 targets which the participating countries to follow voluntarily with flexibility at each country level. Thus, each country has more control over the targets of these goals. These goals are interconnected and while achieving the targets there can be synergies as well as tradeoffs between some of the goals. This is a challenge for developing countries, given the problems they face. In this paper, we discuss the importance of achieving sustainable development goals while ensuring environmental sustainability and propose a framework to discuss the challenges and opportunities the developing nations face in achieving the targets. We identify goals under five dimensions to link them with environmental sustainability: Life prosperity, sustainable economy, affordable technology applications, sustainable environment, and governance. Our contribution to literature stems from the creation of the matrix based on the challenges and opportunities available in developing countries. Further, we highlight that the dimensions of governance and affordable technology have the greatest potential for improvement in developing countries. This discussion provides informative insights into challenges faced in implementing SDGs whilst ensuring environmental sustainability.

**Keywords:** challenges, developing countries, environmental sustainability, strategies, sustainable development goals, opportunities.

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## Introduction

Sustainable development, a term in the development and environment literature since the release of the Brundtland Commission report in the late 1980s, has gained a level of prominence we have never seen in history. This can be attributed to the over-exploitation and misuse of natural resources in the past by humans to meet their demands. Humans in their quest for meeting their wants, have excessively exploited the natural resources, including renewable resources, which have become non-renewable i.e. overfishing, deforestation, and excessive water usage demean the ecosystems' ability to restore the used resources. Sustainable development attempts to meet the needs of the present generation, without compromising the needs of future generations [1]. With this consensus on sustainable development, many institutions both local and international started to focus on sustainability aspects of development. Sustainable development includes three main pillars: Economy, Environment, and Society [2]. It was understood by the scientific community and the political leaders, that for humans to have a common future these three pillars be in balance.

In literature, two terms are used: sustainability and Environmental Sustainability (ES). The former encompasses the three pillars we mentioned. ES is a concept that does not involve society and the economy. ES is important to humans and originates mainly from social concerns as the environment is needed in better condition to meet the wants of the 8 billion people on this planet [3]. ES does not demand restrictions in the use of the environment, but demands optimum resource use so that the environmental services can be used in a way where the substitutability of these resources and replicability of the resources are guaranteed. That is, there is a balance between what we consume from the environment and what we add to the environment. In Goodland's terms humans should limit their economic subsystem within the capacities and limits of the biophysical limits of the overall ecosystems, where society and economy are part of it [3]. If this is exceeded, then it is the very existence of humans that will be threatened. As of now, the earth has been experiencing adverse natural calamities: rain, cyclones, heat, and wildfires etc. Thus, any development should also focus on climate resilience. Climate resilience is defined as the ability to predict, prepare, and respond to hazardous natural calamities related to climate. Development planning should include the aspects of climate resilience as well.

This highlights the fact that whatever the scale of development, it should happen within the carrying capacity of the ecosystems be it on land, air, or water. However, when "development" is included the question in concern becomes more complex. As the definition of development is different and may include a broad range of aspects. In this paper, our focus would be on sustainable development goals, where there is a balance in the three pillars: society, environment, and economy while ensuring climate resilient environmental sustainability especially focusing on ensuring climate resilience (SDG 13). We try to identify and discuss the common issues and challenges in achieving the Sustainable development goals (SDG) in developing countries with a special focus on the climate-resilient environmental sustainability concept. We review the existing literature related to achieving SDGs and sustainable development and aggregate the SDGs based on these identified challenges and opportunities into a matrix, mostly based on the experiences of the developing countries. We identify SDGs under five dimensions to link them with climate resilient ES: Life prosperity, Sustainable Economy, Sustainable technology applications, Sustainable Environment, and Governance. Then we relate these opportunities and challenges with climate-resilient ES. Our contribution to SDG literature stems from the creation of the matrix based on the challenges and opportunities available in developing countries. Further, based on country experiences we propose what would be the way forward in achieving SDGs ensuring climate resilient ES. This discussion provides informative insights on challenges faced in implementing SDGs whilst ensuring climate-resilient ES.

## Sustainable Development Goals (SDGs) and Climate-resilient Environmental Sustainability

### SDGs and their importance

The SDGs are 17 goals with 169 targets which are universal and applicable to all the countries around the world adopted in 2015 and to be achieved by 2030 [4]. Both the Brundtland Commission and the United Nations SDGs identify social equality, environmental protection, and economic growth as the pillars around which sustainable development is built [5]. The global identification of these 17 goals, in a way supported some of these governments to streamline their development agendas [6]. The SDGs have helped institutions to focus more on the sustainable use of natural resources [7]. With these goals, local institutions are indirectly forced to adopt sustainable decision-making, keeping sustainability as the key aspect when making development interventions. For developed nations, a considerable number of SDGs have been already attained especially related to health, poverty, education, Governance, and equality. However, developing nations still need to improve their sustainability rankings and in certain SDGs they underperform compared to the global south [8]. There is a significant amount of improvement needed on these fronts. However, there are also certain aspects that all nations need to pay attention such as environmental sustainability, exploitation of natural resources, and climate change. A climate resilient coping strategies would need a more cooperation between countries, than fighting it alone.

### Climate-Resilient Environmental sustainability

Climate-resilient ES does not need any introduction as the Environment is the core of the sustainability principle. However, ES is different from the sustainability concept. The environmental sustainability also seen as a situation of “balance, resilience and interconnectedness that allows human society to satisfy its needs while neither exceeding ecosystems’ regenerative capacity nor by human activities to diminish the biological diversity of the system” [9]. Which further points out 15 guiding principles under societal needs, preservation of biodiversity, regenerative capacity, reuse and recycle, and constraints of non-renewable resources and waste management. The SDGs have been specifically designed to maintain environmental sustainability [10]. The idea underlying sustainable development has become a metaphor for defining human welfare and environmental management since its inception in the 1980s [10]. So, many scholars have focused their attention on sustainable development in environmental conservation and natural resource management [11-12].

The next issue is the nexus between SDGs and Climate-Resilient ES. Do SDGs and ES align together or in opposite directions? We can see that both SDG and ES are at times work as synergies, benefiting both as a win-win situation and at times SDGs and ES create trade-offs between them. SDGs have been studied by many researchers in the line of synergies and tradeoff. Some studies have tried to identify and categorize the SDG goals [13-14]. Some discuss how these tradeoffs can be transferred into synergies [15]. Further, some literature specifically looks deeper into the synergies and tradeoffs by focusing on specific sectors or SDGs [16]. This solely depends on the SDG goal and the targets. Synergies occur due to achieving progress in one or more targets of an SDG and improving the environmental sustainability score. So, this direction benefits both concepts. However, we understand that not all SDGs result in positive ES scores. Some SDGs, due to their nature will result in negative ES scores. Thus, creating a tradeoff between these two and leaving a puzzle with the policymakers. In addition to the synergies and tradeoffs, the interconnectedness of the SDGs among each other makes this identification very complex and difficult [15, 17-19]. If they are linearly related or only have simple paths, it is easy to identify the synergies and tradeoffs. Since they relate to multiple paths, the identification of tradeoffs is not direct, and it may not be a complete process, even if we do so.

Based on the type of synergies and tradeoffs with SDGs and ES, there are new challenges and opportunities that must be identified. If these are identified, then a better approach or strategy would work while balancing the SDG and ES nexus. Further, they all need to cater to the common threat of climate change. Thus, the action needs to be climate resilient actions. s First, we try to identify the underlying aspect of these issues and challenges in achieving the SDGs and then come up with a framework to cluster the challenges. This exercise would also identify the common issues among countries and the ways to tackle them and propose solutions to overcome them with technology.

**Framework for Challenges and Opportunities with SDGS and ES**

The focus of this study is on the nexus of sustainable development goals and environmental sustainability in achieving climate resilient sustainable development: perspectives from developing countries. Five key areas were recognized that demand immediate consideration. They are Livelihood prosperity, Sustainable economy, Sustainable technology applications, Sustainable environment and Governance. Each of these dimensions encapsulates one, or more or all the SDGs in either of these identified dimensions. And in most cases, there is a greater need for strategies to be introduced into the livelihoods of these people. In the preceding section, we explain under each dimension the most important challenges and the potential opportunities available for developing countries for climate resilient sustainable development and, if possible what acts as the bottlenecks. One of the major obstacles in achieving climatic resilient sustainable development is the inadequate knowledge about the relationship between climate adaptation and the SDG targets for decision making [20].

Livelihood prosperity: The dimension of livelihood prosperity encapsulates seven SDGs. They are no poverty, zero hunger, good health and well-being, quality education, gender equality, clean water and sanitation and reduce inequality (SDG 1, 2, 3, 4 ,5, 6, and 10). Though we cannot weigh down on any of the three main pillars of sustainable development, it is understandable that people/societal factor is very important, as the survival of mankind is important unless all of these efforts would be in vain and environment can thrive without the society and the economy, but the society cannot [21]. As it is evident that most of the SDG are focused on the people factor (SDGs). Most of the goals are directly related to improving livelihoods: alleviating poverty and hunger, reducing inequalities of any sort, and improving access to essential needs for everyone including health and education etc. Countries in the global South are lagging on these indicators for many decades. It took many decades of overseas assistance for Africa to improve its poverty indicators and South Asia still lingers with malnutrition [11]. Millions of people still do not have a prosperous livelihood. Considering the climatic factors, natural disasters and pandemic have worsened the livelihoods of the poor. Thus, livelihood prosperity has been a challenge for years and will be a challenge in the future too. When people’s livelihoods are challenged people go to any extent to survive, and concerns on sustainable development are lost in front of hunger. Since the linkage between livelihood and the climate is sturdy, all the SDGs above are directly linked with the climate and climatic impact have been threatening the livelihood. Natural disasters such as floods, tsunami, droughts, cyclones, and landslides have enormous impacts to the daily lifestyle of people in developing countries. One reason is that people in developing countries lag financial stability to recover from these disasters alone with lack of knowledge to overcome these impacts. So, the livelihood, health, agriculture, properties, and education are always threatened with disasters. So, the developing countries have higher sensitivity in for climate disasters. Hence, vulnerability of people to adapt to the climatic disasters is also low [6].

Sustainable Economy: The dimension of Sustainable economy represents three SDGs including decent work and economic growth, sustainable cities and communities and responsible consumption [8]. This indeed is an important pillar of the economy, a vital component in sustainable development, and ensures that the economy behaves in a sustainable manner. The free market may exploit the natural resources and the environment, thus checks and balances are needed through governance structures to make the economies sustainable, and resource exploitation is done in a sustainable manner. In a sustainable economy, the nation or the firm uses its resources in an efficient and responsible manner, so that it can produce whatever the goods and services in a consistent manner and profit from that venture. If the economy moves away from the principles of efficiency and responsibility, it may achieve profit, but it will not be sustainable, leading to a loss in the long term. The sustainable economy literature terms this as “viability” combining the economic aspect with climate resilient.

Sustainable Technological Applications: This dimension encapsulates two SDGs of Affordable and clean energy and industry innovation and infrastructure. Technology is an important tool in the 21st century [27]. The task and goals can be efficiently achieved in a minimum time with much precision. In some case, humans are replaced by technology. Technology has been identified as one of the most important factors that could help to transform the economy into a sustainable one. The same applies for environmental sustainability and climate resilience. Some of the longstanding issues can be solved with the help of modern, mobile technology. Technology has developed into a state where most of the inventions now are portable and can be located in any part of the world, giving access to millions of people. Advancements in telecommunications, information and communication technology have helped millions of children and adults to have access to the latest knowledge, education and information that are vital to their livelihoods. The boom in these types of technology was very helpful for the people who are very far away from cities. It provides much-needed information and education for them. A substantial amount of literature looks into the impact of technology on the environment and climate. Both country studies, as well as multi-country studies, have found that technological advancements are favorable for the environment [23]. Further, technological innovation and information globalization have the potential to predict environmental quality, and these can be very helpful in achieving the agenda 2030 [24]. The application of Industry 4.0 for environmental sustainability through four scenarios: deployment scenario, operation scenario, integration and compliance with SDGs, and long runs scenario [25]. They find that the integration of Industry 4.0 and SDGs improve environmental sustainability that guarantees better environmental performance with ecological support for climate resilient sustainable development. According to this study, though there are negative impacts the positive impacts outweigh the negatives, supporting the hypothesis that technology can be a useful tool to achieve the SDGs ensuring environmental sustainability and climate stability. Environmental sustainability and climate resilience are hand in hand in sustainable development. Most novel technology applications have proved to be climate resilience. poor concentration on the environmental sustainability cause several unpredictable climate changes and it results several drawbacks to planet and people. Almost all the fields such as all the industries, agriculture sector, pharmaceuticals, transports have made significant impact to the climatic changes. There are several sustainable solutions for Sri Lanka to mitigate the climate issues such as moving to renewable energy sources, digital platforms, and artificial intelligence. Most developing countries have the potential for renewable energy sources such as hydroelectricity, wind and solar energy [26]. But the investment methods and policies should transition to renewable energy productions and overcome the obstacles of financing mechanisms, polices, strategies, scale-up challenges and innovations.

There is an important aspect of the role of science, technology, and innovation in the UN agenda of 2030 [27]. They question the suitability of the current technology to achieve the SDGs. According to them, they suggest the current of technology is that the existing technologies are being used to meet the SDG goals, rather, they propose reorienting the technologies specifically to meet the SDGs.

Governance: Governance has been and is still a main challenge in achieving SDG targets, especially in developing nations. Historically developing nations have been marred by poor governance and state bureaucracies that hinder the achievement of development targets. All the state-level issues, leadership, and administrative aspects can be put under the term governance. Though there is an international understanding on achieving the SDGs, it is the local governments that have to make the initiative for implementing the programs. In literature, governance has been cited as one of the important factors in reaching development targets, as well as climate resilience [28]. By using a sample of OECD countries, the impact of environmental tax, governance, and energy prices on environmental quality was also determined [28]. The findings indicated, in the long run, environmental tax and governance increase environmental quality.

Studies have also highlighted the importance of decentralization in achieving the SDG goal. Especially local governance is very crucial for achieving the targets of SDGs. Local stakeholders are the ones who are involved at the operationalization level of the SDG targets. Further, local actors are well accustomed to the local condition and geography, thus they understand the needs and wants of the people as well the challenges in the local level. Thus, they are the ones who should come up with solutions to tackle those challenges. It was also identified that the three main challenges at the governance level in implementing the SDGs [29]. According to them, a) collective action through inclusive decision-making, b), making trade-offs ensuring equity, justice, and fairness, and c) ensuring a mechanism of accountability for reaching the targets are the important challenges and they cannot be overcome through separate approaches. Thus, an integrated approach is needed to overcome these challenges. It was highlighted that SDG are a novel approach of governance styles: global governance by goal setting [30]. They highlight mainly fours features of this governance approach. The first feature of this governance is that the SDGs are not attached to the international legal system. Furthermore, the qualitative targets provide much freedom for the respective governments to decide on the targets. Second, the functions are through weak institutional arrangements at the intergovernmental level. This leads to a bottom-up, country-specific, non-confrontational stakeholder-oriented governance style. Thirdly, it works through global inclusion and a global goal-setting process. Fourth, this governance through goals allows much flexibility to national choices and preferences providing the governments to come up with achievable targets and they are non-binding.

Sustainable Environment: The fifth crucial factor we identified is the Sustainable environment. This indicates that human interactions with the environment must be within the regenerative and assimilative capacities. A framework was introduced that could be used to assess the interactions between SDGs which may be implicitly linked, and contradictory interactions among the SDGs may result in differing outcomes [33]. As a result, interactions across the SDGs may have divergent outcomes. To identify and analyze the impact of those SDG interactions we have segregated those interactions as synergies and tradeoffs and developed a framework to achieve Environmental sustainability majorly for developing countries. Synergy can be identified when progress in one goal favors progress in another goal while progress in one goal hinders progress in another can be identified as a tradeoff. To develop this framework, we have used a seven-point Likert scale and dividing criteria used by [33].

The framework highlights different categories of causal and functional relationships underlying goal and target progress or achievement. The scale ranges from -3 to +3, with -3 indicating that progress on one objective cancels out progress on another and +3 indicating that progress on one goal is intimately tied to progress on another. A number of crucial dimensions (Livelihood Prosperity, Sustainable Economy, Sustainable technology applications, Sustainable environment and Governance) supplement the scale by describing interactions and defining the context in which they occur. Most interaction scores are determined by these dimensions, and implementing the appropriate policies and technology may result in a higher score in proceeding sections. Positive interactions are granted ratings of +1 ('enabling'), +2 ('reinforcing'), or +3 ('indivisible'), whereas trade-off interactions are assigned a value of -1 ('restraining), -2 ('counteracting) and -3 (cancelling). Thus, the magnitude of the score, in either direction, indicates how influential one SDG or target is on another [33]. More explanation is depicted in table 1.

**Table 1.** Framework to assess SDG Interactions (Source: Nilsson *et al.,* 2016)

| Impact type | Explanation | Score |
|---|---|---|
| **Indivisible** | Inextricably linked to achieve another goal. | +3 |
| **Reinforcing** | Helps to achieve another goal | +2 |
| **Enabling** | Pursuit of one objective allows to achieve another objective. | +1 |
| **Consistent** | One objective does not significantly interact with another objective. | 0 |
| **Restraining** | A mild negative interaction to achievement of another goal. | -1 |
| **Counteracting** | The pursuit of one objective counteracts the achievement of another objective. | -2 |
| **Cancelling** | Do not allow or impossible to achieve another goal | -3 |

Within this framework, we have used SDGs 6, 7, 12, 13, 14 and 15 to analyze the synergies and tradeoffs between the interactions as major targets of those goals are directly linked to natural environment and climatic changes but are lagging far behind to achieve in due time frame [34]. But those are the six goals that are mainly related to achieving the sustainability of natural resources. The above goals are dedicated to clean water and sanitation, affordable and clean energy, sustainable consumption of natural resources, climate change, life below water and on terrestrial ecosystems, halting biodiversity loss and combating land degradation and desertification. According to the literature, we have identified a huge tradeoff between the targets of SDG12 (Responsible consumption and production) between the other SDGs. It had a negative correlation with SDGs 1-7, 9, 10 and 17 [35].

SDGs 3 (Good Health and Wellbeing) and 12 have been identified as a top trade-off pair in 121 nations, making it the most common cross-national trade-off. This tradeoff mostly can be seen in the developing nations like Chad, Sudan, Mali, Niger and vice versa [36]. In those countries when they are going to achieve good health and wellbeing while enhancing the infrastructure facilities most of the natural ecosystems and environments can be harnessed and there will be no sustainability within those systems and as a result there is no responsible consumption or production and there is a higher number of material footprints [35]. So, this interaction can be given the score of -3 and it cancels the interaction.

Accordingly, SDG 6 (Clean water and sanitation) is counteracted by the SDG 12, to achieve SDG 12 multiple dimensions that leads to water pollution should be considered. The agricultural production within a country causes the water pollution as the run-off water from agricultural fields causes the pollution of natural water ways as they are highly contaminated with the agrochemicals that comes from the fields. Not only that, industrial and household wastes that were directed towards the natural water bodies also cause the water pollution. These actions will reduce access to clean water and sanitation. Therefore, SDG 6 is counteracted when achieving SDG 12. So, this interaction is a counteracting interaction and hence the score given is -2.

Goals 6, 7, 12, 13, 14 and 15 are directly related to environmental sustainability. The targets in these goals are mainly linked to the natural environment but are lagging far behind and seem impossible to achieve in due time frame. The goals are devoted for clean water and sanitation,

**Table 2**. The synergies and tradeoffs between SDGs to achieve ES

| | | Acute Climatic Impact Derivers | | | | | Chronic Climatic Impact Drivers | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Extreme precipitation | Damaging Cyclones | Extreme Temperature | Storm Surge | Flooding | precipitation | Snow Cover | Sea Level | Warming Trend | Ocean Acidification | $CO_2$ Fertilization | Drying Trend |
| **Livelihood Prosperity** | 01 SDG | | | | | | | | | | | | |
| | 02 SDG | | | | | | | | | | | | |
| | 03 SDG | | | | | | | | | | | | |
| | 04 SDG | | | | | | | | | | | | |
| | 05 SDG | | | | | | | | | | | | |
| | 06 SDG | | | | | | | | | | | | |
| | 10 SDG | | | | | | | | | | | | |
| **Sustainable Economy** | 08 SDG | | | | | | | | | | | | |
| | 11 SDG | | | | | | | | | | | | |
| **Sustainability Environment** | 13 SDG | | | | | | | | | | | | |
| | 14 SDG | | | | | | | | | | | | |
| | 15 SDG | | | | | | | | | | | | |
| **Sustainable Technological Applications** | 07 SDG | | | | | | | | | | | | |
| | 09 SDG | | | | | | | | | | | | |
| | 12 SDG | | | | | | | | | | | | |
| **Governance** | 16 SDG | | | | | | | | | | | | |
| | 17 SDG | | | | | | | | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| | Proved evidence for a high impact from climate impact drivers to SDGs | | Proved evidence for a considerable level impact from climate impact drivers to SDGs | | Absence of identified evidence |

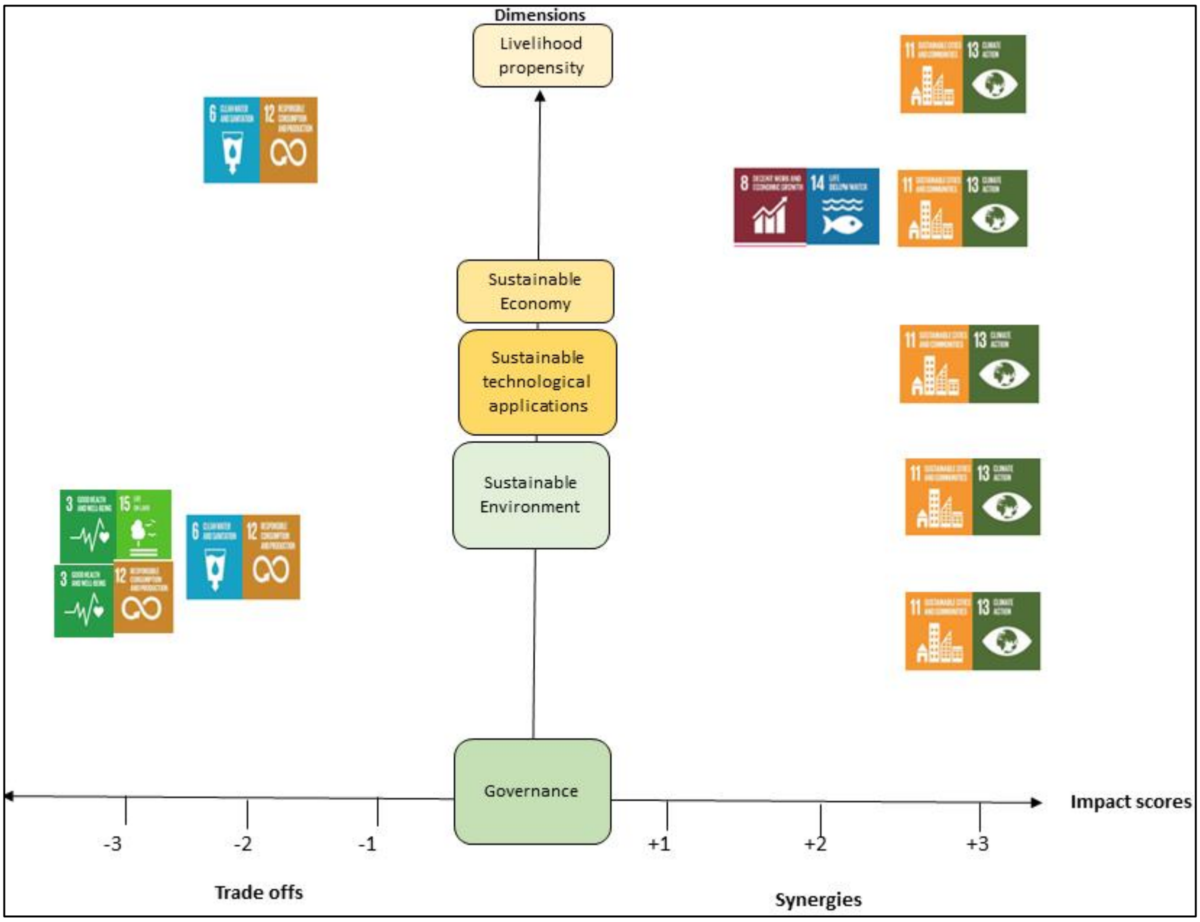



**Figure 1.** Framework to explain the synergies and tradeoffs between SDGs to achieve ES.

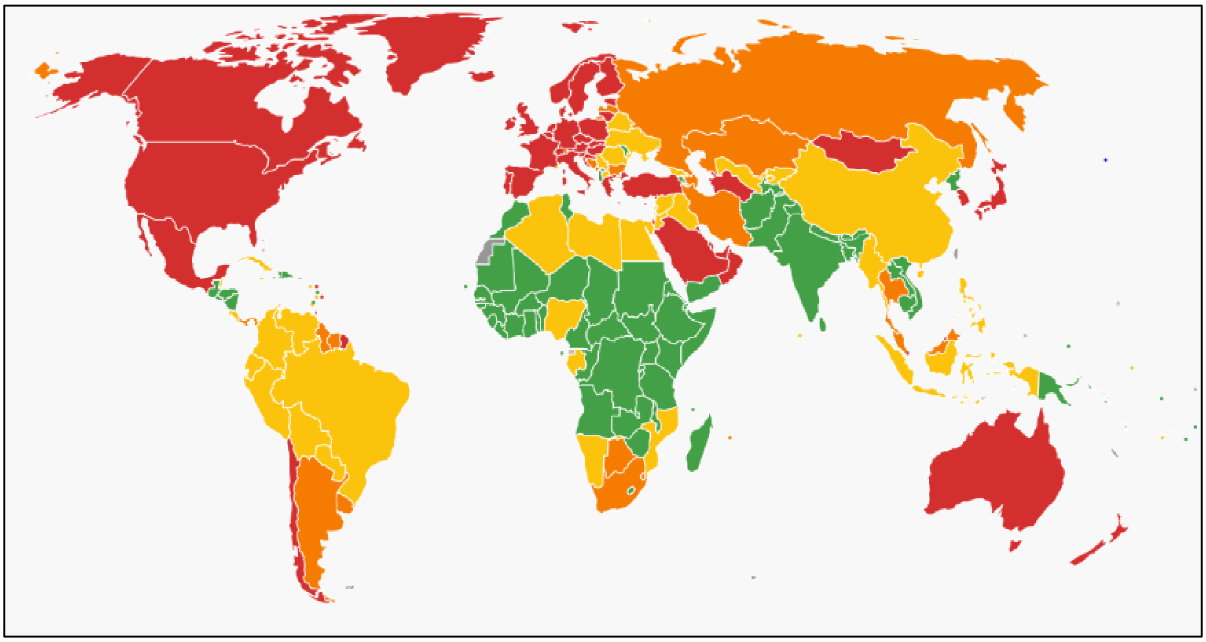
This framework shows how the interactions of different SDGs related to ES are coupled to achieve ES and how those synergies and tradeoffs are explained under five key dimensions. Affordable and clean energy, sustainable consumption of natural resources, climate change, life below water and on terrestrial ecosystems, halting biodiversity loss and combating land degradation and desertification.

## Opportunities and challenges faced by developing nations

*SDG 13 progress in other countries and lessons to Sri Lanka*
When evaluating the SDG performances of developing nations, Africa takes a prominent place. Because SDGs provide the best global framework to close the gaps in indicators between their own indicators. As Africa is one of the emerging regions that perform significantly lower than the global average on important development outcomes and indicators, notably those related to levels of poverty, inequality, and hunger; access to quality health and education, as well as water and sanitation; levels of industrialization and infrastructure; exposure to modern energy; and advances on ecosystem development, including climate change and biodiversity. Working toward convergence on these indicators is thus essential if the goal of 'leaving no one behind' is to be met [37].

According to the Sustainable Development Report 2020 [38], 43 African countries have met the SDG 13 targets, along with more than a dozen other Asian and Latin American countries (Figure 1). When it comes to the developing nations, Sri Lanka, Nepal, Bangladesh, Phillipines, Cambodia and India and some other Asian countries (Table 2) has achieved the targets in the SDG 13. Moldova is Europe's only country to have achieved SDG 13. Projects such as the Great Green Wall in Africa which tries to regenerate landscapes and plant trees across the Sahel and create community-based economic development, as well as a powerful model for climate resilience, adaptation and sustainability. Ethiopia, the Democratic Republic of the Congo, Mali, Vietnam, and Pakistan have all achieved objective 13 targets. In Ethiopia's situation, the government is attempting to cut agricultural emissions, stimulate forest development, invest in renewable energy, and adopt energy efficiency across industries. As Sri Lanka also some country rich with natural resources and it can also initiate the projects like in Africa and Ethiopia.

Sri Lanka has initiated several energy service projects in rural areas. The implementation of solar panels in the *Monaragala* District is also one such example [39]. According to their study they have identified that the new energy supply has improved their quality of life and contributed for the alleviation of poverty but has not led to an increase in income of the livelihoods. But it has reduced the dependency upon fossil fuels or hydro power to generate electricity and ultimately it will reduce the greenhouse gas emissions and enhance the climate resilience.



| | | | | |
|---|---|---|---|---|
| Goal Achievement | Challenges remain | Significant challenges | Major challenges | Insufficient data |

**Figure 2.** progress made towards SDG 13.
(Source: Sustainable Development Report 2020 (https://www.globalcitizen.org/en/content/sdg-13-climate-action-rankings-progress/)

Countries in green have achieved the SDG. Yellow indicates that challenges remain; orange that significant challenges remain; red that major challenges remain; grey that information is unavailable. The United States, the world's second largest emitter, has retreated on goal 13 in recent years and is still far from meeting the targets. In recent years, the Trump administration withdrew from the Paris Climate Agreement, abandoned initiatives to enhance car gas economy, unraveled a plan to increase power plant efficiency, and made it easier for firms to dig for fossil fuels [40]. So, proper policies and strategies should be initiated in Sri Lanka to achieve and sustain the SDG 13.

**Table 3.** Performance on SDGs, selected developing countries (Source: Sustainable Development Report 2023)

| Country | SDG Index | Rank | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chile | 78.2 | 30 | | | | | | | | | | | | | | | | | |
| Thailand | 74.7 | 43 | | | | | | | | | | | | | | | | | |
| Costa Rica | 73.6 | 52 | | | | | | | | | | | | | | | | | |
| Bhutan | 72.3 | 61 | | | | | | | | | | | | | | | | | |
| China | 72.0 | 63 | | | | | | | | | | | | | | | | | |
| Peru | 71.7 | 65 | | | | | | | | | | | | | | | | | |
| Ecuador | 70.4 | 74 | | | | | | | | | | | | | | | | | |
| Indonesia | 70.2 | 75 | | | | | | | | | | | | | | | | | |
| Colombia | 70.1 | 76 | | | | | | | | | | | | | | | | | |
| Malaysia | 69.8 | 78 | | | | | | | | | | | | | | | | | |
| Mexico | 69.7 | 80 | | | | | | | | | | | | | | | | | |
| Egypt, Arab Rep. | 69.6 | 81 | | | | | | | | | | | | | | | | | |
| **Sri Lanka** | 69.4 | 83 | | | | | | | | | | | | | | | | | |
| Iran, Islamic Rep. | 69.1 | 86 | | | | | | | | | | | | | | | | | |
| Bolivia | 68.9 | 87 | | | | | | | | | | | | | | | | | |
| Paraguay | 68.8 | 88 | | | | | | | | | | | | | | | | | |
| Saudi Arabia | 67.7 | 94 | | | | | | | | | | | | | | | | | |
| Guyana | 67.4 | 96 | | | | | | | | | | | | | | | | | |
| Panama | 67.3 | 97 | | | | | | | | | | | | | | | | | |
| Philippines | 67.1 | 98 | | | | | | | | | | | | | | | | | |
| Nepal | 66.5 | 99 | | | | | | | | | | | | | | | | | |
| Bangladesh | 65.9 | 101 | | | | | | | | | | | | | | | | | |
| Cambodia | 64.8 | 103 | | | | | | | | | | | | | | | | | |
| India | 63.4 | 112 | | | | | | | | | | | | | | | | | |
| Lao PDR | 63.0 | 115 | | | | | | | | | | | | | | | | | |
| Ghana | 61.8 | 122 | | | | | | | | | | | | | | | | | |
| Kenya | 60.9 | 123 | | | | | | | | | | | | | | | | | |
| Myanmar | 60.4 | 125 | | | | | | | | | | | | | | | | | |
| Pakistan | 59.0 | 128 | | | | | | | | | | | | | | | | | |
| Zimbabwe | 55.6 | 138 | | | | | | | | | | | | | | | | | |
| Cameroon | 55.1 | 139 | | | | | | | | | | | | | | | | | |
| Ethiopia | 54.5 | 144 | | | | | | | | | | | | | | | | | |
| Nigeria | 54.3 | 146 | | | | | | | | | | | | | | | | | |
| Congo, Rep. | 52.6 | 151 | | | | | | | | | | | | | | | | | |
| Haiti | 52.6 | 152 | | | | | | | | | | | | | | | | | |
| Afghanistan | 49.0 | 158 | | | | | | | | | | | | | | | | | |
| Sudan | 48.6 | 160 | | | | | | | | | | | | | | | | | |
| Niger | 48.3 | 161 | | | | | | | | | | | | | | | | | |
| World | 66.7 | | | | | | | | | | | | | | | | | | |

Legend:

| Goal Achievement | Challenges remain | Significant challenges | Major challenges | Insufficient data |
|---|---|---|---|---|

**Opportunities and Challengers to achieve SDG 13**

We discuss the challenges and opportunities in achieving climate resilience and ES in Developing countries under the main factors that we have identified that needs immediate attention: Livelihood prosperity, Sustainable Economy, Sustainable Environment, Affordable Technology, and governance. Some of these factors may have overlapping targets in the SDG, yet we try to discuss the main challenges under these five themes, irrespective of the interactions they might have with the other dimensions. Developing countries have made significant progress towards achieving the SDGs in recent years. According to the 2020 SDG Index, released by the Sustainable Development Solutions Network, developing countries are performing better than developed countries in terms of progress toward achieving the SDG 13 in certain criteria. But in some criteria the progress has been negative and for some they are stagnant. Particularly in the SDG 13 (Climate Action) some developing nations rank well above other countries. When it comes to climate action developing nations have been working towards reducing their Greenhouse Gas (GHG) emissions and transitioning to renewable energy sources.

Among the Asian countries, Sri Lanka takes 83rd place with a country score of 69.4 and has accomplished 79.1 % progress in achieving the SDG goals. Sri Lanka has significant potential for renewable energy sources such as solar, wind, and hydropower. Developing these resources can help to reduce the country's dependence on fossil fuels and lower GHG emissions. United Nations has pointed out that, increasing access to energy services will have multiple positive effects including, increasing productivity in the agricultural, industrial and tertiary sectors [39, 42-43]. Energy has been identified as one of the important factor central to sustainable development and achieving SDG targets and the way of gaining energy is affecting specially for the SDG 13. This will affect all aspects of livelihoods impacting agriculture, health, sanitation, and equality [44]. Thus, it is understandable that achieving SDGs would only be a dream unless there is energy sufficiency for all countries [45].

Countries would have to revamp their entire economies in order to reduce emissions to the levels needed by the Paris agreement. Following the pandemic situation, countries like Sri Lanka, has the option to start on green economic recovery initiatives that reduce carbon-intensive and environmentally destructive industries such as fossil fuel production as they are rich with economically viable natural resources.

As Sri Lanka is some country rich with renewable energy sources and natural resources, there is a huge potential to reduce the environmental and climate footprints which means the use of natural resources such as water, solar power, forest cover but also the output of greenhouse gas emissions, air pollution, or waste which is crucial to mitigate climate change and offers other important benefits as well. Improving energy and resource use efficiency, investing in renewable energy sources, and making industrial processes cleaner, leaner, and less wasteful would make them more competitive, productive, and less reliant on precious resources. Furthermore, green and sustainable development will increase human health and well-being, secure long-term survival, and preserve natural ecosystems and their services. Further, Climate change presents chances for sustainable, green, nature-positive, and socially responsible entrepreneurship at the national and local levels in Sri Lanka. This encompasses entrepreneurship and start-ups focused on renewable energy and clean technology, as well as a much broader range of activities such as innovations in food systems, sustainable fashion, ecotourism, holistic waste management, re-cycling or upcycling, and green finance.

Global warming is caused by an excess of greenhouse gases, such as carbon dioxide, which traps Earth's heat and generates a thick yet invisible blanket in the upper atmosphere. Forests, in particular, operate as ''carbon sinks,'' removing significant volumes of $CO_2$ from the atmosphere. Plants are the only source of oxygen on our planet, while also absorbing carbon dioxide from the atmosphere and channeling carbon - which is hastening global warming - into the ground via the biosphere. However, if trees are chopped down, the process reverses and most of the trapped carbon is released back into the atmosphere. Hence, removing the forest cover and natural vegetation and degradation of forest cover have been highlighted as major contributors to global warming [46]. As, Sri Lanka is some country rich with a huge vegetative forest cover there is a huge opportunity to make use of it without doing deforestation, but planting more and more trees in order to facilitate climate resilience. Parallel to these implementations, development of policy frameworks and productive actions are required to preserve forest covers through legal frameworks, policies that enact the protection of agriculture lands from converting to alternative uses, strategies to limit human-wild animal conflicts with preserved land covers and protective measures, protect the environmental ecology while implementing the rural development programs especially the natural water bodies and bio-diversity in the area [47].

Sri Lanka is a country which is highly vulnerable to climate change due to its high temperatures, unique and complicated hydrological cycle, and sensitivity to catastrophic weather events [48]. Therefore, Sri Lanka is frequently affected by the variable climatic changes like floods, drought and landslides. Many scholars also found out that the temperature in Sri Lanka is rising rapidly at each and every part of the country through analyzing the meteorological data taken from time to time. As a result, many of the effects like rising atmospheric $CO_2$ concentration, Increasing the concentration of Green House Gases, Increasing the concentration of climate altering pollutants (non-$CO_2$), Progressive increase in acidity of rainfall is happening and those physical effects may create many hazards and vulnerabilities to different sectors. They may have a variety of effects on sectors with socioeconomic results. According to experts, the same physical effects could have distinct consequences on different sectors [47]. Prolonged physical effects may create huge impacts for the farmers, entire agricultural sector and many other sectors and as a result huge economic impacts can be happened. So, it is very much challenging for Sri Lanka to improve the agricultural sector to gain a positive impact for the economy and also to achieve the SDG 13.

Many developing countries like Sri Lanka continue to face challenges such as high levels of Economic drawbacks, inequality, political instability, and environmental degradation. Overall, while developing countries have made progress towards achieving the SDGs, continued efforts are needed to ensure that no one is left behind and that the SDGs are achieved by 2030 [49]. In fact, with respect to SDGs there has been an improvement up until 2019, but with the onset of the Covid-19 pandemic and most of the countries being hard hit, the trends show a stagnation and a downward trend [38]. It was the bottom income cohorts are the ones who were heavily affected by the pandemic. Environmentally also, there has been greater pressure on natural resources and pollution with the onset of the pandemic [50]. Sri Lanka is also one of a country which was hardly hit by the pandemic situation. Further, depending on the country characteristics and how the government approached the pandemic the effect has been different.

**Technology**: Lack of proper financial aids and assistance and the current economic recession have created great challengers to achieve the SDG 13 targets and to implement proper climate resilient projects through integrating the new advanced technologies. Even though, there is a higher intellectual capacity within the country, due to the lack of proper facilities and the technologies it was much difficult to make use of the knowledge of the experts. The non-exclusion policy of the SDG highlights the importance of achieving SDG at a global scale where developing and under-developed countries largely require financial assistance to fill the infrastructure and funding gaps [51]. The worldwide economic recession, geopolitical environmental conflicts are more likely to reduce such support and slower the rate in achieving certain SDG targets. The challenges to achieve the SDG are exhibited within them. The negative interactions between SDG; SDG10, SDG12, SDG13, and other goals impede overall progress [15, 35]. They are not totally applicable to all nations. Some targets, indices and goals are unachievable or difficult to reach by Sri Lanka and other developing nations within their capacities and required financial assistance from developed nations, and suitable alterations to targets, sub-goals that suited them, indices and methods of monitoring progress will be more suitable in achieving the SDG by developing nations like Sri Lanka [33, 35, 52]. The fragmented nature of the collecting and communication of biodiversity information indicates the requirement of prioritizing the existing responsible institutions to build the capacity to develop biodiversity indicators and related metrics to enable effective decision making and monitor the progress of SDG.

Further, the developing countries like Sri Lanka and under-developed countries are lacking with advancing their infrastructure to obtain information, assess and utilize them in the decision-making process; GIS technology. Therefore, it is much difficult for them to predict the climate changes and to take adoptive measures. Certainly, the poor decision-making is a result of lack of awareness, poor use of available information and lack of technological advancements in these countries. The solution would be networking with researchers in developed countries to practice the better use of information and technology in decision-making process with the standardization and verification of the process [52].

**Governance:** Though, we identify governance as the main challenge that Sri Lanka face in achieving the SDG 13 and ES, this also includes other factors such as leadership, political will, administration/bureaucracy, corruption, the efficiency of the state and other institutions etc. In some, this includes all the human-related aspects. Given the level of natural resources endowment and biodiversity in a country, the country should be wise enough to use those resources wisely and productively. Unfortunately, Sri Lanka show very poor level of governance aspects. Governance includes from the national state level to, regional governance, local level as well as governance in institutions. The loopholes still exist in the cooperation and alliances among the public sector, the private sector and civil society and they limit the achievability of SDG 13.

In most of developing nations, the legislation is amendable with the change of political party which is a result of poor growth in GDP [53]. This is a serious long-term issue to achieve a consistent progress in SDG; Goal 16 and enact the policies of enforcing the SDG. Therefore, to maintain a transparent and upgraded legislation system it is essential to store a national legal system untouchable by the governing party for their advantage. This will enforce the other institutions to design efficient and productive policies i.e. environmental legal modelling [54] especially in environmental resource management and protection with an environmental governance point of view [55]. This kind of a legal situation will reduce the overexploitation of biological and natural resources and scarce energy sources, thereby ensure the climate resilience within Sri Lanka.

**Livelihood prosperity:** Poverty hinders the capacity of developing and underdeveloped countries from achieving the SDG i.e. Goal 2,13,4 and 6 [56]. If we can reduce the poverty in Sri Lanka and improve the livelihood wellbeing of the country, it will ultimately result for an economic boost. Then the economic conditions of the rural populace as well as farmers will strengthen and they would be able to adopt for smart climate resilient projects. One long term strategy to alleviate poverty in Sri Lanka is to develop an employment-oriented education system [57]. To popularize the school education system especially in rural, the daily lunch program could improve the attendance of rural children and support to achieve more than one SDG i.e. Goal 1,2 and 4 directly and indirectly 5, 9 and 13. This is a long term plan and when people are knowledgeable most of them will have goods and individual income levels will enhance. Ultimately it will result for the economic development. Well targeted livelihood development and infrastructure development programs; transportation, electricity; with sustainable energy sources e.g. *solar* power, wind-power or hydro-energy will thrive the rural economy, to achieve SDG 7, 8 and 11 and then to achieve SDG 13 through adopting advanced smart climate resilient projects.

Parallel to these programs, the institutional and legislation framework could work with the support of international aids to improve the access to clean water, sustainable agricultural production and practices and sustainable livelihoods under different industries even at rural regions and convert the identity as regional areas. This is essential as low-income countries' development is highly dependent on healthy soil, clean water, and climate-sensitive sectors such as agriculture bear the greatest burden of climate change and pollution [58].

Further, the sustainable city planning in rural communities will deliver them a better shelter, access to basic requirements; food, water, shelter, education and health. This will minimize the slum dwelling in urban areas due to urban migration and enhance the rural economic condition and the possibility to adopt climate resilient projects and to use smart agricultural technologies. Further, the legislations should be imposed against over-fishing, harvesting important and endangered marine species, a strong legal action against the pollution i.e. oil spills, destructions and damages occurred for sea and marine resources. Then it will ultimately reduce the use of scarce resources and nonrenewable energy sources; emission of GHG.

**Sustainable environment**: High demand for agriculture products in international trade; Cinnamon, Coffee, Tea, Floriculture products, accelerated the deforestation of tropical forest cover deforestation, overuse of agricultural land, and thus threatening carbon sequestration [59, 60]. Further, this cause for more of agriculture production that cause the degrade soils, pollute and deplete water supplies, and lower biodiversity and reduce the climate resilience. Therefore, effective agricultural policy framework should be designed and enacted to address the areas such as; agriculture land use policies, regulations and policies in chemical application, import restrictions and pricing policies to protect the local farmer with fair pricing. Policymakers could incorporate a more balanced mix of instruments and those addressing different dimensions of land use while redesigning their policy or strategy documents to implement SDGs [61].

Degradation of ecosystem due to main economic activities is inevitable. Therefore, these conflicted interactions among the SDG should be thoroughly assessed and addressed. Risks imposed by climate change on production; droughts, floods, pest attacks and, deficiencies in the availability of even basic needs; clean water, clean energy are key challenges [62]. And it threatens agriculture production, compromises the safety of urban infrastructures [63]. Insuring the properties and agriculture production against such conditions, especially in developing economies is essential.

Overall, environmental degradation and pollution increase the development gap and heighten inequalities between countries. The main example is that the Low-income countries, where development is highly dependent on healthy soil, clean water, and climate-sensitive sectors such as agriculture bear the greatest burden of climate change and pollution (SDG 10) [64, 65]. Progress in sustainable energy, responsible production and consumption, economic growth, decent work and climate action (SDG 7, 8, 12 and 13) hampered by environmental pollution and the loss of natural capital [66]. affected by land degradation and pollution, and climate-related natural disasters cost $155 billion in 2018 [67].

**Challengers for other developing nations**

According to the [41] Tunisia, the best-performing country in North Africa, is ranked 58$^{th}$ – having accomplished 75.1 percent of the progress with a country score of 72.5, followed by Morocco (72.3%) and Algeria (63.2 %). Nearly 70% of the over 140 million Nigerians currently live below the poverty line of one dollar per day [68]. The rapid urbanization, put at over 5 percent per annum, exerts severe pressure on ailing infrastructure. Nigeria is further ranked as one of the twenty-five poorest nations in the world. This further intensifies youth unemployment. Due to the financial instability prevailing in these countries, it is a huge challenge for them to adopt for most of the climate resilient projects.

Nigeria ranked 146th and accomplished 58.6 % of its performance in achieving the SDG goals [41]. This evidence suggests that the reforms and policies have not recorded the spectacular results expected through SDGs. Thus, poverty alleviation remains a mirage in Nigeria [46]. Twenty of the 29 countries with SDGs scores between 50 and 60 percent are from Africa, while 19 of the 21 countries scoring less than 50 percent are also from the continent. The SDGs are, therefore, a call to action on sustainable development in Africa. Ensuring economic growth positively impacts social and environmental pillars commensurately should be Africa's shared vision on SDGs' implementation [69,70].

Among the developing countries in Asia, India plays a critical role in the adoption and success of the SDGs [71] due to its high share of the global burden of challenges [72], such as extreme inequalities in socioeconomic and demographic indicators, which has a significant impact on global growth rates. The discussion of India, with its massive population, enhances the SDGs' 'Leave no one behind' objective [73]. However, India's current sustainability plan appears to be lacking and calls for greater attention to social and environmental concerns, [70] such as high poverty rates and a huge, undernourished population. India has achieved a 63.4 country score and obtained the 112th country ranking from the SDG goal achievement. It has achieved 78.2 % of performance [38].

## Conclusions

People saw SDGs as a way of new global governance mechanisms to achieve sustainable development. This has been an important approach, particularly for developing nations that are marred by many issues including inefficiency, poor governance, lack of leadership and political will. Though developing nations face a plethora of problems, SDGs provided a framework that national governments were nudged to follow. SDGs also increased the awareness among the general public and people also expected and demanded that the leaders they elect support the achievement of SDG. This has been one of the great innovations that indirectly made the nations to follow better policies and programs to meet the SDG targets. However, achieving the targets are not easy, especially when there are synergies and tradeoffs are present within the SDGs. Thus achieving SDGs while ensuring ES is indeed a task that needs lots of forces to join hands and favorable policies that may not be very popular among the citizens.

In this paper, we discuss the importance of achieving SDGs while ensuring ES and come up with a framework to discuss the challenges and opportunities the developing nations face in achieving the SDG targets. We review the existing literature related to achieving SDGs and sustainable development and aggregate the SDGs based on these identified challenges and opportunities into a matrix, mostly based on the experiences of the developing countries. We identify SDGs under five dimensions to link them with ES: Life prosperity, sustainable economy, affordable technology applications, sustainable environment, and governance. Then we relate these opportunities and challenges with ES. Our contribution to SDG literature stems from the creation of the matrix based on the challenges and opportunities available in developing countries. Further, based on country experiences we propose what would be the way forward in achieving SDGs ensuring ES. This discussion provides informative insights into challenges faced in implementing SDGs whilst ensuring environmental sustainability.

**The way forward**: The future of SDGs would have been different if it is not for the pandemic. Yet, the pandemic has taught us lessons on how to move forward while having modest expectations. Further, global catastrophes have a greater spillover effect on many countries and sectors than regional or local disasters. There have been many indicators and measurements proposed to gauge the progress of SDG indicators. When it comes to developing countries, the main challenges are related to management, governance, and personnel. Unless these issues are tackled it will be very difficult to sustain the benefits of whatever progress that have been met. This also leaves an avenue to discuss moving from quantity to quality in achievements in these indicators. In terms of timeline, it is better to target the foreseeable future than aim for a distant timeline, however, it is also important to realize that in the developing world, progress happens very slowly. People always give priority to livelihoods and economic benefits than to the environment, unless otherwise, they realize that their livelihoods depend on the ES. The middle-income and the public who do not depend directly on the environment, will take some time to understand this reality. Further, technology adoption is still lagging behind in developing countries. Though ICT and mobile technologies have penetrated to the interiors in every country, still the benefits are not fully materialized, even in state institutions. For some, the progress has been affected by the last mile problems. Thus, understanding the bottlenecks at the user end is important. If the bottlenecks are clearly identified, then at least a part of the SDG achievement can be ensured.

Trading and investment enable the developing economies to achieve a significant economic growth in Asia-Pacific region. Now the major concern is to interlink with the actions against climate change to decrease the Greenhouse Gas (GHG) emissions. The connection between trade and investment and climate change actions against the is complex. However, several actions could be promoted; 1. entering into a common agreement to maximize the positive effects by promoting trade and investment in renewable energy and low-carbon technologies, digitalizing possible activities to minimize the transporting and waiting time which directly leads to GHG emission, adopting paperless trade and to make it more “climate-smart” with a low carbon footprint. Further, it could support the adoptions towards climate change by making the goods and services more available and affordable i.e. irrigation systems. Taking government actions to promote a low carbon economy and extending it towards trade by Carbon taxing (C-taxing), i.e. in country C-taxing to avoid Carbon Border Adjustment Mechanism (CBAM). This government income could be investing back in homeland to develop more carbon neutral technologies and efficiency improvements especially in steel, cement, fertilizer and agricultural production, aluminum like industries, to develop infrastructure to generate renewable energy, i.e. solar power and implement reforestation programs [74].

In Summary, it is our understanding that from the experiences of the developing countries, two aspects need immediate attention which can reduce the cost, improve productivity and reduce the damage to the environment. Those two are governance and management, and the use of affordable technologies including Information and communication technology. Other challenges exist under livelihood prosperity, sustainable economy, and sustainable environment dimensions. But all these challenges have been turned into opportunities in countries where there is good governance and political will.

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## Conflict of interest
The authors declare no conflict of interest.

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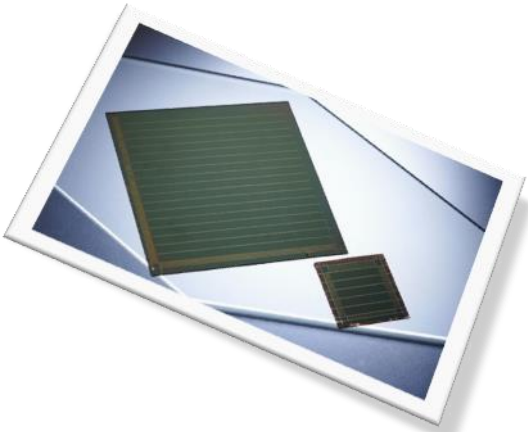
# Advances in solar energy technologies: Harnessing the power of the sun for a sustainable future



# Advances in solar energy technologies: Harnessing the power of the sun for a sustainable future

H.M.T.P. Herath*

**Abstract**

Solar energy has emerged as a key player in the global transition towards a sustainable and clean energy future. This abstract delves into the remarkable advances in solar energy technologies, highlighting their potential to revolutionize the energy landscape. Harnessing the abundant and renewable power of the sun has become an imperative as societies seek to mitigate climate change and reduce their dependence on fossil fuels. Recent developments in photovoltaic (PV) technology have significantly improved the efficiency and affordability of solar panels. Innovations such as perovskite solar cells and bifacial modules promise to further enhance energy capture and utilization. Additionally, advancements in energy storage solutions, such as lithium-ion batteries and novel materials like graphene, are enabling the efficient storage and utilization of solar-generated electricity, even during cloudy or nighttime conditions. Moreover, grid integration and smart grid technologies are facilitating the seamless integration of solar power into existing energy infrastructures. Artificial intelligence and machine learning algorithms are optimizing energy production and consumption, enhancing system reliability and efficiency. Furthermore, concentrating solar power (CSP) and solar thermal technologies are evolving, offering the potential for large-scale energy production and industrial applications. This chapter underscores the transformative potential of solar energy, emphasizing its pivotal role in addressing global energy challenges and achieving a sustainable future. With ongoing research and innovation, solar energy is poised to become a cornerstone of the world's clean energy portfolio, contributing significantly to a eco-friendlier and resilient energy landscape.

**Keywords**: clean energy, photovoltaic technology, renewable, solar power, sustainable

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## Introduction

The world stands at a pivotal moment in history, seeking solutions to address the pressing challenges of climate change and environmental degradation. From ancient civilizations using passive solar heating techniques to modern photovoltaic systems, solar energy has been harnessed in various forms throughout human history. The photovoltaic effect, which refers to the generation of electrical current when certain materials are exposed to light, was first observed in 1839 by French physicist Alexandre-Edmond Becquerel[1]. Then, American inventor Charles Fritts is credited with creating the first true solar cell in 1883 and he coated a thin layer of selenium with a very thin layer of gold to create a semiconductor junction [2].

It's important to note that while these discoveries laid the foundation for photovoltaic technology, it wasn't until the mid-20th century that significant advancements in solar cell efficiency and practical applications were achieved. Today, photovoltaic cells, often made from silicon or other semiconductor materials, are widely used for generating electricity from sunlight in solar panels. Renewable energy sources offer a beacon of hope, with solar energy leading the charge towards a cleaner and sustainable future. The world is at a critical juncture, facing the urgent need to transition from fossil fuel-based energy sources to sustainable and renewable alternatives. At the forefront of this energy revolution is solar power, an abundant and clean resource that has the potential to transform our global energy landscape. Solar energy offers a myriad of environmental and social benefits that transcend traditional fossil fuel-based energy sources, making it a popular and environmentally friendly source of renewable energy.

In this chapter, it will delve into a comprehensive exploration of various topics within the realm of solar energy. The chapter commences with an in-depth analysis of Photovoltaic (PV) Systems and the functioning. Solar Cell Types and their recent advancements are examined to provide a nuanced understanding of the evolving landscape. A significant focus is directed towards Thin-film and emerging materials for PV, exploring the cutting-edge technologies that drive efficiency. Building-Integrated PV (BIPV) are elucidated as a concept, emphasizing its integration into architectural designs. The chapter is then shifted its focus to the Environmental and Social Impact of PV, contemplating the broader implications of widespread solar energy adoption. Concentrating Solar Power (CSP) and Hybrid Solar Power Systems are discussed, including the synergies achieved by combining PV and CSP for higher efficiency. Solar-thermal-electric hybrids and their potential for round-the-clock power supply is explored.

Furthermore, the integration of solar with other renewables for hybrid power plants are examined, encompassing both grid-connected and off-grid hybrid systems. Microgrid applications and community-based hybrids are also be considered to highlight localized approaches. Emerging Concepts in Solar Energy are introduced, shedding light on novel ideas and technologies shaping the future of solar energy. The chapter progresses to Solar Energy Storage Solutions, addressing the challenges and importance of energy storage for solar applications. Solar Energy Grid Integration are discussed with a focus on its environmental impact and sustainability. The role of Artificial Intelligence and smart solar systems are explored as transformative elements in the solar energy landscape. In conclusion, the chapter provides a synthesis of the discussed topics, offering insights into current advancements and contemplating future prospects in solar energy.

### Photovoltaic (PV) systems

Photovoltaic (PV) systems, often referred to as solar power systems, are technology installations that convert sunlight into electricity[3]. These have become increasingly popular as technology advancements and government incentives have made them more accessible and cost-effective. They play a crucial role in transitioning to a sustainable and clean energy future without having negative environmental impacts. These systems are designed to capture photons from the sun and convert its energy into electrical current through the photovoltaic effect. The three types of PV systems are; Grid-Tied PV systems, Off-Grid PV systems, and Hybrid PV systems in Figure 1, Figure 2 and Figure 3 respectively [4-6].

Utilizing a standard grid-tied inverter, this solar setup constitutes a fundamental configuration. The absence of a battery bank for storage characterizes the grid-tied solar PV system. Power generation and consumption are limited to daytime hours within this setup. Notably cost-effective, the system boasts simplicity in design, ease of management, and minimal maintenance requirements. Figure 1 provides a schematic representation of this grid-tied solar system.

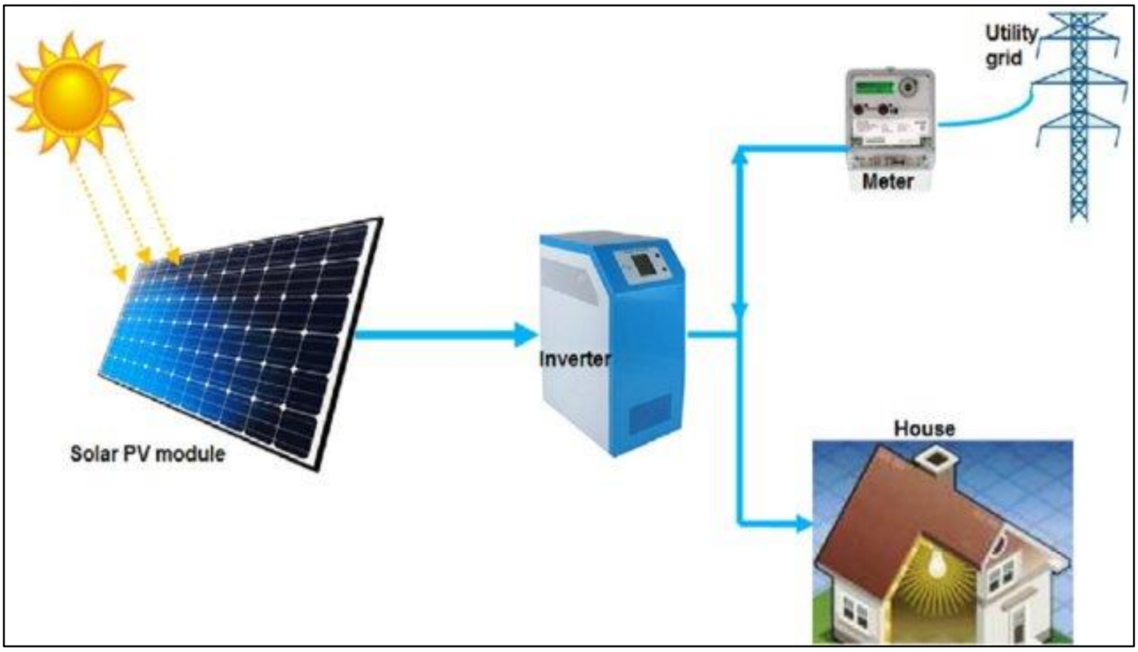


**Figure 1.** Grid Tied PV System (Source: Awasthi *et al.,* 2020)

For individuals unable to easily connect their load to the grid, an off-grid PV system proves advantageous. Off-grid solar PV systems incorporate batteries to store electricity generated during the day, ensuring availability for future use or emergency situations, such as cloudy days or nighttime. The system's design must account for year-round conditions and weather fluctuations. During prolonged periods without sunlight or snow accumulation on PV panels, backup generators become essential. Gasoline, diesel, petroleum, or propane can serve as fuel for these generators. The AC output from backup generators can be directly utilized, or if needed, converted into D.C. for storage in batteries. Figure 2 provides a schematic representation of this off-grid solar PV system.

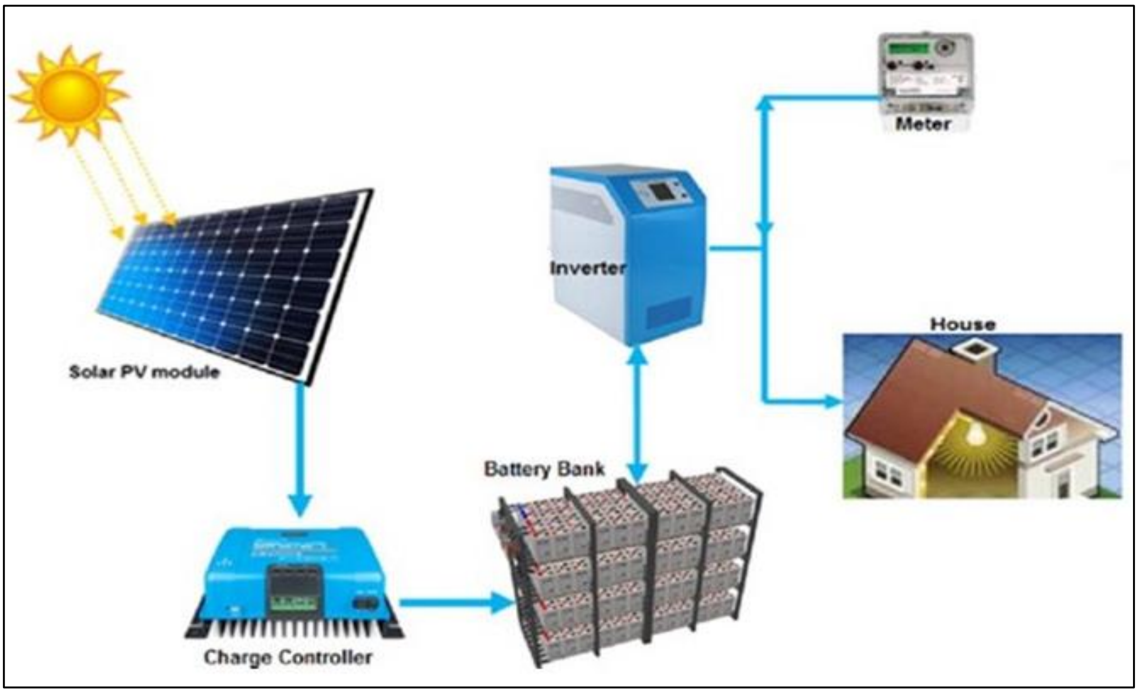


**Figure 2.** Modified schematic diagram of an Off-Grid PV System (Source: Awasthi *et al.,* 2020)

The hybrid energy system illustrated in Figure 3, comprised PV modules and a vertical wind turbine, each equipped with dedicated inverters. To regulate the energy generated by these systems and address the electricity demands of the load source, specifically the residential building, a microgrid controller was employed. This controller also oversaw the charging and discharging of the battery bank and facilitated the buying and selling of power to the utility grid through a smart meter.

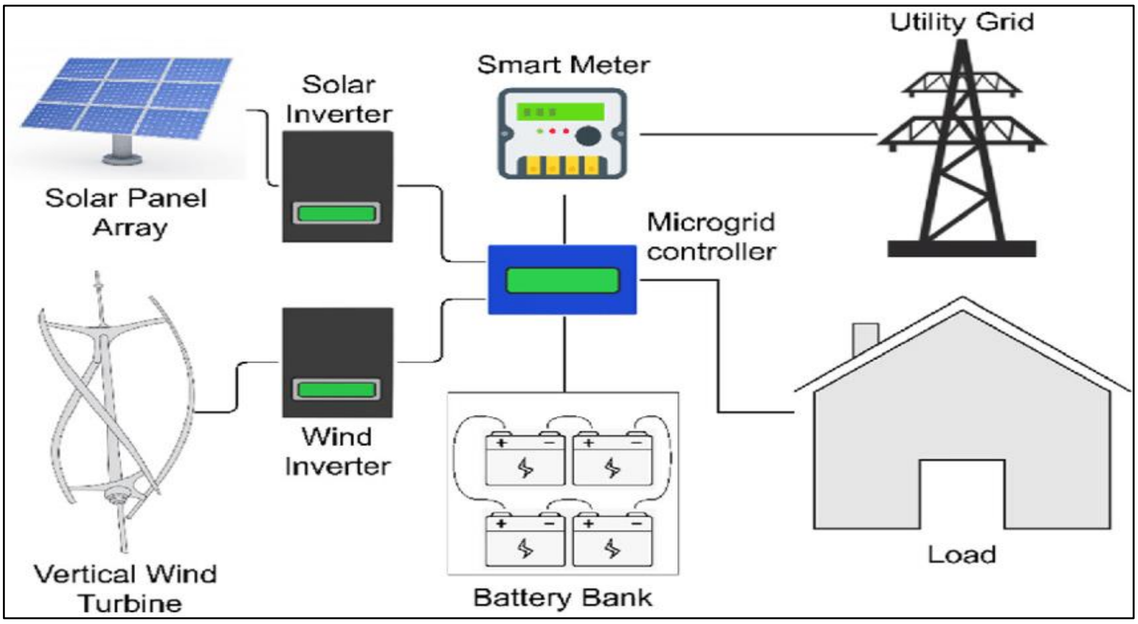


**Figure 3.** Hybrid PV System (Source: Awasthi *et al.,* 2020)

## Solar cell types and its advancements

### Crystalline silicon cells: Improvements and efficiency gains:

Crystalline silicon solar cells, often referred to as c-Si solar cells, have been the dominant technology in the photovoltaic industry for many years [7]. Continuous research and development efforts have led to significant improvements and efficiency gains in crystalline silicon solar cell technology. Here are some of the key advancements and efficiency gains related to crystalline silicon cells:

1. Single-Crystal (Monocrystalline) Silicon Cells:
    - Higher Efficiency: Monocrystalline silicon cells have seen improvements in efficiency due to enhanced cell designs and better materials (pseudosquare wafers of silicon). Their average efficiency is 13-20%, with some advanced designs exceeding 25% [8]. These higher efficiencies mean more electricity is generated for the same surface area.
    - Reduced Manufacturing Costs: Advances in crystal growth techniques, such as the Czochralski method and the Float Zone method, have made monocrystalline silicon wafers more affordable to produce, reducing manufacturing costs[9].
    - Thinner Wafers: Thinner wafers reduce material costs and improve light absorption, making the cells more efficient. New slicing techniques and wafer handling technologies have allowed for thinner monocrystalline wafers [10].

2. Multi-Crystalline (Polycrystalline) Silicon Cells:
    - Improved Grain Structure: Polycrystalline silicon cells have benefited from improved grain structures, which reduce electron recombination and increase overall efficiency [11]. These advances have narrowed the efficiency gap between monocrystalline and polycrystalline technologies.
    - Texturing and Anti-Reflective Coatings: The application of textured surfaces and anti-reflective coatings on polycrystalline cells has improved their light-capturing capabilities and enhancing efficiency.

3. Bifacial Solar Cells:
    - Bifacial Design: Bifacial solar cells can capture sunlight from both the front and rear sides, allowing them to generate electricity from reflected and indirect sunlight [12]. This design can significantly increase energy yield, especially in locations with reflective surfaces like snow or white rooftops.

4. Passivated Emitter Rear Cell (PERC) Technology:
    - Rear Passivation: PERC technology involves adding a passivation layer to the rear side of the solar cell, reducing electron recombination and increasing cell efficiency. PERC cells have become widespread and have achieved efficiencies exceeding 23% [13].

5. Heterojunction Technology:
    - Incorporation of Thin-Film Layers: A crystalline silicon cell sandwiched between two layers of amorphous “thin-film” silicon. This approach can boost efficiency by reducing electron recombination at the cell's surface [14].

6. Tandem Solar Cells:
    - Layering Multiple Cell Types: Tandem cells are stacks of p-n junctions, each of which is formed from a semiconductor of different bandgap energy. Each respond to a

different section of the solar spectrum, yielding higher overall efficiency. By stacking the component cells in order of decreasing bandgap. These designs have the potential to achieve very high efficiencies by optimizing light absorption [15].

7. Improved Manufacturing Processes:
    - Automated Production: Advances in automation and precision during manufacturing have reduced defects and improved the overall quality of crystalline silicon cells.

8. Reduced Material Usage:
    - Thinner Silicon Wafers: Reducing the thickness of silicon wafers while maintaining performance has become more common. This practice helps in reducing material costs and improving light absorption.

9. Recycling and Sustainability:
    - End-of-Life Considerations: The industry has started focusing on recycling and reusing materials from end-of-life solar panels to minimize environmental impact [16].

**Thin-film and emerging materials for PV:**
Thin-film solar cells and emerging materials represent an exciting area of research and development within the photovoltaic (PV) industry. These technologies offer unique advantages and have the potential to complement traditional crystalline silicon solar cells. Here are some popular thin-film and emerging materials for PV:

1. Thin-Film Solar Cells

Thin-film solar cells are characterized by their use of very thin layers of semiconductor materials to capture sunlight and generate electricity. They are generally less efficient than crystalline silicon solar cells but have other advantages, including flexibility, lightweight design, and potential cost savings [17]. Some common thin-film technologies include:

- Amorphous Silicon (a-Si): Amorphous silicon thin-film solar cells are made of non-crystalline silicon, which is deposited in thin layers on various substrates, including glass and flexible materials. While a-Si cells have lower efficiency compared to crystalline silicon, they perform well in low-light conditions and are used in applications such as building-integrated photovoltaics (BIPV) and consumer electronics [18].
- Cadmium Telluride (CdTe): CdTe thin-film solar cells use cadmium telluride as the semiconductor material. They have achieved relatively high efficiency levels and are known for their cost-effectiveness [19].
- Copper Indium Gallium Selenide (CIGS): CIGS thin-film solar cells incorporate copper, indium, gallium, and selenium compounds. Thin-film technologies offer higher efficiencies compared to some alternatives. Additionally, these technologies are known for their flexibility, making them well-suited for various applications. Examples include portable solar chargers and lightweight modules. Their adaptability broadens their usability in diverse contexts.

2. Emerging Materials for PV:

Researchers are continually exploring new materials and innovative technologies to improve the efficiency, performance, and versatility of solar cells. Some emerging materials and concepts in the PV field include:

- Perovskite Solar Cells: Perovskite solar cells have garnered significant attention due to their rapid efficiency improvements and the potential for low-cost manufacturing. Perovskite materials are easy to synthesize and can be applied as thin-films or in tandem with other solar cell technologies. They have the potential to rival the efficiency of crystalline silicon cells [20].
- Quantum Dot Solar Cells: Quantum dots are nanoscale semiconductor particles that can be tuned to absorb specific wavelengths of light. Quantum dot solar cells are being researched for their potential to capture a broader spectrum of sunlight and increase efficiency. They can be applied as a thin-film or integrated into other PV technologies [21].
- Organic Photovoltaics (OPV): Organic photovoltaics use organic materials, such as polymers or small molecules, as the active layer to convert sunlight into electricity. OPV cells are lightweight, flexible, and potentially cost-effective. They are mainly used in niche applications, such as flexible solar panels for portable electronics [22].
- 2D Materials: Two-dimensional (2D) materials, like graphene and transition metal dichalcogenides (TMDs), are being explored for their potential in enhancing the performance of solar cells. These materials have unique electronic properties that could improve light absorption and charge transport [23].

**Building-Integrated PV (BIPV):**

Building-integrated photovoltaics (BIPV) is a technology that integrates solar photovoltaic systems directly into the building envelope, effectively turning the building itself into a solar power generator. Figure 4 provides examples of common BIPV products and their application types. BIPV systems serve both as functional building components and renewable energy generators.

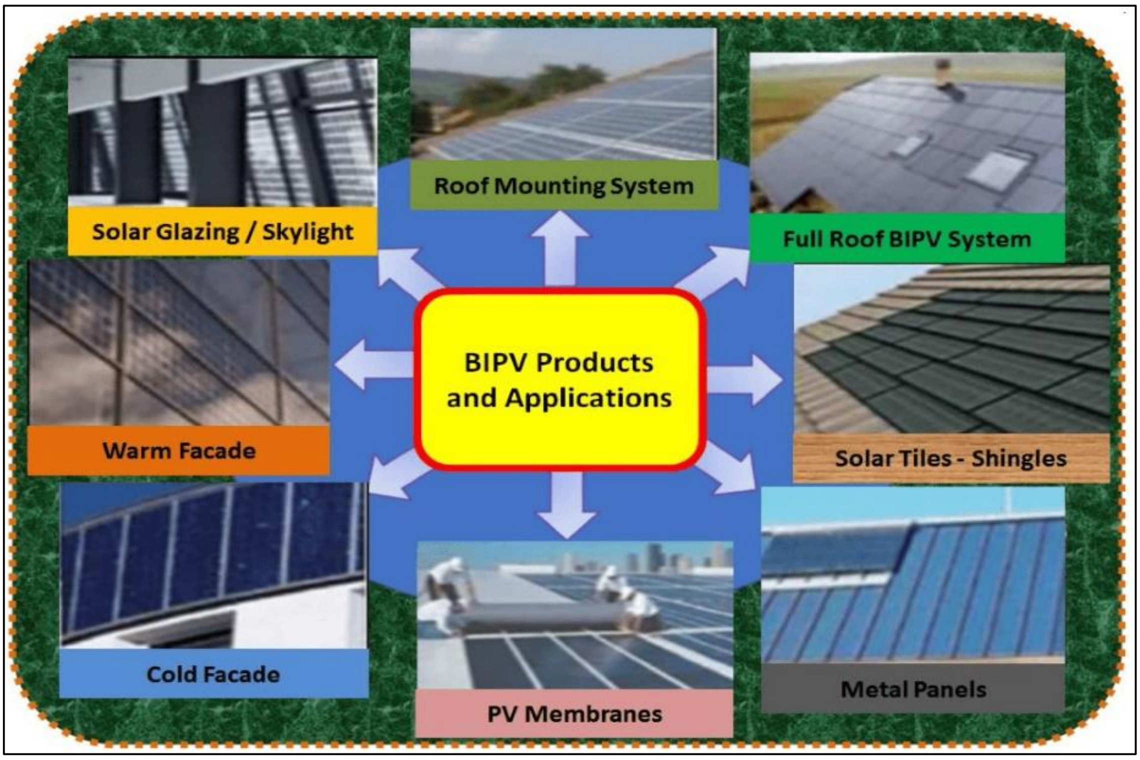


**Figure 4.** BIPV products and their applications (Source: Basher *et al.,* 2023)

Key aspects of BIPV:

1. Integration into Building Elements:

BIPV systems are designed to seamlessly blend with various building components, including:

- Solar Roof Tiles or Shingles: These replace traditional roofing materials, such as asphalt shingles or clay tiles, and capture sunlight to generate electricity. They are designed to be aesthetically pleasing and can mimic the appearance of conventional roofing materials.
- Solar Facades: BIPV can be integrated into building facades, such as curtain walls, windows, or cladding, to generate electricity while also serving as architectural elements. Solar panels can be incorporated into the design, sometimes with transparency to allow natural light to pass through.
- Solar Awnings and Canopies: These are often used in commercial buildings and parking structures to provide shade while generating electricity. Solar awnings and canopies can also serve as charging stations for electric vehicles.
- Solar Balconies and Railings: BIPV systems can be integrated into balconies and railings, adding a dual function of generating electricity and providing safety and aesthetics.
- Solar Building Materials: Some BIPV solutions use solar-active materials directly in the construction of walls, floors, and other building components. These materials can capture sunlight and convert it into electricity or heat [25].

2. Aesthetics and Design:

One of the primary goals of BIPV is to blend renewable energy generation with architectural design. BIPV systems are often customized to match the building's aesthetic requirements, color scheme, and overall design. They can be nearly invisible or designed to make a bold architectural statement, depending on the project's goals.

Energy Generation and Efficiency:

3. BIPV systems generate electricity from sunlight using solar panels or other integrated solar technologies. While they may have slightly lower efficiency compared to traditional solar panels, they contribute to the building's energy needs, reduce utility bills, and often have a favorable return on investment.

4. Environmental Benefits:

BIPV systems reduce the building's carbon footprint by generating clean and renewable electricity. They help decrease greenhouse gas emissions and reliance on fossil fuels for electricity generation.

5. Cost and Return on Investment:

The cost of BIPV systems can be higher than traditional solar panel installations due to the need for specialized materials and design considerations. However, they can provide savings over time through reduced energy bills and potential incentives or tax credits. The return on investment depends on factors like location, energy consumption, and available incentives.

6. Market and Applications:

BIPV systems are commonly used in both residential and commercial buildings. They are especially popular in urban environments where space is limited, and aesthetics play a crucial role in building design. BIPV can be retrofitted onto existing buildings or incorporated into new construction projects.

7. Challenges:

Challenges in BIPV include initial cost, design complexity, and the need for skilled installers. Additionally, the technology is continually evolving, and integrating the latest solar advancements into building materials and designs can be a complex process[26].

**Environmental and Social Impact of PV:**

Photovoltaic (PV) solar energy systems have both environmental and social impacts, many of which are positive but also include some challenges and considerations. Here's an overview of the environmental and social impacts of PV:

Environmental Impact:

1. Reduction in Greenhouse Gas Emissions: PV systems generate electricity without emitting greenhouse gases, helping to reduce carbon dioxide ($CO_2$) and other harmful emissions associated with fossil fuel-based power generation. This has a positive impact on mitigating climate change and air quality improvement.
2. Conservation of Natural Resources: PV systems reduce the need for extracting and burning fossil fuels, which helps conserve finite natural resources like coal, oil, and natural gas. They also have a lower water consumption footprint compared to many conventional power plants, which is significant in water-scarce regions.
3. Reduced Land and Habitat Disruption: PV installations typically require less land area than some other forms of renewable energy generation, such as wind farms. Additionally, PV arrays can be built on brownfield sites or integrated into existing structures, minimizing land use change and habitat disruption.
4. Lower Energy Payback Period: As PV technology advances and becomes more efficient, the energy payback period continues to decrease. This trend contributes to making PV systems more environmentally favorable. The decreasing energy payback period signifies a more rapid offset of the environmental impact associated with the production and use of photovoltaic systems. This improvement aligns with the broader goal of sustainable and eco-friendly energy solutions.
5. Minimal Air and Water Pollution: PV systems have a minimal impact on air and water quality compared to fossil fuel power plants, which release pollutants and toxins into the atmosphere and waterways [27].

Social Impact:

1. Job Creation: The PV industry creates jobs in manufacturing, installation, maintenance, and research and development. This contributes to local and regional economies and provides employment opportunities in both urban and rural areas.
2. Energy Access: PV systems can provide access to electricity in remote or off-grid regions where traditional grid infrastructure is impractical or expensive to install. This improves the quality of life, supports education, and enhances economic opportunities in these areas.
3. Energy Security: By decentralizing power generation, PV systems contribute to energy security by reducing dependence on centralized power plants and foreign energy sources. This can enhance resilience during grid disruptions or natural disasters.
4. Clean Energy Transition: The adoption of PV technology is a significant step in the transition to a more sustainable and clean energy future. It aligns with global efforts to reduce greenhouse gas emissions and combat climate change.
5. Community Solar Programs: Community solar projects allow residents who may not have suitable rooftops for solar panels to invest in shared solar installations. These programs promote community engagement, energy equity, and access to renewable energy[28].

Challenges and Considerations:

1. Resource Use: The production of PV panels involves the use of raw materials, including metals, glass, and semiconductors. Efficient recycling and responsible disposal of old panels are important to minimize environmental impacts.
2. E-Waste Management: As PV systems have a long lifespan, end-of-life management and recycling of PV panels will become more critical to prevent electronic waste from becoming a problem.
3. Land Use Conflicts: Large-scale PV installations may raise land use conflicts, especially in densely populated areas or regions with competing land uses, such as agriculture or conservation.
4. Manufacturing Emissions: The manufacturing of PV panels and other system components can generate emissions, particularly if fossil fuels are used in the production process. Efforts are being made to reduce these emissions through cleaner manufacturing methods[29].

**Concentrating Solar Power (CSP)**

Concentrating Solar Power (CSP) is also a renewable energy technology that focuses sunlight onto a small area using various mirror or lens configurations to generate high-temperature heat. This heat is then used to produce electricity through conventional steam turbines or other heat-driven engines. CSP systems have the advantage of being able to store thermal energy for use when the sun is not shining, providing a reliable and dispatchable source of clean energy[30]. Here are the key components and features of Concentrating Solar Power:

1. Concentrators:

CSP systems use concentrators, such as parabolic troughs, dish reflectors, or tower-mounted heliostats, to capture and concentrate sunlight onto a receiver.

2. Receivers:

Receivers are located at the focal points of the concentrators and are responsible for absorbing the concentrated sunlight and converting it into heat. They can be either linear receivers (used in parabolic troughs) or central receivers (used in tower systems).

3. Thermal Energy Storage:

CSP systems often incorporate thermal energy storage systems that store excess heat generated during sunny periods. This stored thermal energy can be used to generate electricity when the sun is not shining, such as during cloudy periods or at night, providing grid stability and reliability.

4. Heat Transfer Fluids:

In many CSP systems, a heat transfer fluid, such as synthetic oil or molten salt, is used to capture and transport the heat from the receivers to a heat exchanger. This fluid is heated as it flows through the receivers and is then used to produce steam or directly drive a heat engine.

5. Power Block:

The power block is the part of the CSP system where the heat from the heat transfer fluid is used to generate electricity. This can be done through a conventional steam turbine, a Stirling engine, a Brayton cycle engine, or other technologies.

6. Cooling Systems:

CSP plants require cooling systems to dissipate excess heat from the power block and maintain the efficiency of the plant. Depending on the technology, dry cooling or wet cooling systems may be used [31-32].

Types of CSP Technologies:

1. Parabolic Trough Systems:

These systems use curved mirrors to concentrate sunlight onto a receiver tube located along the focal line of the trough. They are one of the most widely deployed CSP technologies [33].

2. Solar Power Tower Systems: In these systems, numerous flat mirrors (heliostats) track the sun and reflect sunlight onto a central receiver at the top of a tower. This approach can achieve higher temperatures and efficiencies than some other CSP technologies [34].
3. Dish Systems: Dish systems use a large parabolic dish to concentrate sunlight onto a receiver located at the dish's focal point. They are often used in smaller-scale applications and for high-temperature research [35].

Environmental Benefits:
CSP technology is a clean and renewable energy source that does not produce greenhouse gas emissions during electricity generation. It helps reduce the reliance on fossil fuels and contributes to climate change mitigation.

Challenges and Considerations:
- CSP plants require a substantial amount of land for the installation of concentrators and receivers.
- High upfront capital costs can be a barrier to widespread adoption.
- CSP is highly location-dependent, with the best performance in regions with abundant sunlight.
- Water usage for cooling systems can be a concern in arid regions [36].

**Hybrid Solar Power Systems:**
Hybrid solar power systems combine two or more different renewable energy technologies, typically solar photovoltaic (PV) and solar thermal, along with energy storage solutions to maximize energy generation and improve system reliability. These systems offer several advantages, including enhanced efficiency and energy availability, making them suitable for a wide range of applications [37]. Here are the key components and benefits of hybrid solar power systems:

1. Solar PV Array:

A solar PV array consists of photovoltaic panels that convert sunlight into electricity. Solar PV is the primary energy source in hybrid solar systems.

2. Solar Thermal Collectors:

Solar thermal collectors capture sunlight to heat a fluid (typically water or a heat transfer fluid) and convert it into thermal energy. This thermal energy can be used for various applications, such as space heating, domestic hot water, or industrial processes.

3. Energy Storage:

Hybrid solar systems often include energy storage solutions, such as batteries, to store excess electricity generated by the PV array during sunny periods. This stored energy can be used during periods of low sunlight or at night, improving system reliability and energy availability.

4. Control and Monitoring Systems:

Sophisticated control and monitoring systems manage the operation of both the PV and solar thermal components, as well as the energy storage system. These systems optimize energy generation and consumption, ensuring efficient operation[38].

Benefits of Hybrid Solar Power Systems:
- Increased Energy Generation: Sunlight brings energy in the term of photon which can be converted to other energy forms where heat is one of them. Then this photon energy also uses to create higher electron concentration in the conduction band by absorbing photon energy. This will lead to generate electricity through the system. This increases the overall energy output compared to standalone PV or solar thermal systems.

- Enhanced Energy Availability: Energy storage allows hybrid systems to provide a continuous and reliable energy supply, even when sunlight is limited or unavailable. This is particularly beneficial for off-grid applications or regions with intermittent grid access.
- Improved Energy Efficiency: Hybrid systems can achieve higher overall energy efficiency by utilizing both electricity and thermal energy for various applications, such as space heating, cooling, or hot water production.
- Diverse Applications: Hybrid solar power systems are versatile and can be customized for various applications, including residential, commercial, and industrial settings. They are suitable for both grid-connected and off-grid installations.
- Reduction in Energy Costs: By using stored energy for on-site consumption, hybrid systems can reduce energy bills and dependence on grid electricity, leading to cost savings over time.
- Environmental Benefits: Hybrid systems reduce the consumption of fossil fuels for heating and electricity, resulting in lower greenhouse gas emissions and contributing to environmental sustainability.
- Energy Independence: The combination of renewable energy sources and energy storage can provide energy independence, especially in remote or rural areas without reliable access to the grid.
- Load Shifting: Hybrid systems can shift electricity consumption to times when it is most cost-effective or environmentally favorable, such as using stored energy during peak demand periods. [39-40].

**Combining PV and CSP for higher efficiency:**
Combining photovoltaic (PV) and concentrated solar power (CSP) technologies can enhance the overall efficiency and reliability of a solar energy system. This approach, often referred to as hybrid solar power generation, capitalizes on the strengths of both PV and CSP systems while mitigating their respective weaknesses. Here are some ways in which combining PV and CSP can lead to higher efficiency:

1. Continuous Energy Generation:

One of the main challenges with PV systems is their intermittent energy production due to variations in sunlight throughout the day and weather conditions. CSP, on the other hand, can provide continuous energy production by using thermal storage systems to store excess energy during the day and release it as needed, even during nighttime or cloudy periods. By integrating the two, you can achieve a more consistent and reliable power supply.

2. Higher Overall Efficiency:

PV panels convert sunlight directly into electricity, while CSP systems capture and convert solar energy into heat before generating electricity. By combining these technologies, you can capture a larger portion of the solar spectrum and increase the overall energy conversion efficiency. This is especially beneficial in regions with high solar resource potential.

3. Optimized Land Utilization:

PV systems require large amounts of space to install solar panels, whereas CSP systems require relatively less land for mirrors or heliostats and a central receiver. By co-locating PV panels with CSP components, you can optimize land use, making it more efficient and cost-effective.

4. Enhanced Energy Storage:

CSP systems often include thermal energy storage, which allows excess heat to be stored and used later to generate electricity. By coupling PV with CSP, excess electricity generated by PV panels during sunny periods can be used to heat the storage medium in the CSP system, increasing the overall energy storage capacity and system flexibility.

5. Redundancy and Reliability:

By having both PV and CSP systems in place, can create a redundant energy source. If one system experiences downtime due to maintenance or unexpected issues, the other can maintain power production. This redundancy improves the overall reliability of the solar energy system.

6. Grid Integration:

Combining PV and CSP systems can provide a more stable and controllable output, which makes it easier to integrate the solar power into the grid. Utilities can benefit from this predictability and optimize their grid operations accordingly.

7. Cost Savings:

By sharing infrastructure, such as transmission lines, substations, and land, it can potentially reduce capital costs and operational expenses compared to deploying standalone PV and CSP installations[41-43].

**Solar-thermal-electric hybrids for round-the-clock power supply:**

Solar-thermal-electric hybrids are a promising approach to achieve a round-the-clock power supply from solar energy. This type of hybrid system combines various solar technologies to harness sunlight during the day and convert it into electricity while storing excess energy for use during nighttime or cloudy periods. The integration of solar thermal, photovoltaic (PV), and energy storage components allows for continuous power generation[44]. Here's how such hybrids work:

1. Solar Thermal Collectors:

Solar thermal collectors, such as parabolic troughs or heliostat fields, are used to concentrate sunlight onto a receiver to generate high-temperature heat. This heat can be used directly for various applications, including space heating, industrial processes, or for generating electricity using a Rankine cycle or Brayton cycle.

2. Photovoltaic Panels:

PV panels are used to directly convert sunlight into electricity. They are highly efficient at converting solar energy into electrical power, but they are intermittent and depend on sunlight availability. Throughout the daylight hours, electricity is generated by PV panels.

3. Thermal Energy Storage:

Solar thermal-electric hybrids incorporate thermal energy storage systems, such as molten salt tanks or phase-change materials, to store excess heat generated during sunny periods. This stored thermal energy can be used to continue electricity generation after the sun sets or when there is insufficient sunlight.

4. Combined Operation:

During the day time, when sunlight is abundant, both solar thermal and PV systems can operate at their peak efficiency. Any excess electricity generated by the PV panels can be used to heat the thermal storage medium, thus improving overall system efficiency. This surplus electricity can also be fed into the grid.

5. Round-the-Clock Power Generation: When sunlight is no longer available, the stored thermal energy can be used to continue generating electricity throughout the night or during cloudy days. This ensures a consistent and reliable power supply [45-46].

<u>Benefits of Solar-Thermal-Electric Hybrid Systems for Round-the-Clock Power:</u>

- Reliability: These hybrid systems provide a reliable source of electricity, even during periods of reduced sunlight, making them suitable for baseload power generation.
- Energy Storage: The integration of thermal energy storage allows for extended power generation hours, reducing the need for backup power sources.
- Efficiency: By combining the strengths of both solar thermal and PV technologies, these systems can achieve high overall energy conversion efficiencies.
- Grid Integration: They can be designed to easily integrate with the grid, providing valuable grid stability and the potential to export surplus electricity.
- Reduced Environmental Impact: Solar-thermal-electric hybrids reduce greenhouse gas emissions by providing clean, renewable power and can potentially replace fossil fuel-based electricity generation [47-49].

**Integration of solar with other renewables for hybrid power plants:**
The integration of solar energy with other renewable sources in hybrid power plants can enhance overall energy reliability, flexibility, and efficiency. Such hybrid systems are designed to capitalize on the complementary characteristics of different renewable technologies to provide a more stable and continuous power supply. Here are some ways in which solar can be integrated with other renewables in hybrid power plants:

1. Wind-Solar Hybrid Plants:

Combining wind turbines and solar panels at the same site can provide a more consistent power output since wind and solar resources often complement each other. During daylight hours when the sun is shining and wind speeds tend to be lower, solar panels can generate electricity. Conversely, during the night and cloudy periods when solar generation decreases, wind turbines can continue to produce power if there is sufficient wind [50].

2. Hydro-Solar Hybrid Plants:

Hydroelectric power generation can complement solar energy by providing a consistent and controllable power source. During periods of abundant sunlight, excess electricity generated by solar panels can be used to pump water into elevated reservoirs or store energy as potential energy. When additional power is required, water can be released from the reservoirs, flowing through turbines to generate electricity [51].

3. Biomass-Solar Hybrid Plants:

Biomass power plants can use organic materials such as wood, crop residues, or waste to generate electricity. Solar energy can be integrated into these systems to reduce the consumption of biomass fuel during sunny days. Solar heat can be used directly or in combined heat and power (CHP) systems to meet the thermal energy needs of biomass power plants, improving overall efficiency [52].

4. Geothermal-Solar Hybrid Plants:

Geothermal power plants harness heat from the Earth's core to generate electricity. Solar energy can supplement the geothermal system during times of high electricity demand or when geothermal resources are temporarily insufficient. This combination can enhance overall capacity factor and grid stability [53].

5. Battery Storage Integration:

Adding energy storage, such as lithium-ion batteries, to a solar hybrid plant can store excess solar energy for later use, effectively extending the availability of renewable power, irrespective of weather conditions. Batteries can also help smooth out fluctuations in renewable energy generation and improve grid integration [54].

6. Microgrid Applications:

Solar can be integrated with other renewables in microgrids, allowing localized generation and storage of renewable energy to serve specific communities or facilities. Microgrid control systems manage the balance between different renewable sources and energy storage to maintain a stable power supply.

**Grid-connected and off-grid hybrid systems:**

Grid-connected and off-grid hybrid systems are two distinct approaches to integrating multiple energy sources, such as renewable and conventional energy, to meet power requirements. They are designed to provide electricity to consumers in various scenarios, and each has its own advantages and challenges. Here's an overview of grid-connected and off-grid hybrid systems:

<u>Grid-Connected Hybrid Systems</u>

Grid-connected hybrid systems are connected to the main electricity grid. They use a combination of different energy sources, including renewables like solar and wind, along with grid power, to meet electricity demand.

Advantages:

- Reliability: Grid-connected systems can rely on the grid as a backup when renewable generation is insufficient, ensuring a continuous power supply.
- Grid Services: They can provide excess renewable energy back to the grid, which can be monetized or used to offset grid electricity consumption.
- Scalability: These systems can easily scale up or down based on power needs without major modifications.

Applications:

- Residential and commercial solar panel installations with grid connections.
- Grid-connected wind farms with conventional power generation.
- Solar or wind power plants supply electricity to the grid.

Challenges:

- Grid Dependency: Grid-connected systems are still partially reliant on the grid, making them vulnerable to grid outages or fluctuations.
- Limited Autonomy: They may not offer full energy independence, as they usually depend on the grid as a backup or supplement [55-56].

<u>Off-Grid Hybrid Systems:</u>

Off-grid hybrid systems operate independently of the main electricity grid. They combine multiple energy sources, including renewables, and use energy storage systems (batteries or other technologies) to meet all electricity needs.

Advantages:

- Energy Independence: Off-grid systems are entirely self-reliant, making them suitable for remote or rural areas where grid access is limited or costly.
- Environmental Benefits: They reduce reliance on fossil fuels in regions where grid electricity is primarily generated from non-renewable sources.
- Reliability: Well-designed off-grid systems with sufficient energy storage can provide continuous power, even during extended periods of low renewable energy generation.

Applications:

- Remote cabins or homes in areas without grid access.
- Remote telecommunications infrastructure.
- Remote industrial or research facilities.
- Emergency backup power systems.

Challenges:

- Higher Initial Costs: Off-grid systems typically require larger energy storage capacities, which can increase initial installation costs.
- Complex System Design: Designing and managing off-grid systems can be more complex due to the need to balance generation, storage, and consumption [57-58].

**Microgrid applications and community-based hybrids:**
Microgrid applications and community-based hybrid systems are innovative approaches to energy generation, distribution, and management that offer a range of benefits, including increased resilience, energy efficiency, and sustainability [59].

1. Microgrid Applications:

A microgrid is a localized energy system that can operate independently or in conjunction with the main electrical grid. It typically consists of distributed energy resources (DERs) such as solar panels, wind turbines, batteries, and sometimes backup generators [60]. Microgrids can serve various purposes:

- Resilience: Microgrids can be designed to ensure a reliable power supply during grid outages. Critical facilities like hospitals, military bases, and data centers often use microgrids to maintain uninterrupted power.
- Integration of Renewable Energy: Microgrids can incorporate renewable energy sources to reduce carbon emissions and reliance on fossil fuels. For instance, a university campus might use a microgrid with solar panels and battery storage.
- Remote Areas and Island Communities: In remote areas and on islands, microgrids can provide a cost-effective and sustainable energy solution, reducing dependence on expensive diesel generators.
- Energy Access: Microgrids can bring electricity to areas without a reliable grid, enabling economic development and improving the quality of life for residents.
- Grid Support: Microgrids can also support the main grid by supplying excess power during periods of high demand or by stabilizing voltage and frequency [61].

2. Community-Based Hybrid Systems:

Community-based hybrid energy systems take the concept of microgrids a step further by involving active participation and ownership from the local community. These systems often incorporate a mix of renewable energy sources and storage technologies while involving the community in decision-making and potentially sharing benefits [62].

- Energy Cooperatives: Communities can form energy cooperatives where residents collectively invest in and manage renewable energy projects like solar farms or wind turbines. Profits can be reinvested in the community or used to lower energy costs for members.
- Community Solar Gardens: These are shared solar installations that allow individuals who may not have suitable rooftops for solar panels to buy or lease a portion of a larger solar array, receiving credits on their energy bills.

- Peer-to-Peer Energy Trading: Blockchain and smart grid technologies enable neighbors to buy and sell excess energy directly to each other, creating a local energy market within a community.
- Microgrid Communities: Entire neighborhoods can develop their microgrids, incorporating solar panels, energy storage, and demand response strategies to collectively manage their energy usage and reduce costs.
- Energy Education and Engagement: Community-based hybrid systems often come with educational initiatives that increase energy awareness and promote sustainable practices [63].

**Emerging Concepts in Solar Energy**

Solar energy continues to be a dynamic field with ongoing advancements and emerging concepts that are shaping the future of sustainable energy production. Here are some of the notable emerging concepts in solar energy:

1. Tandem Solar Cells:

Tandem or multijunction solar cells are designed to capture a broader spectrum of sunlight by multiple p-n junctions with different band gap energies with different absorption properties. This allows them to achieve higher conversion efficiencies than traditional single-junction cells. Perovskite-silicon tandem solar cells, in particular, have shown promise in recent research.

2. Bifacial Solar Panels:

Bifacial solar panels can capture sunlight from both sides, significantly increasing energy generation. They work well in installations where light can be reflected onto the rear side, such as those with white or reflective surfaces. Tracking systems that follow the sun's movement can optimize their performance.

3. Transparent Solar Panels:

Transparent solar panels, also known as solar windows, can be integrated into building facades, windows, and other transparent surfaces. These panels use transparent conductive materials and have potential applications in urban environments, where building-integrated photovoltaics are highly desirable.

4. Solar Paint and Coatings:

Researchers are exploring the development of solar paint and coatings that can be applied to various surfaces, turning them into solar energy generators. These coatings can be used on rooftops, walls, and even roads, expanding the possibilities for solar energy integration.

5. Floating Solar Farms:

Floating solar farms are being deployed on bodies of water, including reservoirs, lakes, and even the sea. These systems not only save land space but also benefit from the cooling effect of water, which can improve the efficiency of solar panels.

6. Solar Thermal Energy Storage:

Advanced solar thermal technologies are being used for energy storage. Concentrated solar power (CSP) plants can store excess energy as heat in molten salt or other materials, allowing for electricity generation even when the sun is not shining.

7. Perovskite Solar Cells:

Perovskite solar cells are a class of emerging photovoltaic technology known for their low cost and high efficiency potential. Researchers are working to address stability and environmental concerns to make perovskite solar cells commercially viable.

8. Flexible and Lightweight Solar Panels:

Flexible and lightweight solar panels are being developed using materials such as organic photovoltaics and thin-film technologies. These panels are suitable for curved surfaces, portable devices, and applications where traditional rigid panels are impractical.

9. Solar Energy in Space:

Space-based solar power (SBSP) concepts involve capturing solar energy in space and transmitting it to Earth using microwave or laser beams. This approach could provide a consistent and abundant energy source, but it is still in the experimental stage.

10. Artificial Photosynthesis:

Researchers are exploring artificial photosynthesis as a way to convert sunlight into storable fuels like hydrogen. This technology could provide a means of renewable energy storage and transportation [64].

**Solar Energy Storage Solutions**

Solar energy storage solutions are essential for maximizing the value of solar power systems by storing excess energy generated during sunny periods for use during cloudy days or nighttime. Effective energy storage enables grid independence, energy security, and a more reliable and sustainable energy supply. Here are some of the key solar energy storage solutions:

1. Battery Energy Storage Systems (BESS):

- Lithium-ion Batteries: These are the most common type of batteries used in residential and commercial solar installations due to their high energy density, efficiency, and long cycle life.
- Lead-Acid Batteries: They are a more affordable option, suitable for smaller residential systems. However, they have a shorter lifespan and lower energy density compared to lithium-ion batteries.
- Flow Batteries: Flow batteries, such as vanadium flow batteries, offer scalability and longer cycle life. They are well-suited for large-scale solar farms and grid applications.
- Solid-State Batteries: Emerging technologies like solid-state batteries promise higher energy density, longer life, and improved safety compared to traditional lithium-ion batteries.

2. Thermal Energy Storage:

- Molten Salt: Concentrated solar power (CSP) plants often use molten salt as a thermal storage medium. It stores heat from the sun and releases it to produce steam and generate electricity when needed [65].
- Phase Change Materials (PCMs): PCMs store and release heat as they change from a solid to a liquid state. That is melting and freezing or crystallization. The system depends on the shift in phase of the material for holding and releasing the energy. For instance, processes such as melting, solidifying or evaporation require energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa. Therefore, PCMs readily and predictably change their phase with a certain input of energy and release this energy at a later time. They can be integrated into building materials for passive solar heating or used in combination with solar thermal systems [66].

3. Hydrogen Energy Storage:

Electrolysis is used to produce hydrogen gas from excess solar electricity. This hydrogen can be stored and later converted back to electricity using fuel cells when solar generation is low [67].

4. Ultracapacitors:

Ultracapacitors, or supercapacitors, can store and release energy rapidly, making them suitable for applications where quick bursts of power are required, such as stabilizing grid fluctuations [68].

5. Pumped Hydro Storage:

Pumped hydroelectric storage involves pumping water from a lower reservoir to an upper reservoir when there is excess solar energy. During periods of high demand, the water is released downhill to generate electricity.

6. Community Energy Storage:

Community-based energy storage solutions involve aggregating individual residential battery systems within a community to create a virtual power plant. This approach can enhance grid stability and resilience.

7. Smart Energy Management Systems:

Advanced energy management systems use predictive analytics and machine learning to optimize the use of solar energy and storage, ensuring energy is available when needed and minimizing grid reliance [69].

**Challenges and importance of energy storage for solar:**

Energy storage plays a crucial role in enhancing the value and reliability of solar energy systems. However, it also comes with its own set of challenges.

<u>Importance of Energy Storage for Solar:</u>

1. Grid Stabilization: Solar energy production is intermittent and depends on weather conditions and time of day. Energy storage helps smooth out these fluctuations, making solar energy more reliable and less disruptive to the grid.
2. Grid Integration: Energy storage facilitates the integration of solar power into the grid by allowing excess energy to be stored during periods of high generation and released during peak demand, reducing strain on the grid infrastructure.
3. Maximizing Solar Output: Energy storage enables solar systems to capture excess energy during sunny periods, which can be used during cloudy days or at night, maximizing the overall solar energy output.
4. Resilience: Energy storage provides backup power during grid outages, enhancing the resilience of homes and businesses that rely on solar energy systems.
5. Time-of-Use Savings: Energy storage allows consumers to store excess solar energy when electricity rates are low and use it during peak rate hours, leading to potential cost savings.
6. Reducing Reliance on Fossil Fuels: By storing excess solar energy, homeowners and businesses can reduce their dependence on fossil fuels, contributing to a more sustainable and cleaner energy future.
7. Remote and Off-Grid Applications: In remote areas and off-grid locations, energy storage paired with solar panels can provide a reliable source of electricity, improving the quality of life and enabling economic development [70].

Challenges of Energy Storage for Solar:

1. Cost: Batteries and other energy storage technologies can be expensive, both in terms of upfront costs and maintenance. While costs have been decreasing, affordability remains a challenge for many consumers.
2. Limited Energy Density: Batteries have limitations in terms of energy density compared to other forms of energy storage like fossil fuels. This means that for very high-capacity storage, a significant amount of space may be required.
3. Environmental Concerns: The production and disposal of certain battery chemistries can have environmental impacts. Recycling and responsible disposal are important considerations.
4. Lifespan: The lifespan of batteries is finite, and they degrade over time. Replacement costs can be a significant factor, and the frequency of replacements depends on the technology used.
5. Efficiency: Energy storage systems involve energy losses during charging and discharging processes, which can affect overall system efficiency.
6. Safety: Certain types of batteries can pose safety risks, including fire and explosion hazards, especially if damaged or improperly maintained.
7. Regulatory and Policy Hurdles: In some regions, regulations and policies may not be well-suited to accommodate energy storage, making it challenging to realize the full potential of solar plus storage systems.
8. Technological Advancements: As technology continues to advance rapidly, some consumers may be hesitant to invest in energy storage systems, fearing that newer and more efficient technologies will become available shortly after their purchase [69].

**Solar Energy Grid Integration**

Solar energy grid integration refers to the process of incorporating solar power generation into the existing electrical grid infrastructure. This integration is critical for effectively harnessing the potential of solar energy on a large scale and ensuring a reliable and stable supply of electricity [71-72]. Here are key aspects and considerations related to solar energy grid integration:

1. Grid Stability and Reliability:

Integrating variable solar energy into the grid without compromising stability is a primary concern. Grid operators must balance supply and demand to maintain frequency and voltage levels within acceptable limits.

2. Grid-Interactive Inverters:

Solar power systems use inverters to convert direct current (DC) generated by solar panels into alternating current (AC) for use in homes and businesses. Grid-interactive inverters are equipped with features that enable them to synchronize with the grid, respond to grid voltage and frequency changes, and shut down during grid outages.

3. Grid Codes and Standards:

Grid codes and technical standards specify the requirements and guidelines for connecting solar power systems to the grid. Compliance with these standards is essential to ensure safe and reliable grid integration.

4. Energy Storage Systems:

Energy storage systems, such as batteries, are often integrated with solar installations to store excess energy during periods of high generation and release it when demand exceeds solar output, enhancing grid stability and reliability.

5. Net Metering and Feed-in Tariffs:

Many regions have implemented policies like net metering and feed-in tariffs that incentivize solar energy generation by allowing solar system owners to sell excess electricity back to the grid or receive compensation for it.

6. Advanced Grid Management Systems:

Modern grid management systems use advanced technologies, including smart meters, sensors, and communication networks, to monitor and control energy flow. These systems help grid operators efficiently manage solar generation and demand.

7. Demand Response Programs:

Demand response programs encourage consumers to adjust their electricity usage based on grid conditions. Solar power can play a role in such programs by providing real-time data on available generation capacity.

8. Grid Flexibility and Energy Storage:

Energy storage systems play a vital role in grid flexibility. They can absorb excess solar energy during periods of low demand and release it during peak hours, helping to balance supply and demand.

9. Distributed Energy Resources (DERs):

Solar panels, along with other DERs like wind turbines and electric vehicle chargers, are part of a broader effort to create more decentralized, resilient, and efficient grids.

10. Forecasting and Predictive Analytics:

Accurate solar forecasting is essential for grid operators to plan for and manage variable solar generation effectively. Predictive analytics can help anticipate cloud cover and other factors affecting solar output.

11. Grid Modernization and Expansion:

In some cases, grid infrastructure may need to be upgraded or expanded to accommodate increased solar generation. This includes strengthening transmission lines, adding substations, and integrating grid-friendly technologies.

12. Grid Resilience:

Solar energy can contribute to grid resilience by providing localized power generation during grid outages, especially when combined with energy storage systems [73-74].

**Environmental Impact and Sustainability**

Solar energy is generally considered an environmentally friendly and sustainable source of electricity due to its many advantages over fossil fuels. However, it's essential to assess its environmental impact comprehensively to understand both the benefits and potential challenges. Here's an overview of the environmental impact and sustainability of solar energy:

<u>Environmental Benefits of Solar Energy:</u>

- Reduced Greenhouse Gas Emissions: Solar power generation produces little to no direct greenhouse gas emissions. By displacing fossil fuels, solar energy helps reduce carbon dioxide ($CO_2$) emissions, mitigating climate change.
- Air Quality Improvement: Solar energy doesn't release harmful pollutants like sulfur dioxide, nitrogen oxides, or particulate matter into the air, contributing to improved air quality and public health.

- Low Water Usage: Unlike many conventional power plants, solar panels don't require significant water for cooling, making them particularly suitable for arid regions or areas with water scarcity.
- Minimal Land Impact: Solar panels can be installed on rooftops, vacant land, and other spaces with minimal impact on ecosystems. This reduces habitat disruption and land degradation associated with some other energy sources.
- Silent Operation: Solar panels generate electricity without noise pollution, making them suitable for urban and residential areas [75].

Environmental Considerations and Sustainability Challenges:

- Energy Intensity of Manufacturing: The manufacturing of solar panels, especially those using certain materials like crystalline silicon, can be energy-intensive and may have associated environmental impacts. However, improvements in manufacturing processes and the increasing use of cleaner energy sources have reduced the carbon footprint of solar panel production.
- Resource Extraction: Some materials used in solar panel production, such as rare earth elements and certain metals, require mining. Sustainable mining practices and recycling efforts can mitigate these impacts.
- Waste and Recycling: Solar panels have a limited lifespan (typically 25-30 years), and their disposal can create electronic waste challenges. Recycling and proper disposal methods are essential to reduce the environmental impact.
- Land Use Considerations: Large-scale solar farms can require significant land area, potentially impacting local ecosystems. Proper siting, land restoration, and ecological monitoring can help address these concerns.
- Intermittency and Energy Storage: Solar energy is intermittent and dependent on weather conditions. Addressing this intermittency with energy storage systems can have environmental impacts, depending on the type of storage technology used.
- Environmental Impact Assessments: Ensuring the sustainability of solar projects requires thorough environmental impact assessments and careful planning to minimize harm to local ecosystems and communities.
- Life Cycle Assessments: To fully understand the environmental impact of solar energy, it's crucial to conduct life cycle assessments (LCAs) that consider the entire life cycle, from raw material extraction to manufacturing, installation, operation, and disposal[76][77][78].

**Artificial intelligence and smart solar systems:**

Artificial intelligence (AI) and smart solar systems are revolutionizing the way solar energy is generated, managed, and optimized. These technologies offer several advantages for enhancing the efficiency, reliability, and integration of solar power [79]. Here are some key aspects of the intersection between AI and smart solar systems:

1. Solar Panel Efficiency:

AI can improve the efficiency of solar panels by analyzing real-time data and making adjustments to maximize energy production. For example, AI algorithms can optimize the tilt and orientation of panels based on the sun's position.

2. Predictive Analytics:

AI-driven predictive analytics can forecast weather conditions, cloud cover, and solar radiation. This information helps solar power plants and grid operators anticipate fluctuations in solar energy generation and take proactive measures.

3. Energy Forecasting:

AI can provide highly accurate short-term and long-term energy generation forecasts, enabling grid operators to manage the integration of solar power into the grid more effectively.

4. Fault Detection and Maintenance:

Smart solar systems equipped with AI can detect equipment faults and anomalies in real-time. This proactive monitoring allows for timely maintenance, reducing downtime and improving system reliability.

5. Energy Storage Optimization:

AI algorithms can optimize the operation of energy storage systems, such as batteries, by determining when to charge and discharge them based on electricity prices, demand patterns, and weather forecasts.

6. Demand Response:

AI-powered smart solar systems can participate in demand response programs by adjusting energy generation and consumption in response to grid signals or pricing signals. This helps balance supply and demand on the grid.

7. Grid Integration:

AI facilitates seamless grid integration of distributed solar systems. It helps manage the flow of electricity, ensuring grid stability and preventing overloads.

8. Energy Management for Homes and Businesses:

AI-driven energy management systems for homes and businesses optimize energy use by coordinating solar generation, energy storage, and consumption. They can also factor in time-of-use pricing to reduce electricity bills.

9. Remote Monitoring and Control:

AI enables remote monitoring and control of solar systems, allowing users to access real-time data and adjust settings through mobile apps or web interfaces.

10. Data Analysis and Insights:

AI can process vast amounts of data generated by solar systems, providing insights into energy production patterns, system performance, and opportunities for improvement.

11. Grid Stability and Resilience:

AI can contribute to grid stability by providing grid operators with real-time information on solar generation, allowing for better management of variable energy sources.

12. Energy Trading and Peer-to-Peer Transactions:

AI can facilitate energy trading and peer-to-peer transactions among solar system owners, enabling a decentralized energy marketplace.

13. Carbon Footprint Reduction:

AI-driven optimization of solar energy systems can lead to higher energy yields, reducing the need for fossil fuel-based energy generation and lowering overall carbon emissions[80][81][82].

## Conclusion and future prospects

The exploration of photovoltaic (PV) systems encompasses various facets, including solar cell types and their advancements, thin-film technologies, building-integrated PV (BIPV), environmental and social impacts, concentrating solar power (CSP), hybrid solar power systems, and emerging concepts in solar energy. Advancements in thin-film and emerging materials for PV have paved the way for more versatile and cost-effective solar solutions. Building-Integrated PV integrates solar elements into construction materials, merging functionality with aesthetics. The environmental and social impacts of PV underscore its potential as a sustainable energy source, though challenges and importance persist, especially concerning energy storage.

Concentrating Solar Power (CSP) introduces a different dimension by utilizing mirrors or lenses to concentrate sunlight for power generation. Hybrid solar power systems take a holistic approach, combining PV and CSP to enhance overall efficiency. Solar-thermal-electric hybrids ensure round-the-clock power supply, addressing intermittency challenges. The integration of solar with other renewables in hybrid power plants and the deployment of grid-connected and off-grid hybrid systems showcase the versatility of solar energy applications. Microgrid applications and community-based hybrids further illustrate the potential for localized, sustainable energy solutions. Emerging concepts in solar energy, including solar energy storage solutions, emphasize the pivotal role of energy storage in maximizing the benefits of solar power. The challenges and importance of energy storage in the solar sector highlight the need for innovative solutions.

Solar energy grid integration is crucial for seamlessly incorporating solar power into existing energy systems. The environmental impact and sustainability considerations emphasize the need for responsible deployment of solar technologies. Artificial intelligence and smart solar systems contribute to optimizing energy production, consumption, and grid management. In conclusion, the diverse topics within the realm of solar energy underscore its multifaceted nature. From advancements in PV technologies to the integration of solar with other renewables, the journey towards a sustainable energy future involves a combination of innovation, environmental responsibility, and social impact awareness. The evolving landscape of solar energy presents an opportunity to address global energy challenges, with the potential to reshape how we harness, store, and integrate solar power into our daily lives. With ongoing research, technological innovation, and supportive policies, solar energy stands poised to play a central role in the transition to a cleaner and more sustainable future for generations to come.

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## Conflict of interest

“Authors have declared that no competing interests exist.”

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# MITIGATING CLIMATE CHANGE AND ITS IMPACT ON FOOD SECURITY BY INTEGRATING ECOSYSTEM SERVICES TO AGROECOSYSTEMS IN SRI LANKA

# Mitigating climate change and its impact on food security by integrating ecosystem services to agroecosystems in Sri Lanka

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## Abstract

Securing food is becoming more difficult in Sri Lanka due to the country's expanding population, especially in light of climate change. This chapter focuses on the key issue of climate change and its many impacts related to food security in Sri Lanka, paying particular attention to AESA. In addition, the chapter emphasizes that Sri Lanka's agriculture is especially vulnerable to changing climatic patterns and explains how it endangers its food security. Agroecosystems are very productive suppliers of biomass-related provisioning ecosystem services. The method of utilization of agroecosystem services has shown itself to be an effective strategy in counteracting this urgent problem. Agroecosystem services include ecological processes and interactions that occur in agricultural systems which lead to food production, environmental stability and human welfare. The topic of this chapter is the importance of using agroecosystem services to improve Sri Lanka's food security under Climate Change. Using a review of existing literature in an attempt, this study documents how collective optimization could occur between agroecosystem services for levelling up agricultural output with minimal undesirable environmental effects. Agroecological concepts and modern agricultural practices integrate providing a holistic method that enables sustainable high outputs while maintaining the biodiversity integrity of the ecosystem. Finally, the formulation of Agroecosystem Services especially under Climate Change gives diverse ways towards attaining Sri Lanka's food security. The emergence of an alternative paradigm that recognizes the complex dynamics between ecological processes, Climate Change, and agricultural production provides a positive solution for sustainable growth within a volatile environment which meets nutritional needs while preserving our natural planetary resources.

**Keywords:** Agroecosystems, food security, environment, agriculture, climate change

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## Introduction

The global undernourished population comprises approximately one billion individuals, primarily concentrated within developing nations. In particular, regions such as South Asia and sub-Saharan Africa suffer from a substantial burden of undernourishment. What's noteworthy is that a significant portion of these individuals inhabit countries that struggle to achieve self-sufficiency in food production, exacerbating the food insecurity challenges faced by these regions. Sri Lanka falls in line with this global pattern, as the livelihoods and overall well-being of its people are intricately linked to the agricultural products they cultivate, and the ecosystem services derived from the surrounding landscape. The unique features of the local agro-ecosystem play a crucial role in supporting their way of life and income generation. Water plays a pivotal role in influencing the production of biomass, crop yields, and a range of regulating and supporting ecosystem services. Across various regions globally, irrigation stands out as a recognized and effective strategy for augmenting yields, thus serving as a fundamental input in enhancing food production.

Many ecosystem services rely heavily on water, from providing biomass and agricultural production to cultural, regulatory, and supporting services. Sustainable management of the water used by livestock, crops, forests, and aquaculture is also crucial for boosting food production. However, water withdrawals for agriculture and other purposes have already strained many ecosystems. An already precarious future for worldwide food supplies is projected to become even more so due to climate change. Significant food-producing regions have surpassed their limits, endangering future supply of water and foods.

Expanding tropical agriculture has led to deforestation, soil compaction, and increased runoff in some tropical regions [2]. There has been a steady increase in the demand for fish and shrimp from aquaculture [3], which puts pressure on aquatic ecosystems worldwide [4]. Recent research shows that the loss of ecosystem services has already impacted agricultural output severely and is predicted to escalate under climate change [5-6]. These adverse consequences encompass a range of challenges, notably the depletion of soil nutrients, the diminishing of biodiversity, increased soil erosion, heightened susceptibility to diseases and pests, and a reduction in the ecosystem's ability to provide buffering and storage capacity to cope with unpredictable rainfall patterns. Because of this, by 2050, crop yields may be 5 to 25% below expected demand [1]. The poorest people, who rely most heavily on natural resources for livelihood, are hit the most by these issues. Comprehending the intricate interplay between ecosystems, water resources, and food production is of paramount importance, as the well-being of all three is inherently linked. Furthermore, the effective management of these relationships has grown increasingly critical to ensure their long-term sustainability.

Due to widespread land degradation caused by poor agricultural methods, food production is severely constrained [7]. Ecosystems are adversely affected by overfishing, habitat degradation, pollution, invasive species, and alterations in river flow caused by dams. As more businesses use land, it is more important than ever for programs that help the poor to make sure everyone has equitable access to natural resources and the benefits they bring. Managing ecosystems, water, and food production properly can prevent irreversible declines in ecosystem services and total food production, but the issue of rights is still crucial for ensuring food security for future generations [8]. Food is provided by natural ecosystems, such as fisheries and forests, and as well as manmade ecosystems, such as agricultural fields.

This chapter Mitigating climate change and its impact on food security by integrating ecosystem services into agroecosystems in Sri Lanka" is crucial for several reasons:

**Climate change vulnerability:** Sri Lanka is an example of a country that suffers the impacts stemming from climate change; such consequences include alteration in heat levels, changes in precipitation patterns and extreme weather. All these changes can revolutionize agriculture leaving crop yield and food production. In the context of climate change, however different agroecosystems could be made more resilient for food security is essential. Food Security Concerns: Climate change poses additional challenges to the issue of food security in Sri Lanka. Temperature and precipitation changes cause alterations in the crop suitability, which directly influence food availability. The search for mechanisms to increase the resilience of agroecosystems has an immediate relationship with food security and a secure population.

**Ecosystem services importance:** Agricultural productivity depends on ecosystem services including pollination, purification of water and soil fertility. Combining these services with agroecosystems allows increasing their sustainability and productivity. The study on how to best deliver ecosystem services in agricultural landscapes improves farming practices that are more productive and robust.

**Biodiversity conservation:** The application of ecosystem services in agroecosystems demonstrates potential for biodiversity conservation promotion. The importance of biodiversity does not only lie in promoting healthy ecosystems but also provides pest control, disease resistance and resilience in ecological systems. Environmental conservation and sustainable food production, such as researching methods of supporting biodiversity in agricultural settings, are complementary.

**Social and economic impacts:** Social and economic consequences of climate change impacts to agriculture extend far beyond farmers' lives where livelihoods, rural communities are impacted. The study targets not only environmental issues but also the socio-economic facets of climate change and food security. Agroecosystems that are sustainable have the potential to deliver benefits for farming societies.

**Policy relevance:** The results of this research could be used to shape and modify agricultural policies as well as environmental protection in Sri Lanka. The knowledge about incorporating ecosystem services into agroecosystems allows policymakers to make grounded decisions of developing strategies and policies that ensure sustainable practice in agriculture.

**Global relevance:** Considering climate change as a global phenomenon, research in Sri Lanka can add to the world's knowledge on CSA. Lessons from integrating ecosystem services into agroecosystems in Sri Lanka could be useful to other similar regions elsewhere around the world.

Overall, the research contributes to significant issues in Sri Lanka such as climate change, food security and sustainability. The study aims to propose solutions and ideas regarding the inclusion of ecosystem services in agroecosystems that can help agriculture cope with climate change.


**Figure 1:** Diagram of agro ecosystem services

## Food security

Enhancing agricultural productivity in a sustainable manner, along with ensuring fair food distribution, plays a pivotal role in achieving food security. Food security, defined as the consistent availability of sufficient nutrition for all, hinges not only on the capacity of individuals, both men and women, to produce and obtain food but also on the presence of effective policies and institutions across various sectors influencing these factors. The agricultural industry will have to spend significant amounts of money to adapt to climate change, which is essential for food security, reducing poverty, and managing ecosystem services. Providing for a burgeoning population depends critically on agroecosystems' ability to use and manage their water and biodiversity resources sustainably. The rise in food production is sustainable; it must be paired with pro-poor policies that ensure that all people, regardless of their socioeconomic status, have equal access to the resources necessary to produce or purchase food. The right to food is already legally enshrined in more than 40 nations [9].

The unexpectedly elevated food prices observed in 2021/22 can be attributed to a variety of factors, including heightened demand, evolving dietary patterns, droughts, elevated agricultural input costs, and policies that promote the utilization of agricultural land and production for bioenergy purposes. The poor, who often spend between fifty percent and seventy-five percent of their income on food, now carry an even heavier load. Food-export bans by major food-producing countries, especially India, are implemented to keep local prices low, but they contribute to the escalation of international food prices. While rising food costs may eventually lead governments to enhance agricultural output, these investments will take years to reduce food prices to reasonable levels.

## Drivers and the prospects of food security

Without regulations protecting everyone's rights, there would be more inequalities in the distribution of resources like land, trees, and water. Due to this, a need arises to increase the equitable and efficient use of natural resources, primarily because the water per person, land, and vegetation resources are expected to continue decreasing, especially for impoverished men and women. Climate change holds paramount significance as it has the potential to disrupt multiple systems, encompassing agriculture, energy, and health sectors. Among the direst consequences of climate variability are the loss of livelihoods, and assets, and increased instances of hunger, with these impacts disproportionately affecting vulnerable populations such as the impoverished, women, and marginalized groups [10].

**Table 1.** Relative factors affecting food security.

| Factors | Impact on Food Security |
|---|---|
| Climate Change | Alters agricultural productivity, Affects water availability |
| Land Degradation | Reduces arable land, Affects crop yields |
| Water Scarcity | Impacts irrigation, Decreases crop yields |
| Population Growth | Increased demand, Strains resources |
| Socioeconomic Factors | Income disparities, Access to food |
| Global Trade Policies | Food export bans, Impact on prices |
| Technological Advances | Improved agricultural practices and yields |

## Demographic drivers

As a result of the world's projected population growth, there will be a pressing need to sustainably boost food production to feed 9 billion people by 2050. Because more people imply more consumption, current projections for population expansion threaten food security, increase water use, pollute natural resources, and degrade ecosystems. The upshot will be clearing forests and other natural areas for human habitation and agricultural use further deteriorating the ecosystem services these ecosystems would provide in the coming decades. Rural residents are under increasing pressure to harvest forest goods like fuel, forage, and lumber from farmland as their access to these resources dwindles, leading to crop competition if the land is not carefully managed. For the sake of the constantly expanding populations in the arid regions of many emerging nations, the task is to increase groundwater recharge and rainwater harvesting on a landscape or river basin scale. Most of the population growth will occur in arid and semiarid regions like Africa and the Middle East, where water stress is already a severe problem due to the region's fragile ecosystems (Figure 2) [11].

Migration has historically been used as a coping mechanism for people experiencing environmental hardships. Although climate change was once cited as a significant factor in migration, it has now become clear that socioeconomic factors are more important. While increased population and worsening social inequality threaten food supplies in certain regions, rising incomes and living standards increase the demand for food. The expansion of the developed world's population is closely intertwined with efforts to combat climate change, ensure energy security, and support the agricultural sector. These demographic factors serve as significant drivers for the mentioned expansion. Notably, a pivotal aspect involves altering the global energy system, transitioning away from fossil fuels and prioritizing biofuel production. This shift carries far-reaching consequences, particularly for ecosystems dependent on freshwater and essential food supplies. Therefore, the demographic influence on environmental initiatives and energy choices underscores the interconnected relationship between population dynamics and sustainable resource management.

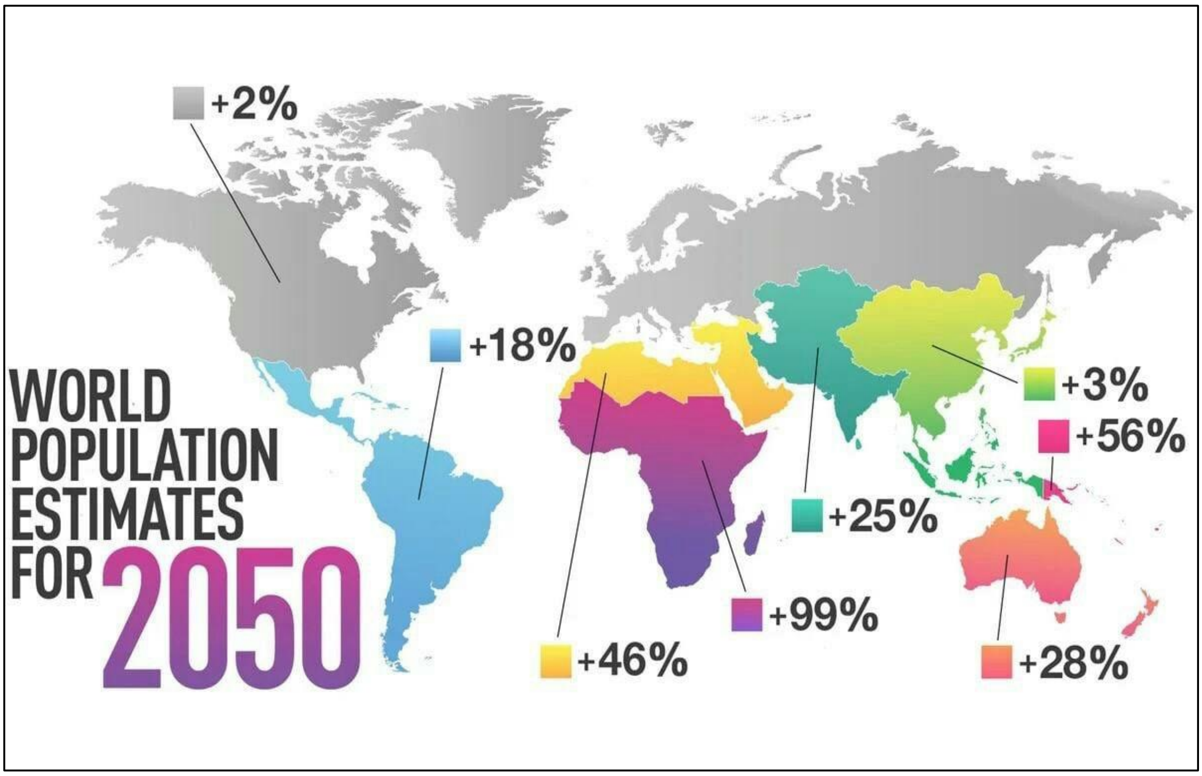


**Figure 2.** World population growth and decline 2010-2050 (Source: UNEP, 2009)

## Climate change

Many impoverished people worldwide may become even more vulnerable due to the compounding effects of climate change and population expansion on their access to food, ecosystems, and water. Vulnerability, lack of education, and illness can all reduce the ability of the poor to cope, and other external shocks like food shortages, price spikes, and economic crises can worsen the matter. Predicting the outcomes of global climate change is an enormous undertaking marked by inherent uncertainties. Nonetheless, there is a consensus on two key forecasts: Two key projections emerge: firstly, that the global average temperature will escalate at an accelerated rate; secondly, that weather patterns will grow increasingly unpredictable, more severe, and potentially more frequent. Many ecosystems are expected to exceed their resilience thresholds, leading to biodiversity loss and inability to sustain crucial ecosystem functions like pest control and water regulation. The influence of climate change on agricultural and forestry systems is multifaceted, encompassing aspects such as increasing temperatures, higher levels of carbon dioxide (CO2), unpredictable precipitation patterns, and added pressures. Consequently, a rise in the occurrence of droughts, heatwaves, food shortages, and severe storms is expected in the immediate future [12-13].

The water industry will feel the consequences of climate change in several different ways. New prediction models are being developed to provide policy responses, but water planners will have less access to historical data for planning, designing, or operating hydrological systems. While climate change is a significant factor in food availability and clean water, the agricultural production industry also contributes to global warming. Growing research suggests a deeper connection between declining forest cover and precipitation may exist than was previously recognized [14].

Food insecurity, environmental disruption, and inefficient water usage are all exacerbated by economic downturns. As a result of the recent global financial crisis, protectionist measures became more common, leading to a decrease in international food commerce and a decrease in funding for development projects and technology R&D. It has also shifted public emphasis from hydrological and environmental concerns to economic ones, which can have unintended effects for food safety.

One of the worst effects of human activity's apparent regression over years of progress is climate change, which is currently affecting food security all around the world. In low-income nations, the increase in food commodity prices in 2021 contributed significantly to the estimated 30 million additional individuals experiencing food insecurity. According to the IPCC, four of the eight dangers that climate change poses to the world's population directly affect food security:

- loss of income and livelihood in rural areas
- loss of livelihoods and coastal and marine ecosystems
- loss of livelihoods and inland water and terrestrial habitats
- Food instability and food system collapse

The impact of climate change on food security varies based on where the population lives. However, there is a cascade of impacts that lead to the impact on food security and nutrition, beginning with the direct consequences of climate change on temperature, precipitation, sea level rise, land degradation, and air composition. The agroecosystems, which impact cultivated plants, animals, woodlands, and aquatic species, are under pressure from all of these sources. The difference in quality, quantity, and consequently price is already noticeable in the post-harvest and agricultural production at this stage. Food security levels depend on the availability, access, utilization, and stability of agricultural and other livelihoods, which are all impacted by quality, quantity, and price.

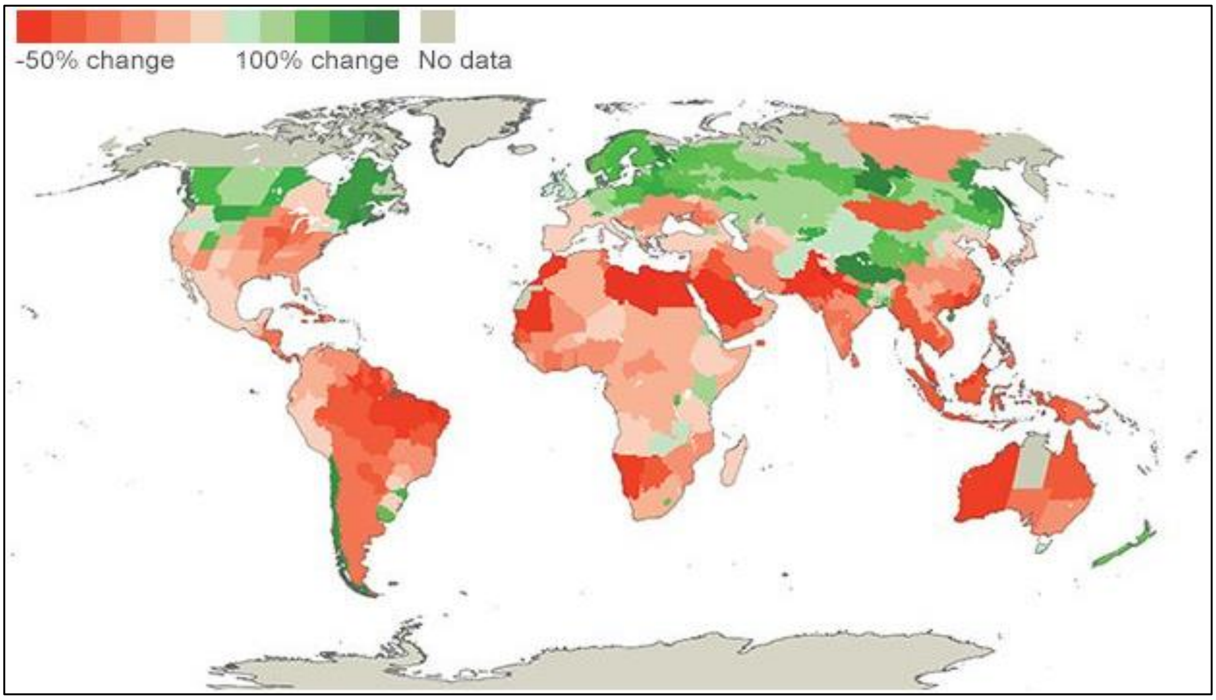



**Figure 3**. Estimated impact of global atmospheric temperature increase of +3$^{o}$C change on crop yields by 2050 (Source: World Resources Institute/ World Bank, 2010.)

## Agroecosystems

Humans are an essential element of an ecosystem, defined as a dynamic complex of plants, animals, microbes, and their nonliving surroundings [15]. Thus, agriculture is also an ecosystem in which plants, animals, and microbes interact with the nonliving environment to produce primary and secondary goods that people then appropriate. Vulnerability and management concerns for the various ecosystem services vary significantly between ecosystem types (Table 2). Furthermore, ecosystems with different degrees of anthropogenic intervention might contribute to food security. Because water flows affect ecosystems, ecosystem services are similarly influenced by water. Natural ecosystem restoration, often known as revegetation, is complex and needs careful preparation.

## Agroecosystems and food security in Sri Lanka

Agroecosystems are diverse in Sri Lanka, and each system plays its specific role within the context of agrarian landscape. Some of the major agroecosystems in Sri Lanka include:

- Rice paddies: Sri Lanka is a staple food that has numerous acres of paddy fields. Paddies are not only providers of food but make a favourable contribution to biodiversity.
- Tea plantations: In Sri Lanka, tea is called Ceylon tea and plantations cover great areas of the central lands as well as in southern regions. The tea growing environment in these regions is temperate.
- Rubber plantations: The cash crop used in Sri Lanka nowadays is rubber and the plantations, many of which are on lowlands. Rubber is one of the major export commodities in this country.
- Coconut plantations: In Sri Lanka, an island country coconut palm is grown and they are planted near the beaches. For both local consumption and export, coconut products like the coconut oil and desiccated are in demand.
- Spice gardens: Called the "Spice Island," Sri Lanka is full of spice gardens. Spices including cinnamon, cardamom black pepper and cloves are cultivated in these agroecosystems.
- Vegetable gardens: Many areas of Sri Lanka vein specialize in small-scale vegetable farming where varieties are grown locally for local consumption. The farmer's vegetables vary from the tomatoes, carrots onions and leafy greens.
- Fruit orchards: Sri Lanka grows various groves of fruit orchards beyond citrus ones including mangos, bananas, papayas and pineapples. These orchards cater for both local and the entire international market.
- Aquaculture: Inland and coastal areas of Sri Lanka characterize aquaculture activities. There is fish cultivation all over the world, as both freshwater native species and sea fishes have been bred in order to satisfy local demand for different kinds of fishes and products made out from them.

These agroecosystems strengthen the agricultural and economic development of Sri Lanka. The variety in crops and methods of cultivation also contribute to maintaining the local population's livelihood. Sri Lanka, a nation with a long history of agriculture, has seen a significant reduction in the contribution of the agricultural sector to the GDP of the country. This sector's contribution has significantly decreased, falling from 33.53% in 1974 to a meagre 11.51% in 2023—a figure that is considerably less than the 15% global average. It's interesting to note that, in spite of the fact that the area dedicated to agriculture increased from 23,420 km² in 1991 to 28,120 km² in 2023, the employment rate in this sector fell from 42.84% to 27.1% in the same time frame [16].

About 80% of Sri Lanka's food needs are met by domestic production, mostly from rice, sugar, fish, and dairy products, which account for 65% of all food imports [17]. The nation cultivates more than 75% of its other food crops, with rice production being essentially self-sustaining. However, regional food production and overall food security are facing significant problems as a result of the changing environment. With an aggregate score of 55.2%, Sri Lanka ranked 79th out of 113 nations in the Global Food Security Index of 2022. Compared to the prior year, this was a minor improvement of 2.3% [18].

The country has been grappling with dramatic alterations in rainfall patterns, drought occurrences, and temperature shifts, all of which pose considerable threats to agricultural productivity, livelihoods, and food security [19]. Rising temperatures have a more adverse impact on rice production than fluctuations in rainfall, particularly when considering various climate change scenarios for Sri Lanka [20]. Another study focusing on Sri Lanka highlighted the positive effects of increased rainfall dry zone of the country, while expressing concerns about the detrimental influence of elevated temperatures on agriculture in the dry zones [21].

Research focused on Sri Lankan home gardens has highlighted their critical role in enhancing food security, delivering valuable ecosystem services, and serving as a cost-effective and pro-poor approach [22],[23]. These home gardens are also commended for their resilience in the context of climate change, owing to their reliance on practices that foster biodiversity [24]. While numerous studies underscore the adverse effects of climate change on agroecosystems, they equally emphasize the urgent necessity for implementing adaptation strategies [25].

**Ecosystem services from agroecosystems**

All people everywhere rely on ecosystem services for their existence and quality of life, making them the key to local and global development potential and human flourishing. As the global population rises, so will the need for ecological services. The ability to produce numerous benefits sustainably is being challenged and, in many cases, is declining. There are four broad categories of ecosystem services, and their relative relevance to local economies may vary by demographic factors such as age, gender, socioeconomic class, and religious affiliation.

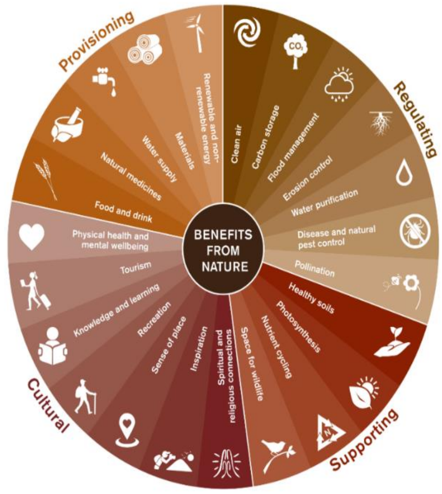
In some instances, technology may replace such systems, although doing so typically comes at a more excellent price than continuing to provide the original service. The costs of substituting for regulatory services may be examined via financially driven decision-making processes, allowing for their inclusion in markets. One way to do this is to calculate how much it would cost to build a water treatment plant to replace a watershed's purifying functions in a given neighbourhood.

Ecologists disagree with this line of thinking, claiming that humans can never fully replace the functions of these natural regulating systems, which benefit society and preserve biodiversity. The debate about the cost of using nature's services centres on this issue [26]. However, it has been shown that, particularly in the case of water, it is often more expensive to replace utilities than to restore or sustain them. The spiritual and inspiring value of a park, the recreational value of a lake for fishing, the aesthetic value of a beautiful park, and the educational value of a museum are all examples of cultural services. Some, like leisure time, are simple to put a price on, while others are intangible and hard to put a price on.

Services that provide long-term support are called "supporting services." Soil formation and nitrogen cycling are two examples. Soil creation, for example, is not a direct market good, but all of these other services might be classified as either [29]. Modest incentives may be needed to keep people producing nonmarket products and services that can accumulate or expand on big or global sizes. The benefits of services like groundwater recharge and climate management to an individual are not proportional to their costs [27]. Hidden social and environmental costs and benefits can be revealed through an ecosystem's market and nonmarket product valuation [28]. This concept may apply to regulatory services as well.

**Table 2:** Types of Ecosystem services provided to the population. (Source: Nature Scot, 2020)

| INLAND WATER | DRY ZONES | CULTIVATED |
| --- | --- | --- |
| Aesthetic values<br>Disease regulation<br>Ecotourism<br>Freshwater<br>Food<br>Flood regulation<br>Nutrient cycling<br>Pollution control<br>Sediment retention | Bee pollination<br>Ecotourism<br>Food<br>Fodder and pasture<br>Fibre<br>Fuelwood<br>Heritage values<br>Medicines<br>Microclimate regulation<br>Spiritual values | Aesthetic value<br>Biofuels<br>Food<br>Fibre<br>Freshwater<br>Heritage values<br>Medicines<br>Nutrient cycling<br>Pest regulation<br>Timber |
| | | |




The chapter considers agroecosystems as providers of ecosystem services, rather than solely focusing on food production as one among several ecosystem services. Therefore, if the agroecosystem deteriorates, numerous ecosystem services will suffer, threatening present and future agricultural output and human lives. Current agroecosystem management practices focus on increasing one or a few desired ecosystem functions, such as crop yields, fuel, fodder, or fibre production, at the expense of other, less directly beneficial agroecosystem services [30]. Economists have sought to put a dollar value on ecosystem services to make more nuanced quantitative comparisons, as seen in Figure 4. This figure provides a visually striking qualitative comparison between two distinct land use patterns and the ecosystem services they offer. The comparison illustrates that intensive provisioning ecosystem services experience a boost, but this enhancement is counterbalanced by a decrease in regulatory, cultural, and supportive ecosystem services when compared to natural ecosystems.

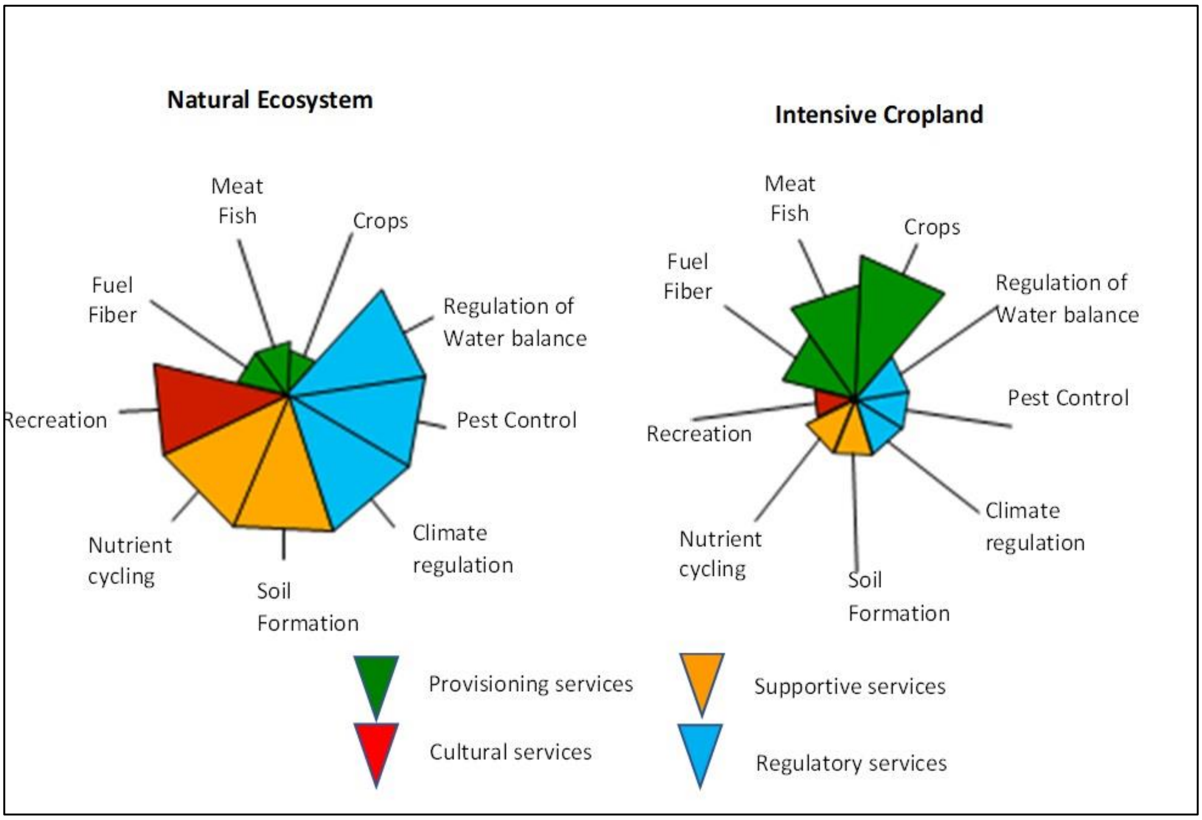



**Figure 4.** Comparison of Intensive cropland and Natural ecosystems (Source: Gordon *et al.,* 2010).

## The need for agroecosystems management to mitigate climate change and for the food security

Natural ecosystems supply food in catch fisheries and forest products, whereas controlled agroecosystems give food in the form of agricultural fields and pastures. In the world's poorest regions, where both access to and timely water supply are issues, water is one of the primary constraints restricting future food production.

The recent progress in ecosystem provisioning services has come at the expense of reductions in other ecosystem services, like those that support or regulate other things people need. This is especially true in the case of food production through agriculture. Those living in poverty or on the margins of society rely more heavily on ecological services than the general population. They are also less equipped to deal with the consequences of reduced ecosystem services, making them increasingly exposed to the phenomenon. Therefore, more careful and well-balanced provision of ecosystem services is required. This implies that you may discover win-win solutions in certain instances, but in others, you may have to cut out on some assistance to pay for others.

Globally, agroecosystems are facing challenges from growing production demands, pollution, intensive monoculture and other unsustainable farming methods, climate change, and resource overuse. To maintain ecological stability, food and nutrition security, and the social security of farming communities, innovative cropping methods are crucial. Using ecologically sound agricultural methods to improve social and economic sustainability and environmental quality is a growing reaction to the various effects of the agricultural system. [31]. Among the several tactics used are integrated pest management, intercropping, cover crops, and conservation tillage. The biotic interactions that dictate the function of an agroecosystem are one overarching theme in the development of the scientific foundation and design of these agroecological activities [32]. Controlling biotic interactions in agricultural systems has the potential to lessen or perhaps completely remove the requirement for the very external inputs that cause pollution, deforestation, and biodiversity loss. Due to government incentives and mandates, as well as new market opportunities for organic goods, the adoption of such low-input practices has increased rapidly worldwide [33].

## Challenges to Agroecosystem Management in Sri Lanka

Farming practices in Sri Lanka form a human-created system that interacts with and is influenced by the broader ecological system. The requirements, services, and interconnections of this ecosystem are unique to the country. The demographic changes and population growth experienced in Sri Lanka also have significant short-term and long-term impacts on its ecosystems. With a growing population, the demand for resources increases, resulting in heightened environmental pressures. To break the cycle of decreasing food availability, escalating land degradation, expanding cultivation areas, and diverting more water for agriculture, it becomes essential to deepen our understanding and recognition of the diverse services provided by various ecosystems, including agroecosystems [34]

While provisioning services are vital for immediate food security, the sustaining services of regulation and support are crucial for securing food availability over the long term and ensuring equitable food access for all in Sri Lanka. The varying nature of ecosystems at regional, national, and even global levels makes it imperative to employ adaptive management strategies in the ecosystem approach. The significance of agroecosystems in the context of food security extends beyond their impacts on other ecosystems [35]. The evolution of agricultural practices in Sri Lanka encompasses a diverse range of agroecosystems, with some of them being particularly abundant in biodiversity. These agroecosystems not only contribute to food production but also provide a variety of ecosystem services. Food sovereignty has garnered considerable focus as an alternative avenue for development in global discussions and policy exchanges, even though its practical implementation is already underway. Given the array of challenges that the island nation has been grappling with, spanning from food security and poverty to climate change and persistent developmental inequalities, the endeavour to elevate Sri Lanka towards food sovereignty demands substantial policy overhauls and transformative adjustments across governance, administrative frameworks, and broader societal realms [36].

## Dry zone agroecosystems and challenges

The term "dry zone" pertains to a significant portion of Sri Lanka. This is because these areas experience greater water loss through evaporation and transpiration than they receive through average precipitation. Sri Lanka, too, has extensive dry zone regions, where one-third of its population resides. These areas contribute to around 44% of agricultural systems and 50% of cattle raising [37] Unfortunately, these regions also face severe challenges such as malnutrition and poverty. Multiple factors, including drought, poor soil quality, and the uncertain outcomes of investing in productivity-enhancing measures, lead to low crop yields in dry zone areas.

In the context of Sri Lanka, the potential for food production in dry zones varies widely. Some areas face conditions so harsh that traditional cropping is infeasible, relying instead on livestock grazing to utilize irregular and widely dispersed rainfall. Meanwhile, there are other regions where a combination of crop and livestock production could be fostered together.

The main hindrances to food production in Sri Lankan dry zone areas are water scarcity and land degradation. As the population grows and migrations occur, natural resources like land and water are strained, posing threats to the sustainability of agroecosystems. In particular, dry zone regions in Sri Lanka face challenges from soil erosion, salinization, and land degradation, issues that are even more pronounced in arid areas.

Desertification poses a significant environmental challenge in Sri Lanka's dry zone regions. This process is driven by various factors, including expanded agriculture, improper grazing practices and restrictions on the pastoralist movement especially in eastern dry regions of Sri Lanka [38]. The traditional notion of desertification suggests a negative cycle of declining production and increasing poverty due to the belief that natural systems are in a permanent equilibrium that can be irreparably disrupted [27]. However, mounting evidence indicates that even degraded areas can recover from their conditions, providing hope for the restoration and sustainable management of dry zone ecosystems in Sri Lanka.

### Agroecosystems and sustainable management

In Sri Lanka, ecosystems, and particularly the productivity of agroecosystems, are facing considerable strain due to escalating demands for water, food, and land. Additionally, certain land and water management practices are contributing to the degradation of the natural resource base. If attempts to enhance food security do not consider ecosystem services, the situation could deteriorate further. It becomes crucial to reverse the current trend of declining food production due to degradation and minimize the need for land conversion and water diversion. Ecosystem services, particularly those provided by agroecosystems, offer a potential pathway to achieve this objective.

For instance, in Sri Lanka, the Ministry of Environment and Wildlife Conservation could play a pivotal role in adopting an ecosystem services perspective to evaluate food security. Integrating agroecosystem management with freshwater and coastal ecosystems could be a viable approach. In the Sri Lankan context, addressing the challenges of birds and animals damaging seedlings and crops could involve promoting habitat connectivity within agricultural landscapes. To ensure the success of the ministry's evolving role, it is essential to define its purpose clearly, secure adequate funding, and offer training and development opportunities.

A shift in ideology and approach is needed, particularly with the adoption of a landscape approach that advocates for integrated management of larger landscapes, encompassing both agricultural and non-agricultural ecosystems. This approach emphasizes the importance of ecosystem protection as one of many tools to restore and sustain ecosystem services while recognizing the connections between protected areas and the surrounding agroecosystems. Despite this, efforts to protect ecosystems facing endangerment should not be abandoned. In the context of Sri Lanka, food production stands out as one of the significant ecosystem services provided by agroecosystems. Improved management practices and supportive legislation could substantially enhance the productivity of these agroecosystems in terms of food production.

Significant components of supporting sustainable practices include providing incentives for farmers, fishermen, forest inhabitants, and cattle herders to conserve and, in some cases, rehabilitate natural services. Ecosystem service payments emerge as a potential solution. Strategies such as rangeland protection, soil-enhancing agricultural techniques, financial incentives, and support for initiatives that boost food production and other ecosystem services could be adopted to rejuvenate degraded land.
In terms of enhancing productivity to deliver food and other services, agroecosystems in Sri Lanka exhibit varying potentials. In this discussion, we will delve into agroecosystems within two distinct biomes, namely dry zones and wetlands, each with its unique water availability. These biomes play a crucial role in sustaining a significant portion of Sri Lanka's population while facing heightened vulnerability due to degradation and the potential loss of vital ecosystem services. According to [39], strategies aimed at enhancing food security among small-scale farming households in Sri Lanka and similar contexts should prioritize households with limited socioeconomic assets. These households face challenges in terms of both agroecological and economic resources, making them particularly vulnerable to shocks, including those stemming from climate change.

To effectively leverage the benefits of increased food production in these regions while reversing the decline in ecosystem services, management techniques that incorporate agroecosystem services are imperative. These strategies must consider gender perspectives and the diverse viewpoints of affected communities to address inequalities in access, ownership, and decision-making authority over natural resources in Sri Lanka.

## Conclusion and recommendations

A proposed approach puts ecosystems at the centre of food security efforts by shedding light on the connections among ecosystems, water, and food. There are possibilities to enhance food production in sustainable and efficient ways by using water and other resources. A suggested approach places ecosystems at the heart of Sri Lanka's food security initiatives, unveiling the intricate ties among ecosystems, water resources, and food production. Notably, opportunities exist to augment food output through sustainable and efficient methodologies that harness water and other resources effectively.

- For Sri Lanka's enduring food security, an integrated water resources management strategy that includes both agricultural and non-agricultural ecosystems is crucial. In Sri Lanka, robust ecosystems exhibit greater diversity and productivity, contributing to various ecosystem services. This includes pivotal water management functions essential for sustainable food security. Therefore, valuing and managing ecosystems, water supplies, and food production necessitates an adjusted perspective.
- Adopting an approach that treats agriculture as a series of interconnected agroecosystems within a broader, ecologically diverse environment is vital. Such systems not only yield food but also encompass a range of ecosystem services crucial for long-term food security. To maximize ecosystem services, a river basin-scale management approach for rain and runoff water sources in multifunctional agroecosystems is imperative. Enhancing water productivity in these ecosystems (water for agroecosystems) would amplify their capacity to fulfil water regulatory and supporting functions (agroecosystems for water).
- The effective implementation of adaptive Integrated Water Resources Management, supported by empowered institutions, facilitates the provision of water for both non-agroecosystems and agroecosystems. This requires collaboration between authorities and experts in various fields such as agriculture, water management, forestry, fisheries, aquaculture, livestock, environment, and wildlife management. In Sri Lanka, achieving this collaborative approach at local, regional, and global levels is crucial to the success of sustainable food security efforts. The country can tap into opportunities to enhance water productivity, tighten nutrient and carbon cycles, and maintain soil and water production in agricultural landscapes while easing pressure on depleted forest resources.
- The dry zone agroecosystems, long-term provision of ecosystem services depends on the holistic utilization of water and nutrients, Promotion of Agroecological Practices, Market Access and Diversification, comprehensive and climate-smart livestock management, and the integrated cultivation of tree crops and livestock.
- The intermediate, mid, and upcountry regions of Sri Lanka require region-specific strategies that consider the unique climatic conditions and agricultural landscapes. specillay, Agroforestry and Watershed Management, Climate-Resilient Crop Varieties, Cold-Weather Crop Strategies and Soil Conservation Practices.
- Boosting yields across extensive agricultural areas in Sri Lanka cannot be increased through novel ecosystem-based practices by manipulating natural processes and benefits offered from within the biosphere to improve productivity in a cost effective way. Here are several ecosystem-based strategies to increase yields: Agricultural Practices, Water Management Techniques, Biological Pest Control Systems and Soil Health Enhancement Methods; Crop Genetic Diversity Using Eco Friendly Inputs.
- Adequate, oxygen-rich water provision is vital for aquaculture and fisheries, supporting physical support, respiration, seed, and feed requirements. Sustainable management of detritus, waste,

nutrient cycling, and carbon sequestration is crucial for the well-being of aquatic ecosystems. Protecting migratory routes, and breeding grounds, and adopting ecologically friendly fishing practices are essential for the prosperity of fish populations in Sri Lanka's capture fisheries.

- By considering these recommendations within the unique Sri Lankan context, a more robust and sustainable approach to food security can be fostered, addressing ecosystem needs, water management, and the intricacies of various agricultural landscapes.
- In livestock systems, herd sizes can be reduced by employing animal management strategies that promote animal health and survival. Feeding practices that utilize crop wastes and other waste products, the proper selection of fodder crops, and higher quality forage can help reduce feed costs. Agroecosystem services can be provided more effectively and efficiently by systems like mixed crop-livestock systems, which incorporate a wide variety of crops and livestock into irrigation networks.

## Policy Framework

Recent worldwide food crises have highlighted the need to strengthen our food system and make it more sustainable. It is common knowledge that water scarcity will be a significant barrier to agricultural expansion in the years to come. By ensuring that both agricultural and non-agricultural ecosystems have access to water, integrated water resources management can help ensure the long-term viability of food production. Consequently, more diversified and productive ecosystems can provide a broader range of ecosystem services, such as water management activities critical for stable food security. To achieve this goal, we must adjust to ecosystem management, water resource allocation, and food security.

- Understanding incentives and trade-offs requires economic assessment of ecosystem services from agricultural and non-agricultural environments. To preserve the long-term viability of agriculture, it must be maintained as a network of interdependent agroecosystems integrated within a wider, wooded environment. Management of agriculture, the environment, water, fisheries, livestock, and wildlife must cooperate at the local, and global levels. One possible aspect of this is the creation of financial incentives for users (such as farmers, fishermen, and cattle herders) to maintain and enhance ecological services.
- Effectively managing all sources of precipitation and runoff within multifunctional agroecosystems at the river basin level is paramount for ensuring the long-term sustainability of a wide range of ecosystem services. When ecosystems can enhance their water production capacity, they become better equipped to regulate and provide essential water services, such as those provided by agroecosystems.
- Provide water to both agroecosystems and non-food-producing ecosystems through adaptive Integrated Water Resources Management, which is supported by institutions that are strong and have the power to do so. An effective approach to enhancing water productivity and ensuring food security involves strategically integrating multifunctional trees within agricultural landscapes. This practice helps optimize the circulation of water, nutrients, and carbon, contributing to soil and water conservation while simultaneously reducing the dependency on remaining forest resources. The use of locally adapted cultivars in dry zone agroecosystems allows for the efficient use of water and nutrients, the provisioning of herds, and the management of trees, crops, and animals in a single system.
- Aquaculture and fisheries rely on oxygenated water for various physiological functions, including breathing, seeding, and feeding, all of which contribute to the upkeep of thriving aquatic ecosystems. Detritus, waste, nutrient cycling, and carbon sequestration must be managed to provide advantages to these aquatic ecosystems. For sustainable capture fisheries, it is essential to ensure the safety of migratory routes and breeding areas and to employ ecologically friendly fishing practices. Multifunctional aquatic ecosystems can supply additional

ecosystem services, such as cattle and aquaculture, rice and fish farming, irrigation and water management, and wastewater-fed aquaculture.

- By preserving both quantity and quality of water, feeding strategies including employing tree fodder, agricultural wastage and other waste materials, an appropriate selection of fodder crops, and grazing management approaches can increase livestock water productivity. Mixed crop-animal systems can increase their environmental benefits, for example, by incorporating livestock into irrigation systems and using multifunctional crops.

The food and financial crises have exacerbated the strain on natural resources. However, these crises have also sparked innovative approaches in perceiving agroecosystems as viable long-term sources of goods and services, provided they are subject to sustainable and equitable management. To safeguard food security, policymakers must champion the responsible stewardship of agroecosystem services. This entails promoting the adoption of technologies and practices, such as sustainable land management, integrated water resources management, and more sustainable agricultural methods, among both male and female farmers.

In Sri Lanka, a prevailing trend in most agroecosystems has been the primary focus on harvesting biomass for essential needs like food, fibre, fodder, and other valuable resources. However, this emphasis on certain outputs has sometimes led to the neglect of other critical supporting or regulatory activities. Water plays a substantial role in overseeing and maintaining a wide array of functions within agroecosystems. For instance, It plays a crucial role in supporting the maintenance of non-agricultural vegetation, including shade trees, grasslands, and aquatic habitats. These elements hold significant value for numerous individuals, particularly those most vulnerable, such as those living in poverty and facing food insecurity. These habitats serve as crucial sources of supplementary food, fodder, and fibre.

Nonetheless, this dynamic gives rise to distinct governance challenges, concerns about how benefits are distributed, and potential environmental consequences. To address these intricacies, it is imperative to implement strategies carefully and diligently monitor their performance in real-world scenarios. This process allows for adjustments to be made where necessary to refine the overarching strategy. By comparing initial estimations of the value of agroecosystem services within conventional agricultural production systems against real-world examples of agroecological landscapes, valuable insights can be gained regarding the effectiveness of an agroecosystem services approach to promoting food security.

This article has underscored the significance of agroecosystem services for agriculture within the specific context of Sri Lanka. It has delved into how improved water and ecosystem management can play a pivotal role in bolstering food security. While the concept itself is not entirely novel, this article has meticulously amalgamated recent findings from diverse fields such as crop production, aquaculture, agroforestry, livestock management, and water management. This fusion of knowledge has provided a comprehensive theoretical foundation and actionable guidance to address the multifaceted challenges associated with enhancing food security through the lens of agroecosystem services.

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## Conflicts of interest
The authors declare no conflict of interest.

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