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Multisectoral Approaches to Accelerate Economic Transformation in the Face of Crisis in Sri Lanka

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Multisectoral Approaches to Accelerate Economic Transformation in the Face of Crisis in Sri Lanka

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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 and 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 2023 “Multisectoral Approaches to Accelerate Economic Transformation in the Face of the Crisis in Sri Lanka” emphasizes the necessity of integrated sectoral approaches in seeking solutions for the current economic crisis in the country. 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.

Sixteen chapters of the e-book discuss timely important approaches in building resilience in the fields of agriculture, food security, education, health, energy, and environment in the face of crisis. Given the rapid change in the socio-economic environment along with the financial crisis in the country, we see a real need to look at things from a different perspective with a broader future vision to address the above-mentioned issues despite their persistence for several years without generating tangible solutions.

We hope that this chapter e-book will provide insights to make science and technology the key driver in accelerating economic transformation through sustainable resource management in the face of crisis in Sri Lanka.

Editorial Board
YSF Thematic Publcation-2023
27th January 2023

Message from the Chairperson /NASTEC

As the Chairperson of the National Science and Technology Commission (NASTEC), it gives me immense pleasure to see that the Young Scientists of Sri Lanka who have gathered as a community to create the Young Scientists Forum (YSF) under the guidance of NASTEC and using their collaborative scientific knowledge in producing solutions to the prevailing economic crisis in the country. This thematic e-publication under the title "Multisectoral Approaches to Accelerate Economic Transformation in the Face of Crisis in Sri Lanka" is one of their efforts in educating the scientific community to mitigate this adverse situation. This is their second consecutive chapter e-publication 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 Education, Health, Agriculture, Nutrition, Food security, Energy and Mineral Resources encountered in the current Sri Lankan economic landscape 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 better state from the current predicament.

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 Dr. Samantha Dissanayaka, Editor-in-Chief and the Editorial Committee of YSF for taking initiative to compile such a comprehensive publication.

Prof. Veranja Karunaratne
Chairperson/ NASTEC
27th January 2023

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 2023. This e-book thoroughly examines the Multisectoral Approaches to Accelerate Economic Transformation in the Face of the Crisis in Sri Lanka. The E-book emphasizes the necessity for vibrant policy intervention, as the issues do. As a result, NASTEC, as the government's policy advisory body for science and technology affairs, 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 16 chapters, each with a different topic linked to the main title. The Editorial Board of the e-book thoroughly evaluated these Chapters to ensure that the main title's major components were covered. All chapters are extremely important and highly debated topics in the current crisis context of Sri Lanka. Therefore, this publication will deliver great service for research and development and also for policymakers in finding effective policy interventions for the current crisis. Besides, 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, as well as Ms. Thilini Munagamage, NASTEC Scientist, for their strenuous effort in making this e-book a reality despite numerous obstacles. I also express my gratitude and congratulate all the young scientists who contributed papers to this e-book.

Mr. Janaka Sampath Geekiyanage
Acting Director/ CEO
27th January 2023

Message from the Chairperson/YSF

The Young Scientist Forum (YSF) is a community of intelligent people in Sri Lanka, which has a strong focus on research and development, realizing that it is a key element for the economic growth of the country. The YSF is formed with researchers from diverse academic disciplines who are committed to integrating scientific knowledge into society for public well-being. In the context of the Fourth Industrial Revolution, the YSF plays a prominent role in suggesting policy development and fulfilling policy gaps in the area of science and technology. Further, the YSF positively interacts with society by sharing knowledge through different platforms like webinars, publications, and symposiums.

Currently the entire nation is struggling with an economic and social crisis due to poor resource mismanagement in the country. With the objective of striving to contribute a positive outcome to the prevailing situation, the YSF created an overview of "Multisectoral Approaches to Accelerate Economic Transformation in the Face of Crisis in Sri Lanka" as a scientific note and compiled an e-book. As the Chairperson of the Steering Committee of the YSF, I am honored to make a note in this valuable compilation, presented as a result of the tremendous efforts put forward by the Editorial Committee of the book and the YSF Steering Committee. This e-book attempts to provide scientific solutions to the contemporary issues of society which are emerged due to the crisis. Therefore, this e-book offers an impression of all the scientific insights as a collection of book chapters with the intention of educating young minds for future advancements of the country.

Further, I would really like to take this opportunity to compliment all of the authors for providing their insightful perspectives on the key themes that called for in-depth discussion. I also want to express my gratitude to all of the reviewers for their kind and diligent assistance in reviewing and improving the quality of the chapters through a rigorous reviewing process.

Mr. Akila Jayasanka
Chairperson/ YSF
27th January 2023

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- We gratefully acknowledge the contributions made by the chapter authors for sharing their knowledge and experience through a chapter of this e-book.

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- We wish to extend our appreciation to the editorial committee members of this e-book for devoting time despite their busy schedules to editorial work and the members of the YSF Steering Committee for the continuous encouragement made to make this task a reality and unique.

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CHAPTER 1

The Role of Universities in Leading the Nation through Crisis: Perceptions beyond Education

A.K. Amarasinghe[1]*, A.M.C.U.M. Athapattu[1] and S.K. Yatigammana[2]

Abstract State Universities play a leading role in the education system of Sri Lanka. The undergraduates trained in State Universities constitute the largest qualified workforce entering the Sri Lankan job market, especially at the executive level in the industry. In addition, academics in State Universities directly train professionals in education through workshops, continued professional development programmes and postgraduate degree programmes. Furthermore, State Universities lead the Sri Lankan educational research arena through supervision, implementation and providing the intellectual framework for Sri Lankan educational research. Moreover, academics in State Universities are directly involved at the policymaking level of the Sri Lankan educational system, contributing to decisions that affect generations to come. This chapter will address how State Universities should approach the emerging market crisis affecting Sri Lanka. As noted in many forums, the long-term solution for the economic crisis, no matter what road it takes, will always pass through comprehensive education reform that would enable the workforce to face the unforeseen challenges of the 21st century. With the economic crisis and its far-reaching impact on Sri Lanka's diverse communities, there is an almost universal consensus that the entire educational paradigm needs to change. Academics should lead this transformation; this chapter explores how academia can help develop an elite workforce, train educators for the challenges ahead, and advance educational research to scale economic recovery and guide the nation in policymaking.

Keywords: Cooperative education, Developmental education, Educational research, Policymaking, Teacher training

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Introduction

Sri Lanka is facing an unprecedented crisis on the economic front and the recovery does not seem immediate. Even though there is no universal consensus on the causes of the crisis, it can be thought of as a symptom of collective mismanagement, policy issues, and a lack of political knowledge of the populace that populist elements could exploit. Predictions by various sources indicate that the recovery might be slow, and sweeping socioeconomic and political turmoil is unavoidable (World Bank, 2022).

Education represents a way out of the crisis and many studies point out that the collective output of an educated society far outweighs the investments put into it. Analysing the economic and social benefits of knowledge and skills derived from competencies acquired in higher education is an essential source of information for transforming societies. This will facilitate discussion on the critical planning areas needed to develop a strategy for graduation where job creation, developing skills, cultivating informed citizenship, partnership in governance, and disseminating knowledge are key concerns (Pee *et al*., 2020). In this chapter, we propose how Universities should react to the current crisis and lead the nation not just in the educational aspect but beyond it. We discuss four key areas that Universities could contribute.

1. Universities as developers of an elite workforce – as Universities are supposedly the institutions that develop highly skilled graduates for the tech-heavy job markets of the future, the current role of the Universities in doing so will be investigated.
2. Universities as the centres for training educators – the educators trained by Universities as undergraduates or participants in training programmes would in turn, educate the next generation. So the effects the Universities have on the worldview of the educators will pass on to society. Extent to which we want to manipulate this process for the betterment of society will be a focal point.
3. Research in Universities as tools for reform – Universities are centres of research, and the research is expected to impact the locality and the nation. Sri Lanka is home to multiple Universities with high quality research activities. What are the barriers that exist in the system that hinders the research from helping society at large?
4. Universities' involvement in policymaking – We investigate how Universities, as institutes, can involve in policymaking to recover from the current crisis in the country.

Changing Paradigms in Higher Education

A University, by definition, is a community of teachers and scholars whose motive is to seek the truth and expand the human knowledge base. The origins of the first

Universities across Eastern Europe, leading to the establishment of Universities globally, stemmed from the idea that there should be no bound to free inquiry and that scholars should be granted freedom to seek knowledge, question established theories, develop ideas and pass it through the generations (de Ridder-Symoens and Rüegg, 2003). Training for a specific vocation was not considered to be the central element of the purpose of the existence of Universities, and this idea is still alive in the definition of a University; as an "institution of higher education offering tuition in mainly non-vocational subjects and typically having the power to confer degrees" (OED definition) (Charikova and Zhadanov, 2017). However, the complexities of modern society, increasing requirements of a workforce that possess higher-order thinking capacities, and the ability of Universities to produce. Such graduates have put a strain on the very definition of a University; society now expects Universities to train an elite workforce that could navigate itself through the intricacies of a technology-driven world and guide itself to economic prosperity (Glenn, 2008).

Universities worldwide have understood the need to produce an empowered workforce in general. *Magna Charta Universitatum* signed 900 years after establishing the first University in Bologne, recognises that "the Universities' task of spreading knowledge among the younger generations implies that, in today's world, they must also serve the society as a whole" (Kulesza, 2004). In the Sri Lankan context, serving the society as a whole is essential more than ever, as the investment the society makes in the State University system, in terms of pouring money into higher education, has seemingly failed to generate the expected output, namely, driving the country forward using the expertise of graduates (Siyambalapitiya, 2005). It is up to the State Universities to address this issue and use their resources to guide the country in generating the workforce it needs to navigate the challenges of the 21st century.

Careers of the Future and How Can Universities Contribute?

According to a report by the Information and Communication Technology Agency (ICTA), the Information and Communications (ICT) industry in Sri Lanka, which employs more than 80,000 workers, is expected to reach USD 3 billion in revenue by 2024 (ICTA-SL, 2019). In the context of the ongoing economic crisis in Sri Lanka, empowering this sector would be a promising mid-range solution for the depletion of foreign currency reserves. Furthermore, most of the employment opportunities in the ICT industry come with a pegged salary attached to it, where the employee earns some portion of the salary in a foreign currency of choice, depending on which country funds the project. This represents an attractive proposition to prospective employees, who are generally worried about stagflation, that is, stagnation of wages combined with inflation, which other employees across Sri Lanka experience. The tech talent pool of Sri Lanka, a considerable proportion of which is trained through the State Universities, has a crucial role to play in the process of the economic recovery of Sri Lanka. Sri Lanka currently harbours more than 300 IT companies and is home to more than 1000 startups, serving in all the areas of ICT and producing a full range of IT products, from software development to innovative solutions. Sri Lankan State Universities produce more than 500 trained ICT professionals per year. However, the market, still under saturated, implies that many more can still be accommodated in the field (ICTA-SL, 2019). Together with the resources at hand, the Sri Lankan Universities can do much more in training ICT professionals for the future.

Information Technology Business Process Management (IT-BPM) is a particular area that Sri Lankan Universities can emphasise. IT-BPM is when foreign brands, multinationals and other corporations engage the services of a third-party vendor to manage certain aspects of their workplace operations (ICTA-SL, 2019). It is a well-established industry with a potential of 20% yearly growth. Being successful in IT-BPM requires communication skills, networking and other essential skills apart from the standard abstract thinking and problem-solving skills imparted by most degree programmes. Our universities have to critically reflect on their degree programmes and incorporate modules that allow students to improve these timely and much-needed skills.

Apart from technology-related industries, manufacturing industries like apparel and electronics represent more resilient means of production that Sri Lanka can focus on in the process of turning around the economic crisis. Process optimisation in these industries is a critical aspect which helps these complex corporations to stay above the competition. To succeed, employment positions that manage process optimisation require higher-order thinking, numeracy and tech-savvy. Most of these positions are filled in by graduates; however, the longstanding complaints from the industry that the graduates lack the competencies required should be taken to notice, and the Universities must incorporate the ideas of stakeholders.

Responding to Developing Labour Market Requirements

One shortcoming of University education in Sri Lanka is the lack of an effective linkage between secondary and tertiary education and general education (Gnanawasa, 2017). The origins of this issue can be traced down to asynchronicity in adopting reforms in school and University education. For example, most Universities moved into a semester-based curriculum in the first decade of the twenty-first century, and the educational paradigms are shifting towards outcome-based education during the second and the third decade. However, reforms in school education that prime students to outcome-based, student-centred teaching is slow to take effect. Universities respond to this by incorporating general education courses into their curricula (Wijetunge, 2006). Notwithstanding the effort taken by some universities, there are still glaring deficiencies in how the graduates are prepared for labour market requirements (Gnanawasa, 2017). Ideas like systems thinking, digital reality, and additive manufacturing are not mainstream in Universities. Some of these concepts might also be unheard of in the Sri Lankan industry. However, the rapidly changing world and the innovative pressure would eventually require the industry to adapt, and when that happens, a trained workforce should be there to control it. The University's role is to anticipate such trends and prepare the graduates for what to expect in the future.

Systems thinking is a way of making sense of the world's complexity by looking at it in terms of wholes and relationships rather than splitting it down into parts (Banathy, 1999). The idea of systems thinking emerged as a management concept, but now it is adopted in engineering, healthcare and any other scenario that involves complex systems (Ison, 1999). Even though thinking of a problem holistically is not unheard of in Sri Lanka, the tools and techniques of systems thinking are something to be learned. Introducing systems thinking early in any higher educational curricula, with taking the correct context into account, will help the graduates to process real-world scenarios and react appropriately when they encounter problems.

The Fourth Industrial Revolution (4IR) conceptualises rapid change to technology, industries, and societal patterns and processes in the 21st century due to increasing interconnectivity and smart automation (Bai *et al., 2020*). We already see some aspects of 4IR in developed countries, and the technology gives a competitive edge to the companies that adopt the ideas most innovatively. Just like the digital revolution, it drives out competitors who do not adopt (Morkovkin *et al*., 2020). Technologies like additive manufacturing, augmented reality, internet of things is revolutionising everything from manufacturing to consumption, and Universities are not in the driving seat this time. Some Sri Lankan Universities have identified the need to introduce these ideas; however, if the Universities are to lead the educational landscape, they should be more proactive and insistent in doing so.

Cooperative Education – More than Internships for University Students

Most bachelor's and B.Sc honours degree programmes offered in Sri Lankan Universities come with internship opportunities, but they are not required for such degrees. Cooperative Education (co-op) is different from an internship as it offers full-time, fully-paid employment to students before graduation. Universities in Canada, USA, and Australia are offering co-op programmes to students, expecting them to interact with the industry in a much more realistic manner. The main difference between internship courses and cooperative education is that cooperative education is a structured educational strategy where students alternate between work and study periods. This integrated and systematic curriculum is achieved through a careful partnership between the educational institution and the occupational field, with each partner contributing to students' learning (Groenewald, 2004). Despite its criticisms, "extended classrooms" in cooperative education are generally viewed as beneficial to students, sponsoring institutions, and the community at large (Braunstein, 1999). Sri Lankan Universities do not have programmes that offer cooperative education, but there are many degree programmes, especially three-year bachelor's degree programmes (previously known as general degree programmes) that can be appended by a fourth-year cooperative education programme, strongly linking higher education with industry. It should be noted that managing a co-op programme is a logistical struggle, and the administrative structure of most State Universities is ill-equipped to handle such a programme at a massive level (Sobolev *et al*., 2022). However, looking at such programmes and how they can develop a workforce that would take the Sri Lankan economy to the path of recovery and beyond would be a wise idea.

The Role of Universities in Developing Educators

Sri Lankan education system consists of three stages, namely primary education, secondary education and tertiary education. In secondary education, students need to be taught relatively profound context on Science and Mathematics. In that sense, a sizable proportion of university graduates are recruited by the government as teachers to teach GCE (A/L) to classes in Science and Mathematics. Nevertheless, the most prominent issue is that none of the government universities' degree programs intends to produce secondary education teachers. There are a few supplementary courses that have been included in some degree programs. This reflects that policymakers believe knowledge is the key component which aids in producing quality teachers. The generalisable dictums that textbooks, curriculum packages and teachers' manuals would greatly support teaching. When these provide inadequate information, teachers manage to build up their own. Higher Education Institutes can focus on how prospective teachers should be taught in order to enhance school education in Sri Lanka. Rich professional development settings have several vital features (Ball and Cohen, 1999) as follows,

1. Development centres around the critical activities of teaching and learning – planning lessons, evaluating student work, developing curriculum
2. Teacher knowledge grows from investigations of practice through cases, questions, analysis, and criticism
3. Learning is built on substantial professional discourse that fosters analysis and communication about practices and values in ways that build colleagueship and standards of practice.

It is essential to take necessary actions to incorporate these strategies for Sri Lankan secondary education level. Professional development activities must allow teachers to engage actively in cooperative experiences sustained over time and to reflect on the process and the content of what they are teaching (Linda, 2004). Teachers individually cannot reconceive their practice and the culture of their workplaces (Darling-Hammond and McLaughlin, 1995). In that case, teacher education plays a significant role, i.e. the pedagogy used in teaching teachers (Korthagen, 2016). Sri Lankan Universities conduct courses/programmes/workshops for teachers/ educators throughout the country, assisting their professional development. The traditional scope of these programs needs to be changed to integrate with ICT to improve teachers teaching styles-the effective use of ICT contributes to the teaching and learning processes in all education sectors. Developing countries, such as

Bangladesh, Afghanistan, Nepal, Pakistan, and Vietnam, have found the consequence of redefining teachers' roles. In response, many professional development programs have been introduced to train teachers in using ICT (UNESCO 2004). There are several research works on the initial implementation of technology-enhanced formative assessment (TEFA) using a Classroom Response System. The TEFA is based on four core principles, question-drive instruction, dialogical discourse, formative assessment and meta-level communication (Ian and William, 2009). The Sri Lankan education system can be merged with ICT by alternating the pedagogy of teaching education.

According to the current practice, teachers are expected to learn through workshops, short courses, and seminars on their own, with no chance to observe and analyse teaching with others. The teacher communities or study groups may foster teacher learning through a collaborative culture and codification of group members, and collective knowledge (Stanley, 2011). Higher Education Institutes can provide a platform to carry on these teacher communities. That would open up the road to school students to visit Higher Education Institutes. It would entice students interested in school education. During the school vacation, their institutes jointly may organise the two-three days science camps. Through the camps, students would be able to engage with the work of scientists and engineers to build skills and knowledge related to laboratory work and technical report writing. There is a considerable improvement in participants' confidence, ability to present the activities' results and their reflection on science and technology. The presentations are almost unique ideas, which could be improved further to a status of a new patent.

Science camps are an extremely positive experience mainly because they create networks and social relations in children and kids interested in sciences, who often feel different because of their interest. During a camp, they can freely express all their potential (Linder and Kubat, 2014). Science camps can be used as a platform to improve Science, Technology, Engeneering and Math (STEM) skills. The STEM education is the combination of four disciplines of science, technology, engineering and mathematics into one unit. Furthermore, STEM education helps enhance students' knowledge and skills and change their attitudes towards real-world problems. According to the latest Science, Technology and Industry Scoreboard report from The Organization for Economic Cooperation and Development, the STEM education system has been successfully practiced in USA, China, South Korea, Germany, Sweden, Finland, Greece and Estonia.

Educational Research as a Tool for Reform: Current State of Educational Research in Sri Lanka

State Universities lead research activities in Sri Lanka, and some State Universities are considered high-output research Universities in the region. Almost all State Universities have dedicated academic staff members in the field of education. The field of education is a popular research area for even non-specialists. So how does the research activity impact the reform of education? Not non-existent, since some of the research would seep into actions of reform of education (Ginige, 2002); however, this mingling of research and educational reforms fails to meet the demands of the modern world. On the other hand, educational research has not passed through to one of the most important stakeholders in Sri Lankan education, the teachers. As noted above, the teachers' involvement in educational research and interaction with the University system does not meet expectations. Research on the educational situation in Sri Lanka, especially the application of new educational paradigms such as constructivism and self-determination theory, can be used to enhance teaching and learning activities. This has been done to some extent as research that leads to academic progress, but it has not been applied to educational practice. When such studies are conducted on a large scale, more practical scenarios emerge, and the results of such studies may be disseminated among teachers and educational administrators. Furthermore, educational researchers should be encouraged to conduct research on education for national development.

Directions for Educational Research on the Theme of National Development

It is a well-known fact that investment in education would pave the way to prosperity. Investing in education is not only the right move, but it is also good for the economy, as an increase in the level of education leads to improvements in health, empowerment, and employment. However, it is necessary to understand which levels of education the public should invest in to maximise the returns. The rate of return patterns established in earlier reviews are upheld: namely, that primary education continues to be the number one investment priority in developing countries; the returns decline by the level of schooling and the country's per capita income; investment in women's education is in general more profitable than that for men; returns in the private competitive sector of the economy are higher than among those working in the public sector; and that the public financing of higher education is regressive (Psacharopoulos, 1994). In Sri Lanka, several studies have gone in the direction of investment returns on education. In the Sri Lankan context, the returns to investment in education are positive but significantly lower than those found in other developing economies. Unlike the case of most developed economies, higher returns from investment in physical capital cannot produce any sizable positive externalities (Ganegodage and Rambaldi, 2011). This is quite an interesting fact, and researchers' interest should be drawn into this topic in the era of demanding ever-increasing finances for higher education in Sri Lanka.

Another critical area that should be of focus is the effectiveness of distance learning methods that were introduced recently. Online and distance learning methods saw the light in the last decade, but accelerated applications were seen, mainly due to the pandemic. Many researchers point out the perceived benefits online education represents, especially in promoting student-centered learning (Christensen *et al*., 2008). However, this research has been primarily done in developed countries, and Sri Lanka has unique challenges in terms of accessibility to the internet, lack of quality content, and inadequate methods of assessment (Perera *et al*., 2021). Nevertheless, Online and distance education is here to stay, and Universities must find out the best and the most innovative ways of utilising online education for the benefit of the country.

There is little to no space to include research in public discourse; similarly, the Universities lack platforms to discuss research findings with policymakers. The Universities, as institutes that lead scientific research in education, should address each of the issues and come up with solutions so that Educational Research can be used as a tool for reforming education. It would help create the workforce the country need to overcome the economic crisis and guide the nation to prosperity.

Leading the Country from Policymaking Perspective: Involving as Institutes, not as Individuals

Policymaking is nothing new to academics, as many academics are involved in policymaking at the national level. However, as institutions, Universities' role in affecting policies is debatable. This phenomenon is different in developed countries, where in some cases, universities go beyond just policymaking to governance. Where once universities were primarily responsible for the dissemination and production of knowledge through their academic functions of teaching and research, they are now increasingly engaged in the dissemination and production of knowledge through their mission of engagement with the external community (Gunasekara, 2006). There is growing evidence to suggest that universities are engines of development. Outside their main social contract of providing excellence in education and research, Universities are expected to support the national policymaking process, not just in education but in other fields as well. In addition to the transmission and extension of knowledge, Universities at the time were being called upon to,

1. play an important role in the general social objective of achieving greater equality of opportunity,
2. provide education adapted to a great diversity of individual qualifications, motivations, expectations and career aspirations,
3. facilitate the process of lifelong learning,
4. assume a public service function, i.e. make a contribution to the solution of major problems faced by the local community and by society at large, and participate directly in the process of social change (Guy et al., 1982).

The relevance in the list above is striking in the discussion we have regarding the role of Universities in the context of economic crisis. Universities are nowadays forced into a constant dialogue with the stakeholders, and this can lead to many fundamental changes in the relationship between universities and their environment. In the existing system of education, how a University can assume a public service function to help society at large is debatable. It does not mean that the Universities' governing bodies do not want to do it, but there is no unified mechanism to achieve this public service function. Jongbloedn *et al*. (2008) points out the main barriers to this being,

1. determination of the research agenda and the educational offerings of universities,
2. internal reward structure of universities,
3. lack of an entrepreneurial culture in universities.

How funding is allocated between and within disciplines will largely determine research portfolio and curriculum choices. In other words, public research agendas and educational program offerings can be very different from the needs of the country. For example, differences between University research portfolios and private sector research agendas. Aligning the organisation's mission with the demands of the external community will require close interaction between the University and its stakeholders. Another institutional impediment to increasing community interaction relates to academic and faculty reward systems. First, the parameters that drive promotions often do not include rewards for local engagement and interaction with communities. The standards give little consideration to working with non-academic communities. This "publish-or-perish" culture can be found in prestigious universities. At more educationally oriented institutions, faculty workload and educational responsibilities determine employment conditions, salaries, and opportunities for advancement.

Finally, the inadequacy of entrepreneurial culture in State Universities hinders productive communication with academia and the industry. In developed countries, Universities get royalties for the consumer products that come to the market as the output of research by the University. In Sri Lanka, this linkage is coming to light recently, and governing bodies often are not conducive to ventures such as commercialisation, which they feel is not the job of academics. All this means that undertaking the public service role is hindered by many institutional barriers, implying that the acceptance of this task is not a straightforward action. However, if the Universities can productively use their business-linkage units to drive their academic and research-related work to the consumers in a reasonable time frame, it would be beneficial to the country, and the revenue generated can ease the burden of the enormous amount of money spent on HEIs from the purse of the public.

The Concept of Developmental Universities

The Developmental University is a model that is main stream in the African continent. Compared to the classical University model, where knowledge is pursued for its own sake, the Development University model emphasises on using knowledge to the prosperity of the society. The outcome document of the Association of African Universities workshop in 1972 states that the emphasis here must be on the pursuit and inculcation of practical knowledge, not esoteric knowledge or knowledge for its own sake. It must be immediately useful for the generality of people and, therefore, locally oriented and motivated (Tijani *et al*., 1973). Many institutes in Africa follow the developmental model. It was easier for them to do so as the Universities were established using the model at hand. According to McCowan (2019), the four main features that characterise the developmental model of the University are, first, it is an institution oriented towards serving society; it appeals to no other purpose than that of attempting to address the needs and promote the benefits of its surrounding communities. The second is that it does so in an egalitarian way, not confining its fruits to the elites but aiming to support in particular, the least advantaged populations. Third, it aims to bring non-academic benefit to the population-i.e. of an economic, social and political nature. Finally, it aims to fulfil this role through the application of knowledge, the turning of the theoretical and abstract towards practical and immediate ends. It is clear why this differs from the classical model and could be used where human development was needed most in that era. With most of our State Universities following the classical model of pursuit and expansion of knowledge for the sake of knowledge, it would be a monumental struggle for us to adopt this paradigm; however, it is a worthwhile venture to look into the aspect of Developmental Universities, and how they were pivotal in the transformation of the continent, will help us understand, in our context, to what extent we can use these ideas.

Conclusions and Future Prospects

The current economic crisis, and the resulting socioeconomic downturn, are not a result of a single policy, nor is it a result of the actions of a single administration or an event (Bhowmick, 2022). It is a result of decades of ruinous policymaking, the dependence on welfare, and a bloated government sector. To come out of the hole that we have dug ourselves as a nation, all the relevant parties must get together and think of short, mid and long-term solutions. Having an educated electorate capable of dissecting election promises and critically analysing the consequences of such promises would help mitigate such events in the long run (Sondheimer *et al*., 2010). On the other hand, education can be used to shape the future and anticipate new opportunities that would drive the country forward. Even more apparent is the strengthening of the belief that education is the fundamental foundation of development (Claudio-Rafael *et al*., 2013). In countries like Sri Lanka, education reform is highly complex for historical, cultural, political and economic reasons, and the expected benefits of achieving the goals set in the global consensus on education have not been realised. This commitment is even more significant in the face of the current crisis and requires all educators to get their hands dirty and work with a common goal in mind. If we expect to be able to justify the enormous amount of money that the public is investing in higher education at public universities, we should take seriously the aspects of leadership that the public expects from Universities across Sri Lanka.

Conflict of Interest

Authors have declared that no competing interests exist.

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CHAPTER 2

Optimizing Nutrition, Health and Education of Children during the Economic Crisis

Y.M. Rohanachandra[1,2]

Abstract Economic recessions affect education, as well as the health and nutrition of children. Children and young people are especially vulnerable to the negative effects of an economic recession. The economic crisis may impact on education through reduced school enrollment, reduced school attendance and higher school drop-out rates due to unaffordability of the cost of education. Economic recession can also reduce the quality of education due to the constraints imposed on state and local funding for schools. The adverse effects of economic recession on education are shown to be long-lasting. During an economic downturn, the healthcare budget is restructured, with significant cuts to public health services which can lead to limited availability of medications and medical equipment. This, coupled with delays in reaching healthcare institutions due to the shortage of fuel, results in poorer physical health outcomes in children such as increased neonatal and infant mortality. The increased prevalence of malnutrition among children has also been described due to increased levels of food insecurity. Economic adversity is associated with elevated family stress, leading to a higher risk of behavioural problems, reduced social competence, and poor cognitive ability in children and adolescents. Poverty and increased family stress are also known to contribute to increased rates of child maltreatment during a financial crisis. This chapter reviews the impact of an economic recession on education and child well-being and suggests possible solutions to continue uninterrupted education and maintain the health of children during the crisis.

Keywords: Child Health, Child Well-being, Economic Recession, Education, Malnutrition

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Introduction

Children and young people are especially vulnerable to the negative effects of an economic recession. Early childhood is a period of rapid brain development and a critical age for achieving development milestones. Hence, deprivation during this period of early childhood can have devastating long-term consequences for physiological, behavioral and socioemotional development. In addition, as coping with stress is a developmentally acquired skill, children are less likely to be able to cope with stressors than adults, making them especially vulnerable to the stressors of financial hardship.

According to the United Nations International Children's Emergency Fund (UNICEF), 2.3 million children in Sri Lanka, which accounts for nearly half of the child population, are in urgent humanitarian assistance as a result of the economic crisis in the country (UNICEF, 2021). The rising cost of living, food insecurity, shortage of medicines, school closures and frequent power cuts have all had a devastating impact on the child population in the country. The UNICEF reported that currently, 2.4 million children and women in the country require nutrition services, approximately 1 million children need mental health services and 1.2 million children are in need of access to education (UNICEF, 2021). The UNICEF estimates that without sufficient, timely and flexible funding, the humanitarian needs of the children and young people arising from the economic crisis cannot be addressed, and the most vulnerable children will not be able to access even life-saving services and social assistance.

Evidence suggests that investments in child development and education are the most effective strategy for economic growth, as childhood development and education directly influence the economic, health and social outcomes of a community (Heckman, 2012). The economic outlook of a country depends on a highly educated, skilled workforce, which can only be achieved through investing in children and adolescents. Interventions focusing on children and adolescents have long-term financial benefits through reduced health expenditure, reduced need for social services, lesser spending on the criminal justice system and reduced need for educational support services (Heckman, 2012).

Given the impact of the economic recession on the child population in the country, urgent measures should be taken to minimize the negative impact of the recession on the children and young people of the country. This chapter discusses the psychosocial impacts of the economic recession on children and adolescents and suggests possible solutions to maintain the well-being and education of children during the current crisis.

Impact of the Economic Recession on Children and Adolescents: Schooling and Education during an Economic Crisis

Economic downturns can affect schooling through several mechanisms. Firstly, with declining household income and the rising cost of living, parents may no longer be able to afford the basic costs of education such as uniforms, stationery and school fees for their children. Secondly, due to financial hardships, parents may need to turn to child labour, either full-time or part-time (Shafiq, 2010). Even engaging in part-time labour leaves children with less time for educational activities, which may hinder their academic achievements. Finally, parents may be forced to work for longer hours to compensate for the loss of income, leaving them less time to supervise their children's education (Shafiq, 2010). At the national level, a reduction in the financial allocation for education, constraints on state funding for schools and a reduction in educational employment may result in a decline in the quality of education (Shafiq, 2010).

Previous studies have shown that an economic recession can influence the rates of school enrollment and school dropout, academic achievement and school attendance. In many countries, a decrease in the rates of school enrollment has been observed during periods of crisis. For example, in Indonesia and Costa Rica, the rates of school enrollment decreased and the rates of school dropout increased during the period of economic downturn (Funkhouser, 1999; Thomas *et al*., 2004). Studies from Korea and Phillippines noted a substantial decrease in the regularity of school attendance at the time of economic crisis (Knowles *et al*., 1999; Moon *et al*., 1999). Several studies have also reported a decline in the academic achievement of students, with a 1000$ reduction per pupil educational expenditure resulting in a 0.08-0.17 standard deviation decline in student academic performance (Shores and Steinberg, 2019). Studies carried out during the great recession showed a decline in students' performance in mathematics, English, and arts. It is also reported that academic performance was especially impacted when children themselves were worried about the family finances (Shores and Steinberg, 2017). Evidence suggests that the effects of the financial crisis on academic achievement are long-lasting. However, the effects of the financial recession on education differ markedly among countries. For example, there was no decline in the school enrollment rates in Nicaragua at the time of the coffee crisis in 2000-2001 (Maluccio, 2005). Similarly, school enrollments remained steady in Mexico and Argentina during their periods of crisis (McKenzie, 2003). This suggests that the effect of a financial crisis on education depends on a number of factors including policy responses and social protection schemes within the country.

Individual and family factors also contribute to a difference in the impact of education within the same country. For example, children from the lower socio-economical backgrounds and those with lower parental education are more likely to drop out of school during a recession. Findings from the economic crisis in Indonesia showed an overall drop of 1% in school enrollment, with the children from the poorest socio-economic backgrounds showing a 2% drop (Thomas *et al*., 2004). There is evidence from Costa Rica that the school dropout rates were lower in children from families with higher parental educational levels (Funkhouser, 1999). Parents who are more educated are likely to have more employment opportunities, have more access to loans, maybe more educated about government assistance programmes and may be more reluctant to withdraw their children from school, all of which might have contributed to a lower dropout rate in this group of children.

Education in Sri Lanka was severely disrupted during the pandemic with schools being closed for extended periods of time. Many schools recommenced their routine educational activities in early 2022, only to be hit by the financial crisis (UNICEF, 2022). The economic recession led to a marked decline in school attendance due to the shortage of fuel and the unavailability of transport. Eventually, schools were closed with a switch to online learning mode, to compensate for the fuel shortage. However, the frequent power cuts limited students' participation in online teaching. Furthermore, the lack of high-speed broadband connections and lack of electronic devices also affected student participation in online learning, especially in low socio-economic families. Moreover, due to the unavailability of guidelines, there is a wide variation in online teaching among schools. In addition, the lack of computer literacy among teachers has also impacted the quality of online education. Student assessments were also affected by the economic crisis. Some examinations were indefinitely postponed due to an acute shortage of paper (George *et al*., 2022). Long periods of school closure are associated with poor motivation, disruption in learning, less engagement with school, poor psychological well-being and hindering social development in children. Interruption of examinations is also known to create additional stress for students and may lead to disengagement from school. Given the lack of policy responses and social protection schemes to safeguard education during the period of crisis, a collapse of the education system in Sri Lanka can be anticipated during the economic recession.

Economic Recession and Physical Health of Children

An economic crisis can negatively impact physical health outcomes through a reduction in GDP allocated for health services, limited availability of medications and medical equipment, delays in reaching healthcare institutions due to shortage of fuel, reduced health insurance coverage and inability to afford private healthcare. This can be compounded by the increase in brain drain during the past few months, when large numbers of health professionals have left the country, resulting in a severe shortage of healthcare workers in some hospitals. The negative effects on physical health differ across countries, which may be due to the differences in the severity of the economic recession and the extent to which the government healthcare expenditure changed due to the crisis.

Studies from previous economic downturns show increased rates of stillbirths, higher perinatal, neonatal and infant mortality and elevated rates of small for gestational age births (Rajmil *et al*., 2014). For example, literature from the economic crisis in Peru in the 1980s shows a 2.5% increase in infant mortality rates during the economic crisis, which accounts for an excess of 17000 infant deaths (Paxson and Schady, 2005). Similar findings have been reported from Indonesia with a 1.4% rise in infant mortality rate during the economic crisis in 1998 (Rukumnuaykit, 2003), and from Sab Saharan countries (Friedman and Schady, 2013), where an excess of 28,000–50,000 infant deaths was reported during the 2009 economic recession. A rise in perinatal, neonatal and infant mortality rates by 20-30% was also reported by Greece during the recession (Rajmil *et al*., 2014). However, not all countries experienced a rise in the infant mortality rate. For instance, a rise in infant mortality rate has not been reported in Canada, Spain and Argentina during their periods of economic downturns (Rajmil *et al*., 2014). It is hypothesized that in countries where the government expenditure on healthcare remained unchanged, the infant mortality rate also remained steady.

Sri Lanka has one of the lowest infant mortality rates (5.9 per 1000 live births) in South Asia, which is far below the rates in India (27 per 1000 live births), Bangladesh (24 per 1000 live births) and Pakistan (54 per 1000 live births). There has been no formal data on the changes in the infant mortality rates in Sri Lanka since the onset of the economic crisis. However, there were several reports of infant deaths resulting from delayed presentation to the hospital, due to a shortage of fuel. There were also reports of limited availability of medications and equipment needed for childbirth, which could result in poorer birth outcomes and higher infant mortality. In addition, difficulty in presenting to the hospital for childbirth due to the fuel crisis is also likely to increase the rate of home deliveries, which can also lead to higher infant mortality. Moreover, resuscitation of newborns was reported to be hindered due to the lack of availability of Endo-Tracheal tubes, which could also add to infant mortality.

National vaccination coverage in children can also be affected by the economic recession, which can lead to increased infectious diseases among children. Data from Greece show a negative impact on vaccination coverage during an economic crisis, especially in children with parents of lower educational backgrounds (Vassiliki *et al*., 2014). Studies from Colorado show a similar trend, with vaccination coverage declining by 6% during the economic crisis (Miller *et al*., 1985). Prior to the economic crisis, Sri Lanka had an outstanding vaccination coverage with 99.1% of children received timely vaccinations (UNICEF, 2019). Evidence suggests that family income, wealth index, location of the vaccination clinic and expense of the vaccination contribute to vaccination coverage in a community (Smith *et al*., 2017). Therefore, declining family income, difficulty in getting to vaccination clinics due to fuel shortages and reduced availability of vaccinations can all lead to a decline in the rates of vaccination in Sri Lanka during the current crisis. In addition, the potency of vaccines depends on the strict maintenance of the cold chain, which requires vaccines to be transported and stored in temperatures between 2-8 °C. Frequent power cuts make it impossible to maintain this cold chain, which may lead to loss of potency in vaccines.

Furthermore, changes in local health systems itself can affect the physical health of children. During a recession, private healthcare becomes less affordable leading to overcrowding of the public health system (Koutserimpas *et al*., 2019). Recruitment of new health staff is often halted and there may be high rates of absenteeism among staff due to shortage of fuel and lack of transport. This combined with the lack of medication and medical equipment may lead to delayed management of urgent patients, postponement of surgical procedures and poor quality of healthcare, which in turn may impact the physical health and well-being of children.

Economic Crisis and the Nutritional Status of Children

A rise in food insecurity during an economic downturn can also negatively affect the nutritional status of children. During the 1991-1998 economic crisis in Cameroon, the rates of malnutrition among children under 3 years increased by 7%, from 16% to 23% (Pongou *et al*., 2006). A rise in the prevalence of wasting (weight for height <-2 standard deviations from the median), stunting (height for age <-2 standard deviations from the median) and anaemia were also noted during the 1997-1998 economic crisis in Indonesia (Bardosono *et al*., 2007) and the prevalence of malnutrition in the USA during the Great Recession was as high as 30% (Jacobs, 1933). Children residing in rural areas, from low socio-economic families and whose mothers had less educational attainment were especially at risk of developing nutritional deficiencies.

In addition to malnutrition, there is evidence that the rates of obesity among children may also increase during an economic crisis (Jabakhanji *et al*., 2017). The change in food consumption patterns, with the substitution of healthy foods like fruits and vegetables with less expensive calorie-dense processed foods, is thought to be responsible for the rising risk of obesity during a recession. According to the Colombo Consumer Price Index, the food inflation in Sri Lanka by 10.8 from 80.1 in June 2022 to 90.9 in July 2022. Preliminary data from the World Food Program shows that approximately 3 in 10 households were insecure by June 2022 and these rates are expected to rise with time (WFP, 2022). According to UNICEF, even prior to the crisis, Sri Lanka ranked seventh in the world in terms of rates of malnutrition in children under 5 years (UNICEF, 2022). Sri Lanka also ranked second in rates of waste in children under five years in South Asia and two in five babies were not meeting their nutritional requirements. In addition to the micronutrition deficiencies, Sri Lanka also has high rates of micronutrient deficiencies of iron, vitamin A, iodine, zinc, calcium and folate to a lesser degree (Samarathunga *et al*., 2021). According to UNICEF, since the onset of the economic crisis, 70% of Sri Lankan household have cut down their food intake from three meals to two meals per day (UNICEF, 2022). In addition, families are noted to switch from nutritious off to more affordable, less nutritious food. This is likely to lead to marked increases in the rates of malnutrition among children in Sri Lanka. UNICEF estimates 56000 children suffer from malnutrition because of the economic crisis (UNICEF, 2022). Furthermore, the multiple micronutrients (MMN) supplementation programmes, which has been effective in Sri Lanka since 2007, is also likely to be affected due to economic loss, which could aggravate the micronutrient deficiencies.

Malnutrition resulting from the economic crisis can have long-term implications for children and adolescents. It is well established that adequate nutrition is vital for brain development, especially in the early years, where brain development occurs most rapidly. Evidence shows that children who suffered from malnutrition during their early years have lower intelligence and school performance and are at a higher risk of developing behavioural problems. These effects of early malnutrition are shown to persist to adulthood, with studies demonstrating greater attentional problems, lower social status and poorer standards of living in adults who suffered from malnutrition during the first year of life (Prado and Dewey, 2014). Furthermore, micronutrients play an important role in immune function and nutritional deficiencies can make children more susceptible to infection. Infections themselves can result in nutritional deficiencies, which can then become a vicious cycle.

Psychological Well-being of Children at Times of Economic Recession

Previous literature shows a decline in the psychological well-being, self-reported mental health and life satisfaction of children and adolescents during periods of recession. Studies from Europe during the 2009/2010 economic crisis indicate that approximately a 20% of adolescents had two or more mental health concerns during this period (Rathmann *et al*., 2016). Findings from Greece reveal a 40% rise in psychological problems among children and adolescents, with a 28% increase in disruptive behavioural disorders, 20% rise in suicide and a 19% increase in substance use (Rajmil *et al*., 2014). Worries about family finances were also reported among adolescents, and adolescents who experienced such worries were seven times more likely to suffer from mental health problems (Hagquist, 1998). Children and adolescents also often react to stressors through acting out behaviours which may contribute to the rise in the prevalence of risk-taking behaviours seen in adolescents during periods of recession (Kokkevi *et al*., 2014).

The elevated levels of psychological problems among children and adolescents during periods of economic crisis are thought to be mediated through increased family stress. The “family stress model” suggests that poor job security, unemployment, food insecurity and change in lifestyle during a recession increase parental stress and place parents at a higher risk of depression and anxiety. Increased parental stress leads to poor marital relationships and increased conflicts among parents, which then “spill over” to their interactions with their children, resulting in harsh and inconsistent parenting, a decrease in sensitive and supportive parenting, less parenting competence and the poor parent-child relationship. This in turn leads to poorer psychological well-being in children (Neppl *et al*., 2016) (Fig. 1).

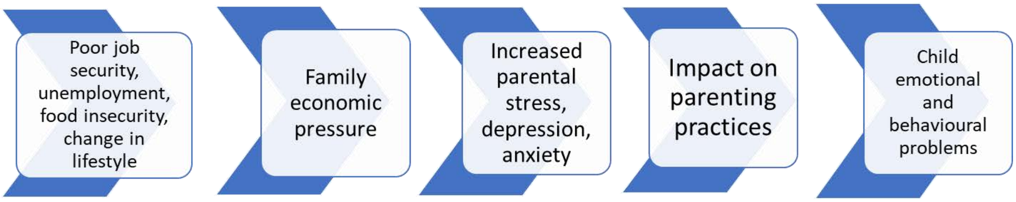

Figure 1. Family stress model (Source: Model recreated based on Conger and Donalan, 2007)

Previous research suggests that older children are more vulnerable to the negative psychological impact of a recession than younger children. Older children, having greater cognitive maturity are more likely to understand the realities of an economic crisis than younger children, which may put them at a higher risk of mental health problems. In addition, parents are more likely to conceal their financial difficulties from younger children, which protects them from negative psychological impacts (Kokkevi *et al*., 2014).

Mental health services are often not considered a priority by public health services and are more likely to suffer from budget cuts. Studies show that during times of financial crisis, there is often a closure of acute mental health wards and a cut down of occupational therapy and mental health rehabilitation services (Ng *et al*., 2013). These reductions in mental health services, combined with reduced availability of mental health services can lead to poor long-term outcomes. Although there are no formal data available as yet, hospital records show that the number of children and adolescents presenting to mental health services has declined during the fuel crisis. In addition, clinical records indicate a rise in the rates of screen time and depression during the crisis, especially through the period of school closure due to transport difficulties.

Impact of an Economic Recession on Child Labour

The influence of the economic crisis on child labour differs with country characteristics and policy responses to the recession. Overall, a financial recession was shown to be associated with a rise in child labour in low-income countries, especially within poorer households. There is some evidence that in middle-income countries, the reduced employment opportunities associated with an economic recession result in lower rates of child labour during a recession (Koseleci and Rosati, 2009). Even in low-income countries, the increase in child labour mainly results from children who join the labour force without dropping out of school (Koseleci and Rosati, 2009). However, students who continue to work while in school are unlikely to have time for educational activities and may be exhausted by their work. Therefore, working students are less likely to get the full benefit from education compared to their non-working counterparts. Evidence suggests that this may lead to an increased risk of school dropout among working children. Furthermore, working children, especially those involved in informal work, for example, such as domestic labour, are at a higher risk of sexual abuse. Such children are often separated from their families and other social networks and are in a position of powerlessness, which makes them highly vulnerable to sexual abuse.

According to available data, 43,714 children and adolescents in Sri Lanka were engaged in child labour in 2016 (International Labour Organization, 2018), which accounted for 1% of the child and adolescent population in Sri Lanka (Fig. 3). Of children engaged labour, a great majority (89%) were engaged in hazardous forms of labour. There has been an improvement in the child labour rates in Sri Lanka over the years (International Labour Organization, 2018). However, a rise in the rates of child labour can be anticipated during the financial recession. In addition, as the job market declines and fewer jobs become available, there is also a risk of an increase in hazardous forms of child labour. The legal age for work in Sri Lanka is now 16 years. Thus, children less than 16 years often engage in work secretly. This carries the risk of being underpaid and overworked, as there is no monitoring of such work from labour organizations.

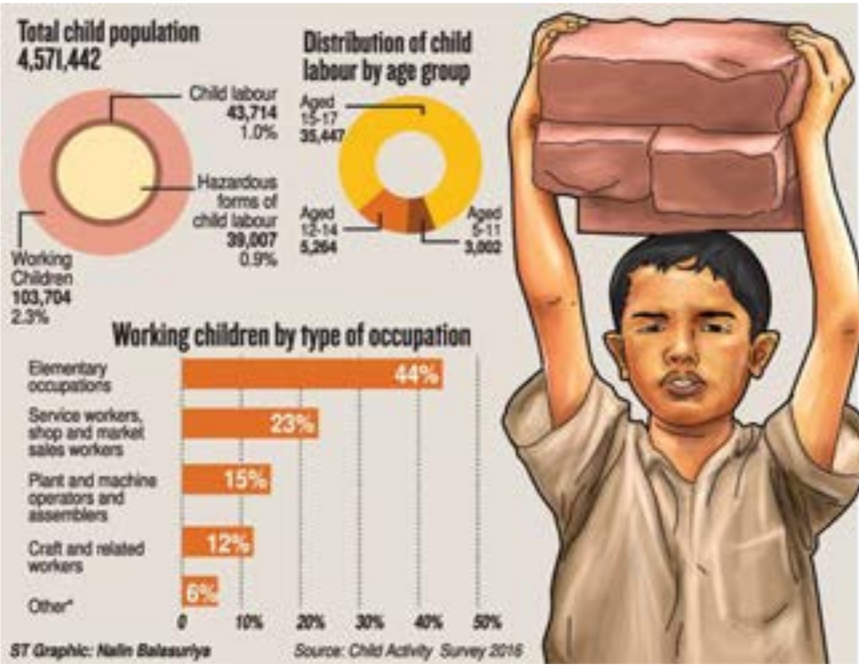

Figure 2. Child labour statistics-2016 (Source: Child activity survey-2016)

Engaging in labour poses a threat to a child's physical and mental well-being. Data from 2016 indicate that 36% of the children engaged in labour in Sri Lanka are exposed to undesirable and unsafe working conditions (e.g., dust, fumes, machinery etc.) (International Labour Organization, 2018). During the financial crisis, further worsening of working conditions can be expected. Therefore, measures need to be taken to protect children from the negative effects of child labour.

Recession and Child Maltreatment

The link between poor socio-economic status and child maltreatment is well established. Evidence suggests that children from lower socio-economic families are three times more likely to be abused and seven times more likely to be neglected compared to those from high socio-economic groups (Sedlak *et al*., 2010). Neighbourhood poverty and familial poverty are known to be the two strongest predictors of child maltreatment (Sedlak *et al*., 2010). In addition, parental substance use, parental stress and stressful life events are also identified as predictors of child abuse. An economic crisis is associated with increased levels of poverty, higher levels of substance use among adults and increased parental stress, all of which could lead to elevated levels of child maltreatment. However, the literature on the association between economic recession and child maltreatment is mixed. The majority of the studies demonstrate an increase in the level of child abuse during a financial crisis (Schenck-Fontaine and Gassman-Pines, 2020). Some studies report no association between the two, and a few report a decrease in the rates of child maltreatment during an economic recession. The regional variation of child maltreatment during a recession may be due to the degree of income inequality in a region and the pre-existing economic conditions within a country (Schenck-Fontaine and Gassman-Pines, 2020). Furthermore, disruption of community child protection services and field visits during a crisis may reduce the reporting of abuse during a recession. Hence, the degree to which the child protective services were affected during the crisis may also impact the reported child abuse rates.

According to the statistics of the National Child Protection Authority (NCPA), 11187 cases of child abuse and neglect were reported in Sri Lanka during the year 2021 (National Child Protection Authority, 2021). In August 2022, the United Nations reported an increase in abuse, exploitation and violence against children and higher rates of institutionalization of children amidst the economic crisis (United Nations, 2022). Even prior to the economic downturn, 707, 000 children and adolescents under 19 years in Sri Lanka lived in poverty, which accounted for 11 % of the population under 19 years. UNICEF reports that poverty is likely to double during the next 24 months, causing 93% of families to be below the poverty line (UNICEF, 2021). Given the clear association between poverty and the risk of child maltreatment, authorities should take measures to ensure the safety of all children during the current crisis.

Interventions to Safeguard Children and Adolescents during the Economic Crisis: Safeguarding Education amidst Economic Recession

Even prior to the economic crisis, Sri Lanka did not have the adequate financial allocation for education. In 2019, the government expenditure on education was 1.9%. of the total GDP, which was a fall of 0.3% from 2015. This is much less compared to the overall 2.9% in South Asia and 3.1% in other low-income countries (World Bank, 2022). According to the Education 2030 Framework for Action, a government needs to spend at least 4-6% of its GDP on education, to meet the benchmark for education. The UNICEF estimates that Sri Lanka needs 6,273,000 US$ to maintain education in the year 2022 (UNICEF, 2021). With the economic crisis, further cuts to educational expenditure can be anticipated. In June 2022, the Secretary of Education stated that the inadequacy of funds allocated to the Education Ministry in the face of the current economic crisis has already become a major challenge. As mentioned above, there is evidence that policy responses and social protection schemes within the country at a time of an economic downturn determine the impact of education. Therefore, the government should ensure that the economic recession does not lead to further cut down in the financial allocation for education. In addition, repurposing funds from Non-Governmental Organizations (NGOs) such as UNICEF, Asian Development Bank and World Bank for educational priorities is also needed.

Another major practical problem is an inability to cover the syllabus due to prolonged school closures, which has caused pressure on both teachers and children. The National Institute of Education, the Ministry of Education and the Department of Examinations should work together towards modifying the scope of the syllabus, focusing on covering only essential components of the subjects, to have realistic expectations from both teachers and students and to avoid undue stress on both parties. All examinations should be carried out in a timely manner, despite the crisis, by maximally utilizing available resources. For example, there is evidence that during their financial crisis, Indonesia managed to continue education by relying on blackboards and reading test questions instead of using printed material, which is a practical measure to continue assessments (Filmer *et al*., 2014).

Relaxation of uniform and stationary requirements would also make education more affordable to families facing financial hardships (Filmer *et al*., 2014). On a few occasions in the past, the government has allowed students to attend school in alternate clothing. One such instance was in May 2016, following inclement weather conditions destroying school uniforms in children, and in October 2021, when school reopened after a prolonged closure due to the pandemic. However, in both instances, these relaxations were only permitted for a short period. There is evidence from Indonesia that relaxation of uniform requirements can promote school attendance and thus, should be trialled in Sri Lanka. Similarly, providing stationary for the poorest children who are unable to afford stationary may also promote school enrollment and attendance. Although several donors and wellwishers around the country have initiated such programmes at a personal level, more widespread, nationwide programmes initiated by the government or NGOs are needed.

A system to identify students who are at a high risk of dropping out is also needed. As mentioned above, evidence suggests that the school dropout rates are highest in the lowest socio-economic class and where the household head is unemployed. Therefore, supporting parental employment, increasing family benefits and conditional cash transfers may be useful to ensure school attendance in these high-risk groups. However, the efficacy of family benefits on education depends on whether or not the family uses these benefits for their children's welfare. Thus, instead of cash benefits, which may be used for other purposes within the family, benefits in the form of services delivered directly to children are known to be more effective. Such benefits can include waiving school fees, free meals in schools or free after-school child care services (Richardson, 2010). Furthermore, Mexico, Brazil and many other countries have successfully used conditional cash transfer programmes to ensure school attendance in high-risk families. Conditional cash transfers include providing families with cash transfers, with the condition that they keep sending their children to school (Koseleci and Rosati, 2009). Such programmes have been shown to be successful in increasing school achievement and maintaining school attendance during an economic crisis, compared to unconditional transfers. Similarly, there is evidence from Indonesia that scholarship programmes offered to carefully selected families also facilitate school enrollment and attendance (Filmer *et al*., 2014). This can be done in Sri Lanka, in collaboration with various NGOs. Given the impact of parental education on school dropout rates, media campaigns promoting the benefits of schooling may also be helpful. This is supported by anecdotal evidence that the media campaign "stay in school" programme helped to maintain educational outcomes during the Indonesian financial crisis (Cameron, 2009).

Earlier this year, it was suggested to allow both students and teachers to attend their nearest school, as a measure to continue schooling during the current crisis. However, short-term transition between schools is likely to create chaos for both teachers and children as the infrastructure, facilities and human resources between schools vary significantly. A more long-term solution is needed, aiming at improving the quality of education in rural schools and small urban schools, making these schools more appealing to students and their parents. This would promote students to attend their closest school, hence, reducing the time and money spent on transport.

Ensuring Child Physical Well-being during the Crisis

Sri Lanka has maintained a relatively stable level of investment in nutrition over the years, which has enabled the country to meet most of the life course interventions recommended by the World Health Organization (WHO) in 2000. However, given the depth of the current crisis, some of these interventions have already been disrupted. There are reports that the "*Thriposha* programme" which is one of the leading nutritional support programmes in the country has been interrupted, making thousands of pregnant and breastfeeding women and young children vulnerable to malnutrition. Similarly, there are reports that lack of funding has disrupted the school meal programme in more than half of the schools, putting more than 1,081,900 eligible children at risk of malnutrition.

Ensuring adequate nutrition at the time of the economic crisis requires multi-sectoral collaboration. The effectiveness of the existing nutritional intervention programmes should be urgently reviewed to determine whether there is room for efficiency gains by redirecting financial resources from the less effective programmes to more effective nutritional interventions (Jayawardena, 2020). For example, there is evidence that the efficacy of the universal pregnant mother's food allowance programme, which accounts for 37% of the government investments in nutrition, is questionable and that a targeted food allowance program focusing on high-risk mothers is likely to be more cost-effective. There is also evidence to suggest that in keeping with the WHO recommendations, changing the universal *Thriposha* programme to focus on undernourished pregnant and lactating mothers would make the programme more economical and would ensure a continuous supply of *Thriposha* to those, especially in need (Jayawardena, 2020). In addition, staple food fortification, which is large-scale food fortification by adding micronutrients to staple foods is a feasible and cost-effective way to meet the micronutrient needs of the population (Jayawardena, 2020). Furthermore, given the clear link between maternal education and child malnutrition, widespread public awareness programmes need to be conducted on the nutritional value of food and maximizing the nutritional value with existing resources (Jayawardena, 2020). Promoting local agricultural production and educating the public on widely available local food sources will also be beneficial in maintaining nutrition amidst the crisis. Continuous surveillance of the nutritional status of the child population is also needed for early identification and treatment of severe acute malnutrition (SAM). For example, by June this year, a total of 14,370 children were diagnosed with SAM at the maternal and child health clinics and referred to the specialist hospital for management (UNICEF, 2022).

Promoting Psychological Wellbeing of Children during the Economic Crisis

Promoting child psychological well-being is also equally important during the crisis. As explained above, during an economic crisis, the mental well-being of children is affected mainly by heightened parental stress (Neppl *et al*., 2016). Therefore, supporting parents during these difficult circumstances is the first step in ensuring the mental well-being of children. The UNICEF reports that providing information to parents on coping strategies to manage their own stress, on the available community support services and about the impact of stress on parenting are useful in times of crisis. In addition, parental education on children's response to crisis situations and children's stress responses at different stages of development are also thought to be beneficial (Snider and Hijazi, 2020). UNICEF also recommends measures to build parental capacity, such as parent groups to support responsive caregiving and positive parenting training to ensure child well-being during a crisis. These interventions should be aimed at the general public and can be carried out through mass media (Snider and Hijazi, 2020). Furthermore, healthcare workers, especially those working with children, need to be vigilant for indicators of psychological distress in parents or children to provide the necessary advice and direct them to appropriate services.

Uninterrupted schooling is also essential to maintain psychological well-being in children. Schools not only provide education but also provide children with a safe place to play, socialize, and express themselves and help to maintain a daily routine. There is also evidence that educational activities and creative and expressive activities have a role in promoting mental well-being in children facing adversities. Hence, creating a supportive school environment is a key strategy to promote psychological well-being in children and adolescents. Positive peer relationships and connectedness are known to maintain mental well-being during economic hardships. Thus, promoting healthy student-teacher relationships is especially useful during a crisis. Capacity-building programmes for teachers on adapting school environments to better meet the well-being and safety needs of children and to improve their basic psychosocial competence, such as understanding the effects of stress in children, active and empathetic listening, and indicators of psychological distress in children is also beneficial (Snider and Hijazi, 2020). Teachers also need to be more accommodating when children are not able to meet the standard stationary or uniform requirements due to financial difficulties. Acknowledging and accepting financial hardships and creating a safe space for children to talk about their difficulties will also help to alleviate the stress and stigma associated with economic difficulties.

Ensuring the continuation of extracurricular activities is vital to maintain the mental well-being of children during the crisis. There is evidence that engaging in extracurricular activities is associated with lower levels of depression and anxiety and higher levels of life satisfaction and optimism (Oberle *et al*., 2020). Children who engage in extracurricular activities are also known to spend less time on screens, hence, protecting them from the consequences of problematic internet use. In addition, ensuring access to mental health services during the crisis is also vital. Using telepsychiatry may be a feasible and acceptable option to provide mental health services to those who cannot attend services due to fuel shortages.

Safeguarding Children from Violence during the Economic Crisis

To ensure the safety of children during the crisis, the Government should designate child protection services as an essential service and avoid budget cuts from affecting these services (Snider and Hijazi, 2020). The child protection helplines should be strengthened to that reporting of child abuse can be done effectively in spite of the crisis (Snider and Hijazi, 2020). Where home visits are not feasible due to the fuel crisis, measures should be taken to continue these services online. Given the close association of poverty and parental stress on child abuse, measures to reduce parental stress and reduce poverty, as mentioned above, will also help to reduce the risk of child maltreatment during the economic recession. It is also essential to combat social and cultural norms that accept violence against children, through public education programmes. Such programmes should also focus on how to access and utilize child protection services even if a violation is experienced. Better coordination between national, district and divisional child protection services and coordination between child protection, health, educational, social welfare and legal sectors are needed to ensure that principles of child protection can be put into practice. More attention should be paid to data collection and monitoring of children at risk, in order to design policies to cater to the changing circumstances.

Conclusions and Future Prospects

An economic recession leads to disruption in education, and poor physical and mental health of children is associated with a higher risk of violence against children. If urgent measures are not taken to address these issues, it will impact future economic growth in the country through its effect on the future workforce. Evidence from previous global recessions suggests that protecting the education sector from budget cuts, supporting parental employment, increasing family benefits, conditional cash transfers, scholarship programmes, relaxation of uniform requirements and media campaigns are useful in maintaining uninterrupted education during a recession. Similarly, there are evidence that ensuring financial allocation for health, redirecting financial resources from the less effective to more effective nutritional interventions, staple food fortification and widespread public awareness programmes on maximizing the nutritional value of existing resources are useful in ensuring the physical well-being of children during a financial crisis. Helping parents to manage their own stress during a crisis and supporting positive coping skills and positive parenting through parent groups are shown to be effective in reducing the psychological impact of a recession on child's mental well-being. Previous literature has also highlighted the importance of maintaining child protective services during times of recession to safeguard children from violence. The government of Sri Lanka need to take this evidence into account to urgently come up with effective and feasible solutions to overcome the negative effects of the economic recession on children and adolescents in the local context.

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CHAPTER 3

Health Sector Approaches to Present Economic Crisis: TARA Framework (Transformation, Adaption, Resilience, and Absorption)

A.T. Matthias[1]*, D.S. Govindapala[2] and S. Jayasinghe[3]

Abstract The health sector is an important element of the global economy. Health and economic sectors are intertwined. Sri Lanka is facing severe and unprecedented social and economic crises in recent history. These are the results of several systemic factors such as corruption, financial mismanagement as well as the COVID-19 pandemic. As health and physical wellbeing are essential to the maintenance of human resources, health sector development during this economic crisis is essential. This means the health sector is increasingly becoming important as a building block to have a stronger economy while contributing to the growth of the economy. As the country recovers from the economic crisis, careful attention needs to be paid to resource mobilization, efficiency of projects undertaken, and the need to yield long term outcomes. Health interventions have to be effective and function with minimal costs. An economic analysis of the health sector is crucial in this regard. A TARA framework (Transformation, Adaption, Resilience, and Absorption) could help policymakers to decide which combination of strategies are required to overcome the crisis.

Keywords: Crisis, Health, Nutrition, Socio-economic, Sri Lanka

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Introduction

Health and economics are interconnected (Frakt, 2018). The relationship between the two sectors is increasingly understood as the effects of the cyclical global economic growth and downturns faced by the health sectors all over the world (Fuchs, 2004). The close relationship between health and economic development is the underlying reason for needing to build health sector resilience to prepare for economic crises. To help the health sector absorb the shocks of an economic crisis, a situational analysis of the vulnerability of the health sector is required. Gathering information and data on the effect of economic crisis is the second step in this process and based on them the ability of a government and authorities to implement effective strategies to mitigate the effects of a crisis on the health sector is the last step. Only if all three steps are carried out, it would be possible to make the health sector stabilize for the vulnerable population during an economic crisis.

Sri Lanka is presently facing one of the worst economic crises it has ever faced in recent years. A multitude of factors appears to have contributed. The key factors include corruption, mismanagement of the economy, losses from COVID-19 and its restrictions, severe reduction in tourism, loss of jobs of migrant workers in the Middle East, and drop in earnings from exports such as tea and garments. All sectors have been affected and the health sector is no exception. Sri Lanka in the past has had remarkable success in lowering maternal and child mortality rates and running effective vaccination programs. However, the country can no longer afford to rest on its laurels. The health policies must adapt now in the face of economic crisis to face the country's imminent health issues. The economic crisis deepens social inequalities. In this context, it is necessary to preserve the public sector to maintain and improve 'Universal Health Coverage'. While doing so, it is necessary to make the health system more sustainable without compromising its functionality to protect the national economy. Instead of compromising the health sector, it should be a driving force to generate income through a healthier workforce and support the recovery from the present economic crisis.

Impacts of Economic Crisis on Nutrition Status

While the economic crisis has impacted numerous sectors across Sri Lanka, the nutrition sector has been particularly affected. According to recent UN data, 6.3 million people have been rendered food insecure, leading to a lack of nutritious diet daily (https://news.un.org/en/audio/2022/08/11243220). Sri Lanka was struggling with the burden of malnutrition even before the economic crisis. With the increasing cost of living, it is expected to become worse. The most vulnerable groups are the under-5-years and the elderly. The causes of malnutrition are two-fold. Inadequate dietary intake and increasing diseases. Due to rising fuel costs, dearth of fertilizer and interrupted fuel supply, the food supply chains have been disturbed heavily and the cost of food has increased tremendously. This will be compounded by worsening poverty which will lead to increase in incidence of communicable diseases such as infective diarrheas and respiratory diseases. Malnutrition that is affecting infants and children in the current times, will have lasting impacts on the cognitive ability and functioning of adults in the future.

Adverse Impacts on Intellectual Development

The COVID-19 pandemic brought the country to a standstill for nearly one year, causing adverse social and economic effects and adding to the burden of the health crisis. The negative impacts of the pandemic on the intellectual development of people, especially children and adolescents, cannot be overlooked. The primary, secondary, and tertiary educational establishments were closed during the lockdown period disrupting educational activities. The demand for social distancing precluded the full functioning of the education system until the pandemic was mitigated in the country. Thus, the Government of Sri Lanka responded by promoting online education for school children and university students. Nonetheless, the adapted strategy was confronted by many obstacles such as poor knowledge on technology among both the students and teachers, lack of infrastructure and other facilities for online learning, especially among low-middle-income families living in rural areas of the country. This has widened the existing opportunity gaps in Sri Lanka's education. Apart from the missed formal education, lack of stimulation, reduced social interactions and creative play have shown to have a negative impact on the neurodevelopment of children. A significant reduction in cognitive functions was observed among children born during the pandemic compared to children born pre-pandemic (Deoni *et al*., 2021). Most importantly, a decrease in global cognitive functioning has been reported among adolescents who suffered the illness (Frolli *et al*., 2021). The lack of social interactions has made the adolescents less resilient in times of personal crisis. In addition, the lockdown and restrictions on physical gatherings within the country and travel bans imposed by many countries have limited the access to continuous professional development activities for professionals in all fields.

Poor Nutrition Impacting on Intellectual Development

The present economic crisis has affected the health and well-being of both children and adults in Sri Lanka. Children are likely to be long-term victims of this crisis due to the negative impact of poor nutrition on their intellectual development. Nutrition plays a crucial role in neurocognitive development in children from pregnancy through childhood. Thus, poor maternal and childhood nutrition may lead to impaired cognitive functions. The time and the type of nutritional deficiency are important determinants of cognitive deficit (Nyaradi *et al*., 2013; Roberts *et al*., 2022). Evidence suggests that the first two years of life are the most vulnerable period for nutritional deficiencies in diet (Bryan *et al*., 2004). Adolescence is another critical period during which poor nutrition may interfere with cognitive maturation (Luna and Sweeney, 2001).

Although the human brain requires all nutrients for development and function, micronutrients such as iron, folic acid, zinc, and vitamin B12 are considered essential for cognitive development (Bourre, 2004). Micronutrients are commonly found in animal-based food and the high prices have significantly reduced the affordability of many Sri Lankans. Childhood malnutrition is associated with cognitive and behavioral compromise in adult life. Impaired IQ in adulthood is linked to moderate to severe malnutrition during infancy (Waber *et al*., 2014). Therefore, the present economic crisis would have significant impacts on cognitive performances of people causing a threat to the Sri Lankas's future growth prospect.

Increasing School Dropouts due to Economic Crisis

Sri Lanka has gained impressive indices in terms of literacy because of the free education system in the country. The free education from year one to university level, complemented with the provision of textbooks, uniform material and meals for free, incurs a heavy expenditure on the government. Despite the universal free education provided, school dropout has been a drawback of the education system. In 2016, the Household Income and Expenditure Survey of the Department of Census and Statistics reported a 19.6% school dropout rate among children of low-income families after the age of 14. Among the early school leavers between 15-16 years of age, lack of educational progress and/ or interest was the prime reason (66%) for school dropouts, while 36.6% had left due to financial difficulties. Although the schools returned to a semblance of normality for a few months after the COVID-19 pandemic, the school closures became inevitable amidst the economic crisis in the country. Further, internet-based remote education is far from equitable due to the lack of facilities for the children of low-income families. Recurrent school closures and the inability to access online lessons likely impede children's educational performances and interests, causing more school dropouts. Moreover, the massive surge in fuel prices has increased the transport cost by many folds, directly affecting the school children. Loss of income and rampant inflation have driven more than 10% of the 22 million Sri Lankans into poverty (https://www.voanews.com). Therefore, more school dropouts due to the economic hardships of the families are inevitable in the present economic crisis. Inadequacy of government funds for the free supply of uniform materials and meals for school children will invariably increase the number of school dropouts. Inequality gaps in educational opportunities are expected to be widened during an economic crisis. The effects of lost educational opportunities will be most felt by the poor socio-economic groups whose only way of rising out of the disadvantaged social class would be a quality education.

Lack of Books, Digital Access and other Consumables for Teaching

The economic crisis has compromised the Sri Lankan education system in many ways. Depreciation of the rupee, dollar crisis, import bans, and the paper shortage has significantly decreased the availability of books and stationery needed for education. School children, university students, postgraduate students, and professionals in different disciplines have been affected by the shortage of books. The textbooks are provided free in government schools; every year, 80% of textbooks need to be printed for each grade. The printing of school textbooks has dropped by 50% this year due to the severe shortage of paper and printing materials. Thus, many school children are yet to receive their textbooks in government schools. On the other hand, the students attending international schools need to buy their textbooks. The import bans have resulted in a shortage of international curriculum books in the country and the high prices of the available books have limited the affordability for these children. Furthermore, both the cost and the shortage of paper have restricted the photocopying of educational material, adding to the burden further. Conduction of examinations at schools and other educational establishments has come to a halt due to the paper shortages at present. In addition, shortages are seen in other consumables required for teaching due to the import bans and high production costs. During the long periods of lock downs, schools proceeded to use internet-based classes. In some instances, the devices were provided and programs were run at zero cost to the user. Though there was some success, many smaller schools and poorer children were not able to access internet, leading to inequalities in access to education due to the digital divide. The long power cuts and high cost of telecommunication further compromised the online teaching programmes (Hayashi *et al*., 2022).

Direct Impact of Economic Crisis on Health

A negative impact on health is inevitable with an economic downturn. Limited access to healthcare, malnutrition, stress, poor quality of life, and unhealthy behavioral changes owing to the economic crisis have the potential to cripple a health system. The sudden collapse of Sri Lankan economy has threatened the free health system in the country. Lack of foreign revenue, import bans, and fuel crisis have caused severe shortages in medicine and equipment, interrupting the health services. The accessibility to health services has limited due to lack of transport facilities and tremendous rise in transport cost. Millions of people are left without essential medicines as a result of shortages and skyrocketing prices of medical amenities including medicines. Discontinuation of medical treatment and regular clinic follow up ultimately culminate in emergency hospital admissions with worsening of chronic medical conditions of many patients. Thus, incurring more expenditure on the healthcare system by requiring in-hospital care, high dependency or intensive care, severe morbidity and mortality. This will lead to a vicious cycle as more resources will be used to tackle emergencies than routine setting.

Micronutrient Deficiency on Adult Health

The spiking food prices and shrinking crop yields have already spiraled Sri Lanka's economic crisis into a food crisis. Even staples such as rice have become unaffordable for millions of families due to high inflation (over 90%) of food prices in the country (https://www.dw.com). The world food programme estimates that one out of four Sri Lankans skips a meal regularly. Nearly 61% of families are trying to cut costs by reducing portion sizes and consuming cheaper but less nutritious food (https://www.news.un.org). Generally, a mixed diet is required for adequate micronutrient supply. Lack of daily nutritional requirement in diet will lead to malnutrition, especially micronutrient deficiencies. Although required in small quantities, micronutrients, including vitamins, minerals, and trace elements, are essential for human growth, development, and physiological functioning (Annweiler and Beauchet, 2017). Severe micronutrient deficiency status among adults usually result in a complex syndrome of typical signs and symptoms (Shenkin, 2006). Iron, vitamin D, folate, and vitamin B12 are adults' commonly recognized micronutrient deficiencies. However, most of the micronutrient deficiencies are sub-clinical or present with non-specific symptoms (Biesalski and Jana, 2018). These deficiencies can accelerate physiological aging, reduce immunity, eyesight, hearing, and cognition (Annweiler and Beauchet, 2017). Therefore, micronutrients play a pivotal role in adult health and directly affect their physical and psychological well-being. Lack of energy, increased susceptibility to diseases and poor mental health among affected individuals will reduce their productivity and contribution to the country's economic growth.

Potential Changes in Diets that are Calorie Dense

Evidence suggests that along with an economic crisis, dietary quality is like to plummet. During the great recession, negative dietary behaviors were observed in children and adults. The intake of dark green vegetables and protein was significantly reduced while sugar intake was increased among individuals in food insecure households. Amidst an economic crisis, growing poverty significantly limits the purchasing power of households. Thus, higher-priced food is replaced with less expensive food which are often less nutritious (Dobrovolskij and Stukas, 2013). The sudden economic downturn in Sri Lanka is likely to have similar effects on many Sri Lankans. Nearly 30% of the population is food insecure and has adopted different resilience mechanisms compromising food quality.

Restrictions to Physical Activity due to Economic Pressures

Critical links observed between job loss and physical inactivity in young adults during 2008-2009 Great Recession in the USA helps understanding the effects of economic pressure on physical activity. The negative impacts on mental health during an economic crisis is an important determinant of decreased physical activity (Alam and Bose, 2021). Shortages of essentials for living, high transport cost, and regular interruption to the power have hampered the earning capacity of people in the country. The demand for additional income has made people work extra hours restricting their time for physical activities. Shortages of essential supplies such as fuel and gas has resulted long-waiting in queues for days leading to physical inactivity.

Chronic Stress Induced Effects

Many studies have demonstrated economic recession and its effects are linked to increased development of mental illness. Higher incidences of mood disorders, anxiety depression and suicide were reported among workers from different parts of the world during the global economic crisis in 2008 (Mucci *et al*., 2016). The negative impact on the mental health leads to both physical and mental underperformance. Chronic stress related to economic hardship may lead to alcohol dependence, family disharmony and domestic violence. Chronic stress due to economic downturns has been associated with increased incidence of non-communicable diseases such as hypertension, diabetes and asthma (Modrek and Cullen, 2013; Loerbroks *et al*., 2014).

Health Impacts of Hazardous Employments

Deterioration of occupational health and safety (OHS) is expected during an economic crisis. The closure of small and medium-sized enterprises, downsizing of companies and staff cutdowns increase job insecurity and work-related stress, causing a negative impact on the mental health of workers. High layoffs due to production cutdowns have been shown to increase the incidence of diabetes and hypertension (Modrek and Cullen, 2013). The economic pressure can lead to adverse organizational changes compromising the OHS standards and established measures. The restricted budget allocations for OHS may hamper the provision of protective gear, training, technical support and guidance for workers, increasing the risk of occupational hazards, especially in hazardous employments. Job insecurity and difficulty in finding alternative employment at a time new recruitment are being curbed, have created an unhealthy work atmosphere, where workers feel compelled to carry on despite poor occupational health and safety measures. The decision to curb recruitment of new staff has created an unhealthy work atmosphere.

Challenges for Healthcare during Economic Crisis

The positive correlation between health and per capita gross domestic product (GDP) has been well established and this relationship is known as "Preston curve" (Bloom *et al*., 2018). Thus, an economic recession inevitably creates a negative impact on health services. In such situations, restructuring of health systems may compromise care provision, especially to the most vulnerable populations. The effects on health services due to sudden economic downturns seem to be universal, although the degree of impact varies based on many factors. The key challenges of economic crisis on healthcare is discussed below.

(i). Fewer Allocations to Health and Lack of Drugs and Equipment

In response to economic downturns, the governments try to maintain demands in the economy and protect households. This countercyclical spending of governments limits the finance allocations to healthcare, challenging the provision of quality healthcare services that meet patients' needs and expectations. Such financial reallocations were evident in many European countries during economic recessions, where money was taken from the health sector to finance spending in other areas (Thomson *et al*., 2014). The economic crisis in Greece has resulted in a reduction of the share of general government expenditure on public health below 11.5% compared to a mean of 15% in other EU countries in 2012 (Economou *et al*., 2015). Similarly, in Sri Lanka, fuel import was prioritized over medical imports to overcome the fuel shortage in the country during the economic crisis.

Sri Lanka is one of the developing countries with a free healthcare system that provides universal population coverage. The total public health expenditure in Sri Lanka accounted for 1.5% of GDP in 2021, which was higher than the other South East Asian countries. The allocations to health are likely to be reduced in the wake of severe financial crisis. This is visible with the country experiencing scarcities in drugs, problems related to purchasing consumables and equipment. Interruptions to the supply chains in the government healthcare establishments have resulted shortages in medicines, equipment and consumables. The private medical imports have significantly reduced as the bank requests to open letters of credit are being declined, contributing to further shortages. Salary reductions and associated decreased purchasing ability of individuals have limited their affordability for healthcare and medicines in the private sector. Thus, the health system is overwhelmed with many people seeking free healthcare. The shortages have limited non-emergency surgeries and routine laboratory investigations in many hospitals within the country. Patients are requested to buy medicine from private-owned pharmacies due to the unavailability in hospitals.

(ii). Loss of Human Resources

Depreciation of currency reserves, widespread shortages, rampant inflation, and worries of prolonged political and economic uncertainty have increased cross-border migration activity through both regular and irregular channels in the country. Over 300,000 Sri Lankan passports had been issued within the first half of 2022, compared with 382,000 passports issued in the whole last year. The high skilled to unskilled migration has resulted in the loss of human resources in many sectors. Although the evidence suggests that migration in developing countries leads to an increase in per capita international remittances and a decline in living in poverty, highly skilled migration causes a loss of public resources invested in their education (Adams and Page, 2005; Datar, 2010). Furthermore, high-skilled migration is particularly important in health and educational systems, where shortages will lead to devastating consequences. Many consultants and postgraduate trainees are resigning and leaving the country. Some of the specialties are losing their cadre at a rapid rate. This has left a gap in some of high-end services at a specialist's level. The government's decision to reduce state employees' retirement age may further add to the loss of human resources. Although this austerity measure is intended to cut down the state sector expenditure, it poses a threat to the provision of specific services, including health services, owing to shortages in high-skilled labour.

(iii). Impact on other Proposals by External Factors

Amidst economic crises, governments get forced to seek international financial assistance. Usually, international financial support is offered with accompanied economic adjustment programmes (EAPs) requiring substantial reductions in public spending, as evident in many EU countries that suffered economic recessions in the past (Thomson *et al*., 2014). In 2012 bailout conditions required a reduction in public health expenditure to less than 6% of GDP in Greece (Economou *et al*., 2015). In early September 2022, International Monetary Fund (IMF) officially agreed to an extended fund facility arrangement to restore the macroeconomy in Sri Lanka while ensuring economic growth. The programme entails fiscal revenue generation through major tax reforms and cost-recovery-based pricing for essential supplies such as fuel and electricity, which may add to people's financial burden. Further, the lending organizations such as the IMF will advocate for privatizations, removing subsidies and restrictions to the provision of health and education free at the point of delivery. These structural changes are well-known to affect the health of people who are already facing severe economic hardships. Vulnerable groups such as infants and children tend to be the victims (Thomson *et al*., 2017). IMF suggested structural adjustments had been associated with adverse consequences on health system access and neonatal mortality, women's rights, and gender equality (Bohoslavsky and Rulli, 2021).

Crisis Management and Meeting Challenges in the Future

There are frameworks to manage crisis facing the health sector. To formulate the way forward, the strategies used in response to a shock (economic crisis) can be understood if it is broken down in to different segments; absorptive (buffering the system from shocks with little or no change in structure), adaptive (limited adjustments in the system structure or processes), or transformative (significant functional or structural change) (Kagwanja *et al*., 2020). We have modified this by adding a fourth response, namely resilience (significant functional reserves and reserves in resources) to strengthen the capacity to absorb future shocks. This TARA framework (Transformation, Adaption, Resilience, and Absorption) helps to categorize and guide the responses to a crisis (Table 1).

Table 1. Framework of strategies for managing the crisis

Segment	Strategies
Transformation	• Strengthening the primary care system • Strengthening community care systems • Formalizing the referral pathway
Absorption	• Restricting waste of existing resources • Reallocation of resources and utilization of existing resource • Adapting evidence-based policies • Securing resources
Resilience	• Interconnected institutions to share resources and work collectively during crisis • Multiskilled human resources pool or ability to shift skills • Policies to plan for future shocks • Reserve resources to counter shocks
Adaption	• Capacity building of workforce • Modifying guidelines • Revenue generation through public private partnership (PPP) and offering courses and services • Improving information systems

Absorptive Strategies

(i). Wastage of Existing Resources

In an economic crisis, reducing the wastage of existing resources is essential. Wastage of drugs can be reduced by introducing an effective health system information management. This will need forecasting drug requirements. It is prudent to disburse funding directly to Provinces for allocation and distribution according to local priorities and needs. This will match the allocations to needs in a more efficient manner, compared to a centralized system. A robust quality assurance (QA) systems need to be implemented to improve the utilization of drugs and devices.

(ii). Reallocation of Resources and Utilization of Existing Resources

Hospitals are the largest consumers of the health system budgets and working efficiency of hospitals needs to improve to reduce costs. The cluster system to have an apex hospital and help run services at the apex hospital on behalf of the peripheral hospitals is a way to ensure that existing services are used maximally. The establishment of a central database with the availability of drugs, devices and consumables at different hospitals will allow the redistribution of non-moving stocks to needy hospitals. Currently, this does not happen even within a hospital. To strengthen the newly proposed cluster care system, the primary care units must have basic diagnostic capabilities and transportation capacity to convey samples to cluster laboratories. The establishment of mobile laboratories will also be helpful. Strengthening of the cluster laboratories at district hospitals has to be done.

(iii). Adapting Evidence-based Policies

Poor-resourced and low-middle-income countries tend to follow the American or European guidelines for disease management in clinical settings. One issue in using these guidelines is the scarcities of the recommended drugs and treatment modalities in low-middle income countries. The other major drawback is the high cost of the treatments. To reduce costs during a crisis, local guidelines with available drugs need to be drafted by professional colleges. An excellent example worthy of replication is the recently launched Provision of Essential Ischemic Heart Disease Care during the Economic Crisis of Sri Lanka by the Colleges. Such guides are likely to reduce unnecessary costs.

(iv). Securing Resources

The economic crisis has caused a setback in all aspects of health care. The preventive health is likely to be affected due to food insecurity and a lack of nutritious food. This could be coupled with a higher intake of fast food increasing NCDs. The curative sector is mainly affected due to a lack of medical equipment and shortages of drugs. When securing resources and funds to improve the health system, several key steps have to be implemented. The first step will be a national policy or strategy on the utilization of external support and using it together with existing resources. (Balabanova *et al*., 2010). Without this strategy, the haphazard utilization of existing staff and existing infrastructure will exhaust the existing system. Furthermore, disease control activities must be integrated with other health services at the level of service delivery wherever possible. Certain interventions such as school children and vulnerable populations may need special programs, though certain common disorders such as NCDs can be managed along with existing service delivery. With incoming funds and resources, there need to be concrete ways of assessing success and performance. These need to be successfully measured and this should encourage health systems to perform better but not at the compromise of quality.
The available evidence base on successful health system approaches is scarce. Countries such as Sri Lanka need to invest in research to analyze what works best for them (Sanders and Haines, 2006).

Adaptive Measures

(i). Capacity Building of Workforce

All workers are affected during an economic crisis. Healthcare workers are no exception. They have job insecurity, decreased purchasing power due to the rise in the cost of living and reduced employment opportunities (Stuckler *et al*., 2009). Salary cuts, increasing taxes, and reduction of incentives will aggravate the problems

(Jesus *et al.,* 2019). The migration of healthcare workers contributes to the shortage of healthcare workers in many developing countries. The main drivers of migration at present are better quality of life, career development and social security, and the desire to have better opportunities for children overseas (de Silva *et al*., 2013). The migration of health workers affects Sri Lankan social, economic, political, and cultural context. It is prudent to minimize the brain drain to prevent devastating consequences in future years.

Building capacity in primary care is essential to improve the functioning of family medicine and those in primary care. All practicing health workers ought to have facilities for in-service training, postgraduate training, and continuing professional development opportunities in order to improve their performance. Healthcare workers can be empowered with confidence to use telemedicine to reduce costs of transportation. Other measures include enhancing the remuneration for health workers at government institutions to incentivize retention, particularly in underserved sites, and to limit the need for health workers to supplement their incomes via private sector work. Other reasons for migration of healthcare workers that need to be addressed include a lack of a transparent transfer scheme, being posted to regions away from home leading to disruptions of families, lack of administrative support to build infrastructure when specialists are allocated to a hospitals.

(ii). Revenue Generation through PPP

PPP is the contractual agreement between public and private sectors to provide a product or service to its nation (Bennett, 1991). The need for PPP in healthcare in Sri Lanka is required as the government has resource limitations in meeting all healthcare needs of the population. This has to be done without undermining the policy of providing "health free at the point of delivery". Fee-levying for health provision is not an option to a country that is suffering from poverty. However, the government could consider incorporating the private sector through well-structured PPP to,

- Improve infrastructure in state hospitals
- Utilize underutilized services in state sector hospitals
- Lease/ rent government facilities to generate income such as specialized lab services
- State-owned family practice centers that can provide private health care after working hours
- Subject experts and specialized labs to open their services to the private sector: Genetics and tropical diseases
- Research centers at in-state universities to provide services at a cost to the private sector

Revenue can also be generated by offering courses and recruiting overseas students for electives and for training in certain fields in medicine. Tropical medicine is one such specialty that Sri Lanka can offer to the rest of the world as there are large numbers of patients with dengue, leptospirosis, and other tropical infections.

(iii). Improving the Information Systems

Establishing and improving the health information system in the country is essential for development. This will help hospitals to manage the data in a better way. This will also reduce duplication of work and use of resources from those repeatedly access healthcare services. If a proper information system is in place, activities such as disease surveillance and notification can be effective and help manage epidemics successfully which will in turn cut the costs.

Transformative Measures

(i). Empowering Primary Care and Community Health Services

Primary health care consists of community health services. These are the MOH areas that are manned by a medical doctor and supported by public health field staff. They deal primarily with maternal and child health and communicable diseases and health promotional activities. They have defined catchment areas that coincide with local government administrative units. The second part of primary care is curative services consisting of Divisional hospitals providing both hospitalization and ambulatory services and Primary Medical Care units providing only ambulatory care which function with non-specialist medical doctors and other staff (Perera, 2015). At present in Sri Lanka, the primary care system is by-passed by patients due to the lack of a proper referral system in place. Other reasons for primary care to be not popular are, the free access to specialized services, no integrated patient information system, and lack of availability of drugs and treatments for the management of NCDs.

To strengthen primary care services, the concept of a shared care cluster system has been introduced by the Ministry of Health, Sri Lanka. Services will be grouped around a hospital providing specialist care at the apex with surrounding primary care curative institutions at the divisional and primary levels. The objective is to provide universal access to continuing care that makes the best use of the existing system and the optimum use of resources. The cluster system is assigned to bring about a system of accountability for care as it will have a defined catchment area and defined areas of responsibility. There needs to be a national plan that involves ensuring the availability of essential drugs and basic laboratory tests for NCDs to limit the necessity to bypass primary level units. If this system is put in place, there will be more efficient usage of resources and reduce wastage of costs for investigations and treatments as duplication of investigations bypassing will not take place (Perera, 2015).

(ii). Streamlining the Referral System

Health costs can be reduced largely by formalizing the referral pathway in Sri Lanka. If the referrals are streamlined, aftercare will take place smoothly after acute hospital admissions and follow-ups will be thorough thereby reducing unexpected hospital admissions. However**,** Sri Lanka has a system of fee-levying private practice by state medical officers and specialists that is parallel to the public sector hospitals. The former has no referral structure and could undermine or bypass the formal structure. Therefore, forcing a referral system to the public sector could have unintended consequences. For example, it could encourage patients to seek care in the private sector where state sector officials are working part-time and then be re-referred back to the state sector, bypassing the waiting lists. This form of financial driven corruption is observed though its frequency and distribution are not known**.**

Resilience

Resilience is defined as "an ability of households, communities, and nations to absorb and recover from shocks, whilst positively adapting and transforming their structures and means for living in the face of long-term stresses, change, and uncertainty". Enhancing hospital 'resilience 'against economic crisis is crucial at this time (Foroughi *et al*., 2022). The ways to address resilience in the context of economic crisis and health services are listed below:

(i). Interconnected Institutions to Share Resources and Work Collectively

A specially formulated system where institutions can list their available resources with the central government and offer them to other institutions when not being used is useful. This can reduce overhead costs and initial capital of expensive equipment.

(ii). Multiskilled Human Resource Pool or Ability to Shift Skills

Sri Lanka, via the Post graduate Institute of Medicine of the University of Colombo trains a large number of specialists every year. During their compulsory overseas training, they acquire new skills which can be used by a group of institutions and satellite clinics. For example, highly trained specialists could be designated to work in two or three institutions supported by providing transport facilities. Though these options are not a solution they may help in mitigating the problems to some extent.

(iii). Policies to Plan for Future Shocks

The economic reforms are taking place now and it is time for the health sector to plan for economic fluctuations. Lessons learnt during the economic crisis have to be studied in depth and adapted in order to plan for the future. A system approach to counter future shocks is essential. The resilience of a system or a network to counter shocks and adapt and flourish will depend on its ability to sense disruptions early, improve interactions within the networks and adapt to meet the challenges (Mayar *et al*., 2022). Strengthening primary care is an example of how the health system could sense and respond to health issues early and at the front-lines. A well-functioning cluster referral system would be an example of a network of institutions provides care to a population with minimal duplication of work. Enhancing the capacity to locally produce drugs and devices are examples of having reserves to respond to scarcities. Such shocks have the ability to make the system evolve to a new balance or the emergence of a novel status. The current crisis would therefore be an example of a situation that triggers a transformative change to country's unique health system. Therefore, the goal should be to adapt while preserving its strengths in providing equitable health care at a lower cost.

Conclusions and Future Prospects

The health sector is a pre-requisite when recovering from the economic crisis and it is an essential factor that allows smooth functioning of the other sectors. As a result, it will take a center stage when the economic crisis begins to affect the wider populations. A malfunctioning of health sector will lead to adverse health consequences and compromise the recovery efforts because health is not only an outcome of development but it is also an essential driver for development. Furthermore, a smoothly functioning health sector is necessary for education, social cohesion, and productivity. Policymakers, stakeholders and the citizens should take serious note of the potential consequences of the economic crisis on health and vice versa and address these issues before they worsen beyond a point of no return, leading to an unprecedented catastrophe. We propose a TARA framework (Transformation, Adaption, Resilience, and Absorption) to guide policymakers through the crisis.

Conflicts of Interests

Authors have declared that no competing interests exist.

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Creating Opportunities for Rural Economic Development and Food Security in Sri Lanka by Contributing Underutilized Plants to the Global Food System

CHAPTER 4

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Abstract The agrifood system has the potential to make a substantial contribution to improving the economic status of the rural communities in Sri Lanka. In recent times, most of the agricultural projects around the world have tended to focus on high productivity. Because of this, many agricultural countries, including Sri Lanka, preferred to cultivate high-yielding and high-demanding crops. This resulted in a reduction in crop diversification and a contraction in food patterns. But nowadays, this trend is changing and the research community is focusing on a healthy and diversified dietary pattern. Countries suffering from high inflation and food insecurity give priority to getting quality food at a minimum cost. Therefore, the attention of the world community has turned to finding sustainable sources of food that fulfil both the nutritional and economic upliftment of rural communities. Referring to that, underutilized crop/plant species can be introduced as a new potential candidate for the agro-food industry. Underutilized crops are nutrient-dense, health-promoting, and climate-resilient food crops such as cereals, tubers/yams, fruits, and vegetables. These species have the potential to be used in low-input agriculture, which will be a huge relief to rural farmers. As Sri Lanka is a biodiverse country with many underutilized plant species, there is great potential to utilize these neglected edible plants to ensure the economic development and food security of the rural population. This chapter discusses how the promotion of underutilized plant species and their multiple uses in local as well as global markets can improve the rural economy and livelihood in Sri Lanka.

Keywords: Economy, Food security, Rural, Underutilized crops

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Introduction

Sri Lanka is a biodiversity hotspot and is home to a large number of plant species with diverse benefits (Mallavarachchi *et al*., 2019). Only a very few of these plants are used for human consumption and other needs, and many other plants are abandoned without being used. Many of these abandoned plants were used as food in the past, but some plant species have reached a state where they are not used at all today. As a result of this neglect, rural communities around the world are denied economic and health development opportunities, and their economic and food security is at risk. Among the underutilized plants, there are many plant species whose identity is unknown and their nutritional value is not yet recognized. As a result, many plant species have been neglected and their nutritional or economic benefits are not known.

Underutilized plants (UP) that contribute to Sri Lanka's rich biodiversity include vegetables, fruits, grains, as well as economically important trees and herbs. These plants are highly adaptable to adverse environmental conditions and require low levels of inputs and management practices, and are an ideal solution to some of the current issues in the agriculture sector such as climatic change (Hunter *et al*., 2018). Various factors have led to the designation of these plants as underutilized or neglected. The main reason is that many of these plants have been removed from use despite their nutritional and economic value due to the ignorance of the people. There are many other reasons for labelling this species as "underutilized" such as selling only in local village markets, seasonality issues, poor taste, high price ranges and some legal barriers and government policies (Rathnayake *et al*., 2020).

Relative to food demand, only a small number of staple crops are used to supply 90% of food requirements (Grote *et al*., 2021). Accordingly, rice is always used as a staple crop in Sri Lanka. Moreover, even if we look at the global food supply, a very minimal amount of crops such as wheat, corn and rice are being consumed and 87% of the world's plant species are still underutilized (Grote *et al*., 2021). As the impact of the narrowing of the consumption of plant species is recognized as the greatest threat to global food and nutrition security, there is a growing need to search for new food crops. Hence, there is a strong focus on UP around the world, mainly investigating the nutritional value and economic benefits of plants. Researchers are introducing these plants as future food crops and it is noteworthy that Sri Lanka is a country populated by these UP. UP are plant species that can be used not only for food needs but also for several special purposes such as providing essential oils, timber, herbal extracts natural food colorants or industrial pigments and raw materials for various industries. Due to the important bioactive compounds and active ingredients present in these plants, they have been recognized as a hidden treasure in the global context. Therefore, Sri Lanka has great potential to address the global market and especially to improve the economic development of the rural people by means of using these plants.

Moreover, UP are an important germplasm resource for future crops that can attract global markets by improving beneficial properties such as nutritional quality and abiotic stress tolerance. Similarly, developing value chains/marketing strategies to harness the untapped potential of underutilized plants has the potential to meet global food demand and thereby strengthen Sri Lanka's economic progress. In this regard, these plants can contribute in various ways to create opportunities to ensure food security and rural economic development in the country. For example, natural antioxidants, extraction of phytochemicals from plants, production of value-added products, and using them in nutritional and pharmaceutical products can provide economic benefits. Proper management of stock production of these plants along with proper scientific studies can create a stable environment for these underutilized agro-food plants in the global food market. With that, many people suffering from poverty in Sri Lanka and the entire economic process of Sri Lanka can be directed towards a new path.

Therefore, UP show sustainable potential for food, culinary diversification, health and income generation and this is already gaining popularity in third-world countries (Jacobsen *et al*., 2013). Sri Lanka has valuable economic and nutritional resources, but since they are not properly managed, the country is in an economic crisis and at a risk in terms of food and nutritional aspects. Currently, the engagement of the scientific community and other professional authorities in seeking proper guidance and more sustainable solutions using available resources to these problems is evident. Thus, it is important to study the most effective approaches adopted by other countries regarding such plants. By doing so, it is necessary to get the attention of the local and global food markets related to those plants, and through that, the economic process of the country as well as the nutritional needs of the country should be remedied.

Underutilized Plants in Sri Lanka

Underutilized plants cope better with most agroecosystems and are often found in home gardens and village territories (Sahoo *et al*., 2021). Most UP are rich in many bioactive compounds including phytochemicals, antioxidants and micronutrients, which are useful in diversifying diets and overcoming micronutrient deficiencies in rural communities (Hettiarachchi and Gunathilake, 2020). These plants, which are easy to adapt to low-input agriculture, have many agronomic and economic advantages and are underutilized due to poor human attention and disuse. As discussed by Amarathunge *et al*. (2021), Sri Lanka has five species belonging to the genus *Salasia* recognized under the National Red List in 2012. These species have many health benefits and many multinational companies use this species for pharmaceutical production (Amarathunge *et al*., 2021). Similarly, there is a number of plant species that have been identified recently with numerous advantages in Sri Lanka (Fig. 1) (Hettiarachchi and Gunathilake, 2020; Peduruhewa *et al*., 2021).

Figure 1. Different plant species, all with the potential to contribute to the nutritional and economic status of Sri Lanka. (1) *Morinda angustifolia* (ahu); (2) *Phyllanthus emblica* (nelli); (3) *Pouteria campechiana* (lavalu); (4) *Syzygium cumini* (ma dan); (5) *Dimocarpus longan* (mora); (6) *Salacia reticulata* (himbutu); (7) *Coccinia grandis* (kowakka); (8) *Polyscias scutellaria* (koppa kola); (9) *Talinum triangulare* (gasnivithi);(10) *Commelina diffusa* (girapala);(11) *Lagenaria siceraria* (diya labu); (12) *Maranta arundinacea* (hulankeeriya); (13) *Dioscorea alata* (dandina); (14) *Setaria italica* (thana hal); (15) *Panicum miliaceum* (meneri) (Note: photo credit by https://www.wikipedia.org)

Currently, some scientific studies have been done on the UP of Sri Lanka (Peduruhewa *et al*., 2021). The reported study shows that these plants can greatly contribute to Sri Lanka's export industry. Due to the active substances and nutrient components of these plants, there is a high potential for many products such as food, medicine, perfumes and oils. For example, according to Hettiarachchi and Gunathilake (2020), Sri Lanka is rich in important neglected vegetable spices such as *Solanum macrocarpon* (Ahas-batu), *Solanum torvum* (thibbatu) and *Canavalia gladiata* (awara). These species are rich in medicinal benefits such as antibacterial and anticancer activities (Oboh *et al*., 2005; Ciau-Solís *et al*., 2018). Furthermore, Perera *et al*. (2022) have identified *Drypetes sepiaria* (weera)*, Manilkara hexandra* (palu) *and Schleichera oleosa* (kon) as important underutilized fruit species*.* Perera *et al*. (2022) have also discussed two types of wild berries *Salacia chinensis* (Himbutu) and *Dovyalis hebecarpa* (Ceylon gooseberry) and studied their active compounds. It has been revealed that these two species are rich in phenolic compounds such as phenolic acids, tannins, stilbenes, anthocyanins and flavonoids. Moreover, these berries contain anthocyanin (Puupponen-Pimia *et al*., 2001; Pap *et al*., 2021), which has been named as an important plant for human health that can be used to prevent inflammation, diabetes and cancer (Kalt *et al*., 2020). Sri Lanka is therefore a country with great potential to benefit from UP, as these plants are present in all climatic zones throughout the country, showing great diversity.

Potential of Underutilized Plants to Contribute to the Global Food System and Rural Economic Development in Sri Lanka

In recent years, mankind has been experiencing seriousness of hunger and food insecurity, and countries around the world are scrambling to find solutions to the acute crisis. For example, the nutritional status of children and pregnant women in Sri Lanka is at high risk due to the high economic crisis along with the food crisis. Hence, the concept of "quality food for less money" is needed to be popularized in Sri Lanka. This concept is spreading around the world and many research groups have proposed it as a solution to the existing food crisis. Furthermore, the subject experts have emphasized that, replanting and consumption of neglected plants as an effective way of solving the current issue (Jacobsen *et al*., 2013). Due to this, more attention has been given to UP. Moreover, the proposals state that these UP are not only for consumption but can be popularized as commercial crops and revolutionize the world market (Fig. 2). Accordingly, this will be a way to eliminate poverty as well as nutritional insecurity for third-world countries. In Sri Lanka, priority setting to improve the conservation and sustainable use of UP has not been done systematically. For that, it is essential to understand the current and potential distribution of UP to face the future challenges of global food security. However, it is important to study the demand and importance of these plants in Sri Lanka.

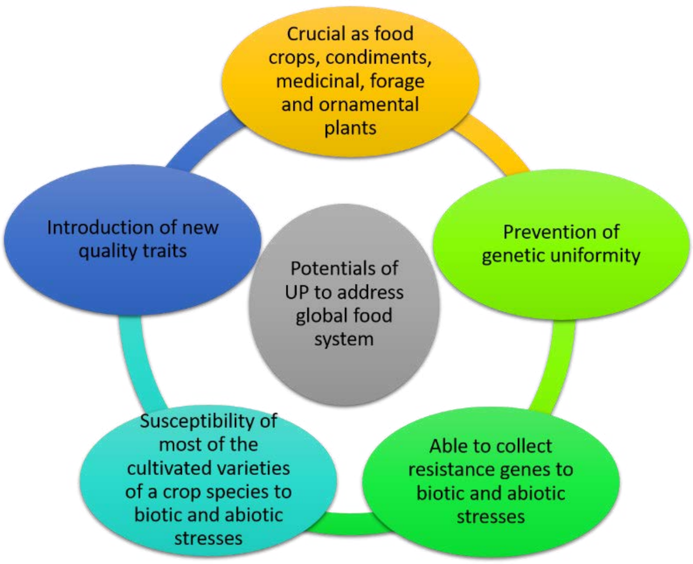

Figure 2. Potentials of UP to contribute to the global food system and rural economic development in Sri Lanka

Nutritional Benefits

The most valuable aspect of UP in Sri Lanka is its potential to improve the nutritional status of the human diet along with economic benefits. It is a known fact that UP has a high capacity to supply essential micro and macro nutrients to the human body. Therefore, apart from obtaining healthy food from plants, it will also be possible to develop value-added products. Further, extraction of natural bioactive compounds can also be used to produce nutritional drugs/nutraceuticals using these plants (Memariani *et al*., 2020). On the other hand, extraction of natural bioactive compounds such as antioxidants and phenols from plants is a growing trend worldwide. As UP is already been confirmed by many scientific studies as an antioxidant and phenol-rich plant, this will be a good potential for Sri Lankan farming community to generate income and address the global market (Hughes, 2009).

Looking at the studies on underutilized fruits in terms of nutritional aspects, it is understood that Sri Lanka is keeping a valuable resource underutilized. Perera *et al*. (2022) have discussed the importance of underutilized fruits of *Syzygium cumini* (madan), *Carissa carandas* (maha karamb), *Salacia chinensis* (himbutu), *Flacourtia indica* (ugurassa), *Malpighia emarginata* (barbados cherry), *Dovyalis hebecarpa* (ceylon gooseberry) and *Aegle marmelos* (beli). According to their findings, these species contain important nutrients including dietary fiber, phenolic compounds, antioxidants, vanillin and some important minerals (magnesium, sodium, iron and aluminum (Perera *et al*., 2022). In another study, *A. marmelos*, *Garcinia mangostana* (mangosteen), *Averrhoa bilimb* (bilimbi), *Averrhoa carambola* (star fruit), *Cynometra cauliflora* (nam nam) and *F. indica* have been studied on their nutritional properties (Abeysuriya *et al*., 2020). After examining vitamins and other nutritional factors, it was concluded that these species are rich in antioxidants, vitamin C, dehydroascorbic acid, phenols, and iron. Hettiarachchi *et al*. (2021) investigated the ability of *Annona* spp. (*Annona squamosa*, *Annona reticulata,* and *Annona muricata*) to inhibit protein denaturation. These plant extracts showed significant inhibition of protein denaturation by more than 50%, which can be seen as a significant finding for obtaining health and economic benefits. Many of these UP species can be found across the country and there is a need for climate change adaptation strategies and research that can increase resilience to future changes in climate (Ratnayake *et al*., 2019).

Sri Lanka's underutilized vegetables, yams and grains can be promoted as a healthy food source worldwide. For example, several legumes such as *Phaseolus lunatus* (butter bean), *Vigna umbellate* (tonga beans) and *Canavalia gladiata* (sword beans) have been identified as plants with bioactive peptides by (Ciau *et al*., 2018). These species are neglected by Sri Lankans and are abundant in village areas. *Solanum macrocarpon* (ahas batu), *Solanum torvum* (thibbatu) and *Basella alba* (water spinach) are cheap sources of antioxidants which are domesticated in Sri Lanka (Lakshminarayana *et al*., 2005; Oboh *et al*., 2005; Sivapriya and Leela, 2007; Ciau-Solís *et al*., 2018). Moreover, there are many neglected leafy vegetables with high nutritional value in Sri Lanka. For example, *Commelina diffusa* is an underutilized, less expensive and better nutrient source in Sri Lanka. Trace elements including Ca, Fe, Zn and Cu and important phytochemicals were found in the tender shoots of *C. diffusa* (Peduruhewa *et al.*, 2021).

Yams are another UP that has been largely neglected by the modern community. Studies on underutilized tubers such as *Dioscorea alata*, *Amorphophallus campanulatus*, *Canna indica* and *Dioscorea pentaphylla* have found these species to contain satisfactory amounts of fiber, antioxidants, and phenols along with minerals (K, Ca, Mg, Fe, Cu, Zn) (Gunasekara *et al*., 2020). Underutilized grains like *Panicum miliaceum* (Meneri or Proso millet) and *Paspalum scrobiculatum* (Amu or kodo millet) in Sri Lanka and some underutilized tuber crops including *Lasia spinose* (Kohila) and *Nelumbo nucifera* (nelum) consist with higher dietary fiber content. Furthermore, these plants possess important activities such as inhibiting the activities of α amylase and amyloglucosidase in the human body (Chiranthika *et al*., 2021). *Nelumbo nucifera* is another underutilized tuber that contains beneficial amounts of fiber along with significant functional properties such as water and oil-holding capacities (Chiranthika *et al*., 2022). These are only a few selected scientific studies conducted in Sri Lanka regarding the nutritional properties of UP. Thus, it is clear that the production of nutritional supplements and the introduction of value-added food products can have a positive impact on the rural economy of Sri Lanka.

Health Benefits and other Importance

The use of synthetic drugs has become a serious health threat and causes cancer, diabetes and neurodegenerative disorders (Weerasinghe and Dahanayake, 2021). It has been reported that the consumption of UP species, which are rich in bioactive compounds enables avoiding diseases. Hence, there is a need to develop medicines using natural plant extracts (Weerasinghe and Dahanayake, 2021). Due to the bioactive compounds present in these plant species, enables avoiding diseases (Chhikara *et al*., 2018). Several studies have identified the health benefits and important bioactive compounds of UP in Sri Lanka. *Momordica dioica* (thumba karavila) is one of the UP that has received much attention in the research community for its health benefits. According to Anjana *et al*. (2019), extracts of *M. dioica* fruits and roots contain specific phytochemicals (alkaloids, tannins, fixed oils, flavonoids, sterols and amino acids). These compounds lead to numerous health benefits including antibacterial activity and anticancer activity (Sharma *et al*., 2019; Anjana *et al*., 2019; Carvalho and Conte-Junior, 2021). *Annona muricata* (Anoda) offers many health benefits for joint pain, neuralgia, arthritis, diarrhea, dysentery, fever, malaria, parasites, rheumatism, skin rashes and worms. This plant is also important to increase breast milk after giving birth and to treat cancers (Coria-Téllez *et al*., 2018). Moreover, the plant is used to treat various diseases such as respiratory and skin diseases, internal and external parasites, bacterial infections, hypertension, inflammation, and diabetes (Coria-Téllez *et al*., 2018).

Annona muricata is highly available in Sri Lanka and the bark, leaves, fruits, flowers and roots of this plant are used to treat various diseases (Ayurvedic Medicinal Plants of Sri Lanka Compendium, 2021). *Solanum torvum* (Wild eggplant/ Thibbatu) can be identified as another plant that is widely available in Sri Lanka with numerous health benefits. The plant is used in cough-related diseases and is useful in cases of enlarged liver and spleen (Sivapriya and Leela, 2007). *Colocasia esculenta* (gahala) is a plant that was eaten in the past but is now reluctant. The corm contains valuable bioactive molecules related to anticancer and control of metabolic dysfunctions (Mitharwal *et al*., 2022). Similar findings described the antioxidant properties of *C. esculenta* and its ability to destroy carcinogens (Pereira *et al*., 2020). *Maranta arundinacea* (hulankeeriya), is a plant rich in prebiotics that can increase the biomass of probiotics (Jayampathy and Jayethilaka, 2018). The antioxidant activity of *M. arundinacea* shows clear activity against free radicals in pharmaceutical applications (Lima Souza *et al*., 2022).

Apart from nutritional and health benefits, many other benefits are associated with UP. Plants such as *Sphaeropteris lepifera* and *Tetragonia decumbens* are used in landscape designs. Thus, ornamental plants and flowers have the potential to promote underutilized ornamental plant nurseries (Mauro *et al*., 2022). According to Ashraf *et al.* (2018), there are many other hidden benefits associated with UP to improve employment opportunities and reduce poverty. Mushroom production is one of them. Wild mushrooms with good nutritional benefits such as *Lentinus squarrosulus* and *Pleurotus tuber-regium*are available in Sri Lanka (Miriyagalla *et al*., 2019). Extraction of bioactive substances, fragrance products and natural pigments or dyes are also important economic benefits associated with these underutilized plants.

Current Status of Underutilized Plants in Sri Lanka

The current consumption of UP in Sri Lanka is highly dependent on consumer awareness. Adequate awareness of UP and a lack of proper understanding of its benefits are the main reasons for the low consumption of these species. A recent study investigated that consumer willingness to pay for UP in Badulla district is based on several factors such as consumer age, income, family members suffering from non-communicable diseases, number of children in the family and attitude towards health benefits of food (Karunarathna *et al*., 2020). Thus, it appears that the use of UP in Sri Lanka is mostly based on awareness and its benefits. This shows the importance of socializing the valuable benefits of these plants. The Department of Agriculture implemented various approaches to introduce UP-based and value-added food products for Sri Lankans. In parallel to this, in 2017, the Biodiversity for Food and Nutrition Sri Lanka project introduced UP-related food on the theme "Biodiversity for Food & Nutrition and True Sri Lankan Taste” (Fig. 3). In this way, the public, school children and the international community were also educated to introduce the UP and explained its value to society expecting the investors' attraction to food security and rural development in Sri Lanka.

Figure 3. Food festival to raise awareness and promote UP in Sri Lanka (Biodiversity for food and Nutrition, Sri Lanka, 2017)

In the last few decades, extensive and diverse research studies regarding these plants have been done in Sri Lanka (Peduruhewa *et al*., 2021). While much of this interest has focused on the specific projects of individual researchers, a number of significant programs have also been launched to promote underutilized species as alternative crops for agricultural systems or as new sources of food production. There is widespread recognition among many stakeholders in Sri Lanka that underutilized crops should always be promoted to improve food security and boost the rural economy. Although all this is well understood, the main obstacle to the proper use of these UP in Sri Lanka is that research studies, awareness programs and other plans are not carried out consistently with proper formality.

Ensure Rural Economic Development and Food Security Using Underutilized Plants

Low-input agriculture is one of the major sources of income for rural farmers. Cultivation of UP (fruits, vegetables, tubers, and other species) under low management packages will provide better income for poverty reduction (Ngome *et al*., 2017). Opportunities such as the cultivation of UP, development of innovative food products and supply of raw materials can improve people's livelihood through new employment opportunities without high competition. High concern for health and nutritional factors related to UP-based products can create demand across the country. Examples of such businesses include value-added products such as jams, jellies, pickles and marmalades. A number of UP-related products can be seen in high demand in the world market. Thus the main processed products consumed by people are jam, RTS - fruit drinks, chutney, candy, pickles, squash and concentrates. Along with that, various processed products such as canned jackfruit bulbs in syrup, squash, raw jackfruit pickles, roasted jackfruit seeds, jackfruit seed flour and candied jackfruit are prepared from jackfruit (Ashraf *et al*., 2018). Therefore, Sri Lankans also have the same ability to develop these products with the availability of different UP varieties available in an innovative manner. Meanwhile, exporting products made from these UP can earn a large amount of foreign exchange for the country. Currently, there is an awareness of UP in the international market with a huge demand for these species and their products. Therefore, with proper guidance and government intervention, even small businesses can make global market connections to gain more profit in this industry.

In evaluating market opportunities, high demand for functional foods can be seen nowadays, creating a potential market for plant species with rich bioactive compounds. In many countries, the demand for functional foods and beverages is growing rapidly due to increasing health consciousness and lifestyle choices. With UP's high abundance of bioactive compounds, these plants have a clear potential to extract bioactive compounds for use in the functional food and nutraceutical industries. This would be a good solution to improve the economy by carrying out commercial cultivation of identified plants in villages. Connecting with the global community is the main concern of promoting entrepreneurs in UP-related businesses. There are several platforms recently created by the word food-related organizations. Williams and Haq (2002) documented an account of current research and research proposals for improved collaboration on UP (Padulosi *et al*., 2002) and various international research organizations have been established to focus on enrolling with UP. Global Facilitation Unit (GFU) is a multi-agency initiative working globally to promote the widespread use of underutilized plant species by supporting and facilitating the work of other stakeholders (Kour *et al.,* 2018). By working with such organizations and guidance from them, the proper use of these plants makes way to improve the living conditions of the rural people.

Considering the examples of countries where plants have been promoted, their success is mainly based on the effective integration of these plants into modern food production methods. The disconnection between the agriculture, environment, health and nutrition sectors and the lack of coordination between these sectors can also be cited as the limitations to the spread of these plants in Sri Lanka. All parties involved need to support this process and enable this action by building partnerships and improving awareness and understanding among various stakeholders including researchers, universities, government agencies, relevant national ministries, local governments, municipalities, small-scale producers and civil society considering this as a national task (Ratnayake *et al*., 2021).

Any nation can boost the use of UP to address healthier diets and better nutrition by taking two critical strategic initiatives: (i) create strong research collaborations to carry out nutritional composition research (ii) create multi-sectoral platforms or focus on ones that already exist that can use this new information to more effectively integrate UP into pertinent national nutrition and food security policies, strategies, and activities. Brazil has made good progress towards promoting UP by taking advantage of the multi-sectoral governance mechanisms already in place under the Fome Zero (Zero Hunger) strategy (Hunter *et al.*, 2019). The Food Acquisition Programme (PAA), the National School Meals Programme (PNAE), the Minimum Price Guarantee Policy for Biodiversity Products (PGPM-Bio) and the National Plan for Organic Production and Agroecology (PLANAPO) among other Brazilian policies and programs, all offer acceptable chances and entry points for UP. For Brazil to strategically target a number of its policies and actions, such as promoting diverse UP in dietary guidelines, supporting UP production through public procurement strategies, including in schools, and giving UP priority in pertinent national strategies/action plans and agriculture and nutrition policies, these policies and governance frameworks have been essential.

Limitations to Promote Underutilized Plants in Sri Lanka

Even though many UP are nutritionally valuable and superior to most mainstream crops, why are they not more integrated into our food systems and why are farmers not going for commercial cultivations of these plants? or why is the diversity in our agriculture, food systems and diets shrinking? Despite increasing awareness of their nutritional value, there remain many barriers limiting the integration of UP into food systems. Agricultural projects targeting food availability and consumption have primarily focused on increasing the yields of a select few energy-rich commodity crops and raising income from the sale of these crops to improve food and nutrition outcomes. This has resulted in several crops being over-researched and over-produced (for example, rice, wheat and maize) at the cost of more nutritious food species, including fruit, vegetables and legumes, which are generally under-researched and insufficiently available (Kour *et al*., 2018; Mabhaudhi *et al*., 2019). Instead of this major concern, there are many other barriers and limitations to neglecting of these plant species by consumers and the farming community.

(i). Cultivation Related Barriers
Poor genetic diversity due to the limited variety of alleles for genes within the species of many UP and barriers related to seed networks (low quality and discontinuation of seed distribution) have a direct impact to cultivate UP. Similarly, the transformation of land usage, such as forest to agriculture and agriculture to housing has led to changes in natural habitat and reduced the availability of wild species and the suitability of cultivated UP. Poor influence by the relevant authorities such as government parties and private agriculture industries and poor coordination between research studies and knowledge dissemination programs reduce the interest of farmers to engage with UP cultivation (Kandagatla *et al*., 2019; Hunter *et al*., 2019).

(ii). Marketing and Value Chain Related Barriers
Value chain development and marketing of UP involve greater risk and low monitory support is given to developing UP into a commercial scale. Banks or investors are afraid of taking risks due to the poverty of most farmers. Apart from that, there are several other barriers such as a lack of market knowledge, beneficial market

linkages, entrepreneurial skills, business support and inefficient value chains that lead to low price incentives (Kandagatla *et al*., 2019).

(iii). Consumption and Demand Related Barriers

The negative perception of UP, particularly by the young generation, hinders its use. They are considered “poor man’s crops”, foods associated with famine or periods of hardship. However, several large global economies, such as India, Brazil and Nigeria, have a substantial and fast-growing middle class and wealthy consumers in larger cities. These people are potential UP consumers and could be targeted through their interest in connecting with their food cultures and their preference for nutritious, pesticide-free and healthy foods. However, there are barriers related to consumption such as widespread cultural erosion, a lack of innovative food recipes, little knowledge of beneficial economic practices or the potential to improve food and nutrition security and a lack of consumer demand, which translates into a lack of product awareness (Raner *et al*., 2019; Padulosi *et al*., 2021).

Conclusions and Future Prospects

With the identified opportunities for UP, the potential remains to integrate these plants into the production sector, domestic consumption and global food systems to improve health and the economy. Agricultural and related government institutions should immediately carry out required scientific studies and production processes. To establish a social, economic, and environmentally friendly food security system in the country, measures need to be taken and expedited to promote these plants among different communities (Fig. 4). There is sufficient evidence to establish and promote UP across the country with viable laws and regulations. Therefore, soon, the Department of Agriculture, Rural Development Authorities, the Association of Small and Medium Enterprises and the banking sector should be acquainted with this. Besides, it is necessary to initiate proper awareness programs and well-timed agendas in Sri Lanka to initiate sustainable food systems. In future plans, strengthening of seed banks of UP is needed to ensure biodiversity conservation, availability and accessibility. The development of markets and agribusinesses that ensure the availability and affordability of diverse UP-based foods to low-income consumers and the revitalization of local knowledge and cultural heritage related to UP crops must be accelerated. It is also important to create new policies as well as more coherent and coordinated actions on UP at national and global levels. So far, various types of research and promotion programs have been conducted at the university and government levels in Sri Lanka. But the main problem is that these research findings are not disseminated to the essential/relevant groups in society. Therefore, consumers and small-scale farmers as well as rural people are not aware of the benefits of UP in and around their vicinity. Therefore, it is more important to introduce a more efficient national program to make farmers and consumers aware.

Moreover, practical applications of UP-based research studies are needed to be conducted in an effective manner. For example, in Brazil and Kenya, extensive and formal programs have been launched in relation to UP (Münke *et al*., 2015). Referring to promotional programs, they have conducted many nutrition programs in schools through UP-based foods and various publicity programs were also launched for the general community. To prevent misconceptions and neglect related to these plants, they introduced new types of healthy foods in association with well-known chefs in the country (Münke *et al*., 2015). It is therefore important for Sri Lanka to launch such promotional programs and other various programs related to UP in the future.

Figure 4. Future prospects of UP in Sri Lanka

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Conflict of Interest

Authors have declared that no competing interests exist.

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Meat, Fish and Milk Analogues as Future Foods in Sri Lanka

CHAPTER
5

M. Silva* and C. Senanayake

Abstract Sri Lanka is currently experiencing a severe economic crisis. The agri-food sector of the country is badly affected where over 30% of the population in Sri Lanka is "Food Insecure" as estimated by the World Food Program. Increased levels of poverty, increased food inflation rates, shortage of essential food items, inaccessibility to basic dietary requirements, and failure to afford even the staple food commodities have paced the whole nation at a greater risk of hunger and malnutrition. Sri Lanka as an agriculture-based country, food security can be achieved through sustainable food production with the effective utilization of readily available and/or underutilized local materials. Formulation of essential foods using readily available, underutilized, and low-cost plant materials would be one of the timely solutions to fulfill the basic dietary and nutrient requirements. Placing the protein requirement of a diet as a priority, it is aimed to discuss the possibilities of using plant-based alternatives (analogs) for meat, fish and milk, products. The productive formulation of meat, fish and milk analogs can fulfill the quantity and the quality requirements of the dietary protein intake. This chapter provides insight on how the modern food industry in Sri Lanka should upgrade for sustainable food production to assure food security through plant-based meat, fish, and milk analogs. This chapter discusses the potential raw materials that can be used to develop these analogs focusing on the locally available underutilized, less expensive, and excess materials aligning to the present situation in the country.

Keywords: Fish analog, Meat analog, Milk analog, Plant-substitutes, Sri Lanka

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Introduction

Protein is a vital nutrient in a balanced diet. They are important for the maintenance of optimal health and coordination of bodily functions including, growth, development, reproduction, lactation, etc. (Jung *et al.,* 2015). Amino acids are the precursors of protein, which can be of two types, essential and non-essential amino acids. Essential amino acids are of great importance as they cannot be synthesized by the human body, which needs to administer through the food that we eat (Parikh *et al.,* 2021). Animal sources are of great importance in providing essential amino acids to the body. Meat, fish, and milk could be considered as major sources of protein for consumption.

Consumption of animal protein primarily depends on different factors including, economic, cultural, religious, social, personal and marketing (Dietz *et al.,* 1995). Sri Lanka is a multi-religious country, where Buddhism is the major religious group that accounts for about 70% of the population. Other religious groups include Hindus (12.6% of the population), Muslims (9.7% of the population) and Christians (7.4% of the population) (Country Policy and Information Note Sri Lanka – Religious Minorities, 2021). Major ethnic groups in Sri Lanka are comprised of Sinhalese (74.9% of the population), Sri Lankan Tamils (11.2% of the population), Indian Tamils (4.2% of the population), Sri Lankan Moors (9.3% of the population), Malays (0.2% of the population) and Burghers (0.2% of the population) (Department of Census and Statistics, 2014). Even though global animal protein consumption keeps uprising due to high consumer preferences and low prices (Devine, 2003), the present situation in Sri Lanka has negatively affected the consumption of animal-derived product.

Animal Protein Production and Consumption in Sri Lanka: Meat Production and Consumption

Livestock rearing is an essential part of rural livelihood in Sri Lanka. By 2021, local livestock comprised 1.13 million cattle, 0.33 million buffalo, 0.36 million goats, 0.01 million sheep, 0.1 million swine, 24.31 million poultry, and 0.02 million ducks (Department of Census and Statistics, 2021). The livestock sector contributes about 1% to the national GDP (Livestock Statistical Bulletin, 2020). The locally available meat supply for consumption showed an increasing trend throughout the past few years and it was 240,000 MT in 2017 (Food Balance Sheet, 2019). The average meat supply for consumption was reported as 209,000 MT for the period 2013-2017 (Food Balance Sheet, 2019). The average per capita per year supply of meat for the period 2013-2017 was 10 kg (Food Balance Sheet, 2019). Higher consumer purchasing levels of livestock over the past few years resulted due to several factors including, urbanization and increased per capita income. However, religious and sociocultural beliefs also greatly influence meat consumption. About 70% of the contribution from the Livestock sector to the national GDP is from the poultry sector (Livestock Statistical Bulletin, 2020).

Chicken meat is the most popular choice of animal protein in Sri Lanka over the years, mainly due to its low price. In 2006, the Sri Lanka government declared chicken meat an essential food commodity. A high growth rate in the broiler chicken meat sector is observed over the past few years due to the involvement of the private sector. Demand for chicken meat is mainly fulfilled through local production. The local chicken meat production in 2021 was reported as 236,790 MT (Department of Animal Production and Health, 2012-2021). A smaller quantity is fulfilled through importation (Poultry Sector Analysis and Forecast, 2020). Per capita availability of chicken meat has increased over the past few years. In 2021, it was reported as 10.69 kg/year (Department of Animal Production and Health, 2012-2021).

Goat production is practised broadly in the dry and intermediate zones in Sri Lanka. Goats are managed through intensive and semi-intensive farming. The primary purpose of rearing goats is to obtain meat (mutton). Per capita availability of mutton was increased over the years except for a significant drop (50% drop compared to 2019) in consumption observed in 2020. In 2021, the per capita availability of mutton was 0.15 kg/year (Department of Animal Production and Health, 2012-2021). A majority of local mutton consumption is fulfilled through local production which was reported as 2,500 MT in 2021 (Department of Animal Production and Health, 2012-2021). In the same year, the importation of mutton was 880.59 MT which was approximately 26% of the total consumption of mutton.

The swine sector is considered as an important component in the livestock sector after the poultry and dairy sectors in Sri Lanka. Swine farming is practised mainly in the coastal region of Sri Lanka. Simple management and less susceptibility to diseases make swine farming an economically viable livestock sector (Alahakoon *et al.*, 2016). By 2021, pig population, pork production and per capita availability of pork were 1,785,229,820 MT, and 0.44 kg/year respectively (Department of Animal Production and Health, 2012-2021). The price of pork was almost stable in the years 2016-2018 (~ Rs. 650/kg), however, a notable increase in the price was observed after 2019 and the price of pork continued to increase. In 2021, the price of pork was approximately Rs. 741/kg (Department of Animal Production and Health, 2012-2021). The swine sector shows promising potential for further improvements and expansion through effective farm management, product quality improvement and efficient marketing.

Beef production in Sri Lanka showed very slow growth during the last decade primarily due to religious and cultural beliefs. Cattle slaughtering is notably reduced in some provinces in Sri Lanka. Total beef production was recorded as 29,540 MT in 2020, where Eastern Province recorded the highest production (12,518 MT) and Sabaragamuwa Province recorded the lowest production (512 MT) (Livestock Statistical Bulletin, 2020). In 2021, the total beef production was 26,650 MT (Department of Animal Production and Health, 2012-2021). Per capita availability of beef has been reduced over the past few years. Per capita beef production was 1.7

kg/year in 2012 and 1.2 kg/year in 2021 (Department of Animal Production and Health, 2012-2021). Buffalo meat is not much popular in the country because slaughtering of buffaloes has been completely banned in the country.

Fish Production and Consumption

The fishery industry is a very important and well-established sector in Sri Lanka, which has been the major source of income for the people in the coastal region since ancient times. By 2020, it was reported that the contribution of fish to animal nutrition (protein) intake was about 52.4% (Fisheries Statistics, 2021). The fishery sector in Sri Lanka contributed 1.1% to the national GDP and is comprised of two main subsectors; marine and inland fishery and aquaculture. The major contribution to local fish production is from the marine fishery (77.8%) and in 2020 it contributed 0.9% to the national GDP. Local fish production was 428,740 MT in 2020 (Table 1) and per capita consumption of fish was reported as 15.1 kg/year in 2020 (Fisheries Statistics, 2021).

Table 1. Annual fish production in Sri Lanka from different subsectors from 2015-2020 period (Source: Fisheries Statistics, 2021)

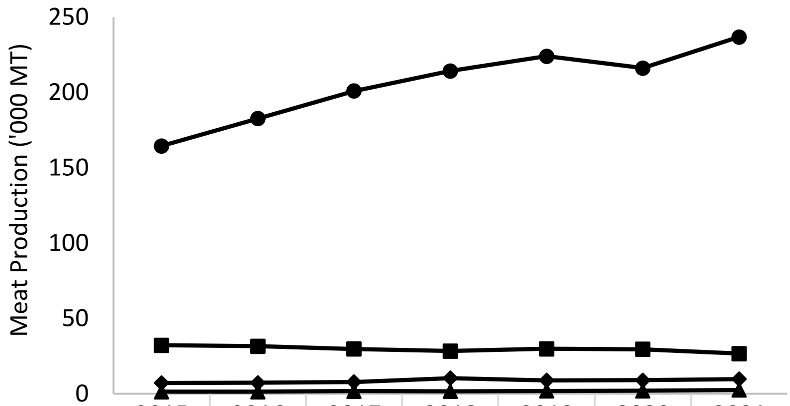
	Fish Production in Sri Lanka (MT)		
Year	**Marine Fishery**	**Inland Fishery and Aquaculture**	**Total Fish Production**
2015	452,890	67,300	520,190
2016	456,990	73,930	530,920
2017	449,440	81,870	531,310
2018	439,370	87,690	527,060
2019	415,490	90,340	505,830
2020	326,930	101,810	428,740

Milk production and consumption in Sri Lanka

Milk is considered as a nutrient-dense food rich in proteins and other essential micronutrients (Górska-Warsewicz *et al.,* 2019). Frequent consumption of milk confers several advantages including maintenance of good bone health (Park, 2009), prevention of periodontal disease (Adegboye *et al.,* 2012), benefits in reducing cholesterol absorption (Park, 2009). Total milk production in Sri Lanka was 436,872,312 L in 2021 (Department of Animal Production and Health, 2012-2021) and the milk supply is mainly from cow and buffalo milk. The reported data indicated that local production satisfied 40% of the domestic requirement for milk. In the current context in Sri Lanka, milk powder has become a necessity. Thus, a large amount of money is spent annually on the importation of powdered milk. According to Lakmali *et al.* (2022), Sri Lanka spends $300 million per annum on importation of milk powder. Another reason that the consumption of powdered milk is favored over fresh milk consumption is due to the high market prices of fresh milk. By 2021, it was given that the retail price of 1 L of fresh milk was Rs. 182.20 (Department of Animal Production and Health, 2012-2021).

Effect of Economic and Political Factors on the Animal Protein Production and Consumption of Sri Lanka: Meat Production and Consumption

Local chicken meat production was badly affected after 2019 due to the spreading of the COVID-19 virus in the country. This resulted in slow growth in other meat production (Fig. 1). The low availability of human resources and their poor distribution among local producers had an enormous effect on the local producers. The effect was so high that the small-scale and medium-scale producers had to cease their production, and even the large-scale producers had to cut down their production. Thus, the low availability of meat products, the rapid rise in production cost, and increased consumer prices were the ultimate results.



	2015	2016	2017	2018	2019	2020	2021
Chicken Meat	164.45	182.69	200.98	214.20	224.01	216.16	236.79
Mutton	1.35	1.35	1.74	1.63	1.88	1.96	2.50
Pork	7.18	7.28	7.89	10.43	8.90	9.00	9.80
Beef	32.18	31.54	29.79	28.42	29.87	29.54	26.65

Figure 1. Meat production in Sri Lanka during 2015-2021 period (Source: Department of Animal Production and Health, 2012-2021)

Sri Lanka is currently experiencing the worst economic crisis ever. Food prices reached a record increase in August 2022, with an approximately 94% inflammation rate. The recent economic crisis resulted in an acute shortage of essential supplies like food, medicine, fuel, etc. This situation has imposed restrictions on the importation of improved live animals and animal feed materials as well. This effect was so prominent in the importation of maize, which was the main raw material in poultry feed. In 2019, the importation of maize was reduced by 2%, and it was not allowed to import in 2020 (Poultry Sector Analysis and Forecast, 2020). The rapid depreciation of the Sri Lankan rupee caused over 100% inflation in food prices and further restricts the importation of meat and meat products in the last 3 years (Table 2). These factors contribute to low per capita availability and high product prices.

Table 2. Meat and meat products importation during 2015-2021 period (Source: Department of Animal Production and Health, 2012-2021)

	Import Quantity (MT)			
Year	**Chicken Meat**	**Mutton**	**Pork**	**Beef**
2015	591.58	502.71	0.04	72.63
2016	252.59	485.16	0.59	67.10
2017	271.52	949.30	0.59	61.36
2018	277.16	853.95	116.83	53.85
2019	195.85	1214.09	143.58	59.36
2020	128.58	1067.20	82.88	24.67
2021	54.73	880.59	67.24	34.34

Fish Production and Consumption

The local market price of fish has increased rapidly over the past few years which made it unaffordable to the majority of consumers. According to the most recent statistics, the average price of 1 kg of big fish is about Rs. 3,200.00 - 3,500.00 and while the prices of small fish have increased by 40%. The major reason for the steeply rising fish prices is the recent price hike of diesel and kerosene oil. At present, the number of multi-day vessels going out for fishing has dropped by about 60% as they require diesel to run. The rising price of kerosene oil significantly decreased the number of fishermen that go into the deep sea as they usually carry out sufficient quantities of kerosene oil. This situation badly affected the small-scale fishers and caused quitting the industry. In Sri Lanka, about 50% of animal protein and 11% of total local protein consumption is coming from seafood consumption (Central Bank Annual Report, 2021). These values are significantly higher than the global values of 17% and 7% respectively. However, the present situation caused an inadequate supply of fish for consumption.

Importation and Consumption of Powdered Milk

At present, Sri Lanka is experiencing a severe shortage of powdered milk thereby, increasing the price of powdered milk to the highest level. Long queues outside the local milk stores were a common sight and in one instance, a token system was introduced by the Sri Lankan government to manage the situation. Local milk importers faced a huge burden due to the dollar shortage prevailing in the country at present. In 2021, it was reported that the imported powdered milk was 88,482 MT (Fig. 2). It was about a 14% reduction in importation compared to 2020. The current market price of 1 kg and 400 g powdered milk are approximately Rs. 2,800.00 and Rs. 1,100.00 respectively.

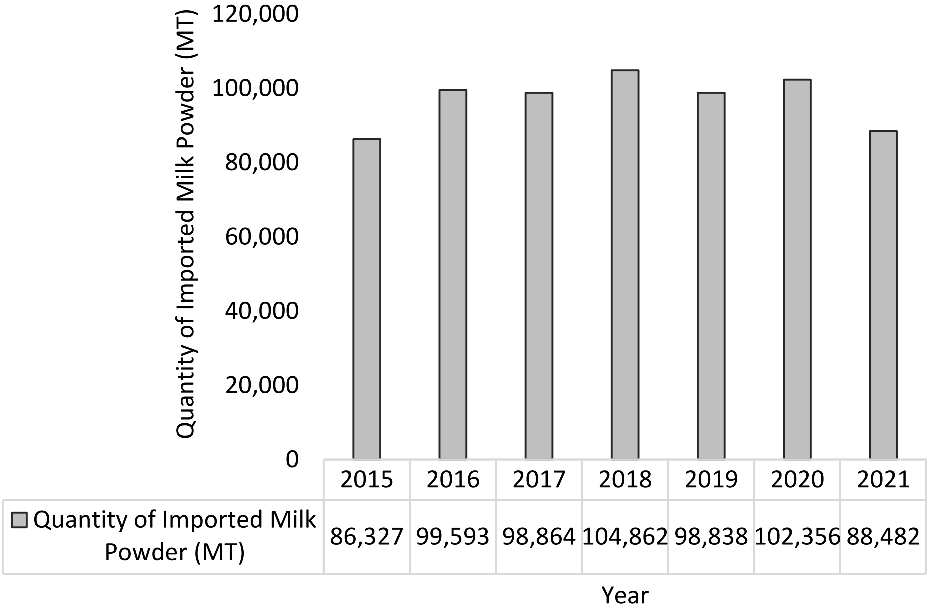


Figure 2. Annual importation of milk powder in Sri Lanka during 2015-2021 period (Source: Department of Animal Production and Health, 2012-2021)

Necessities of Introducing Plant-based Analogues to Sri Lankan Food Industry

Throughout the past decades, the agri-food sector in Sri Lanka has supplied an adequate quantity of safe and nutritious food products to consumers at an affordable price. However, the current economic crisis in the country has badly affected the agri-food sector and has placed the whole country at risk of hunger and malnutrition due to the shortage of main food items as well as has increased food inflation significantly. Under these situations, people are switching to low-cost foods which often contain lesser protein and other nutritional values. The inadequate access to animal protein and other food supplies has led people to cut down or skip their food intake. It has been estimated by the World Food Program that over 30% of the population in Sri Lanka is "food insecure". United Nations International Children's Emergency Fund (UNICEF) has reported that currently 7 out of 10 families have cut down the three meals to two to mitigate the current economic crisis in Sri Lanka. Malnutrition among children aged under 5 years is considered as an emerging issue in the country. As per the UNICEF's statistics, Sri Lanka is now ranked as the second highest in acute malnutrition among children under 5 years in South Asia. It is predicted that the current food insecurity situation is expected to continue further, and hence immediate actions are required.

The food processing industries in Sri Lanka should undergo a drastic upgrade considering the prevailing economic crisis. More sustainable food production should be achieved while providing nutritious and convenient foods to consumers at an affordable price. With the continuous increase in the price of most animal-based products in the market, many people are adopting plant-based foods to fulfill their dietary and nutritional needs. Therefore, adopting plant-based alternatives to meat, fish, and milk has become one of the prominent solutions for Sri Lanka. Proper formulation of meat, fish and milk alternatives from plant materials can provide the same nutritional properties as their real products. Generally, these animal-based products are considered as the main protein sources in our meals and their alternatives can fulfil both quantitative and qualitative properties of protein requirements. Moreover, the production of higher quantities of animal-based food products can have negative impacts on environmental sustainability and some ethical/religious beliefs of people also discourage the slaughtering of animals and consumption of animal food products. Moreover, the production cost and the raw material cost of plant-based food products are reasonably lower than the animal-based products. Plant-based meat alternative products can be traded at comparatively lower price. Due to all these reasons, consumers are trying to rely on plant-based food products, and believe that plant-based diets are healthier than animal-based diets. Therefore, the introduction of plant-based analogues that replace real meat, fish and milk products is a timely solution to fulfill the basic dietary needs of individuals at an affordable price as an economically and environmentally sustainable strategy to assure food security. Therefore, based on the higher consumer demand and the prevailing economic crisis of the country, food manufacturers should focus on the creation of plant-based food products as alternatives to animal-based products mainly depending on the locally available raw materials.

Meat, fish and milk analogs can be considered as next-generation plant-based food products as they can mimic the nutritional and sensorial properties of real meat, fish and milk products. Moreover, the production of analogs can be considered a more ethical, sustainable, economically beneficial and commercially viable suggestion for the future agri-food sector in Sri Lanka. Simultaneously, consumers can fulfill their dietary and nutritional requirements in healthier and more affordable ways which in turn will help to decrease the risk of hunger and malnutrition in the population.

Introduction to Meat, Fish and Milk Analogues

Meat, fish or milk analogs like non-animal protein analogs can be defined as food products that have similar structural properties to real meat, fish or milk, but fairly differ in composition (Malav *et al.,* 2015). They are generally healthier and less-expensive food products in comparison to their real form. However, it should mimic the nutritional properties of respective real food products using plant-based ingredients. Meat analog is one of the popular plant-based alternatives around the world. Meat analogs are also named as meat substitutes, mock meat, faux meat, or imitation meat (Sadler, 2004). In the market, three forms of meat analogs are available including coarse ground meat analogs (burgers, sausages, meatballs and nuggets), emulsified meat analogs (deli meats and frankfurters) and loose fill (meat fillings) (Borders, 2007). The most popular commercial meat analog producers in the world are "Beyond Meat" and "Impossible Foods". In Sri Lanka, the most common meat analog types are vege-burgers, veggie sausages and texturized vegetable proteins (TVPs). Generally, meat analogs are produced using a combination of plant ingredients as it helps to mimic the nutritional, organoleptic and structural properties of real meat. Among the ingredients, protein-containing plant ingredients are the major source that contributes to the sensory, nutritional and structural properties of the meat analog. Generally, a single protein source or combination is used to develop meat analogs. Some of the commonly used protein rich plant-based ingredients are soy, pea, lentils, wheat gluten, peanut, bean varieties, legume varieties, root and tuber crops, mushroom varieties and algae (McClements and Grossmann, 2021). Carbohydrate and lipid sources should also be incorporated into meat analogs. Moreover, additives like colors, flavors, flavor enhancers, preservatives and micronutrients are sometimes added especially during commercial production (McClements and Grossmann, 2021).

Even though meat analogs are very popular and moderately established food products in the industry, fish analogs and milk analogs production are still emerging areas. These fish analogs especially have similar nutritional and sensory properties to the real fish while mimicking of structural properties of real product in the development of fish analog is very difficult. Several fish analog products such as chunks, burgers, nuggets, cakes and fillets have been successfully commercialized (Kazir and Livney, 2021). The protein source is a highly important raw material that should be used in fish analog production to mimic the nutritional, sensorial and structural properties of real fish. Similar to the meat analogs, legume varieties, seaweeds, root and tuber crops, wheat and some vegetables have been used in the formulation (Kazir and Livney, 2021).

Even though most people still consume dairy milk or secondary dairy products, there is a growing market for milk analogs or dairy milk alternatives. Milk analogs generally have a milk-like appearance and consistency. Some of the commercially available plant-based milk products are soy milk, almond milk, cashew milk, coconut milk and oat milk (Paul *et al.,* 2020). Milk analogs are colloidal suspension or the emulsions of plant ingredients that develop by applying the plant tissue disruption method through soaking, mechanical disruption, enzymatic hydrolysis, separation, formulation, homogenization and thermal treatments or the homogenization method as shown in Fig. 3 (McClements and Grossmann, 2021). In some cases, sweeteners, flavors and stabilizers are used as additives during commercial production (Yadav, 2017). Milk analogs can be developed in a powdered form by applying spray drying techniques (Yadav, 2017).

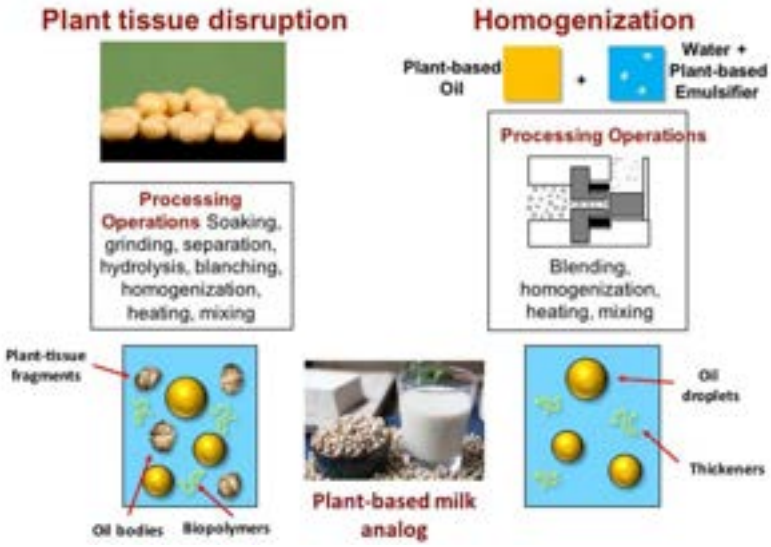


Figure 3. The process of plant-based milk production (McClements and Grossmann, 2021).

Locally Available Raw Materials for the Production of Meat, Fish and Milk Analogs

Plant-based meat, fish and milk analogs can be prepared using several different plant ingredients. However, the selection of major ingredients for the analog formation should be carefully conducted to assure the nutritional, sensory and functional properties of the final product. Moreover, if the production of plant-based products is going to assure the future food safety of Sri Lanka, the entire production process should be economically, commercially and environmentally feasible. Similarly, plant-based analog production should be sustainable. Factors such as availability and the price of the raw materials and the availability and the simplicity of the technology requirements are some of the key essentials to assure sustainable production. Sri Lanka as an agriculture-based country, several underutilized as well as low-cost raw materials are available throughout the country and these ingredients can be used to develop plant-based analog products. Within this section, it is aimed to discuss the potential to use locally available underutilized plant materials in the formulation of analogs.

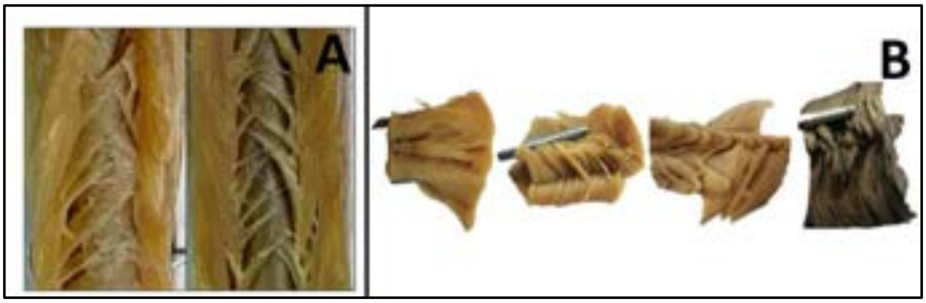


Figure 4. Product structure of meat analogs prepared from A) soybean isolate and B) yellow pea isolate (Wittek, 2021; Ferawati, 2021).

Meat Analogs

Soybean can be considered the major raw material in meat analogs as most of the meat analog products are formulated using soy protein isolates. However, Lee *et al.* (2022) have developed meat analogs by partially replacing soy protein isolates with rice protein isolates in a combination with some other minor ingredients such as corn starch and wheat gluten. Meat analogs prepared with 25 – 100% (w/w) of soy protein isolate with rice protein isolate showed higher nutritional values as the addition of rice protein isolate supplemented the methionine to the product where it is lacking in the soy protein isolate. Therefore, this study suggested the potential to use rice protein isolates in the formulation of meat analogs. Xiao *et al.* (2022) incorporated rice bran into meat analog products and they observed better physicochemical properties and changes in the secondary structural properties of proteins in the meat analog in a beneficial way. Rice bran is a byproduct developed during the rice milling process and has no strong commercial values associated with it. However, the addition of rice bran to the meat analog will help to improve the nutritional properties of analogs as the rice bran is rich in dietary fibers and antioxidants (Dang and Vasanthan, 2019). It can also provide the bulk of the product from waste material as a cost-efficient option. Therefore, there is a great possibility to use rice ingredients such as rice protein isolates and byproducts of rice milling (rice bran) in the development of meat analogs. Moreover, it could be beneficial if rice manufacturing related by-products such as broken rice is incorporated with meat analogs. As many rice varieties including traditional verities are currently available in Sri Lanka, further research can be carried out to understand the effectiveness of using these local resources in meat analog production.

Since ancient times, Jack fruit tree is considered as one of the essential plants in Sri Lanka as it helps to save many people from starvation. Even though the rice is the staple food in Sri Lanka, people used to consume boiled jackfruit bulbs as the main meal. As a tropical country, jackfruit can be grown in most areas of Sri Lanka. These potentials help strengthening the food security in Sri Lanka. Jackfruit is an excellent source of essential micro and macronutrients including carbohydrates, proteins, fiber, minerals and vitamins. Immature jackfruit curry is one of the meat-like vegetarian dishes in Sri Lanka. The immature jackfruit is commonly used to replace the meat ingredients in many dishes. According to the literature findings, immature jackfruit was incorporated in vegan sausage and obtained products with great sensory properties and consumer acceptance (Keerthana Priya *et al.,* 2022). Ghangale *et al.* (2022) also developed plant-based meat analogues using jackfruit which were having a desirable appearance, taste, chewiness, flavor and a good overall acceptability. Therefore, to assure the food security of the country, immature or matured jackfruits can be suggested to use as an ingredient in nonmeat protein alternatives. The incorporation of jackfruits in meat analogs provide convenient form of jackfruit product to consumers and provide more entrepreneurial opportunities in rural areas. However, further research is required to extend and optimize the applications in meat analog production.

There is a greater potential to use legumes in meat analog formulations. Even though legumes can be cultivated in many areas of the country, commercial applications are very low. Legumes are defined as “poor man's meat” as legumes can fulfill a significant part of human nutrition by providing proteins, calories, minerals and vitamins (Iqbal *et al.,* 2006). Legumes have 17 - 40% protein, which is equivalent to cereals (7 - 13% protein) and meat (18 - 25% protein) (Gunathilake *et al.,* 2016). Therefore, legumes can be added to meat substitutes as a low-cost source of protein, especially for the low-income population and it can help to prevent protein deficiency. However, the price of the legume varieties is drastically changed with the prevailing economic crisis in Sri Lanka. Therefore, it is important to consider the price of the legume varieties in the formulation of meat analogs in order to prevent the higher fluctuation of the price of the final products. Among the different legumes available in Sri Lanka, mung bean, cowpea and soybean can be considered as most popular in Sri Lanka.

Mung bean contains approximately 20-31% protein and can be considered as protein-rich food. Storage proteins mostly consist of albumins, globulins and prolamins-like proteins and the most abundant essential amino acids are leucine, lysine, phenylalanine/tyrosine, valine, isoleucine and histidine (Yi-shen *et al.,* 2018). Even though the production of mung beans has decreased with the fertilizer issue in Sri Lanka, the commercial value of mung bean is still high. “*Mung mas*” is one of the popular dishes in Sri Lanka and is generally used as a vegan dish as a replacement to meat. This dish is not only rich in nutritional value but also has fairly similar textural and sensorial properties to meat. Considering the proteins’ quantity and quality, and the favorable textural and sensory properties, mung bean can be introduced as one of the most suitable plant ingredients that can be used in meat analog formulation. However, fluctuation of the market price of mung bean has limited the sole use of mung bean in the formulation of meat analogs. Therefore, use of mung bean powder with the combination of other legume varieties would be a viable option during this critical period. For instance, Samard and Ryu (2019) have developed meat analogs using isolated soy protein, mung bean protein, peanut protein, pea protein and wheat gluten using intermediate moisture extrusion and obtained good quality products. Meat analogs produced with mung bean flour showed a successful outcome which was having enhanced protein content, better protein quality, higher dietary fiber and mineral contents (Sharma *et al.,* 2017). The combination of mung bean, cowpea and horse gram also provided the meat analogs with better qualities (John and Bosco, 2022). Horse gram still remains as an underutilized legume variety in Sri Lanka even though it has better nutritional properties. Having high protein contents (17.9 - 25.3%) and essential amino acids, minerals and vitamins can provide better nutritional value to the meat analog products at a low cost (Herath *et al.,* 2020).

Meat analogs have also been developed using cowpea as the main raw material. Cowpea curd protein was mixed with cocoyam-modified starch (Rosida *et al.,* 2021). Combination of 30% of cowpea curd protein with 30% of cocoyam starch provided meat analogs with better nutritional and physical properties. Besides, Lindriati and Triana (2022) have developed meat analogs with concentrated soy protein and cocoyam powder using a household pasta machine. Similarly, there is potential to use other yam varieties like *Dioscorea* spp. (Kiri ala, Raja ala, Java ala, Hingurala etc.) in the development of meat alternatives. Moreover, cassava, sweet potato, taro, *Lasia spinosa* (Kohila), and *Nelumbo nucifera* (Nelum ala) roots can also be potential raw materials for meat analogs. As most of the mentioned yam varieties are still underutilized food commodities, the production of protein-rich products by incorporating yam flour or starch will help to fulfill the protein requirement in the country at a very low cost. Furthermore, the commercial level production of yams will enhance the financial stability of farmers as well.

Mushroom is one of the common protein sources used in Sri Lanka. Many households grow and sell edible mushroom varieties as a small-scale household businesses. However, the shelf life of mushrooms is limited to a few days or other treatments like drying can extend the shelf life for several months. Mushrooms can be incorporated into meat analogs as a nonmeat protein alternative. Incorporation of mushrooms in the production of meat analogs showed improved textural and nutritional values and improved flavor properties due to the umami flavor of mushrooms (Cho and Ryu, 2020; Mohamad *et al.,* 2020; Kim *et al.,* 2021). Furthermore, meat analogs developed using 15% of mushroom with soy protein isolate and 35% water closely mimicked the physicochemical, textural, visual and inner microstructural properties of beef (Yuan *et al.,* 2021). Therefore, mushroom can be considered as a potential source of protein to use in meat analog formulation.

Fish Analogs

Due to religious, ethical and financial concerns, Sri Lankans are generally fulfilling their protein requirements through fish and other seafood products. Fish is a rich source of protein having a 15–20% of protein percentage and a good and healthy source of lipids, minerals and vitamins (Venugopal and Shahidi, 1996). Fish substitutes or fish analogs are already entered the food market with the aim of providing alternative fish products for vegetarian and vegan consumers. However, during the production of fish analogs, the main focus is to mimic sensory properties such as appearance, taste and smell rather than the structure or the taste (Kazir and Livney, 2021). It can be seen that fish or seafood analogs are already present in the market or still under the development level, most of the plant ingredients that have been used to develop these products are available in Sri Lanka. Therefore, adopting fish analogs to the Sri Lankan food industry would be a promising strategy to assure the future food safety of the country. Several fish alternatives for tuna chunks, fish burgers, fish cakes and crab cakes using legume blends containing pea, chickpea, lentils, soy, fava beans and navy beans have been formulated. Furthermore, fish filets and crab cakes have been developed using soy, wheat and potato. The combination of soy, potato, konjac and wheat is used to develop fish fingers, tuna pate, fish cakes and smoked salmon alternatives. Seaweed which is one of the emerging food ingredient has been incorporated into many food products (Kazir and Livney, 2021). Therefore, all these fish alternatives and the ingredients used to develop these products are evident in the possibility of introducing more fish analog products to the Sri Lankan market. As a range of underutilized legumes, roots and tuber crops and other vegetables are available in Sri Lanka, more research can be conducted to identify the possible ingredients and to formulate the fish analogs with better nutritional, organoleptic qualities at low-cost.

Milk Analogs

Cow milk is considered as one of the complete foods as it provides major nutrients including proteins, fat and carbohydrates. However, with the present economic crisis and the limitations set for export goods, the availability and the price of cow milk has severely impacted. Consequently, most people can't afford to buy milk as they did before. Therefore, it is high time to strengthen the production and consumption of alternatives for cow milk.

Soybean milk is one of the non-animal milk alternatives used globally and in Sri Lanka. The protein content present in soy milk is comparable to cow milk (Krans, 2017). However, considering the assurance of future food security in Sri Lanka, soymilk production and consumption can be widened. Other possible milk analogs that can be strengthened in Sri Lanka are kidney bean milk, coconut milk, cocoa milk and rice milk. The kidney bean is a rich source of proteins (20 -30%), vitamins and minerals (Paul *et al.,* 2020). The kidney bean is good for diabetic patients as the glycemic index is low. Even though the kidney bean is a nutritionally rich healthy legume variety, it is still considered as an underutilized crop. The value-added kidney bean food products are also not prevalent in the Sri Lankan food market.

Coconut milk can be considered as one of the essential ingredients used in the preparation of vegetable curries in Sri Lanka. The household use of coconut is very high compared to the coconut-incorporated food products available in the market. Other than the curries, coconut milk is used as an ingredient in confectionaries, bakery products and other desserts. However, the fat content of coconut milk is higher than the protein percentage (Paul *et al.,* 2020). Therefore, complementing other non-animal milk ingredients would be the best choice in the development of coconut milk as a cow milk analog. Even though rice is consumed as a staple food in Sri Lanka, rice milk can also be used as a milk analog. Rice is rich in carbohydrates (~90%) and less in protein (~10%) as well as threonine and lysine (Jiang *et al.,* 2016). Therefore, to mimic the nutritional properties of cow milk, rice milk can also be fortified with other suitable ingredients. Even though it is not widely popular among Sri Lankan consumers, almond milk, peanut milk and coca milk are some of the other milk analogs available in the global market. Overall, more research is required to formulate milk analogs with plant ingredients. Special attention should be placed to mimic the real nutritional properties of cow milk by fortifying it with other suitable ingredients at low cost.

Conclusions and Future Prospects

The development of plant-based meat, fish and milk analogs is one of the feasible approaches to assure the food security of Sri Lanka. Plant-based analogs can successfully satisfy nutritional requirements and dietary demands at a low cost. Sri Lanka as an agriculture-based country, various plant commodities can be suggested to use in the formulation of plant-based analogs. Nevertheless, several factors such as availability, affordability, nutritional profile and the sensory properties of the raw materials as well as the availability of technologies to develop these plant-based analog products should be considered during the formulation of the products and the optimization of the processing conditions. However, more research, surveys and background studies are required to identify consumer preferences and the adaptability to the Sri Lankan food industry. Scaling-up the production would be another challenging task. Yet, there are various challenges to be faced while mimicking the nutritional and structural properties of real meat, fish and milk with analogs. Therefore, it is important to properly understand the association between structural properties and nutritional profiles of the potential raw materials with the required analogs' characteristics through properly designed research activities.

Conflict of Interest

Authors have declared that no competing interests exist.

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Trends in Development of Non-dairy Probiotic Beverages from Tender Coconut Water: An Avenue for Expanding Export Market of Sri Lanka

CHAPTER 6

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Abstract The clear liquid obtained from coconuts *(Cocos nucifera L.)* is called coconut water. As a refreshing beverage, coconut water is popular with customers for its nutritional value and health benefits. The function of coconut water in health and medical applications is highly supported by science, which increases the demand and consumption of coconut water across the globe. Sri Lanka's coconut business has experienced significant growth in coconut products. It has high demand in the American, European, Middle Eastern, and East Asian markets. Although Sri Lanka has sustainable coconut cultivation, there is still a lack of innovation in producing new coconut-based products for the market. Coconut water is a good source of probiotics. The demand for non-dairy probiotic foods is a consequence of the shortage of dairy-based probiotics on the market and the health issues such as lactose intolerance. Tender coconut water naturally ferments with a variety of autochthonous microbes that possess both probiotic properties and biopreservative properties. Fermented coconut water beverages can be produced naturally using the indigenous microbial consortium at a low cost and as an organic, value-added product with a longer shelf life according to the bio-preservation concept. Therefore, the coconut industry in Sri Lanka could create an avenue for potential foreign markets and fill the possible market gaps in non-dairy probiotics and coconut-based products.

Keywords: Beverage, Biopreservation, Coconut water, Non-dairy, Probiotics

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Introduction

The COVID-19 pandemic and economic crisis have forced many enterprises to close their doors. Meanwhile, the demand for coconut products in Sri Lanka surged in 2020 (Coconut industry in Sri Lanka - EDB Sri Lanka, 2022). Unfortunately, this opportunity was not fully utilized by Sri Lanka. While the demand for coconuts appears to expand consistently, the global supply is declining periodically (Mufeeth *et al*., 2021). Despite the existing tender coconut water products on the export market, none has attained the expected standards.

Since its inception, the agriculture sector has been a significant economic driver in Sri Lanka by increasing employment and ensuring food security while making a significant economic contribution to the country. In 2018, agriculture accounted for 22% of the country's exports (Prasannath, 2020). Tea, rubber, coconut, and other crops such as cardamom, nutmeg, cinnamon, and pepper comprise most of the export crops. The coconut sector is the third-most significant industry in the country, after rubber and tea (Prasannath, 2020).

To meet the growing demand for healthy living, the market for coconut water was estimated at USD 4.27 billion in 2019 and is expected to increase by 16.1% in 2027 (Coconut Water Market Size & Share Report, 2022). For centuries, Sri Lankans have been consuming coconut water as a refreshing drink. Until now, tender coconut water has not been utilized properly. Though we have good cultivation of tender coconuts, innovation in product diversity on coconut is still lacking. The increasing demand for coconut water-based products has given rise to an industry that has optimized the use of underutilized resources.

Consumers demand nutritious foods that contribute to their health and satisfy their sense of taste. This demand can be met by functional food, which explain the interest in the development of fermented product as these foods and their components have numerous health benefits (Kumar *et al.,* 2015). In recent years, there has been a surge in interest in adopting healthy diets that aid in disease prevention and as a result, the study and development of new functional foods like probiotic foods have grown in importance (Prado *et al.,* 2008; Kumar *et al.,* 2015). Probiotic foods are typically sold as fermented milk and yoghurts.

Dairy probiotics are being sold commercially in a variety of forms all over the world. In recent years, a new market for vegetarian probiotics has emerged due to the growing popularity of vegetarianism among consumers, especially in developed countries (Kandylis *et al*., 2016). Furthermore, the development of dairy probiotics is hindered by health issues related to lactose intolerance, cholesterol levels of dairy products, and allergies to milk proteins (Prado *et al.,* 2008; Vijaya Kumar *et al.,* 2015). As a result, the market for non-dairy probiotic food items has gained importance in recent years. Cereal-, fruit and vegetable-, and soy-based fermented food products are becoming more popular among non-dairy alternatives for probiotic food products. Studies have shown that non-dairy materials like coconut water can also be used to make probiotic products (Prado *et al.,* 2008; Kumar *et al.,* 2015; Panghal *et al.,* 2018). Hence, if we can provide a probiotic solution through tender coconut water-based products, it will be a promising opportunity to meet the global demand by expanding the product range. Simultaneously, it will take a good place as a functional beverage in the international market.

The technical definition of probiotics is “live microorganisms that, when consumed in particular quantities, have health benefits in addition to those of basic nutrition” (Prado *et al*., 2008). Probiotics have been linked to a variety of health benefits, including improved gut health, improved immunological response, lower blood cholesterol, and cancer prevention (Kechagia *et al*., 2013). Products containing both probiotics and prebiotics are available in the market. Prebiotics are defined as "non-digestible food ingredients that selectively boost the growth and/or activity of one or a particular number of microorganisms in the colon, creating good impacts on health, when consumed in adequate proportions" (Schrezenmeir and de Vrese, 2001). Contrarily, synbiotics are food products that combine probiotics and prebiotics (Schrezenmeir and de Vrese, 2001). For instance, a probiotic product must contain the minimum number of bacterial cells as 10^8 – 10^{10} colony-forming units (CFU) per day to show effective health benefits (Martinez *et al*., 2015; Zawistowska-Rojek, 2016). However, there may be slight variations in this amount. As described in different studies, there should be a minimum count of 10^6 CFU/ml of viable cells at the consumption point to be effective as a probiotic product (Gallina *et al*., 2019; Terpou *et al.,* 2019). Earlier, probiotics have been used to ferment food. However, recently probiotics were added as supplements (Ranadheera *et al*., 2010). Typically, when producing a probiotic food product, the selection of probiotic strains, carrier food matrices, and prebiotics-like factors should be thoroughly concerned to maximize the functional efficiency of probiotics (Ranadheera *et al.,* 2017).

Coconut Industry in Sri Lanka

Sri Lanka's agriculture industry has traditionally been a significant economic strength for the country as it promotes food security, employment, and the reduction of poverty in rural communities (Prasannath, 2020). The coconut tree is one of the most significant agricultural crops in Sri Lanka. Due to its wide range of uses, the tropical plant known as coconut (*Cocos nucifera*), which is grown in equatorial and sub-equatorial regions is also referred to as a "tree of life" (DebMandal and Mandal, 2011; Prades *et al*., 2012; Costa *et al*., 2015). Coconuts are cultivated in over 90 countries as an oil and food source with the greatest number of coconuts being cultivated in Asia, the Pacific Islands, and South America (HOE, 2018). The main coconut-producing countries include Brazil, Sri Lanka, Papua New Guinea, India, Indonesia, the Philippines, Vietnam, Mexico, Thailand, and Malaysia (HOE, 2018; Aidoo *et al*., 2022).

After paddy cultivation, coconut cultivation plays an important role in sustaining livelihoods in Sri Lanka because it can withstand harsh climatic conditions, so the economic loss is less (Ranathunga *et al.*, 2018). Sri Lanka is the fourth-largest exporter of coconuts that also provides coconut-based products like desiccated coconut, brown fiber, virgin coconut oil, and coconut water to the global market (Coconut Industry in Sri Lanka - EDB Sri Lanka, 2022). According to the estimation of the Sri Lanka Export Development Board, compared to previous years, export revenue for coconuts and items derived from coconuts in 2020 was 664.58 USD million and increased by 25% to 836.1 USD million in 2021 (Table 1).

Table 1. Annual export growth rates of coconut-based export products 2017 – 2021 (in US$ Millions)

Product	Export revenue in 2017 (USD)	Export revenue in 2018 (USD)	% Growth compared to 2017	Export revenue in 2019 (USD)	% Growth compared to 2018	Export revenue in 2020 (USD)	% Growth compared to 2019	Export revenue in 2021 (USD)	% Growth compared to 2020
Coconut Products	588.24	589.04	0.14	613.85	4.21	664.58	8.26	836.1	25.81
Coconut Kernal Products	312.94	296.45	-5.27	304.71	2.79	342.88	12.53	434.57	26.74
Coconut Fibre Products	186.14	188.41	1.22	196.59	4.34	205.93	4.75	248.35	20.59
Coconut Shell Products	89.16	104.18	16.85	112.55	8.03	115.77	2.86	153.18	32.31

(Source: Export Performance Indicators 2011-2020, Economic and social statistics of Sri Lanka – Central Bank Report 2020, and Coconut Industry in Sri Lanka - EDB Sri Lanka, 2022).

Coconut is the second-largest crop grown on plantations with a total area of about 402,649 ha (or 25% of the gross cultivated area) (Liyanage *et al.*, 1984). Coconut cultivation in different districts of Sri Lanka is shown in Fig. 1. In Sri Lanka, coconut plantations yield between 2,500 and 3,000 million nuts annually accounting for 12% of all agricultural products on a total of 409,244 acres of cultivation land (Sivarajah, 2010). Products made from coconut have been exported from Sri Lanka since the 19^{th} century. Fibres, desiccated coconut, virgin coconut oil, fresh coconut, copra, coconut milk powder, coconut cream, and coconut water are the products that Sri Lanka exports (Prasannath, 2020). Brown fibre and desiccated coconut are two immensely popular Sri Lankan products in the global market. Due to its unique white appearance and flavor, Sri Lankan desiccated coconut ranks fourth in the world's export market (Export Performance Indicators, 2011-2020).

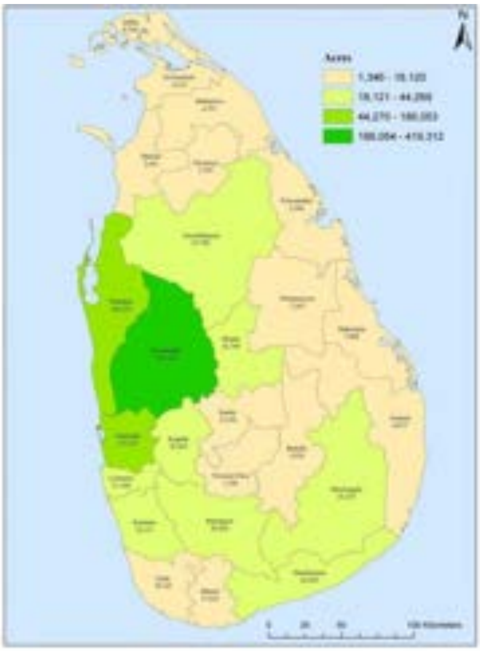

Figure 1. District-level distribution of coconut cultivation in Sri Lanka. (Source: Department of Census and Statistics, 2017).

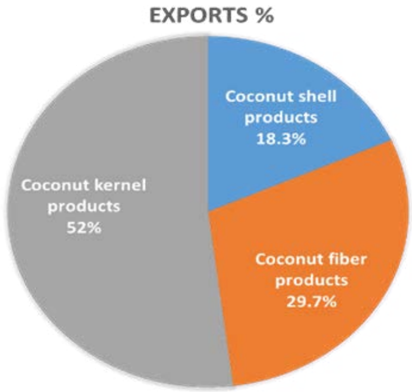

Figure 2. Composition of Exports Coconut Sector – 2021. (Source: Sri Lanka Export Development Board).

Due to the unique drum technology for extracting fibre that yields long, pure fibre that is better suited for the brush industry, Sri Lanka is in a leading position in brown fiber exports. Overall, the global market prefers Sri Lanka's coconut products because of their superior quality, favorable environment, eco-friendly farming and production methods, techniques for social compliance, in-depth industrial knowledge, and ongoing product innovation (Prasannath, 2020). The recent export range of Sri Lanka's coconut products is shown in Fig. 2.

The agriculture sector, specifically, the coconut industry in Sri Lanka has a crucial macroeconomic impact on the Gross Domestic Product (GDP) of the country. More than 2,175,000 holdings are used for coconut cultivation making the sector the most holdings used for food crops (Pathiraja *et al*., 2015). The industry supports the livelihoods of almost 700,000 people and employs 135,000 more people indirectly, according to the Coconut Research Institute of Sri Lanka (Coconut industry in Sri Lanka - EDB Sri Lanka, 2022). The United States, Germany, Netherlands, China, United Kingdom, Canada, Japan, Australia, India, and Mexico are the major markets for coconut products from Sri Lanka (Coconut Industry in Sri Lanka - EDB Sri Lanka, 2022). Among them, the United States is the top consumer of Sri Lankan coconut products. According to Fig. 3, the value of coconut products exported to the USA is USD million 152.65, while the value of exports to Germany, the second-highest market, is USD million 65.11.

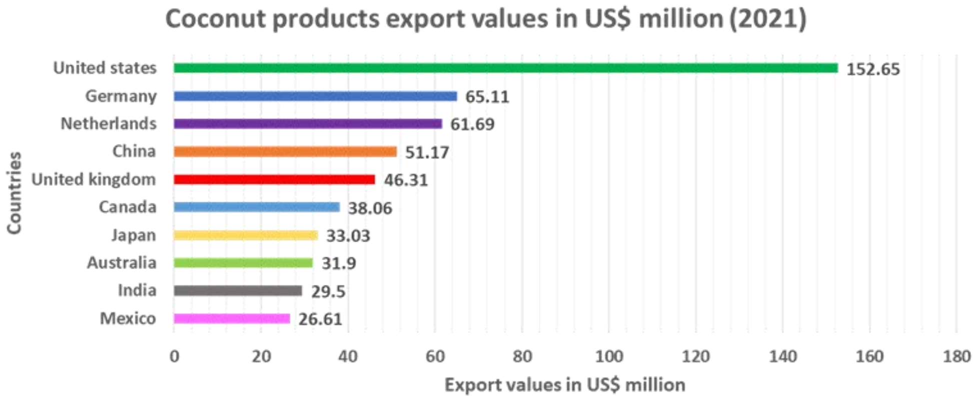

Figure 3. Major export market countries and export values for Sri Lankan coconut industry (Source: Sri Lanka Export Development Board).

The combined sweet and acidic flavor of coconut water has led to significant demand for coconut water-based products as a substitute for carbonated beverages in the global market. This is mainly because coconut water has significant health benefits over carbonated beverages (Mohan *et al*., 2020). Fig. 4 explicitly shows the demand for coconut water consumption in Europe countries. According to the data from Sri Lanka Export Development Board, Sri Lanka exports three major coconut water-based products to the global market; tender coconut water, natural coconut water vinegar, and king coconut water. Bottled coconut water is a popular product from Sri Lanka that meets the demand worldwide. Producers of tender coconut water from Sri Lanka also supply various value-added varieties such as flavored and fizzy coconut water to markets in the United States and Europe. Therefore, introducing a new tender coconut water-based beverage will expand the global export market and that could boost Sri Lanka’s revenue and profitability.

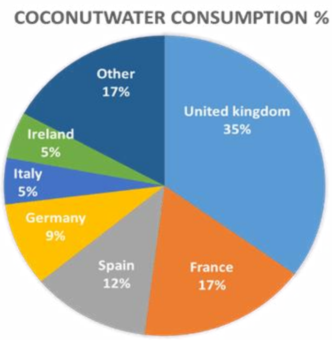

Figure 4. European consumption of coconut water quantity, by country, 2019 (Source:https://www.cbi.eu/market-information/processed-fruit-vegetables edible-nuts/coconut-water/market-potential)

Since coconut is a necessary component of Sri Lanka's daily diet, 63% of coconuts are consumed domestically, while the remaining is exported as value-added coconut products to generate revenue (Mufeeth *et al*., 2021). According to Sri Lanka's current coconut demand estimated by the Coconut Development Board, the country's coconut sector needs about 4 billion nuts annually, but only 2.8 to 3.0 billion are now being produced (Coconut Industry in Sri Lanka - EDB Sri Lanka, 2022). The cultivation of coconuts needs more attention in the aspect of the export market. For sustainability in the export market, strategic investment in research and development is required for new product development and innovations along with continuous process improvement. Both government and private sectors need to be involved in this.

Nutritional and Medicinal Value of Tender Coconut Water

The most important part of the fruit is the endosperm which contains edible parts such as white kernel and coconut water. The clear liquid portion of the coconut endosperm, coconut water is a common by-product. Studies revealed that 25% of the weight of the fruit accounts for coconut water (Sukendah and Ratna, 2018). Fresh coconut water has a pH range of 4.2 to 6.0 and is colorless, naturally flavored, sterile, and mildly acidic (Awua *et al*., 2011). About two months following the inflorescence's natural opening, coconut water starts to form. Depending on the stage of harvesting, coconut water can be divided into two categories: tender (young) coconut water and matured coconut water (Giri *et al*., 2018). Due to its improved taste, functional health benefits, natural hydration qualities, and nutritional advantages, coconut water is one of the rapidly growing beverage categories (Gangwar *et al*., 2018). Moreover, 95.5% of coconut water is composed of water, with 4% of carbohydrates, 0.5% of iron, 0.1% of fat, 0.02% of calcium, and 0.01% of phosphorus (Sukendah and Ratna, 2018). Coconut water has been found to contain tryptophan, lysine, tyrosine, histidine (essential amino acids), glucose, fructose, sucrose (sugars), vitamin B complex and C (vitamins), cellulose, fatty acids, and citric, malic, and tartaric (organic acids), mineral salts, and phytohormones (Awua *et al.*, 2011; Sukendah and Ratna, 2018). The general physicochemical properties of tender coconut water are shown in Table 2.

Coconut water has gained popularity in both perception and consumption among customers due to its distinct chemical composition of sugars, amino acids, minerals, vitamins, enzymes, and phytohormones which are vital elements for the human body (Yong *et al.*, 2009; Mohan *et al*., 2020). Natural sugars present in coconut water such as sucrose, fructose, and glucose provide a distinctly sweet flavor. The high mineral content (Table 2) of coconut water plays an important role as a refreshing beverage (Chaubey *et al*., 2017). It has similar properties to those of carbohydrate-electrolyte sports beverages. It also contains minerals like sodium, magnesium, potassium, phosphorus, calcium, and chloride that can replenish the electrolytes lost during perspiration, therefore this could be a promising option for temporary intravenous rehydration (Saat *et al*., 2002; Chaubey *et al*., 2017; Zulaikhah, 2019).

Due to its low calorie, sodium, and potassium content, tender coconut water is a good alternative to sports drinks (Zulaikhah, 2019). The electrolytes in tender coconut water produce an osmotic pressure comparable to that of blood (Mohan *et al*., 2020). Because of its rich nutrition profile, the demand for tender coconut water-based products is expected to be high. However, coconut water is susceptible to deterioration when it is exposed to the environment. The biochemical composition and physical appearance change rapidly due to microbial and enzymatic activities (Prades *et al*., 2012). Therefore, coconut water-based products need to be processed properly.

Tender coconut water has various medicinal properties including antioxidant, antithrombotic, antiatherosclerotic, cardioprotective, antibacterial, antiviral, antifungal, antiprotozoal, hypolipidemic, anticholecystitic, anticancer, immunostimulatory, hepatoprotective, antidiabetic, and hormone inducing properties (Prado *et al.,* 2015; Zulaikhah, 2019). Coconut water can improve digestion and help to overcome constipation (Zulaikhah, 2019; Mohan *et al*., 2020) because it includes soluble fibre that facilitates bowel movement. The antioxidant content of tender coconut water is higher than that of matured coconut water (Tan *et al*., 2014). Therefore, it can alter free radicals that may cause oxidative stress-related illnesses such as cardiovascular diseases, cancer, and all-cause deaths (Prado *et al.,* 2015; Zulaikhah, 2019). Additionally, internal and external inflammation can be treated by its dietary components (Zulaikhah, 2019). Furthermore, it can be used to reduce inflammation in skin rashes (Zulaikhah, 2019). Tender coconut water is extremely helpful to someone with kidney stones because of its mineral content, particularly magnesium and potassium (Tan *et al*., 2014), and it also helps prevent urinary tract infections (Zulaikhah, 2019).

Table 2. Physicochemical properties of coconut water obtained from 5-6 month-old tender coconuts (Source: Tan *et al*., 2014)

Physicochemical Parameters	**Mean values**
Total soluble solids (°Brix)	5.60 ± 0.14
Titratable acidity (% of malic acid)	0.09 ± 0.00
pH	4.78 ± 0.13
Fructose (mg/mL)	39.04 ± 0.82
Glucose (mg/mL)	35.43 ± 0.51
Sucrose (mg/mL)	0.85 ± 0.01
Potassium (mg/100 mL)	220.94 ± 0.32
Sodium (mg/100 mL)	7.61 ± 0.04
Magnesium (mg/100 mL)	22.03 ± 0.07
Calcium (mg/ 100mL)	8.75 ± 0.04
Iron (mg/L)	0.29 ± 0.08
Protein (mg/mL)	0.04 ± 0.01
Total phenolic content (mg GAE/L)	54.00 ± 3.13

Health Benefits of Probiotics

Probiotic-containing foods are known to have several health benefits some of which have been shown by science and others still require more studies. They have a positive effect on mineral metabolism, bone stabilization, Crohn's syndrome, and bowel disease symptoms (irritable bowel syndrome (IBS) and inflammatory bowel disease (IBD)), as well as the symptoms of food allergies and low-density lipoprotein (LDL) cholesterol levels (Schrezenmeir and de Vrese, 2001; Prado *et al*., 2008; Granato *et al*., 2010). They also have anticarcinogenic properties, antimicrobial, antimutagenic activities, and antihypertensive properties (Granato *et al*., 2010). Several dangerous bacteria for human health including *Escherichia coli*, *Salmonella enteritidis*, *Serratia marcescens,* and *Shigella sonnei* are suppressed by specific *Lactobacillus* strains (Schrezenmeir and de Vrese, 2001; Granato *et al*., 2010). Probiotic microorganisms have been shown to aid the host's natural defences as well (Granato *et al*., 2010). They have also been demonstrated to improve humoral immune responses (Granato *et al*., 2010; Kechagia *et al.,* 2013). Stabilization of the gut microbiota is the characteristic of non-immunologic gut defence which is mediated by probiotics (Schrezenmeir and de Vrese, 2001). Additionally, probiotic bacteria help the host develop non-specific resistance to microbial infections and regulate immune reactions to potentially dangerous antigens, possibly suppressing hypersensitive reactions (Granato *et al*., 2010; Kechagia *et al.,* 2013). Fig. 5 depicts the summary of the health benefits of probiotics.

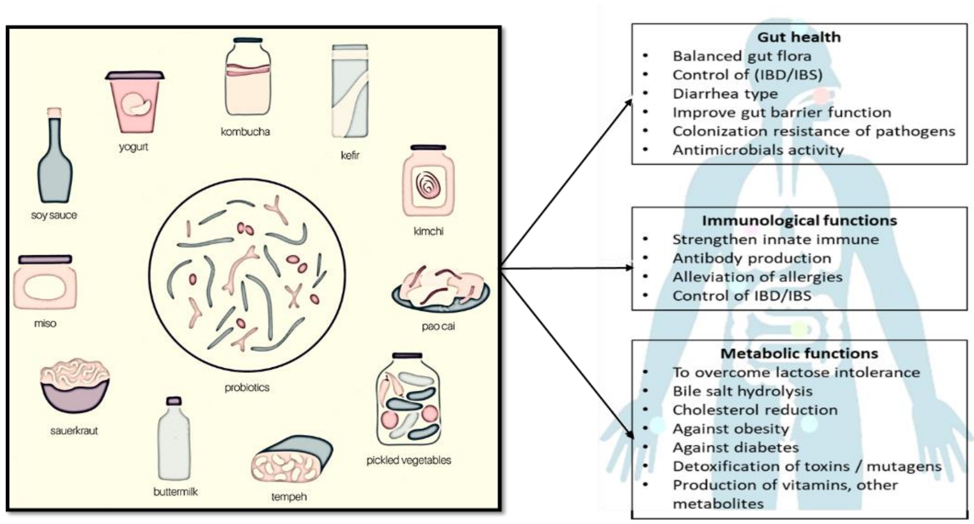

Figure 5. Beneficial effects of probiotics on human health

Trends in Non-dairy Probiotic Beverages

Across the world, people consume a variety of traditional products created through lactic acid fermentation from non-dairy sources. Earlier, milk and other dairy products offered the probiotics' therapeutic features; but, lactose intolerance, high cholesterol, allergic reactions to milk proteins, and financial considerations are restricting the development of dairy probiotics (Prado *et al*., 2008; Kandylis *et al*., 2016; Panghal *et al*., 2018). Lactose intolerance affects 75% population of the world (Panghal *et al*., 2018). Lack of production of the lactase enzyme by the intestinal brush border which hydrolyzes lactose into absorbable carbohydrates (such as glucose and galactose) to produce energy is the basic cause of lactose intolerance (Silanikove *et al*., 2015). Because of the problems with dairy-based probiotics, developing nations are forced to look for dairy substitutes such as fruits, vegetables, cereal, and legumes that are rich in nutrients and promote health. Products made from fruits, vegetables, cereals, and legumes are possible carriers of probiotic microorganisms that have beneficial nutraceutical properties (Panghal *et al*., 2018).

There are numerous conventional non-dairy probiotic beverages available worldwide and they are not a novel concept (Table 3, Kandylis *et al*., 2016). The estimated value of the global market for functional foods and beverages in 2015 was USD billion 129.39 and it is expanding at a compound annual growth rate of roughly 8.6% (Panghal *et al*., 2018). Probiotic food revenues are expected to increase because of the ageing population, growing healthcare costs, consumers' healthcare concerns, and changing lifestyles (Panghal *et al*., 2018). Additionally, non-dairy probiotic beverages provide a less expensive alternative to dairy products for the delivery of probiotics in developing nations (Kandylis *et al*., 2016). Customer desire to purchase functional foods has increased because of claims made by the functional food and beverage industry about the health benefits of their products (Siró *et al*., 2008; Panghal *et al*., 2018). Consequently, a substantial market for non-dairy probiotic beverages is created.

Table 3. Some available non-dairy probiotic beverages in the global market

Type of nondairy probiotic beverage	Probiotic strain	Reference
Fruit-based probiotic products		
Grapes probiotic (Hardaliye)	*L. casei* subsp, *L. paracasei* subsp. *Paracasei Pseudoplantarum, L. sanfranciscensis, L. brevis, L. pontis, L. acetotolerans, L. vaccinostercus*	Prado *et al*., 2008; Panghal *et al*., 2018; Kumar *et al*., 2015
Blackcurrant probiotic juice	*L. plantarum*	Panghal *et al*., 2018, Kumar *et al*., 2015.
Peach probiotic juice	*L. delbrueckii*	Panghal *et al*., 2018
Olive probiotic drink	*L. plantarum, L. pentosus, L. brevis Pediococcus cerevisiae, L. mesenteroides*	Panghal *et al*., 2018

Durian fruit probiotic (Tempoyak)	*L. mali, L. brevis, L. mesenteroides*, *L. fermentum*	Panghal *et al*., 2018
Cashew apple probiotic juice	*L. casei*	Panghal *et al*., 2018; Kumar *et al*., 2015
Mango probiotic juice	*L. delbrueckii, L. acidophilus, L. casei, L. plantarum*	Kumar *et al*., 2015; Panghal *et al*., 2018
Sweet lime probiotic	*L. acidophilus*	Panghal *et al*., 2018.
Orange probiotic juice	*L. plantarum*	Panghal *et al*., 2018; Kumar *et al*., 2015
Pomegranate juice	*L. bulgaricus*, *L. plantarum*	Panghal *et al*., 2018
Coconut water beverage	*L. plantarum, L. casei*	Kumar *et al*., 2015; Kandylis *et al*., 2016; Panghal *et al*., 2018
Vegetable-based probiotic products		
Carrot-based probiotic (shalgam juice)	L. plantarum, *Leuconostoc*, *Pediococcus*	Prado *et al*., 2008; Kumar *et al*., 2015; Panghal *et al*., 2018
Beetroot juice	*L. casei, L. acidophilus, L. plantarum*	Prado *et al*., 2008; Kumar *et al*., 2015; Kandylis *et al*., 2016; Panghal *et al*., 2018
Moringa leave juice	*L. plantarum, Enterococcus hirae*	Kandylis *et al*., 2016; Panghal *et al*., 2018
Tea leaves probiotic drink (Kombucha)	*S. cerevisiae, S. ludwigii, S. bisporus, Zygo saccharomyces, Torulopsis* sp.	Panghal *et al*., 2018
Bamboo shoots juice	*Lactococcus lactis, L. brevis, Leuconostoc fallax*	Panghal *et al*., 2018
Cucumber probiotic drink (Khalpi)	*L. plantarum* and *Pediococcus pentosaceus*	Panghal *et al*., 2018
Radish leaves and Turnip based probiotic drink (Nozawana-Zuke)	*L. brevis, L. plantarum, L. fermentum, L. fallax, Bacillus coagulans, P. pentosaceus*	Panghal *et al*., 2018
Cereal and legume-based probiotic products		
Boza - Barley, oats, millet, maize, wheat or rice	*L. plantarum, L. coprophilous, L. acidophilus, L. brevis, L. fermentum, S. uvarum Leuconostoc mesenteroides, Leuconostoc reffinolactis*	Prado *et al*., 2008; Kumar *et al*., 2015; Kandylis *et al*., 2016; Panghal *et al*., 2018
Togwa - Maize flour and finger millet malt	*Streptococcus, Lactobacillus, L. planetarium*	Prado *et al*., 2008; Kandylis *et al*., 2016; Panghal *et al*., 2018
Bushera - Sorghum	*Streptococcus, Lactococcus, L. brevis, Enterococcus, Lactobacillus*	Prado *et al*., 2008; Kandylis *et al*., 2016; Panghal *et al*., 2018
Chhang - Rice	*Lactobacillus fermentum, L. salivarius and L. plantarum*	Kandylis *et al*., 2016

Mahewu - Maize	*Lactococcus lactis*	Prado *et al*., 2008; Kumar *et al*., 2015; Kandylis *et al*., 2016; Panghal *et al*., 2018
Pozol - Maize	*Lactococcus lactis*	Prado *et al*., 2008; Kandylis *et al*., 2016; Panghal *et al*., 2018
Kefir Soy	*L. kefir, L. mesenteroides L. brevis, L. helveticus,* yeasts like *Kluyveromyces marxianus, Kluyveromyces lactis*	Kumar *et al*., 2015; Kandylis *et al*., 2016; Panghal *et al*., 2018
Soy milk product	*Lactobacillus fermentum, Lactobacillus plantarum, Lactobacillus casei, Lactobacillus acidophilus, Bifidobacterium animalis subsp. lactis*	Kumar *et al*., 2015; Kandylis *et al*., 2016

Fermented Tender Coconut Water as a Non-dairy Probiotic Beverage

Tender coconut water is still an underutilized resource in Sri Lanka. In recent years, with the development of science and technology, coconut water has become increasingly popular as a microbiological culture medium and a raw material for brewing vinegar, wine, and jellies (Muralidharan and Jayashree, 2011; Rethinam, and Krishnakumar, 2022). Therefore, there is an opportunity to develop a functional beverage using tender coconut water in the country. Tender coconut water is a suitable base to create a non-dairy probiotic product because the complex carbohydrates and phenolic compounds in coconut water may work synergistically with bacteria to maintain gut health (Dey, 2018). The high sugar content in the manufacturing of fermented beverages also contributes to the perception that coconut water is a significant source of carbohydrates (Chang and Wu, 2011; Mohamad *et al*., 2017). According to studies, coconut water could support the survival and expansion of bacteria (Awua *et al*., 2011). Additionally, in laboratories with low resources, coconut water could be utilized as a medium for bacterial growth (Awua *et al*., 2011). There are numerous non-alcoholic beverages made from coconut water that has been fermented with lactic acid bacteria, particularly with *Lactobacillus* sp. (Lee *et al*., 2013; Prado *et al.,* 2015; Kantachote *et al*., 2017).

In some recent studies, probiotic coconut water beverages have been developed by incorporating probiotic bacterial strains externally. *L. plantarum, L. acidophilus*, *L. casei*, *B. clausii*, *S. boulardiiwere,* and *Bacillus coagulans* strains were successfully used to produce fermented coconut water beverages (Lee *et al*., 2013; Kantachote *et al*., 2017; Pachori and Kulkarni, 2017; Gangwar *et al*., 2018; Giri *et al*., 2018; Goveas *et al*., 2021). Moreover, *L. plantarum* strain has been identified as a predominant bacterium in natural tender coconut water (Prado *et al.,* 2015). The *L. plantarum* strain was used to develop a fermented coconut water beverage that exhibited inhibitory activity against pathogenic microorganisms (Prado *et al*., 2015). It has been discovered that the best growth conditions for this strain are at 37 °C for

8 hours in the presence of the extract of yeast, sucrose, and soy protein hydrolysate. After 28 days of refrigeration, the developed beverage contained the desired cell count of *L. plantarum*, which would satisfy the daily recommended intake of probiotics (Prado *et al*., 2015). Probiotic *Lactobacillus casei* L4 has shown a good growth rate and pH reduction during the fermentation of coconut water (Giri *et al.*, 2018). Furthermore, high viability counts, and better organoleptic properties have been observed after 28 days of storage at 4 ^{0}C while proving the potential probiotic properties of tender coconut water. The study by Kantachote *et al*. (2017) investigated the potential probiotic properties of mature coconut water fermented with *Lactobacillus plantarum* DW12. The fermented beverage in this study could be probiotics because the *L. plantarum* DW12 strain has been reported to survive roughly $10^7 – 10^8$ CFU/ml at room temperature (25 ^{0}C ± 3) for a week and 4 ^{0}C for 4 weeks. In another study, the cultures of *L. casei* L26 and *L. acidophilus* L10 used to ferment coconut water (Lee *et al*., 2013). As a result, both cultures have shown viable cell counts of approximately around 10^7-10^8 CFU/ml after 26 days of storage at 4 ^{0}C while being good probiotic strains to the coconut water substrate (Lee *et al*., 2013).

Tender coconut water has a limited shelf life because its nutrient content favors the growth of pathogen microbes. However, natural fermenting lactic acid bacteria that are developed during the fermentation of coconut water can act as a bio-preservative (Kantachote *et al*., 2017). Therefore, naturally fermented tender coconut water is a great niche for autochthonous lactic acid microflora which comprises probiotic and bio-preservative capabilities. To maintain the quality of the final product, the metabolic products and the final pH must be controlled. For that careful strain selection and continuous monitoring during the manufacturing process are required (Bhadekar and Parhi, 2016).

Potential Markets for Probiotic Tender Coconut Water Beverage

Coconut-based products have tremendous export potential. The potential for creating novel and diverse products from coconut is enormous. It is a technologically successful business to manufacture products related to coconuts. There is a good opportunity for organic and sustainable coconut product manufacturers to meet global demand as consumers around the world become more conscious of the quality of the food they eat and move toward more plant-based alternatives.

In terms of Sri Lanka's economy, exports are a significant component of international trade. Sri Lanka's coconut export sector has consistently performed better export volume, export revenues, and the quantity of innovative, distinctive items available on the market. A good approach to address the present need for a non-dairy probiotic beverage is to develop coconut-based probiotic food products and tender coconut water is an excellent substrate in which probiotic microbes can be grown. Consumers' growing knowledge of the adverse health effects (chronic health issues including obesity, cardiovascular illnesses, and diabetes) of artificially carbonated beverages has increased the demand for processed coconut water with fresh qualities (Mohan *et al.*, 2020).

Though Sri Lanka has sustainable coconut cultivation, still no attempts were taken to produce non-alcoholic fermented probiotic beverages. An indigenous microbial consortium can be used to create probiotic tender coconut water beverages which can also exhibit the biopreservation ability. These bio-preservatives can extend the shelf life of the product without the use of any chemical preservatives, and it is a cost-effective process. Due to the great nutritional content and health advantages of tender coconut water, the product can have good market growth. Fig. 6 shows the proposed production flow chart for developing probiotic tender coconut water beverages. Tender coconut water-based non-dairy probiotic beverages will be a healthy and profitable food product for the country. It will take a good place as a functional beverage in the international market. Therefore, the country's export market will also expand to America and Europe.

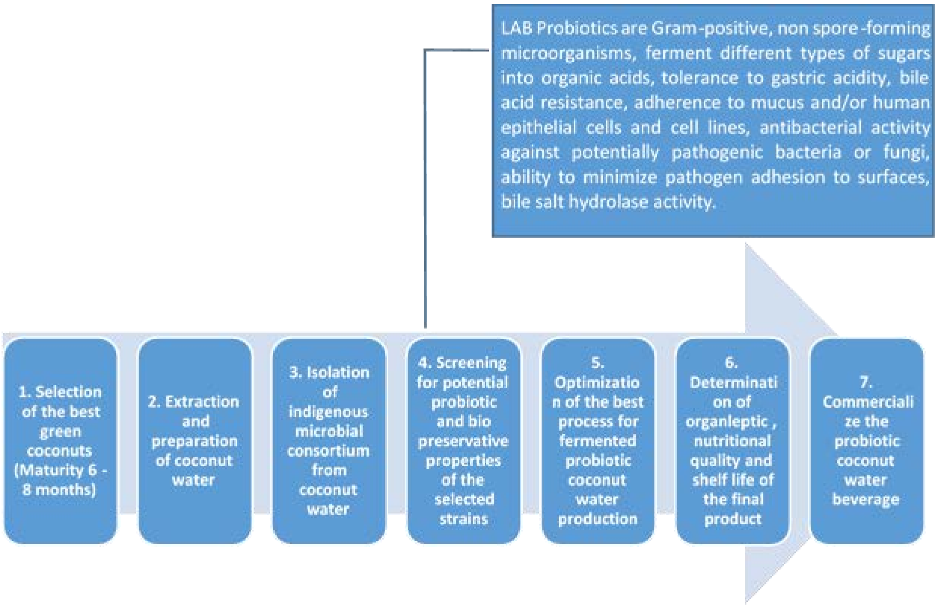

Figure 6. The production process of probiotic coconut water beverage

Conclusions and Future Prospects

Due to ethical reasons and sustainability in food production, the demand for dairy-alternative products is rising worldwide. This could be a good opportunity for the Sri Lankan agriculture sector, especially the coconut industry to capture that export market. The coconut industry should give more attention to innovations in product development to fill the market gap. There is a demand for non-alcoholic and probiotic plant-based beverages in the global market. The potential probiotic benefits of tender coconut water are supported by scientific research evidence.

Additionally, numerous effective probiotic strains have been found to create coconut water-based probiotic beverages. Therefore, there is a need for scientific research to determine how those strains work together to create more effective and unique probiotic products from coconut water which can be a good substitute for dairy probiotics. At the global level, scientists are working on producing probiotic beverages using coconut water and coconut milk by adding external Lactic acid bacteria strains or using indigenous microbial consortium (*L. plantarum, L. acidophilus, L. casei, B. clausii, S. boulardiiwere,* and *Bacillus coagulans*). Tender coconut water is a nutrition-rich healthy beverage. If a probiotic solution can be created through tender coconut water-based products, it will create a new avenue for Sri Lanka in the global market. To achieve the desired health benefits of a probiotic food product, probiotic stability should be maintained in the final product during storage. Therefore, new technologies are required to ensure the probiotic stability of food products.

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Conflict of Interest

The authors have declared that no competing interests exist.

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CHAPTER 7

Banana Leaf Food Packaging: An Alternative and Ecofriendly Solution for Food Industry in Sri Lanka

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Abstract Plastic and paper, the two most often used materials for food packaging, are responsible for global warming, animal hazards, plastic landfills and deforestation. Moreover, these synthetic packaging materials cause destructive environmental issues. Recently, there has been a growing interest in using banana (*Musa* spp.) leaves for packaging due to many benefits. Despite this, its usage mostly ceased by synthetic packaging materials, as plastic banana leaves have long been utilized extensively throughout Asia and Africa for food storage and preservation. Food items like rice, fish, meat, fruits and vegetable-based products are packaged using banana leaves. Due to their availability in tropical nations like Sri Lanka, they are affordable there. Additionally, it is recyclable, biodegradable, customizable and has a higher shelf life after processing. In light of the price of materials for single-use food packaging, banana leaf containers are valued and better suited to Sri Lanka's economy. Even if these kinds of bio-packaging techniques have some shortcomings, those are treatable when compared to the irreversible effects of plastics. With the proper implementations, banana leaf packaging is welcome in the country as it builds up its economy and targets green ingenuity. With an emphasis on the potential advantages and applications of this sustainable packaging material, this paper analyzes the significance of banana leaf packaging in Sri Lanka.

Keywords: Banana leaves, Banana leaf packaging, Bio-packaging, Food packaging, Sustainable packaging

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Introduction

South Asia is the largest banana (*Musa* spp.) producer in the world due to its optimal climatic conditions. In Sri Lanka, the banana is one of the most widely grown fruits; banana farming takes up around 54% of all fruit-growing territory. In addition, the nation's banana industry occupied roughly 60,000 ha of land in 2017 (Ranathilaka *et al*., 2019). However, after the fruit is harvested, the leaves are either dumped or allowed to disintegrate. Banana leaves are readily available in Sri Lanka in large quantities and can be used to create value products at a low cost for packaging. It is a popular choice for food packaging in many parts of the world, particularly in Asia and Africa. It is also an inexpensive food packing material used in South East Asian and African nations such as India, Sri Lanka, Bangladesh, Nepal, and Thailand (Ezeudu *et al*., 2020).

The leaves are perfect for wrapping and steaming food items because they are large, flexible and waterproof. It is used to wrap rice, curries, and fatty foods, as well as to steam foods such as grilled meat, fish, bread, and roti to bring out the peculiar flavor of leaves (Sarma *et al*., 2020). Fresh fruits and vegetables are perfect for packaging since the leaves preserve moisture. This is crucial, especially in underdeveloped nations where storing and moving food can be difficult. Additionally, it only applies to a selected group of food commodities and is not suitable for all food products (Padam *et al*., 2014). It gives locals employment opportunities and generates revenue for the nation thus, can be considered as a profitable venture (Almalky, 2020). Additionally, it is a sustainable and eco-friendly packaging choice that aids in halting environmental degradation than plastic or paper packaging (Hailu *et al*., 2014). Therefore, banana leaves are not only attractive, but they could also play a significant role in eco-friendly food packaging.

It is well-recognized that eating foods that have been wrapped in banana leaves is safe because they are a natural source of antioxidants, which can help preserve packaged goods for longer (Sasikala and Umapathy, 2018). Foods that are wrapped in banana leaves do not come into contact with the leaves directly. As a result, there is a decreased risk of food contamination from bacteria and other pathogens (Mohamed *et al*., 2021). However, current research findings suggest that this might not be the case. The wrapping technique should serve as an efficient barrier against bacteria and other microbes. Additionally, due to the interactions between food, packaging, and the internal environment of the food, there may be safety concerns from bacteria. As a raw material, the quality of banana leaves is also crucial for preventing microorganisms, and the containment of larger packaging is also debatable. This chapter aims to assess how banana leaf food packaging affect product quality and safety and how it affects the economy of Sri Lanka.

Banana Cultivation in Sri Lanka

Bananas are one of the most significant fruit crops in the world and belong to the genus *Musa* in the family Musaceae (Brown *et al*., 2017). They are recognized for their flavor, nutritional content, and year-round availability. The tropical and subtropical regions are where the banana is grown and is primarily consumed (Varma and Bebber, 2019). India, Ecuador, Brazil, China and the Philippines are the top five banana-producing countries in the world (Molina *et al*., 2005).

As Sri Lanka is a tropical nation, the banana is considered a commercial fruit crop in the country and considerable land extend is devoted to banana cultivation (Wasala *et al*., 2012). Due to the better profitability of the banana crop, the number of farmers growing them has increased (Hirimburegama *et al*., 2004). Additionally, year-round production is also generated from banana farming, which attracts more farmers in the country. Sri Lanka grows 29 varieties of bananas (Liyanage *et al*., 1998). According to Perming (2014), six types of bananas are most frequently grown by Sri Lankan farmers, with Embul, Kolikuttu, and Seenikehel being the most popular. Although bananas are grown in all the districts in Sri Lanka, the Department of Agriculture-Sri Lanka recommends that Hambantota, Jaffna, Kalutara, and Ratnapura are the ideal for commercial-scale banana growing, and the ideal conditions for good banana cultivation are 24 °C to 29 °C temperature, 1500 mm to 3000 mm of annual rainfall, a pH of 5.5-7, and sandy loams or laterite soils (Department of Agriculture, 2020).

Plants have a variety of applications besides producing fruits. All the parts of a banana plant are helpful. The banana fruit is the most economically helpful portion of the tree, while peels, stems, and flowers are also edible. Other than that, banana stem fibers are used in many crafting and garment sectors (Bezazi *et al*., 2020). Furthermore, banana leaves are used for packaging and wrapping material for food and desserts (Kora, 2019). Moreover, there are several other medical uses for the rhizomes of the banana plant.

Banana Leaves as Solid Waste

In the past, intercropping was used to cultivate bananas in local and regional production systems. However, large-scale commercial mono-cropping of bananas is also common, particularly aiming at export markets. Due to the extensive cultivation, there are also significant solid wastes, mainly foliage. During the harvest and post-harvest processes, bananas generate a significant amount of by-products or solid waste. According to Sellin *et al*. (2013), 1.5 tons of leaves are produced for every ton of banana yield. Estimated solid waste produced from banana cultivation is summarized in Table 1 with the help of previous records (Kamdem *et al*., 2013; FAO, 2019; Sogi, 2020).

Table 1. Cultivated extent and Foliage solid waste generated from banana cultivation in the world from 1970-2017

Year	Cultivation (Million hectares)	Foliage-solid waste (metric tons)
1970	5.9	45
1980	6.6	51
1990	7.7	59
2000	9.5	73
2010	10.3	80
2017	11.2	86

There is a large extent of banana cultivation and solid waste generation from banana plantations in Sri Lanka. Therefore, it is necessary to recycle or use leaves for other purposes, such as packaging materials for instant meals.

Banana Leaves as Packaging Material

Food packaging is used to protect foods from contamination from the surrounding environment and maintain/control the quality and safety of the product as a containment. Numerous innovative technologies have been developed regarding food packaging (Brody *et al*., 2008). On the other side, natural packaging materials are frequently cherished cultural and historical artifacts alongside the food they are used for packaging where significant preferences for natural materials over synthetic (Seo *et al*., 2016; Friedrich, 2020). Banana leaves are mainly used for wrapping food items before cooking (Singh *et al*., 2020).

Several countries such as India, Indonesia, Thailand, China, Malaysia, Philippines, Singapore, Vietnam, Cambodia, Laos, Myanmar, Brunei Darussalam, Timor Leste, Papua New Guinea, Solomon Islands, Fiji, and Vanuatu, as well as rural communities all around the world, are still using banana leaves as a packaging material (Ng, 2015; Kraig, 2013; Ángel-Bravo, 2021). Recently, it has gained popularity in the West and other regions to reduce our reliance on plastic and another disposable packaging, particularly in South America, Africa, Europe, Middle East, North America, Oceania, and Asia Pacific region (Jones, 2003). This is really important because it helps to reduce the amount of waste that is produced from plastics all over the world (Varkey *et al*., 2021). For example, in Sri Lanka, there is online purchasing for steamed banana leaves for packaging. Furthermore, "*Hela Bojun*" style traditional food outlets use those leaves as packing material, and some large hotels use banana leaves for packaging to draw in international visitors with a traditional appearance.

The midrib of a banana leaf (Fig. 1) is cut off (Fig. 3) or not (Fig. 2), and the lamina is used for food packaging purposes. There have been different traditional folding and packaging designs for different food items for their containment and packaging purposes (Fig. 4), giving uniqueness (Laistrooglai *et al*., 2000). Specified species are favored for the packaging, such as *M. branchyacarpa* in Indonesia (Harijati *et al*., 2013). The most frequently anticipated characteristics of leaves are large lamina (large width and length) and leaf toughness.

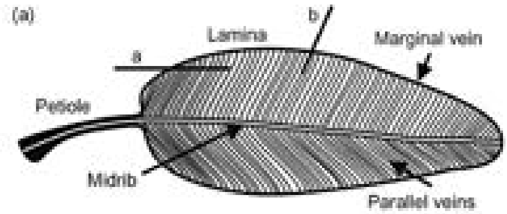

Figure 1. Top view of a typical banana leaf (Adapted from Shapira *et al*., 2009)

Figure 2. Food packaged with banana leaves (Adapted from Ángel-Bravo, 2021)

Figure 3. Traditional “ombus ombus” food packaged using banana leaves (Adapted from Fitriani *et al*., 2017)

Figure 4. Different designs for food packaging by processed banana leaves (Adapted from Banana leaf technology, 2022)

Banana leaves have many benefits in wrapping food items, especially in Asia. Leaves give meals a livelier, more natural appearance while keeping them fresh and wet because the leaves are large, flexible and waterproof (Harijati *et al*., 2013). Another benefit of using banana leaves for food packaging is that the leaves can keep the food warm, which is helpful for transporting hot foods (Wandsnider, 1997). Since banana leaves are plant material, leaves are also hypoallergenic. Furthermore, unlike conventional plastics, banana leaves are fresh and free of chemical hazards (Astuti, 2009). Leaves do not transfer color or pigments to food items wrapped in them (Harijati *et al*., 2013). Moreover, foods cooked in coconut oil impart a delightful flavor when packaged in banana leaves. This entails enhancing taste and developing folk foods (Laistrooglai *et al*., 2000).

Because of its readily accessible nature, packing food items with banana leaves is inexpensive and profitable compared to plastic packaging according to (Lestari *et al*. (2016). Foods can be packed or wrapped and used for steaming, baking, roasting, and grilling due to the thickness of the leaf, which prevents direct flame and lends an enticing, delicious aroma to the dish (Kora, 2019). Additionally, fruit consistency is maintained because of the leaves' capacity to slow down the ripening process, which prevents quality alterations, including weight loss and fruit color changes during storage (Forero-Cabrera *et al*., 2017). Banana Leaf packing could be practically feasible anywhere because they are easy to transport; leaves are lightweight, compact, and stacks easily. These biodegradable packaging materials effectively protect products against alterations in temperature, light, moisture, humidity, compression, impact, vibration, and biological contamination (Kumar and Gupta, 2012). Bio-based packaging is expected to be quite successful for products with a limited shelf life that don't require a lot of gas barrier qualities or water vapour barriers (Weber *et al*., 2002).

Eco-Friendliness of Banana Leaf Packaging

At present, with the increase in demand for healthy foods, more companies are moving into packaging their products in banana leaves. This is mainly because of banana leaves are natural, biodegradable, and sustainable material that can be used to package various food items. Biodegradable raw materials are welcomed by society for environmental acceptability and commercial viability (Mohanty *et al*., 2000; Mohanty *et al*., 2002). When it is placed in water, the leaves break down into smaller pieces within 24 hours (Fiallos-Cárdenas *et al*., 2021). Moreover, banana leaves can be recycled easily or can be made to decompose (Abdullah *et al*., 2013; Padam *et al*., 2014; Singh *et al*., 2020). Furthermore, the used banana leaves can be used for the utilization of the animal as feed (Akinyele and Agbro, 2007).

In Sri Lanka and worldwide, 90% of single-use plastics and 50% of total plastics are from the food packaging sector (Balachandra and Abeysekara, 2021). Another study predicted that there would be around 938 MT of plastic garbage in 2020, of which 300 MT would be recycled and 261 MT/D would be disposed in an open landfill (Ministry of Environment, 2021). In order to transition from a plastic society to a sustainable society and accomplish the Sustainable Development Goals (SDG) by 2030, it is vital to first reduce the amount of single-use plastics (Nakajima, 2022). If banana leaves were used in place of plastics, which are not biodegradable and have an eternal existence, they could avoid the unfavorable adverse effects of plastic packaging (Joyner and Frew, 1991). The use of plastics can also cause human health risks For example, chemicals used in making hard plastics and polymers for food containers can leak into packaged foods and eventually can lead to cancer, diabetes, and fertility problem in humans (Saido *et al*., 2014).

Economic Benefit of Banana Leaf Food Packaging in Sri Lanka

For sales, packaging is a crucial component, and it could be the first element for purchasing decisions of the consumer (Silayoi and Speece, 2004; Ampuero and Vila, 2006). Therefore, consumer preference is greater for eco-friendly packaged foods (Schleenbecker and Hamm, 2013; Orzan *et al*., 2018; Georgakarakou *et al*., 2020). Furthermore, environmental-friendly packing comes more prior to a food purchasing demand (Seo *et al*., 2016). Therefore, banana leaf packaging, like natural food packaging, will have more influence on product demand when it is well implemented, thereby uplifting the economy from the business viewpoint.

An estimated 289,218 MT of plastic-related goods were imported into Sri Lanka between 2016 and 2018 (Jambeck *et al*., 2015). These figures also show a higher expenditure on plastic food packaging in Sri Lanka. Additionally, there is a variety of costs associated with recycling plastics. Sri Lanka could make some savings and assist in seeking solutions for the country's current inflation by using natural banana leaves in place of single-use plastics for packaging different food items. This could be a viable alternative to paper packaging which is not feasible in the country because paper is scarce even for printing newspapers and textbooks. Therefore, to support the uplifting of the country’s economy, it would be worth promoting eco-friendly and readily available food packaging materials that are cheap in the country. On the other hand, an effort is required to produce banana leaf packaging, including folding and tying. Additionally, Sri Lanka's banana leaf packaging industry might flourish, creating more jobs in rural areas and raising the country's Gross Domestic Production (GDP) (Ranasinghe and Sugandhika, 2018). The industry could run with minimum cost as there are no significant upfront costs for machinery and related raw materials because they are produced as a by-product of the main fruit industry in the country. Most banana-producing countries use banana waste for feedstock production (Ulloa *et al*., 2004). Hence, possibility exists in Sri Lanka to use banana leaves for potential feedstock purposes even after using them as a packaging material. Therefore, the country can befit from banana cultivation as fruits are used for consumption and leaves are used for packaging.

Foods Packaging using Banana Leaves

Banana leaves were often used to wrap and store various traditional foods. Different foods are packed and stored using banana leaves, including ready-to-eat cultural cuisine, fruits, vegetables, and meats (Table 2).

Table 2. Foods frequently packaged using banana leaves

Food Category	Food Item	References
Traditional foods	Khoricha Pickle	Narzary *et al*. (2016)
	Tamale	Kraig and Sen (2013)
	Fish Peps	Irawati *et al*. (2003)
	Nasi Lemak	Ng (2015)
	Pulut Panggang	Ng (2015)
	Kuih Nagasari	Ng (2015)
	Voandzeia Subterranean Cake (Okpa)	Igbonekwu *et al*. (2022)
	Som Fug (Fermented Minced Fish Cake)	Valyasevi and Rolle (2002)
	Tape Ketela	Aryanta (2000)
	Ombus-Ombus	Fitriani *et al*. (2017)
Rice based foods	Cooked Rice	Ng (2015)
	Porridge Rice	Harijati *et al*. (2013)
Dairy based foods	White Cheese	Zakariah *et al*. (2019)
	Tempeh	Hicks (2002)
	Confectionery Fats	Mustafa *et al*. (2012)
	Soft Cheese	Hatta *et al*. (2013)
Meat Based Foods	Tempoyak (Fish	Rahma *et al.* (2021)
	Fish	Mao and Odyuo (2007); Ahmadi *et al*. (2019)
	Stick Meat	Olaoye *et al*. (2018)
	Chicken	Irawati *et al*. (2003)
Fruits	Fruits	Latifah *et al*. (2009)
	Banana Fruit	Hailu *et al*. (2014)
	Lulo Fruit	Forero-Cabrera *et al*. (2017)
	Rambuttan Fruit	Latifah *et al*. (2009)
	Mangoes	Watt *et al*. (2020)
	Papaya	Kebede *et al*. (2020)
	Pineapple	López *et al*. (2022)
	Jackfruit	Kora (2019)
	Mangosteen	SCUC (2006)
	Durians	Rahma *et al*. (2021)
Vegetables	Vegetables	Sarma *et al*. (2020)
Grains	Raw Coca Beans	Guehi *et al*. (2010)
	Grains	Mobolade *et al*. (2019)

Microbiological Safety of Banana Leaf Packaging

There are several advantages of using banana leaves as packaging material, including their natural antimicrobial properties. This is due to the leaves ability to repel germs and other microbes. Banana leaves contain compounds that can avoid contamination from harmful bacteria and fungi, making the material a safe and effective way to package food (Table 3). However, before harvesting, plants are vulnerable to pest and microbial disease attacks (Budiyanto *et al*., 2018). In addition, when utilizing banana leaves for packing, an infection may occur if insufficient sanitizing procedures are practised. In contrast, banana leaves could have the chance to be an attachment of food-borne pathogens due to their waxy leaf surfaces than other leaves (Chua and Dykes, 2013).

Table 3. Resistance of banana leaves against different bacteria and fungi

Bacteria and Fungi	References
Escherichia coli	Karuppiah and Mustaffa (2013); Bisht *et al*. (2016), Bankar and Dole (2016), , Salama *et al*. (2020)
Staphylococcus aureus	Karuppiah and Mustaffa (2013), Asuquo and Udobi (2016), Salama *et al*. (2020)
Pseudomonas aeruginosa	Karuppiah and Mustaffa (2013), Ismail *et al*. (2018), Salama *et al*. (2020)
Enterococcus faecalis	Karuppiah and Mustaffa (2013)
Shigella dysenteriae	Asuquo and Udobi (2016)
Bacillus subtils	Salama *et al*. (2020)
Tricophyton mentagrophytes	Harith *et al*. (2018)
Penicillium oxalicum	Bisht *et al*. (2016)
Aspergillus flavus	Salama *et al*. (2020)
Alternaria alternate	Bisht *et al*. (2016)
Candida albicans	Bankar and Dole (2016), Salama *et al*. (2020)
Saccharomyces cerevisiae	Salama *et al*. (2020)

After packaging, there might be contamination and incorporation of spoilage and pathogenic organisms. Previous studies in to this aspect reported an increase in fermenting bacteria in a tempeh sample with banana leaf packaging but, that was not significantly differentiated with plastic packaging (Erdiansyah *et al*., 2022). There was heavy contamination of microbes in banana leaves packed after 48 hours (Igbonekwu *et al*., 2022). Hetta *et al.* (2013) demonstrated that packaging indirectly affects contamination, but the production chain causes more contamination than banana leaf packaging of soft cheese.

Studies have shown a link between moisture and air with the quality of wrapped food (Hailu *et al*., 2013; Hailu *et al.*, 2014). The packaging of banana leaves is also susceptible to rotting because of microbial contamination and oxygen access.

Therefore, it is important to take some precautions to ensure the safety of banana leaves as packaging material. The leaves should be washed thoroughly before being used. It is also important to ensure that the leaves are not contaminated with other materials, such as pesticides. Overall, using banana leaves as a packaging material is safe and effective, as long as some basic safety precautions are followed.

Storage Food Quality of Banana Leaf Packaging

The shelf-life of fresh-cut banana leaves was 13 days when kept under ambient environmental conditions (Kuljaroensub *et al*., 2019). This indicates the possibility of using banana leaves to store foods for 1-2 weeks. Concerning the food during storage, several factors may affect the shelf life of the food in banana leaf packaging, such as type of food, storing temperature and type of packaging. In most cases, banana leaves are preferable for short-term packaging (Jeenusha and Amritkumar, 2020). Regarding fruit storage, the research evidence has shown that bananas can be preserved for 18 days when wrapped in banana leaves (Hailu *et al*., 2014). Furthermore, Latifah *et al*. (2009) reported that the rambutan fruits stored in banana leaves as primary packaging material could preserve for six days without any quality defects and there were no significant differences in sensory qualities of the fruits compared to other packaging methods, and the ripening was also controlled. Moreover, the lipid oxidation of fish is retarded due to the antioxidant content of banana leaves, and fish can be preserved under freezing conditions with good quality (Ahmadi *et al*., 2019).

It is possible to store products in banana leaves under freezing conditions. However, it is important to consider the type of product being stored and the specific freezing conditions (Ranasinghe *et al*., 2005). For instance, extra care should be taken to avoid the leaves from tearing when storing especially sensitive products. In addition, the leaves disintegration and decomposition result in an extremely short shelf life compared to other artificial packaging materials. Additionally, research studies indicate that banana leaves are generally recommended not to be stored below freezing, as this can cause the leaves to become brittle and break (Bassette and Bussière, 2008). Therefore, at the commercial level, banana leaf production for packaging needs more consideration of the storage temperature. Besides preserving foods during storage, the deformation and mechanical damage are significantly reduced when banana leaves are used as the primary packaging of foods (Latifah *et al*., 2009; Forero-Cabrera *et al*., 2017).

Constraints for Banana Leaf Packaging and Potential Solutions

There have been some constraints with banana leaf packaging. However, some of those are restricted to a few ethnic foods alone (Padam *et al*., 2014). The packaging is not watertight and can allow moisture to enter the food, leading to spoilage (Yildirim *et al*., 2018). Another way of potential contamination is that leaves are not sterile and can therefore introduce microbes into the food when it is used in the fresh form (Barlocher and Kendrick, 1974). Leaves are not strong and can tear easily, leading to food contamination during storage (Jumaidin *et al*., 2021). Although banana leaves are used widely worldwide as containers for foods like rice, fish, vegetables and meat, where leaves are durable, they cannot withstand high temperatures (Mustafa *et al*., 2012). The microbiological deterioration of food as a result of contamination and poor sanitation measures of banana leaves could end up with poor food quality, thereby immediate health complications and fatality (Chua and Dykes, 2013). Another issue is that human resources need to be used to manage the packaging of banana leaves instead of machineries (Kora, 2019). The following measures could be adopted to avoid constraints related to food packing using banana leaves.

- Proper sanitation practices can make banana leaves free from microbes (Kuljaroensub *et al*., 2019; Igbonekwu *et al*., 2022).
- Making biofilm on leaf surfaces such as the gelatin layer is helpful in controlling some microbial spoilage (Perumal *et al*., 2022).
- Drying of leaves before packaging. For example, rural communities in India and Africa use open sun drying of the leaves (Hailu *et al*., 2014; Babu *et al*., 2018). Due to the rising understanding of the significance of sustainability of packaging, there has been a growth in the usage of dried or radiated banana leaves as packing material in recent years (Irawati *et al.,* 2003; Han *et al*., 2018).
- Bioplastic layering on leaves makes them more waterproof than raw banana leaves during food packaging (Jeenusha and Amritkumar, 2020).
- Bio-pulping and bio-bleaching methods can be used to make banana leaves more suitable for packaging (Jeenusha and Amritkumar, 2020). This can be done using the xylanase enzyme (Walia *et al*., 2017).

Conclusions and Future Prospects

This review discusses the applicability of banana leaves as an alternative and ecofriendly packaging material in Sri Lanka. Banana leaf as a packaging material, suits for most food types, except for liquid items. These packaging materials are indeed biodegradable and best suited instead of single-use plastics, taking into consideration environmental pollution caused by plastic materials. They can contribute to national economy by raising the demand for environmental-friendly packaging, reducing synthetic packaging material costs and creating employment opportunities. Additionally, more research into storage potentials of different food items, spoilage and pathogenic contamination and the quality of food commodities packaged in banana leaves should be conducted. This could address most of the constraints associated with banana leaf packaging, thereby facilitating the development of a new business venture in the country.

Conflict of Interest

The authors have declared that no competing interests exist.

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The Role of Low-input Poultry Production Systems in the Face of Economic Crisis in Sri Lanka

CHAPTER 8

W.N.U. Perera* and G.L.L.P. Silva

Abstract Access to a nutritious diet can be one of the foremost challenges for most Sri Lankans today. In such a resource limited setting, an approach to a low-input poultry production system (LIPPS) is reviewed as a sustainable option to ensure nutritional security and economic resilience in vulnerable groups in the community. A shift in poultry production to a low-input system, targeting small- and medium-scale producers, can be encouraged to provide access to a nutritionally balanced diet and a source of income. Indigenous poultry genetic resource, diverse management system and feed resource base, short supply chain and low productivity are typical characteristics of a LIPPS. These characteristics have made the LIPPS instrumental in achieving food and nutritional security, economic resilience, women empowerment, sustainability and climatic adaptability especially among vulnerable groups in society in the face of crisis.

Keywords: Food security, Indigenous, Low-input, Poultry, Women empowerment

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Introduction

Being one of the fastest-growing livestock subsectors in Sri Lanka, poultry contributed to 0.38% GDP, which is 64% of the total contribution of livestock sector in 2019 (CBSL, 2020). However, presently it is shrunk by 40% due to the current economic downfall of the country (DAPH, 2022). The poultry industry is mainly managed by private organizations, while government involvement has been limited to monitoring of importation of parent/grandparent stocks and feed ingredients (Premaratne and Samarasinghe, 2020). Among different subsectors of the livestock industry, poultry is the only subsector that has achieved self-sufficiency and has been capable of maintaining sustainability. Even though the categorization according to the production scale is not well demarcated, the contribution from the large-scale poultry manufacturers is indeed significant (DAPH, 2021). The private sector provides inputs to almost all the levels of the market chain and is vertically integrated which helps them to minimize the impacts of external shocks on the production line/supply chain. In such scenarios, large-scale private poultry farms belonging to multinational companies or large-scale national enterprises act as individual organizations leading market integration in the poultry industry in Sri Lanka (Silva and Dematawewa, 2020).

With the import ban on maize accompanied with fertilizer crisis, the local production of maize which is used as the main ingredient in poultry feed, is still insufficient to fulfil total demand. This has led to a steady increase in feed prices and a significant drop in feed production. Accordingly, small- and medium-scale poultry producers have become more vulnerable to market pressures (CBSL, 2021; DAPH, 2021). Moreover, large-scale companies had to minimize their production capacities due to the scarcity of feed ingredients and lack of commitment mainly by small- and medium- scale poultry producers (DAPH, 2022). Liyanagamage *et al*. (2022) showed that 42% of the layer farmers have left the industry due mainly to the inaccessibility to the inputs and the markets, as a result of the global pandemic situation and the subsequent financial crisis faced by the country. Moreover, a 33% reduction in the self-mixed feed production in 2021 (DAPH, 2021) could mainly be attributed to the increasing prices of feed ingredients. Haphazard and illogical price controls over the poultry products imposed by the government in curbing the situation is just a masking attempt and would not be supportive in simmering down the present crisis of the industry as such a move does not address the cause of the problems the industry faces.

In 2018, although the local poultry production capacity remained unchanged, it was poorly decided to increase the importation of parent day-old chicks (DOC) by 74%, leading to an 11% increase in commercial DOC production in 2021 compared to 2020 (DAPH, 2021). During the same period, most of the small- and medium- scale poultry producers left the business in the face of crisis and, as a result, the sale of DOC markedly dropped from the predicted quantities causing around 17 million DOC to be drowned at hatcheries. The financial loss incurred by the breeder farms is estimated at approximately 1.69 billion rupees (DAPH, 2022). In contrast, there was a 9% increase reported in chicken meat production in 2020. This increase has mainly contributed by the culling of poultry breeder and layer birds (DAPH, 2022) which provided a full picture of the tragic consequence of farmers leaving the industry, temporarily or permanently.

Given the fact that we were enjoying a well-developed, properly managed and best performing poultry industry in the region, the question now remains is how to revive the industry and how long will it take. More importantly, until the revival takes place, what approaches are available with us to cater to the needs of the country, especially the issue related to increasing child malnutrition, and the looming protein deficit. It is reasonable to believe that the economic transformation required while managing the crisis will not be supportive of incentivizing the demand for high-cost inputs. Accordingly, the potential role in the low-input poultry production systems (LIPPS) in a resource-poor setting, mainly to support the economic resilience of small and medium-scale poultry farmers and food security of the nutritionally vulnerable groups in Sri Lanka, is therefore taken as the focus of this book chapter. The chapter has been organized to describe the LIPPS in detail and the opportunities it creates and potential it carries to manage the nationally important nutritional crisis.

Characteristics of a Low-input Poultry Production System

The potential contributions and impacts of low-input, extensive, small-scale scavenging poultry production systems, in resource-poor areas differ significantly from high-input, intensive systems. 'Backyard poultry system' or 'village chicken' production system is the most widespread and viable operation in the rural as well as peri-urban areas of the country (Silva *et al*., 2016). The term ‘family poultry’ is also used for these LIPPS as their high reliance on family labor (Thieme *et al*., 2014). Given that the number of birds reared under LIPPS is usually under 200, LIPPS can also be categorized as small-scale poultry (Wong *et al*., 2017). Therefore, the potential overlapping between the terms ‘small-scale poultry', 'scavenging chickens', 'village chickens', 'backyard poultry, and 'family poultry' is highlighted. Overall, a LIPPS can be recognized with a few main characteristics, which are discussed below.

(i). Utilization of Locally Available Genetic Resources

As in the other countries of the region, Sri Lanka is blessed with high diversity in animal genetic resources (Pushpakumara and Silva, 2008). In terms of poultry, this diversity is supported by the indigenous poultry species that vary widely in body size, color, shape and other phenotypic characteristics. For example, the typical village chicken (*Gam kukula*) with different plumage colors such as red, black, brown, and white or multicolor, the naked neck (*Penda kapapukukula/ Mas kukula*), the long-legged (*Porakukula*), the crown chicken (*Kondakukula*) and the frizzled feathers (*Käperikukula*) are considered as most common indigenous chicken breeds available in Sri Lanka (Liyanage *et al*., 2015). Being originated as a blend of different genotypes, the indigenous chicken forms a unique genetic resource, showing the highest likelihood of survival in harsh conditions due to their disease resistance, ability to scavenge and avoid predators, and their broodiness (Jiang *et al.*, 2010; Wong *et al*., 2017). Even though this unique genetic resource in Sri Lanka was challenged with the introduction of high-producing layer and broiler strains to the poultry industry, indigenous chickens still play a vital role in food security and in supporting the livelihood as an additional source of income for the rural dwellers in Sri Lanka. The LIPPS could be thus described as a sustainable system mainly due to their lower input requirements. These are the very reasons that the indigenous village chicken has become a vital resource in the face of the current crisis in Sri Lanka.

(ii). Extensive or Semi-intensive Management Systems

Defining family poultry production systems and their contributions, Animal Production and Health Guidelines by Food and Agriculture Organization (Thieme *et al.*, 2014) categorized family poultry production systems into four categories: small-scale extensive scavenging (1–5 adult birds), extensive scavenging (5–50 birds), semi-intensive (50–200 birds), and small-scale intensive production (> 200 broilers or>100 layers). Out of these categories, small-scale intensive poultry production systems in Sri Lanka are mostly practiced with improved commercial strains. The requirements of high-input, intensive poultry production systems are comparatively specific, ranging from reliable access to inputs, including commercial stock, feed, labor, and health services, to efficient marketing channels. On the other hand, farmers practicing LIPPS can decide on either an extensive or semi-intensive system that best suits their location, i.e., access to an urban market (Abeykoon *et al*., 2013; Silva *et al*., 2016), situation and objectives (Wong *et al*., 2017).

The free range or extensive management system was the most practiced method for village poultry in Sri Lanka. With the ability of indigenous chickens to withstand adverse environmental conditions, they need little care as they are ready to take up the environmental shocks with appropriate adjustments inherited. Thus, under prevailing production system, they are usually provided with simple shelters made from locally available materials or no shelter where birds spend night-time on trees or any simple enclosure in the kitchen or the farmer's dwelling to be protected from theft and extreme weather conditions. During the daytime, birds are allowed to freely scavenge from the surrounding environment with the supplements from the kitchen such as refusals (Gunarathne *et al*., 1993). However, evidence indicates a positive association between children's exposure to livestock feces and diarrhea (Zambrano *et al*., 2014). In addition, low production, disease, and predation are recognized as constraints in extensive systems (Silva *et al*., 2016; Wong *et al*., 2017).

It is therefore encouraged to move beyond the subsistence level toward semi-intensive systems with added improvements to the housing and management conditions to overcome the constraints in extensive management systems. Department of Animal Production and Health has recommended few housing types that can be utilized in LIPPS (Fig. 1; Silva *et al*., 2016). It is aimed that housing would reduce predation (e.g., mongooses, snakes etc.), theft and diseases spread by the migrant birds. Moreover, from the production point of view, housing would facilitate feed supplementation, provide a suitable environment for laying eggs and brooding purposes, and facilitate the collection of poultry manure as an environmental service from LIPPS.

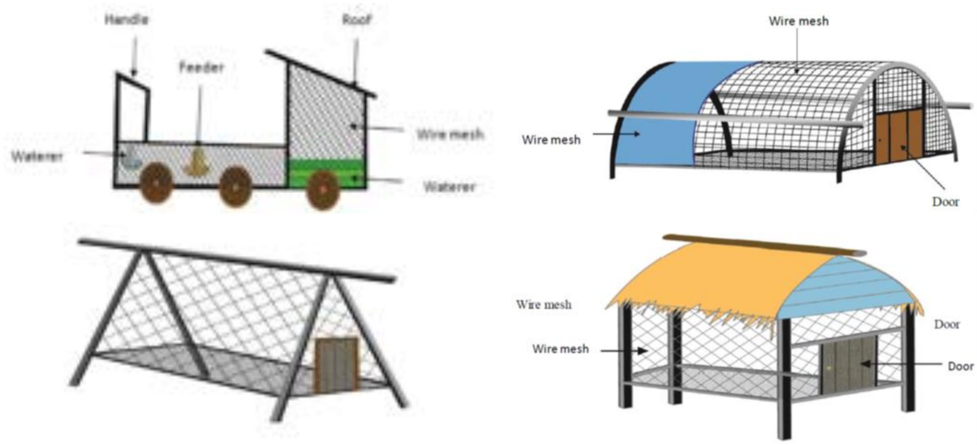

Figure 1. Examples of movable poultry houses for low-input poultry production systems (Source: Silva *et al*., 2016)

(iii). Dependence on Scavenging Feed Resources

Low-input poultry production systems are mostly using the scavenging feed resource base that transforms feed ingredients in the environment that are less suitable or unavailable for human consumption and have no monetary value, including plant seeds, earthworms, and insects, into edible and nutritious food products (Sonaiya, 2004). On the other hand, feed cost is considered as the main cost component in high-input poultry management systems, accounting for more than 70% of the total cost of production (van der Poel *et al*., 2020). Comparatively, LIPPS allows feed cost reduction mainly due to the contribution from the scavenging feed resources. This was evident by a cost-benefit analysis of village chicken production systems in Puttalam district, Sri Lanka, done by Wijayasena *et al*. (2014) who reported that the feed cost is of only 32.1% of the total production cost of village chicken. However, land limitation leading to low access to scavenging grounds, narrowing the feed resource base has been recognized (Silva *et al*., 2016) as a threat for the sustainability of scavenging production system. Therefore, it is necessary to allow LIPPS to become a part of mixed or integrated farming systems to ensure the access to low-cost feed resources. It will also allow efficient use of resources and result in economic resilience with fewer vulnerabilities to external shocks, such as limited feed ingredient availability, high prices of commercial feed and limited access to the input markets due to fuel shortage.

(iv). Low Productivity

Compared to intensively selected commercial poultry strains, indigenous chicken breeds have a lower productivity in producing eggs and meat. Even under ideal housing and feeding conditions, productivity in indigenous chicken breeds is much lower than that of commercial strains (Sørensen, 2010), mainly due to their poor genetic potential in production. In addition, indigenous birds kept in village settings expend a significant amount of energy in scavenging for feed and evading predators, lowering their growth rate and egg production. Moreover, village chicken hens show high broodiness and spend up to 75% of their time for hatching eggs and rearing chicks (Pym and Alders, 2012). Despite those inferiorities in production, being co-evolved with their environments, indigenous poultry breeds have high adaptability and survivability in harsh conditions.

As a result of the current crisis in Sri Lanka, many poultry production operations, particularly the maintenance of intensive closed-house poultry systems are continuously challenged by power (electricity and fuel) disruptions, and consequently, the livability and performance of birds deteriorate. Most of the poultry operation systems are now moving back to the semi-intensive systems where the environment in the poultry houses is not artificially controlled to match the optimum environmental conditions corresponding to the imported commercial strains. In such a limited setting, despite the high cost of maintenance of improved strains, and yet not meeting the optimum production from commercial strains under semi-intensive systems, indigenous poultry production will be a suitable alternative, at least until the situation is normalized in the country.

Higher broodiness shown by indigenous breeds of chicken (approximately 20 d; Jiang *et al*., 2010) is commonly associated with reduced egg production. Nonetheless, when properly planned, the broodiness in hens in LIPPS can be directed to obtain the DOC via natural incubation for the next production cycle at zero cost (Wijayasena *et al*., 2014). On the other hand, it will generate an extra income by selling DOC from indigenous poultry breeds (Abeykoon *et al*., 2013). In conjunction with their multifaceted contributions to the household, the comparative productivity, as measured by the benefit-cost ratio, is higher in indigenous chicken breeds (Ahuja *et al*., 2008).

(v). Short Supply Chains

Low-input poultry producers primarily sell their products through local channels without the requirement of a formal market resulting in short supply chains (Akinola and Essien, 2011; Abeykoon *et al*., 2013). Thus, if the farmer practices direct marketing without intermediaries, a high income can be guaranteed as the revenue is not being divided among the operators in the market channel, especially the middlemen. This is a win-win situation to both producer and the consumer as no hidden costs are involved and food supply chain is short. The importance of short supply chains was well-experienced during the COVID-19 lockdowns and during the fuel crisis that limited the access to food ingredients threatening the food security of most segments in the country. Therefore, in addition to selling the LIPPS products at household levels, the concepts of farmers' markets and society shops should be encouraged to support short supply chains for products from LIPPS. It will provide resilience in adapting to economic or environmental shocks or changes (Wong *et al*., 2017).

Role of LIPPS in the Face of Crisis

(i). Food and Nutritional Security

According to Crop and Food Security Assessment Mission report in September 2022, food and nutritional security in Sri Lanka has deteriorated since the beginning of 2022, with over 6.2 million people (28% of the population) estimated to be moderately acute food insecure, while 66,000 are severely acute food insecure and in need of immediate food assistance. Many vulnerable households have been widely adopting food and livelihood-related coping strategies, including cutting the number of daily meals, reducing the size of meals and purchasing food on credit. The highest level of acute food insecurity has been reported in the estate sector and among female-headed households, households with no education, the Indian Tamil population and Samurdhi programme beneficiaries (FAO, 2022). Given the low investment and low-input engagement with the women empowerment component, LIPPS could be a suitable and viable option for majority of nutritionally vulnerable groups in Sri Lanka. Moreover, with a short supply chain, the products of LIPPS would be locally available without the need for an established marketing system and could make a speedy return on investment. Moreover, access to the local and household markets will not be challenged in the face of a fuel crisis, assuring consistent food security.

Avian eggs contain all nutrients required to support the development of chicks and thus carry nearly a perfect balance of nutrients (Vizard, 2000) to meet human nutrition requirements. Eggs have been recognized as the lowest-cost source of protein, vitamin A, vitamin B12, riboflavin, iron and zinc (Drewnowski, 2010) and are also a good source of folate, selenium, vitamin D, and vitamin K (Applegate, 2000). In addition, their high concentration of micronutrients and ability to counter multiple micronutrient deficiencies make eggs one of the precious food sources. In addition to the supply of nutrients to the household, selling extra eggs creates an additional income (Wijayasena *et al*., 2014). Not only for the eggs but also for the chicken meat, LIPPS can utilize indigenous breeds such as the Naked neck (Abeykoon *et al*., 2013), which are reported with a comparatively higher growth rate than other indigenous chicken breeds. Even though LIPPS will not meet the conventional measures of productivity commonly used in the commercial poultry meat sector (feed conversion ratios or daily weight gain), it can be considered as a viable approach to ensure nutritional security and economic resilience in vulnerable groups in the society. Thus, LIPPS can be a year-round food source when threats to production, particularly diseases, are addressed and controlled (Wong *et al*., 2017).

(ii). Economic Resilience

The selling of indigenous village chicken products, either from a high-input or low-input setting, allows having a premium price compared to commercial eggs and meat. According to Silva *et al*. (2010), village chicken eggs get 30% - 40% of the premium price compared to commercial farm eggs in the Sri Lankan context, mainly due to the high market demand attributed to minimal use of pharmaceuticals during production (FAO, 2010) and comparatively limited supply. Different studies conducted in Sri Lanka and globally show that income generated from selling the products from LIPPS would support the nutritionally and economically vulnerable groups in the society (Abeykoon *et al*., 2013; Wijayasena *et al*., 2014; Wong *et al*., 2017). In addition to providing protein sources, revenue from selling products such as meat, eggs, and manure from LIPPS will allow households to purchase a greater variety of food and cover schooling and healthcare costs (Wong *et al*., 2017). The LIPPS can be easily incorporated into mixed production systems with crops and other livestock, as a way for vulnerable households to minimize the impact of external risks.

The payback period of 9.48 months reported for village chicken production systems in the Puttalam district (Wijayasena *et al*., 2014) depicts that LIPPS can be used to recover from this crisis at household levels in a shorter period. Moreover, as Wijayasena *et al*. (2014) reported, with a 1.27 benefit-cost ratio and Rs. 68,548 net present value of the investment, LIPPS can attract more individuals who need a low level of investment. Even though farm welfare is not deeply concerned by the majority in Sri Lanka, the preference for an organic production system to promote animal welfare is critically considered in the developed world. Therefore, in the future, it can also be a good tagline to promote LIPPS in the Sri Lankan context targeting the export market for free-range eggs and chicken meat.

(iii). Women Empowerment

The role of women in LIPPS management activities is well recognized in many parts of the world including Sri Lanka (Wijayasena *et al*. 2014; Wong *et al*., 2017). Promoting LIPPS is a viable option for addressing many issues such as malnutrition and food insecurity in the country under the current crisis. Women empowerment through LIPPS could be a strategic action in managing the household economy and food security. Women empowerment is especially considered an impetus for children's education. In a situation where the higher level of acute food insecurity has been reported in female-headed households (FAO, 2022), the benefits of LIPPS to the livelihoods of not only women, but also children, the elderly, and the chronically ill should not be overlooked.

(iv). Climatic Adaptability

Global warming and related consequences are affecting every living being on this planet earth where there is no exception for animal production systems though they are man-made and managed systems. With increasing climate variability, more frequent weather extremes are expected, justifying the requirement of development of genotypes with high adaptability (Wong *et al*., 2017). Whilst commercial chicken breeds have lost the coping mechanisms to tolerate higher ambient temperatures (Soleimani and Zulkifli, 2010), indigenous breeds such as Naked neck depict a greater degree of heat tolerance mainly through genetic variation in feather development (Melesse *et al*., 2011; Abeykoon *et al.*, 2013). According to Muir *et al*. (2008), 50% or more of the genetic diversity in ancestral breeds is absent in pure commercial lines due to the limited number of breeds incorporated in development of commercial lines. The LIPPS, especially the systems incorporating the indigenous chicken types provides the opportunity to sustainably utilize the adaptive capacity of the indigenous genetic resources. Thus, healthy and diverse genetic characteristics maintained through the LIPPS may not only ensure the long-term survival and productivity of poultry as an industry by addressing future needs in selection and breeding but may also contribute to ecosystem health by providing environmental services.

(v). Sustainable Utilization of the Resources

The concept of sustainability in a farming system identifies the collaborative activities that operate with low environmental impacts yet ensure food and nutrition security for present and future generations. According to Marambe and Silva (2012), responsible utilization of biodiversity is one of the main characteristics of sustainable agriculture systems. Thus, sustainable systems are protective and respectful of diversity and the environment (Hoffmann and Baumung, 2013). Production of LIPPS cause minimal disturbance to the existing resources but fosters and contributes positively to ecosystem health and can reduce biodiversity loss by having a rich pool of genetic diversity (Liyanage *et al*., 2015). Nevertheless, the LIPPS is involved in scavenging systems (extensive management) in diverse environmental conditions including relatively harsh climate conditions allowing the use of resources unsuitable for crop production (Ibrahim and Schiere, 2002).

Economic output from livestock and poultry is primarily contributed by commercial breeds in leading production systems in the country. The contribution coming from LIPPS is a crucial supplementary role which provides an opportunity for reaching vulnerable communities with its products, promoting the ecosystem with the environmental services it generates and delivering the future with diverse genetic resources it preserves (Marambe and Silva, 2012). Besides all these long-term benefits, LIPPS also could bring solutions to the present crisis in food security, nutrition, and health of vulnerable communities.

Low-input poultry production systems can use diverse genetic resources to explore the adaptive capacities of indigenous poultry breeds, which can thrive under harsh environmental conditions. Sri Lanka inherits diverse production systems and domesticated animal genetic resources that can be instrumental in formulating strategies for facing the crisis. The situation created by the current economic crisis can be a good turning point to drive the country to remedy the problem of malnutrition through LIPPS. Any sustainable improvement to the productivity of the

LIPPS will enhance usable biomass production in most households while conserving the natural resources, with benefits to most nutritionally and economically vulnerable groups of the society.

Challenges and Limitations

Despite the benefits of LIPPS to the livelihoods of Sri Lankans during the present crisis, there are some challenges and limitations in popularizing LIPPS. For example, in a case study on the determinants of market participation by indigenous poultry farmers in Anuradhapura District in Sri Lanka (Abeykoon *et al.*, 2013), the association between the participation decision and religion was evident where less preference was shown by Buddhist households. In such scenarios, slaughtering the birds for meat and adapting short supply chains for products from LIPPS via farmers' shops will be challenging. Therefore, it is recommended to consider the willingness of potential community groups to engage in LIPPS for meat-purpose birds beforehand, to ensure the farmer engagement in LIPPS in the long run. On the other hand, it can be speculated that LIPPS for egg production is less affected by cultural aspects such as religion. Furthermore, the potential social issues, especially in extensive management systems, such as birds invading neighbors' lands and cultivations and the environmental problems with the smell, are anticipated mainly in populated areas with limited land availability. Hence, selecting suitable regions for popularizing the LIPPS is vital before introducing LIPPS as a new venture.

Government intervention is another crucial factor in popularizing LIPPS, especially in the form of community development programs among the most nutritionally and economically vulnerable groups of society. In those contexts, a systematic approach towards popularizing LIPPS, mainly in minor administrative units, i.e., Grama Niladhari divisions, is recommended. Addressing smaller community groups would facilitate the effective delivery of necessary knowledge and skills in poultry rearing via support groups guided by regional livestock and veterinary officers, especially for those new to poultry farming. Unlike commercial DOC production, the DOC production of indigenous chicken types is yet to be formalized. It is therefore recommended to facilitate the production and distribution of indigenous DOC among potential community groups through government coordination, especially considering the biosecurity issues. Irrespective of the scale of operation, the provision of formulated feeds as supplements can improve productivity to meet the maximum genetic potential of the indigenous birds. Since it will add a considerable cost to purchase commercially available formulated feeds for LIPPS, educating the farmers to formulate a balanced diet with locally available feed ingredients is also recommended.

Conclusions and Future Prospects

The current crisis in Sri Lanka, particularly in the poultry industry, has given an excellent opportunity to appreciate the rich and diverse poultry genetic resource available in the country. Moreover, among two targets of high productivity vs sustainability, this crisis invites us to re-analyze the best that will match Sri Lanka in the long run with or without the crisis. The introduction and/or promotion of LIPPS in such a resource-poor setting and their need for low investment and high net present value would attract the society's most vulnerable groups. Furthermore, the indirect contributions by LIPPS to a sustainable environment and women empowerment should not be overlooked. In summary, the silver line in the dark cloud in the face of crisis could be bringing nutritional security leaving no vulnerable household behind, with a mechanism supported by well-planned investments and commitment to LIPPS.

Conflict of Interest

The authors declare no conflict of interest.

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CHAPTER 9

Fish Waste Valorization to Active Food Packaging: Towards Blue Economy of Sri Lanka

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Abstract Sri Lanka is an island nation blessed with marine resources. Fisheries and aquaculture play a considerable role in gross domestic production of the country. However, the disposal of fish waste during the processing and by-catch are becoming serious concerns in terms of environmental pollution. A considerable amount of fish waste is discarded annually without utilization. Hence, fish waste is a rich source of several biopolymers and additives. The biopolymers of concern in food packaging are collagen, chitin, chitosan, and gelatin abundant in fish by-products and discards. The majority of packaging is currently made of single-use plastics which contribute significantly to environmental damage. Polymers made from fish waste are a viable alternative to synthetic polymers and can be used to make bioplastics that are either bio-based or biodegradable. Biopolymers employed in active packing are distinguished by their ability to permit passage of certain components while blocking the passage of other elements that might damage the food. Therefore, biopolymers from fish by-products are widely used in developing active packaging systems in a variety of foods to extend their shelf life. The sustainable utilization of fish waste, converting the problems into potential, and all other activities related to the use and protection of marine and coastal resources may help Sri Lanka to develop a blue economy via the valorization of fish by-products. Therefore, utilizing fishery wastes and its by-products for the development of marine biopolymer derived active packaging is a viable and vital solution for overcoming issues related to the environmental and economical concerns.

Keywords: Active packaging, Biopolymers, Blue economy, Fish waste, Valorization

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Introduction

The problem of fishery wastes has increased dramatically since the last couple of years and is becoming a global concern affecting the biological, technical, operational fractions and socio-economic drivers of the nations. The research may contribute to the assistance and its efforts in building a circular related to the blue economy which aims enhancing the value of material flows and to achieve sustainable utilization and production of marine resources. In spite of the low value traditionally assigned to fishery by-products, huge mass of unused/under-utilized resources of this kind has a great potential to produce bioactive compounds with wide pharmaceutical and biotechnological applications such as proteins (enzymes, collagen), protein hydrolysates, lipids, astaxanthin, and chitin (Shahidi *et al*., 2019). In accordance with the circular blue economy and the zero-waste concepts, fishery by-products and wastes should be utilized in the manner of minimizing the environmental impact, by ensuring that the whole process of recovery provokes a lower impact than other waste management practices (Zhao *et al*., 2022).

Preservation of food products is a critical task where scientists are struggling to extent the shelf life of the types of food products. Packaging is one of the viable techniques to overcome this issue. Since most packaging nowadays is made from one-time-use plastics, which is a major contributor to environmental pollution. Therefore, the biopolymer-based active packaging could be a possible solution to overcome this issue (Zhao *et al*., 2022). Active packaging is a mode of the package at which the envelope, the product, and the environment interact to prolong shelf-life or to enhance safety and/or quality of the food product. Therefore, the utilization of fishery by-products and waste to extract the biopolymers to develop an active packaging system is a recent hot topic among researchers around the world. Furthermore, generated waste and underutilized by-products are modelled into economically beneficial ways, which may mainly influence the economic status of the nation in terms of the blue economy. In this article, the potentials of fishery by-products and waste utilization to achieve a circular blue economy to boost particularly Sri Lankan economy are explored.

Marine Resources in Sri Lanka

As a country with a coastline of 1,770 Km, Sri Lanka has exclusive commercial fishing rights over 517,000 Km^2 of ocean and 21,500 Km^2 of territorial waters. There are over 610 different species of coastal fish known from Sri Lankan waters, with the most often obtained species including *Sardinella* spp., *Amblygaster* spp., *Rastrelliger* spp*., Auxis thazard, Anchova commersoni*, and *Hirundichthys coromandelensis* being the most often caught (Athauda and Chandraratna, 2020). One of the most promising industries in the nation, fishing benefits from the 262,000 ha of freshwater and 158,000 ha of brackish water found in the country's inland water bodies. There were 176 fresh fish species identified in Sri Lanka, including Hiri kanaya (*Labeo* spp.), Lula (snakehead), and catfishes (butter catfish, stinging catfish, and walking catfish) (Athauda and Chandraratna, 2020). In addition to finfish being caught, freshwater prawn is also captured from aquatic resources where they are abundant. Furthermore, brackish aquaculture resources available in Sri Lanka are *Chanos chanos*, *Mugil* spp., *Etroplus suratensis*, penaeid prawns, *Scylla serrta* (mud crab) and *Crassostrea* spp. (oysters) (Raphael, 1976). It contains many different types of coastal habitats that play an important role in keeping coastal ecosystems sustainable and protecting coastal bio-diversity such as estuaries and lagoons, mangroves, sea grass beds, salt marshes, coral reefs, and extensive stretches of beach and dunes.

Gross Domestic Production (GDP) and Exporting Trend

The contribution of the fishing industry to the nation's GDP has been 1% in 2020 and 2021 (CBSL, 2021). While inland fish production increased by 2.4 % to 104,000 MT in 2021, marine fish production declined by 1.5% to 332,000 MT. Marine fish accounted for 76% of overall fish production in 2021. There has been a significant impact on marine fishing in recent years due to deep-sea drought and substantial postharvest losses (CBSL, 2021).

In recent years, the fisheries sector's export revenue has increased steadily and currently account for around 2% of GDP. Sri Lanka exports both fresh and frozen fish (fin fish, crustaceans, mollusks, and aquatic invertebrates). A rise from 2019 and 2020 export revenues led to a total of 316 million US dollars in 2021 (Annual Performance Report, 2021). Tuna accounts for 51.5% of Sri Lanka's overall exports of fish and fisheries goods. The export market in Europe accounts for 16.7%, Japanese market for 3.7%, United Nations for 36.6%, and the rest of the world for 43.3%. With regards to the international markets, the European Union accounts for 36% of Sri Lanka's fish exports, followed by the United States of America (27 %), and Japan (27%) (Annual Report-CBSL, 2017). In addition, the fast-expanding potential for fish exports has yet to be fully explored in light of the recent easing of the export prohibition on fish and fisheries goods to European Union nations and the GSP tax assistance granted by the United States of America to Sri Lanka. Moreover, according to the Ministry of Fisheries, fish exports climbed by 25.6% in terms of volume and by 58.6% in terms of rupees in 2021 after the European Union lifted its restriction on fish exports in 2016. In addition, fish shipments to Sri Lanka decreased by 34.5% between 2020 and 2021 (Annual Report-CBSL, 2017).

Types and Volume of Fish Waste

More than 50% of fish tissues, including fins, heads, skin, and viscera are estimated to be discarded. The annual disposal from the world's marine fisheries exceeds 20 million tons or 25 % of the total catch. These discards consist of "non-target" species, fish processing byproducts, and garbage (Caruso, 2016). These discards account for 5.2 million tons annually in the European Union (Mahro and Timm, 2007). The number and species composition of fisheries wastes vary by fishing region, resulting in a highly varying total amount of discarding. Similar to the majority of food businesses, the primary source of fish waste is fish processing activities which generate several types of waste. It is possible to generate wastes that are either solid (fish carcasses, viscera, skin, and heads) or liquid (washing and cleaning water output, blood from drained fish storage tanks) (Ariyawansa, 2013). During the processing of fin fish, roughly one-third of the weight is preserved as edible components such as fillets while the other two-third is wasted mostly as guts and frames (Knuckey *et al*., 2004). Depending on the kind of final product, the processing of shrimp also produces 20 - 25% waste. Fish that has decomposed to an unsuitable degree for human consumption may emit waste (Ariyawansa, 2013). Fish wastes may be used to create a variety of by-products and value-added products such as food supplements (proteins, gelatin, and shark fin soup), feed, medications (chitin, liver oil, calcium, and Isinglass), and fish leather (Arvanitoyannis and Kassaveti, 2008).

Due to the increasing trend in Sri Lankan fish production, the waste from the fish industry is also increased simultaneously, which is estimated to be around 40-45 % of total production. There are no any distinct studies done to explore fish waste generation in Sri Lanka. The Colombo central fish market in Sri Lanka generates about 4MT fish waste daily (Ariyawansa, 2013). The main factors attributing to fish waste generation are poor onboard fish handling, improper storage facilities in multiday fishing, catching methods, type of fishing gear used, percentage of by-catch, poor post-catching technology to store the fish, and lag time between the catch and marketing. According to Ariyawansa (2013), post-harvest losses of edible fish materials in Sri Lanka owing to inappropriate handling are around 25% of total fish fate generation, as measured by declining quality indicators.

Disposal Methods

Historically, fish byproducts were often dumped as rubbish, given directly to aquaculture, livestock, and pets or employed as silage and fertilizers. Other species collected inadvertently (by-catch) that have minimal value are either kept and sold or dumped overboard with fish processing waste (Ariyawansa, 2013). Even recreational anglers toss a high number of non-target and target fish overboard (Islam *et al*., 2021). In other nations, disposal of by-catches are not used but instead burned or thrown at the ocean, producing environmental issues (Bozzano and Sarda 2002). The majority of fish processing industries are disposing their processing wastes to the contractors or directly to municipal garbage collection. The contractors and municipal garbage wastes utilize those for landfilling purposes. Only a few industries utilize solid fish wastes to produce fish meal being used for animal feed production (Ariyawansa, 2013). There was no evidence found regarding the fish oil extraction and fish silage production from the fish wastes. Stronger regulations are being imposed, and new disposal methods are needed since fish wastes (both solid waste and wastewater) might be a substantial source of protein, lipids, and minerals with high biological value (Rebah and Miled, 2013).

Magnitude of the Problem due to Fish Wastes

The waste and by-products from fish processing may accumulate to significant levels, which is bad for the ecosystems. Additional effluents are produced while cleaning equipment and flushing away the offal with spray water. Low-value fish by-products are routinely dumped in landfills or flushed back into the ocean (Alfio *et al*., 2021). Large amounts of landed fish are currently being lost or discarded between landing and consumption, posing a significant economic and environmental risk in most fish distribution networks (Coppola *et al*., 2021). Changes in the composition of communities and the variety of benthic assemblages might result from the disposal of organic wastes (Arvanitoyannis and Kassaveti, 2008). Because of this, scavenger fish species have an easier time finding food, and if the concentration is high enough, it might lead to local anoxia of the seabed ecosystem (Garcia, 2003). Some of them are consumed by seagulls, while the remainder may be eaten by benthic scavengers. More dogfish (*Scyliorhinus canicula*) are being thrown back into the ocean because of overfishing in northern Spain, while more *Raja radiata* are being thrown back into the ocean because of overfishing in Greenland shrimp fisheries (Garcia, 2003). For certain seabird species, the availability of discards as a food supply is credited with growth in that population which can affect the ecosystem balance (Votier *et al*., 2004). According to research by Gremillet *et al*. (2008), fisheries debris is essentially unhealthy junk food for gannets which stunts the development of their young.

Substantial amounts of organic matter will be generated due to the disposal of fish wastes back to the oceans, where they may change the ecosystem by increasing nutrient and oxygen demand (Garcia, 2003). Organic matters are sensitive to bacterial breakdown. As a consequence, biological oxygen demand (BOD) level increase, and so does the water's oxygen concentration. High organic loading from discards has been linked to oxygen depletion in New Zealand hoki (*Macruronus novaezelandie*) fisheries as well as the North Eastern Atlantic (Goi, 1998). Anaerobic decomposition of organic matter results in the breakdown of proteins and other nitrogenous compounds releasing hydrogen sulfide, ammonia, and methane, all of which are potentially hazardous to the ecosystem and toxic to marine organisms (Islam *et al*., 2004). Plant growth is promoted by nutrients generated from decaying organic waste and excessive plant growth, along with oxygen depletion, may result in changes in ecosystem structure, both of which are features of eutrophication (Islam *et al*., 2004). A study conducted near to the fishery harbors revealed that the BOD of the of sea water were higher than recommended value (<4 mg/L) of environmental quality standards by Central Environmental Authority of Sri Lanka due to the organic matter accumulation of improper fish waste disposal (Weerasekara *et al*., 2015). Furthermore, Hettige *et al*. (2014) reported that sea water of western province were poor in quality in terms of BOD due to the improper discharge of organic matter to the sea without any pre-treatments.

Fish populations may initially grow near the location of discharge due to a combination of factors including an increase in food and nutrient availability and the complexity of the surrounding environment. Algal blooms, toxin generation, and low levels of dissolved oxygen are all exacerbated by an increase in nutrients. The long-term effects include a rise in phytoplankton biomass and a general decrease in benthic and fish population diversity (Bonsdorff *et al*., 1997). Consuming water contaminated with algal toxins is fatal for many fish species. It is now well established that eutrophication causes substantial changes in the species richness, structural complexity, and functional integrity of marine ecosystems across large geographic areas. In many cases, eutrophication raises the biomass and productivity of certain types of phytoplankton (Riegman, 1995). The predominant kind of phytoplankton has changed from diatoms to dinoflagellates and the average phytoplankton size has decreased with nanoplankton is dominating (Kimor, 1992). The loss of recreational water usage infrastructure is another potential problem brought on by the massive discharge of processing fish wastes and debris. The geographical and temporal scale of the consequences of seafood processing discards may vary depending on the volume and kind of waste produced. However, the consequences are felt most acutely on a local basis since processing firms often generate effluent throughout the year, leaving little time for the ecosystem to recuperate. When trash from many processing plants is deposited in the same location, negative impacts are more likely to occur (Islam *et al*., 2004).

In Sri Lanka, the Marine Pollution Prevention Act No. 35 of 2008 is the national legislation to prevent and control marine pollution. The marine environmental protection authority under the Ministry of Mahaweli Development and Environment implements the provisions of this Act (Kularatne, 2020). The negative impacts of fish by-products/discards on the environment may be reduced if the material is recycled into useful goods using cutting-edge technology. Protein, fatty acids, and minerals may all be found in fish by-products and by-catch. The skin of many fish species is a significant protein source; other parts, such as the trimmings and bones are rich in calcium and the head, intestines are rich in lipids (Kandyliari *et al*., 2020). Fish by-products are a growing and reliable source of high-value bio-compounds for biotechnological and medical uses because of their high concentrations of collagen, peptides, chitin, polyunsaturated fatty acids (PUFAs), enzymes, and minerals (Shahidi *et al*., 2019). In addition, fish wastes may be recycled into useful products including fishmeal, fish oil, fish silage, fertilizer, and biodiesel/biogas, which would be a welcome relief to the problem of fish waste. Fish waste has a wide variety of potential applications including but not limited to animal feed, food packaging, , dietary supplements, natural pigments (after extraction), enzyme isolation, moisture maintenance in foods (hydrolysates), and most importantly a sustainable and alternative source of fish collagen (Subhan *et al*., 2021).

Fish Waste Biopolymers

Fish by-products contain relatively large concentrations of biopolymers. The discarded materials from fishery industry have attracted attention over the last decades, triggering researchers to develop methods to process them into useful products, making the most of their biochemical heterogeneity. The most common products currently derived from fish by-products are collagen, chitin, and gelatin.

(i). Collagen

Biomass obtained from the fish-processing industry and fisheries in particular fish and sea urchin wastes, undersized fish, and by-catch creatures such as jellyfish, sharks, starfish, and sponges, might become a substantial, but an underused source of collagen (Rodrguez *et al.,* 2018). Utilizing waste and underused biomass will aid in the development of a sustainable path for generating collagen with a considerably reduced environmental impact (Coppola *et al*., 2020). Collagen is the most prevalent animal protein as it may be found in all connective tissues including skin, bones, ligaments, tendons, and cartilage as well as interstitial tissues of parenchymal organs (Coppola *et al*., 2020). There are 28 distinct forms of collagens found in nature while type 1 is the most frequent and plentiful (Weng *et al*., 2015), as well as the primary component of marine collagen. Collagen from fish waste could also find application in the food industry in terms of food Packaging. Typically, fish discards or by-products, particularly the skin has a substantial quantity of protein, the majority of which is collagen (Silvipriya *et al*., 2015). In addition to the food industry, pharmaceutical and biological sectors, fish collagen is a possible alternative for its human equivalent. The yield and characteristics of collagen depend on the source and extraction technique of the raw material. The fish collagen includes a greater quantity of the amino acids serine and threonine than human collagen (Hashim *et al*., 2015). Low levels of glycine, proline, and hydroxyproline contribute to marine collagen's low denaturing temperature (Subhan *et al*., 2015). Several physical treatment methods such as ultraviolet irradiation, dehydrothermal treatment, and chemical treatments such as glutaraldehyde, carbodiimide, and 1-ethyl-3-(3-dimethyl- aminopropyl) have been used to improve the strength and stability of collagen (Hayashi *et al*., 2012; Subhan *et al*., 2021).

(ii). Chitin and Chitosan

Chitin (Beta-(1-4)-poly-N-acetyl-D-glucosamine) is the second most common polysaccharide found in nature after cellulose (Elieh-Ali-Komi and Hamblin, 2016). There are three naturally occurring crystalline structures of chitin distinguished by the number of chains per cell, degree of hydration, and unit size (Lionetto and Corcione, 2021). Shrimp and crab shell wastes have been widely used to separate chitin from many types of crustaceans (Alabaraoye *et al*., 2018). As a result, the production of value-added items such as chitin, chitosan, and their derivatives as well as their use in a variety of sectors is critical. The use of chitin and chitosan in several aspects of the food industry has sparked considerable attention (Shahidi *et al*., 1999). Chitosan has extremely low toxicity when chitin is deacetylated to approximately 50 (Hudson and Jenkins, 2002). The antibacterial and antifungal characteristics of chitin and chitosan have the potential to minimize the number of synthetic food preservatives used. N,O-carboxymethylated chitosan, a water-soluble derivative, has antifungal properties as well. Marine extract chitin/chitosan's most likely application methods are either package wraps or direct food coatings (Hudson and Jenkins, 2002). Chitin and chitosan films are superior to synthetic wraps because of their decreased oxygen permeability and enhanced moisture transfer. Chitosan films have also reduced browning in fruits that have been physically damaged (Hudson and Jenkins, 2002). Chitin and its derivatives have several biological applications in the field of therapeutics including anti-inflammatory, antioxidant, antibacterial, immunity-boosting, anti-cancer, and drug transport actions (Villamil *et al*., 2017).

(iii). Gelatin

Gelatin is a denatured protein formed by partly hydrolyzing collagen and then heating it (Mohammed, 2020). During hydrolysis, the natural molecular links between individual collagen strands are broken-down resulting in a combination of single or multistranded polypeptides, each with extended left-handed helix conformations and comprising 50-1000 amino acids (Coppola *et al*., 2020). Acid and alkaline hydrolysis yield type A and type B gelatins, respectively (Coppola *et al*., 2020). There is a lot of interest in extracting and utilizing gelatin from fish waste because of religious and health concerns regarding disease transmission to people (Etxabide *et al*., 2017). Gelatin is a well-known commercial biopolymer having gelling and film-forming characteristics that make it valuable in food, pharmaceutical, and other related industries (Pal and Suresh, 2016). It has been proven that gelatin films created from cold-water (cod, salmon or Alaska pollack) and warm-water (tilapia, carp or catfish) fish species have markedly different mechanical and water vapor barrier capabilities due to changes in amino acid compositions. This is connected largely to the amino acid concentration which impacts the melting point of fish gelatin and therefore the manufacturing process (Gómez-Guillén *et al*., 2009). In general, the amino acid content of cold-water fish gelatins is lower than that of mammalian gelatins. As a result, these fish gelatins have lower melting points which may be advantageous in the thermo-mechanical manufacture of fish gelatin-based products due to lower energy consumption and cost, thereby increasing their commercial viability (Caba *et al*., 2013). Fish gelatin formed from warm-water fish, on the other hand, may have improved heat stability, which may be advantageous in some applications. Possible species of fish waste sources and the extracted biopolymers are listed in the Table 1.

Table 1. Sources of fish by-products and produced biopolymers

Biopolymer	Byproduct	Sources	Reference
Gelatin	Skin	*Thunnus albacares, Priacanthus hamrur*	Nurilmala *et al*., 2020 Rajasree *et al*., 2020
	Scale	*Katsuwonus pelamis*	Qiu *et al*., 2019
Chitin/Chitosan	Scales	*Cyprinus carpio*	Zaku *et al*., 2011
		Labeo rohita	Kumari and Rath, 2014 Kim *et al*., 2001 Muslim *et al*., 2013
		Oreochromis niloticus	Alcalde and Fonseca, 2016
		Chlorurus sordidus	Rumengan *et al*., 2017
			Rumengan *et al*., 2017
		Lutjanus argentimaculatus	Takarina and Fanani, 2017
		Lutjanus sp.	Irawan *et al*., 2018
Collagen	Skin	*Tilapia, Salmo salar, Oreochromis niloticus,*	Li *et al*., 2020, Hoyer *et al*., 2012
	Scale	*Lophius litulon*	Ge *et al*., 2020
	Cartilage	*Oreochromis* sp., *Larimichthys crocea*	Xu *et al*., 2020, Feng *et al*., 2020
		Carcharhinus albimarginatus	Jeevithan *et al*., 2014

Extraction Techniques

(i). Collagen

Many extraction processes are feasible depending on the marine source. However, the conventional method for separating collagen entails preparation, extraction, and recovery. The majority of preparations are comprised of washing, cleaning, separation of animal parts, and size reduction by cutting or mincing the samples to permit further processing (Fig.1) (Jongjareonrak *et al*., 2005). Following preparation, a minor chemical pretreatment is performed to improve extraction effectiveness and remove non-collagenous components. A number of pretreatments may be performed depending on the raw material and extraction technique (alkaline or acid treatment). Because cross-linked collagen is present in animal connective tissue, pretreatment with a diluted acid or base prior to extraction is employed to destroy cross-linked collagen (Schmidt *et al*., 2016). Indeed, some hydrolysis occurs, preserving the collagen chains (Schmidt *et al*., 2016).

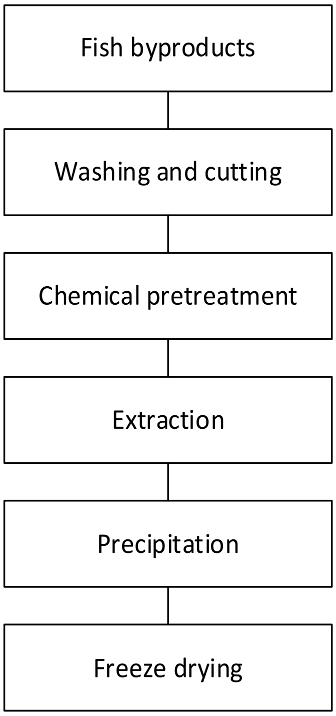

Figure 1. Collagen extraction process (Adapted from Jongjareonrak *et al*., 2005)

(ii). Chitin and chitosan

Chitin is commonly recovered from fish waste using three basic steps: demineralization (calcium carbonate and calcium phosphate separation), deproteinization (protein separation), decolorization (pigment removal), and deacetylation (remove acetyl groups). Chitin is found in crustaceans and shellfish as part of a complex protein network onto which calcium carbonate deposits form the hard shell. To remove chitin from shellfish, two primary constituents, proteins and inorganic calcium carbonate must be deproteinized and demineralized. Several methods for producing pure chitin have been developed and implemented throughout the years, but none have gained widespread acceptance. Chemical or enzymatic treatments may be used for both deproteinization and demineralization (Fig.2). The three phases are the standard technique for generating chitin. Deacetylation of chitin to chitosan is often achieved by treating chitin with a 40-50 percent sodium hydroxide solution at 100°C or higher to remove part or all of the acetyl group.

- **Chemical Method:**

Chemical Deproteinization: Chemical deproteinization process is performed to depolymerize the biopolymer in a heterogeneous manner using chemical means. Several chemicals are being used as deproteinization reagents, including NaOH, Na_2CO_3, $NaHCO_3$, KOH, K_2CO_7, Ca $(OH)_2$, Na_2SO_3, $NaHSO_3$, $CaHSO_4$, Na_3PO_4, and Na_2S. In addition to deproteinization, NaOH causes partial deacetylation of chitin and hydrolysis of the biopolymer, lowering the molecular weight of the biopolymer (Younes and Rinaudo, 2015).

Chemical Demineralization: The most typical technique for removing minerals and calcium carbonate from chitin is acid treatment with HCl, HNO_3, H_2SO_4, and CH_3COOH. The breakdown of calcium carbonate into water-soluble calcium salts while simultaneously releasing carbon dioxide makes demineralization an easy process. These treatments are influenced by the degree of mineralization of each shell, extraction length, temperature, particle size, acid content, and solute-to-solvent ratio. Due to the fact that it takes two molecules of HCl to convert one molecule of calcium carbonate into calcium chloride, calcium chloride is reliant on acidity (Shahidi and Synowiecki, 1991).

- **Biological Method:**

Biological Deproteinization: Numerous investigations have revealed that bacterial proteases aid in the deproteinization process. One example is the enzymatic deproteinization of previously demineralized shrimp waste to produce chitin and nutrient-dense protein hydrolysate. Alcalase, a serine endopeptidase generated by *Bacillus licheniformis* was employed for deproteinization because of its selectivity for terminal hydrophobic amino acids which results in a non-bitter hydrolysate and allows for simple adjustment of the degree of hydrolysis (Joseph *et al*., 2022). Fermentation which may be accomplished by endogenous microorganisms (also known as auto fermentation) or by introducing specialized strains of microbes can reduce the cost of employing enzymes. This approach may use single-stage, two-stage, co-fermentation or sequential fermentation. A variety of microorganisms have been proposed for crab shell fermentation. Lactic acid fermentation and non-lactic acid fermentation are two types of fermentation that can be used (Arbia *et al*., 2013).

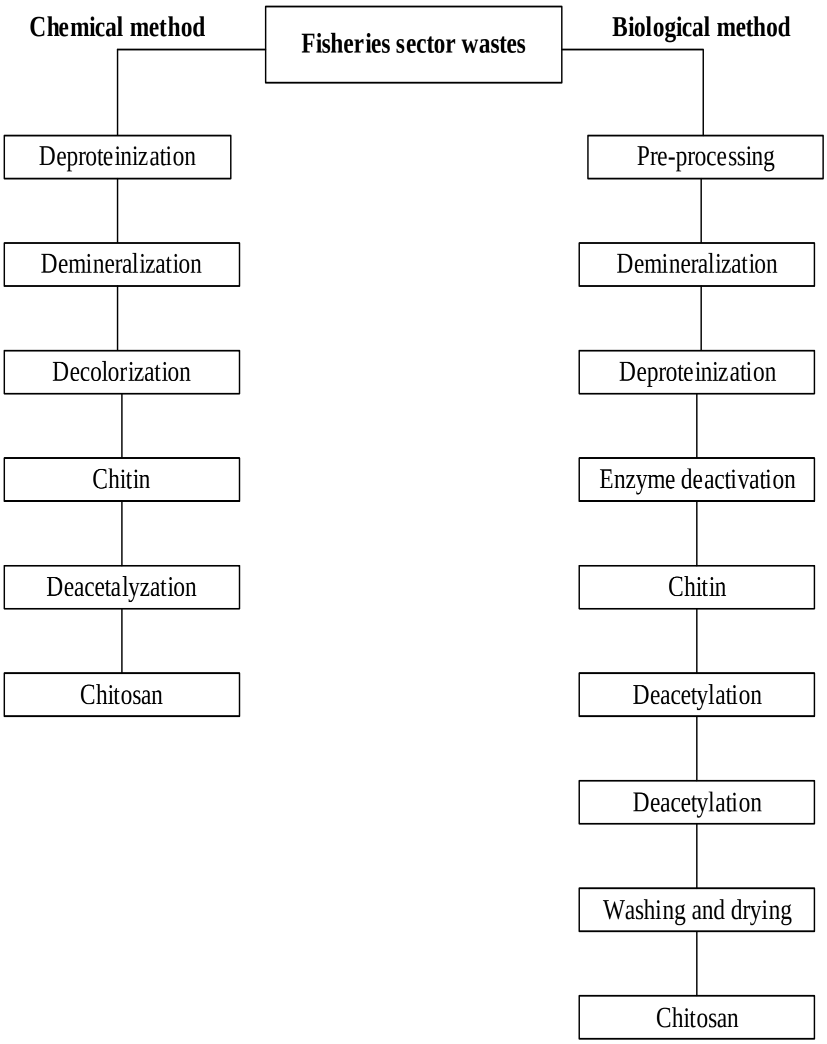

Figure 2. Chitin and chitosan extraction process (Adopted and modified from Hamed *et al.,* 2016)

(iii). Gelatin

Gelatin-based biopolymer films are gaining popularity as edible food packaging due to their biodegradability (Olden *et al*., 2020). Significant changes in the physical and chemical properties of gelatin have been reported after being subjected to chemical treatments such as acylation, esterification, deamination, cross-linking, and interactions with acids and bases (Gómez-Estaca *et al*., 2016). Thermoreversible gels may be made by cooling an aqueous solution of gelatin at a concentration greater than 0.5% to about 35-40 °C. The gelatin content, structure, molecular mass, pH, temperature, and presence of additives all contribute to the gel's stiffness or strength. Collagen and gelatin are typically processed using a wet (or solvent) process, which involves dispersing or solubilizing the protein in a solvent, depositing the material using film casting, compression molding, extrusion, etc., and then removing the solvent, either by drying the material or by employing a solvent-non solvent exchange mechanism (Gómez-Estaca *et al*., 2016). One or more plasticizers are commonly utilized to control the rheological features during processing and to maximize the final qualities, notably the deformability (Gómez-Estaca *et al*., 2016). Gelatin extraction process is elaborated in Fig.3.

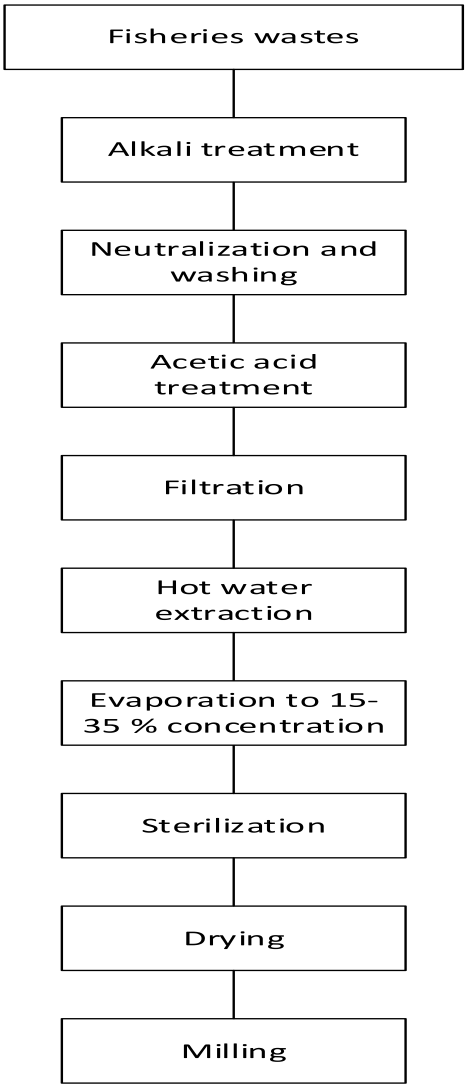

Figure 3. Gelatin extraction process (Adapted and modified from Boran and Regenstein, 2010; Muhammad *et al*., 2016)

Fish Waste-based Active Packaging

Most packaging nowadays is made from disposable plastics, which is a major contributor to environmental pollution. Polymers made from fish waste are a viable alternative to synthetic polymers to make bioplastics that are either bio-based or bio-degradable (Claverie *et al*., 2020). From time to time, the phrases "biopolymer" and "bioplastic" have been used interchangeably to refer to a broad variety of polymers with diverse properties and functions (Jariyasakoolroj *et al*., 2020). Some bio-based polymers such as bio-based polyethylene are not biodegradable while being made from renewable resources like starch and cellulose (Ferrari *et al*., 2019). One of the greatest challenges facing scientists today is the development of biodegradable packaging materials that can protect food from oxidative deterioration and UV radiation as well as restrict microbiological growth, without sacrificing the product's physical and mechanical qualities. Controlled release of the active component which protects against spoilage microorganisms is achieved by combining active food protection agents with film-forming material.

Active Packaging from Fish Waste Derived Biopolymers

Collagen is employed both in its natural state and as collagen biomaterials in the food industry (Timorshina *et al*., 2020). A comparable or slightly lower molecular weight and denaturation (melting) temperature characterize marine collagen compared to mammalian collagen. Collagen membranes have the ability to contract and expand, making them a potential candidate for use as edible enteric coatings in the meat processing industry (Ahmad *et al*., 2016). Marine collagen may be made more heat-resistant with the application of appropriate crosslinking methods. The advancement of collagen membranes has been impeded by their poor heat stability, poor mechanical properties and hydrophilicity. Collagen films are often prepared using plasticizers, most commonly glycerol at concentrations between 20 and 30 weight percent. However, as a result of weakening attractive intermolecular interactions along polymer chains, these small, low-volatility molecules increase free volume and chain mobility (Lionetto and Corcione, 2021). Numerous efforts have been made by researchers to find solutions to these problems. Studies have shown that collagen casings' mechanical properties and antibacterial activity against *Escherichia coli*, *Staphylococcus aureus*, *Bacillus subtilis*, and *Salmonella* are considerably improved when antibacterial tea polyphenols are added (Xie *et al*., 2020). Cross-linking collagen with proteins that are resistant to heat is another way in which its structure may be modified (Wu *et al*., 2017). The biopolymer-based packaging material’s thermal stability, tensile strength, elongation strength at break, and fourier transform infrared spectroscopy could be improved by crosslinking collagen with heat-resistant proteins (Wu *et al*., 2017).

The biodegradable food packaging material is made from a functional oligosaccharide like chitin/chitosan that has great film-forming characteristics. Chitosan is widely used in the manufacturing of films with high resistance to water absorption (Mujtaba *et al*., 2019). Intermolecular hydrogen bonding or electrostatic interactions between polyphenolic compounds and the hydroxyl or amino groups on the chitosan chain may alter the functional properties of chitosan to withstand the water absorption. Furthermore, incorporating montmorillonite into chitosan enhances its oxygen barrier properties, making it more effective in delaying the oxidation of perishable foods. The nanoparticles also increased their UV-blocking capabilities, which means that food may be stored for longer. The film-forming polymer chitosan is ideal for incorporating such an addition (Mujtaba *et al*., 2019). The effect of active substances such as plant extracts and nanofillers on the functional characteristics of chitosan films has been the subject of a number of studies (Mir *et al*., 2017; Aider *et al*., 2020). Chitosan derivatives having a wide range of properties are utilized in food industries to develop packaging materials that do not smell or cause any damage (Flórez *et al*., 2022).

Marine gelatin has been utilized by several researchers for developing active packaging materials. Active warm-water fish gelatin film with an oxygen scavenging system was created by Byun et al. (2012) by adding α-tocopherol and iron chloride nanoparticles which makes use of oxygen scavenger mechanisms, in an attempt of decreasing the amount of oxygen present in packaging. It is also important to prevent the buildup of ethylene in packaged foods in order to lengthen their storage time and keep their quality consistent. Because it is not consumed in the process, TiO2 has an infinite potential to scavenge ethylene, unlike traditional scavengers and it has potent antibacterial action (Nataraj et al., 2014). Therefore, antimicrobial packaging with ethylene absorbers made of gelatin sheets containing TiO2 nanoparticles (Nataraj et al., 2014).

Application Methods/ Casting Methods

(i). Electrostatic Spinning Technology

Electrospinning is a versatile technique for continuously producing nanofibers with a fiber diameter range from sub-nanometers to micrometers. The positively charged polymer solution is pushed via a syringe at high voltage, the droplets form a Taylor cone owing to the presence of elongational viscosity resulting in a continuous and stable jet. This non-thermal processing method is known as electrostatic spinning (Leidy and Ximena, 2019). One of the simplest and most effective methods for preparing nanofibers at this time is electrostatic spinning technology because it can effectively protect thermally unstable active substances, has less impact on bioactive substances, and does not require strict environmental conditions like temperature, pressure or chemical substances (Gagaoua et al., 2022). By using an electrostatic spinning technique, polymers may generate nanofibers with a higher specific surface area which is useful for making nano complexes.

(ii). Three-dimensional Printing Technology

The use of Three-dimensional (3D) printing has allowed for the development of more complex foods based on user preferences while also reducing material waste. Common 3D printing processes include stereolithography and extrusion-based printing. Extrusion-based 3D printing is widely used to create prototypes of sensors, indicators, and tags for use in the food packaging sector (Coppola *et al*., 2020). Making use of data from 3D mathematical models, 3D printing creates the desired thing swiftly and accurately by physical stacking (Pal *et al*., 2016). Extrusion-based additive manufacturing or fused deposition model for short, refers to the process of creating 3D models by depositing material layer by layer. With the help of a heated nozzle, a filamentous material such as thermoplastic is deposited along a predetermined path. The completed layers are dropped into a stack when the table is lowered (Coppola *et al*., 2020).

Innovative Facts

Compared to food packaging made from a single material, composite packaging will have better mechanical properties, water resistance, and oxygen barriers. Compound modification has been a significant topic of research in recent years. In this process, two or more polymeric molecules are mixed such that their effects might complement one another. Although biopolymers containing natural active ingredients are the most common kind of active food packaging, it is important to choose the appropriate components with caution (Yilmaz *et al*., 2022). The presence of unpleasant scents from the active compounds may reduce the organoleptic quality of the product despite the fact that the inclusion of certain active chemicals may have antibacterial and antioxidant effects. Natural polyphenolic compounds such as curcumin, anthocyanins, gallic acid, and catechins are used in the creation of biopolymer-based active packaging films (Roy *et al*., 2022). Adding indicators to smart active packaging materials will assist in the monitoring of food safety, and active chemicals like crosslinkers, plasticizers, and antimicrobial agents will improve the functional properties of packaging materials in many ways.

Requirements and Special Features

Since the use of synthetic packaging films has led to significant environmental concerns, biodegradability is one of the most important technical characteristics of biopolymers created from fish leftovers. One of the most important features of packing material is its capacity to allow water vapor to pass through without allowing oxygen to enter and spoil the food. It depends on the film's porosity and permeability, which shift with changes in temperature, pressure, and humidity. Because dry goods and fruits and vegetables need films with extremely low and moderate water vapor permeability to minimize ambient moisture absorption, the water vapor permeability level is application-specific. Strong oxygen barriers in films and coatings protect food against oxidation by keeping it from coming into contact with air, which may cause discoloration or surface softness (Caba *et al*., 2019). In terms of oxygen barrier qualities, it is well known that highly unsaturated dietary lipids, like those present in fish and shellfish, suffer a substantial drop in quality due to oxidation, as demonstrated by the appearance of off-odors, off-flavors, nutritional losses, and color or textural degradation (Caba *et al*., 2019). The ability to control film thickness is vital for the creation of films that are suitable for use in food applications since it impacts the films' final performance (mechanical, water vapor permeability, light transmission, and transparency) (Kaewprachu *et al*., 2016).

Materials used in food packaging must meet strict standards including those for acceptable sensory attributes, biochemical, physicochemical, and microbiological stability, toxin-free status, and safety. Natural polymers (typically produced from solutions comprising biopolymer, plasticizer, and solvent) are perfect in every way since they are biodegradable and harmless to the environment. Their permeability and mechanical properties typically fall short of those of synthetic polymeric materials. As a result, it is becoming increasingly important for the food industry to have access to biodegradable packaging films that not only have excellent thermal and barrier properties but also remarkable mechanical properties, allowing them to extend the shelf life of food products by shielding them from unwanted contamination. Therefore, biopolymers are currently advocated as a green alternative to petrochemical polymers due to their low cost, high renewability, and easy accessibility (Bocqué *et al*., 2016). Several scientists are looking at the viability of producing biopolymers with the optical, barrier, and mechanical properties required for food packaging (Caba *et al*., 2019). By incorporating active agents into packaging polymers, food packaging with antimicrobial and/or antioxidant properties may remove or limit microbial growth and delay the oxidation of pigments and lipids contained in food (Bocqué *et al*., 2016). To some extent, this kind of "active packaging" may help reduce the monetary costs associated with perishable food spoilage. Increased customer satisfaction may be achieved via better visual appeal which is achieved mostly through the transparency and gloss of packing sheets (Caba *et al*., 2019).

Concept of Fish Waste Derived Active Packaging for Blue Economy in Sri Lanka

Blue Economy is a marine-based economic development that leads to improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities (Everest-Phillips, 2014). The term "Blue Economy" was coined by Gunter Pauli, who published a book in 2010. The theory of Blue Economy was presented with two concepts. First, nature's efficiency, in which the blue economy imitates the natural ecosystem and functions in line with what nature offers effectively, not reducing but rather enriching environment. The second concept is zero waste which implies that trash from one source becomes food or energy for another allowing the ecosystem's living systems to become balanced and sustained (Rani and Cahyasari, 2015). Fishery discards can give a significant contribution to the economic transition and an optimal solution for fisheries-based industry as well as a useful tool for a blue economy towards the zero-waste goal (Nawaz *et al*., 2020). Recently, it has been proven that blue economy approach can be successfully applied to the seafood industry reusing by-products. This approach could be in principle extended also to fishery by-catch contributing to finding eco-friendly solutions for the environmental and economic issues of the planet.

It's estimated that byproducts from processing fish and seafood, mostly shells and bones, contain 50-70% of the original material composition (Sayari *et al*., 2016). There is value in this biowaste, but it will need research and new ideas to realize it.

Negative effects on marine life have also been related to the inappropriate disposal of fishery wastes to the environment. Further, collagen, chitin/chitosan, and gelatin films generated from marine resources are some examples of biodegradable bioplastics that are of interest due to the concern on the environmental pollution. The sustainable production, provision of services, and all other activities related to the use and protection of marine and coastal resources may help Sri Lanka develop a blue economy via the valorization of fish byproducts. Waste valorization is a key-principle and a crucial driver towards a virtuous waste management system, zero-waste production, and an ever-more circular blue economy. It promotes economic growth by minimizing the depletion, loss of biodiversity, and pollution of marine resources. The most important challenges facing the blue economy in terms of sustainable management include the restoration, protection, and preservation of biodiversity, productivity for resilience, core system, and intrinsic value of marine ecosystems (World Bank, 2020).

Marine biopolymer-derived active packaging has a higher function than regular plastic since it helps preserve the goods for longer. The environmental impact study has to include the expanded capacity's potential to reduce retail and maybe, consumer waste (Zhang *et al*., 2015). Environmental benefits from avoided waste and the emissions associated with its disposal, both at the raw material supply end and at the retailer, are expected to add significant value to this type of packaging due to biopolymer films are already demonstrating superior performance compared to conventional plastic films. However, in most cases, selection and availability of unique technology for valorization, manipulation and casting/application of active packaging for food products are the important limitation in this sector. Further, the cost of processing can increase the final product, as a result it may end up with less market demand. Therefore, a trade-off between several technologies has to be applied to obtain the best environmental and economical solution.

Besides, fish meal and fish silage production serve a significant role in fish waste utilization, there is a severe concern over the microplastic accumulation in marine organisms and the transmission of microplastic through the food chain (Tanaka and Takada, 2016). Nowadays, several meals (soya meal, blood meal, poultry by-product meal, and cotton meal) replaced fish meal and fish silage as animal feed. Therefore, scientists are looking forward with innovative solutions for fishery wastes. Biopolymer extraction from fish wastes could be a possible solution for microplastic accumulation in the food chain and declining trend for fishmeal demand. A considerable amount of money has been spent annually on marine environmental reconstruction to overcome pollution. Instead, there is a huge economic potential for marine discards if those are utilized properly. Moreover, there are several export potentials for biopolymer derived active packaged food products in the global market.

The Sri Lankan government has been very vocal about their desire to advance the Blue Economy in international forums. Furthermore, Sri Lanka and Indonesia as for the blue economy, partnerships have been formed. Therefore, Sri Lankan government should formulate the policy discussions and national acts to promote the blue economy by the way of utilizing and treating marine waste into economically beneficial techniques such as marine bio-polymer derived active packaging systems. Lack in local research in this field is of serious concern to achieve these objectives. Furthermore, inadequate technologies and funding potentials raise another concern. Innovative and modern research projects should be promoted by the government policy discussion. National and state universities would be key drivers in achieving the blue economy by utilizing the fish wastes in an effective manner. Against this backdrop, we may suggest that joint knowledge in sharing and collaborative research studies with technologically advanced countries and personnel from these fields would be a possible solution to overcome these shortcomings.

Conclusions and Future Prospects

The post-pandemic economic crisis has drastically affected the country's economy. As a solution, several proposals and recommendations have been proposed to several sectors by experts to overcome the economic crisis. The concept of blue economy is adopted in several countries to boost their economy while achieving sustainable development of marine resources. Therefore, transforming problems into potential benefits is a key that is discussed under blue economy concept. From this viewpoint, fish waste valorization could be a possible solution to overcome such issues while boosting the economy by developing marine biopolymer-based active packaging systems. Furthermore, the concepts of this study could be useful for future policy decision and amendments related to marine waste-related issues and advancements of blue economy.

Conflict of Interest

Authors have declared that no competing interests exist.

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Importance of Seagrass Restoration to Uplift Small-Scale Coastal Fisheries in Sri Lanka

CHAPTER 10

S.K. Dodampahala

Abstract Seagrasses provide several ecosystem services such as sequester large amounts of carbon from the atmosphere to reduce the effects of climate change, stabilising the coastal lines against erosion, providing refuge for fish, supporting complex food webs and functioning as nurseries for larger groups of pelagic fish and benthic invertebrates. Congregation of various fish species that are of commercial importance have made seagrass meadows vital to the fisheries industry. Seagrass meadows are undervalued in Sri Lankan coastal fisheries, especially in lagoons. However, most of these deeper seagrass meadows found in the subtidal are destroyed due to destructive fishing practices, coastal development and nutrient enrichment which creates artificially induced sedimentation that smothers seagrasses with sediment and algae. Destruction of seagrass meadows in the subtidal has reduced refuges for subtidal fish and marine invertebrates that are native to the area. Seagrass restoration is an effort to retrieve damaged seagrass cover, enhance ecological resilience, improve the survival of biodiversity, and improve the environmental conditions where seagrass meadows are found. This chapter highlights the necessity of restoring seagrass meadows to improve the livelihoods of economically impoverished fishers and improve coastal fish stocks in Sri Lanka.

Keywords: Coastal fisheries, Restoration, Seagrass, Sri Lanka

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Introduction

Seagrasses are monocotyledons collectively found as meadows and have evolved to survive in saline water in lagoons, estuaries, and offshore habitats across the world (McKenzie, 2008). They are characterized by having long leafy blades that give buoyancy to the leaves to facilitate photosynthesis during low and high tide periods. Their rhizomatous stems covered with root hairs anchor the plant to the sediment, giving them protection against coastal erosion and its roots can store carbohydrates and nutrients. Seagrass is found around the world as confirmed by numerous mapping studies, they can occur in tropics, temperate climates, and even polar-artic climates (UNEP, 2020). Currently, the most up-to-date global seagrass area can be estimated to be nearly 300,000 km^2 (UNEP, 2020). Seagrasses sequester carbon dioxide from the atmosphere and function as refugia for many of the world's marine organisms (Waycott *et al*., 2009).

There are only 72 species of seagrass from 6 families i.e., Cymodoceaeceae, Hydrocharitaceae, Posidoniaceae, Ruppiaceae, Zannichelliaceae and Zosteraceae around the world (Short *et al*., 2011). The indo-tropical bioregion has 33% of the world's species of seagrass with each seagrass species occurring in the region based on the level of wave intensity, i.e *Enhalus accroides* appearing when there is low wave action. Due to their large cover and slow growth, they are less likely to recover immediately after disturbance (Unsworth *et al*., 2018). Species such as *Cymodocea serrulata, Halodule uninervis* and *Halophila ovalis* occur temporarily in the area until they are replaced by pioneering species such as *Halodule uninervis* and *Halophila ovalis* (Unsworth *et al*., 2011). Spatial and temporal dynamics of seagrass meadows found in river estuaries, reefs, coast, and deep water can widely vary and can influence seagrass growth, survival, and biodiversity in seagrass meadows (McKenzie *et al*., 2020).

Seagrass meadows provide a wide range of ecological and socio-economic services, such as coastal protection through sediment accretion, act as nurseries for juvenile marine fin fish and marine invertebrates until maturation and as sustenance for marine herbivores, allowing fishers to catch organisms that inhabit seagrasses and serve as attractions for ecotourism (Jiang *et al*., 2020; Jones *et al*., 2021). They are invaluable to low-income small-scale fisher communities which also include traditional fishers that are in proximity to seagrass meadows (Unsworth *et al*., 2018). Despite their importance in the fishing industry, Seagrass meadows around the world are undergoing degradation primarily due to unregulated coastal development, dredging, land reclamation, algal blooms, development of aquaculture industries, mechanical damage from boat anchoring and introduction of invasive marine species (Short *et al*., 2011; UNEP, 2020). Climate change is a well-known cause that is threatening the survival of this keystone species in the next few decades, with some seagrass meadows showing no signs of natural recovery even after the direct threat is removed (Waycott *et al*., 2009).

The decline of seagrass habitats has obvious impacts on global fisheries which further leads to ecological and socio-economic consequences (Cullen-Unsworth *et al*., 2014). While there have been efforts to increase seagrass cover through passive ecological restoration efforts, these efforts have been mostly slow and offer less promise in successfully allowing seagrass recolonization (Fonseca *et al*., 2000; Greening *et al*., 2011). Hence, active seagrass restoration techniques have gained attraction over the years as opposed to passive restoration in rehabilitating degraded seagrass patches. As a result of the development of a restoration policy with adequate resourcing, collective stakeholder accountability, collaborative community participation and knowledge sharing of advancement of species-specific seagrass techniques (Tan *et al*., 2020). Seagrass restoration can ensure the survival of diverse marine organism communities in the intertidal/subtidal zones and rejuvenate existing coastal ecosystem services including fish that utilizes seagrass meadows as nurseries. Other benefits of seagrass restoration include sequestering carbon and nitrogen stocks, low turbidity of the water, and in some cases restored species such as scallops and oysters are co-dependent on seagrasses (Orth *et al*., 2020). Restoration of seagrass meadows undergoing degradation in coastal communities reliant on seagrass meadows is still a novel concept in many parts of the world, despite predicted cost-benefit analyses that have been implemented a few decades ago (Thorhaug, 1990).

Fishing in Seagrass Meadows around the World

Globally, seagrasses play a major role in coastal fishing, especially among small-scale fishing communities (Unsworth *et al*., 2018). However, ecosystem benefits are typically difficult to be quantified as the value of these marine plants is under-recognized among conservation managers and local communities that are in proximity to seagrass meadows despite their inherent socio-economic value (Nordlund *et al*., 2017; UNEP, 2020). Seagrass meadows have been instrumental in helping fishers as vital fishing grounds for a very long time despite new interest to study the relationship between humans and seagrass meadows (Nordlund *et al*., 2018). These marine meadows are prized by fishers for their ability to function as biodiverse nursing grounds for fish and invertebrates for both commercial and subsistence purposes (Cullen-Unsworth *et al*., 2014). However, in many of the global studies done on seagrass-dependent fishing communities, only large fishing groups were easily recorded in using seagrass meadows as information on small-scale and traditional fishing practitioners are typically scarce, harder to track and monitor (Worm *et al*., 2009).

Recent studies have shown some fishers, particularly from low-income households are dependent on seagrass meadows primarily because they do not have the means of investing in motorboats to travel long distances and purchase high-quality fishing gear instead, they rely on low-tech fishing gear, fishing traps and collection by hand to continue their fishing livelihood (Jones *et al*., 2022). Fishers from wealthier households have access to fishing resources and utilize seagrass meadows for low-effort and high-reward fishing, especially in Indonesia, the Philippines and Thailand. In some regions of South-East Asia and South Africa, gleaning fishing or catching marine invertebrates by walking in seagrass meadows during low tide is practised in remote communities and has been continued for several generations dating back to prehistoric times (Hockey & Bosman, 1986; del Norte-Campos *et al*., 2006). Fishers practising gleaning or gleaners catch finfish and invertebrates during fishing seasons and are very selective of meadows to catch their haul; they choose sites with higher invertebrate abundance which often relate to seagrass meadows with complex trophic structures that contain large numbers of finfish and invertebrates (Furkon *et al*., 2020).

In coastal small-scale fishing, gender is a strong indicator of the type of fishing activity done in low-income fishing communities. According to Furkon *et al.* (2020), women are most of the gleaners in invertebrate catching. Yet, there are no additional studies to confirm whether gender alone drove the participation of low-income fishers to fish in seagrass meadows. Seagrass meadows are viewed as an alternative fishing ground or a contributor of adaptive capacity in events when fish stock is scarce due to the intensification of fishing and human impacts on oceans (Halpern *et al*., 2015). A study by Jones *et al*. (2022) found that apart from the reliability of seagrass meadows to fish, the equipment largely used in seagrass fishing is minimal and does not strain fishers' financial resources. However, communities that are financially stable with motorboats and specialized fishing gear are more likely to shift fishing in seagrass meadows to offshore fishing where overfishing of finfish is present which consequently affects the health of seagrass meadows in nearshore environments (Silas *et al*., 2020). Other forms of indirect damage to seagrass meadows are caused by the advancement of aquaculture technologies in bivalves and seaweeds that involve mechanical seagrass clearing (Herrera *et al*., 2022).

Seagrass Meadows in Sri Lanka

There are 15 species of seagrass from 9 genera found in Sri Lanka. *Enhalus acoroides*, *Halophila decipiens*, *H. beccarii, H. ovalis*, H. *stipulacea*, *H. minor*, *H. major*, *H. ovata*, *Thalassia hemprichii*, *Cymodocea rotundata*, *C. serrulate*, *Halodule univernis, H. pinifolia*, *Ruppia maritima and Syringodium isoetifolium* are found in the north, north-east and eastern coasts of Sri Lanka (Udagedara and Dahanayaka 2017). They all extend to 37,137 ha of the country's coastline. The country has a rare species of seagrass, *Halophila beccarii* which is now vulnerable and found only in a few localities (IUCN, 2021). There is very limited information documented on seagrass meadows in Sri Lanka and only a few literature have recorded the existing distribution of seagrasses. Their economic value to the country and the fishers that utilize these grounds are not well-understood or not appreciated in the media and public (UNEP, 2020). Previous investigations of seagrass surveying done for Dugong and Seagrass Conservation Project-Sri Lanka have found the presence of seagrass species such as *Enhalus acoroides*, *Cymodacea rotundata*, *C. serrulata* and *Halodule* *pinifolia* (IUCN, 2021) in Palk Bay and Gulf of Mannar. These locations are two of the contested areas of fishing between Sri Lankan and Indian fishers due to the proximity of maritime borders and competition for marine resources (Ibrahim, 2020).

Seagrass meadows have been on the decline due to offloading of nutrients and waste from industrial activities, sedimentation and destructive fishing gears particularly anchoring in seagrass meadows and trawling. The external threat to seagrass decline has been the effects of climate change and *La Nina* events (Udagedara and Dahanayaka, 2017). Despite seagrass remaining unpopular among Sri Lankan populace, seagrass meadows are designated as National Determined Contribution (NDC) in their ecological and commercial merits as well as their ability to mitigate the effects of climate change (UNEP, 2020). Currently, various conservation groups both from universities and Non-Government Organizations have been monitoring current seagrass populations and are attempting to find methods to restore degraded seagrass patches (Munasinghe, 2016). The country has gained recognition by the UN for endorsing worldwide conservation of seagrass for March 1st (ICRI, 2022).

State of Fisheries in Sri Lanka

The Sri Lankan fisheries industry is composed of coastal (1-10km), offshore/deep fishing (10-100 km), aquaculture, and inland fishing sectors such as prawn farming and freshwater fishing (NARA, 2017; 2018). Contribution of both coastal and offshore fisheries contributes around 1.3% of the country's GDP (Nadarajah *et al*., 2018). Fisheries are done in small communities and these communities are concentrated in the western, north, north-eastern, and southern coastal areas of the island. At least 60% of the Sinhalese and Tamil ethnic population of those areas are fishers by trade (Arunathilake *et al*., 2008). Most fishers engage in deep-sea fishing where boats travel long distances to the Indian Ocean where they spend several days (also known as multi-day boats) at sea to catch large and high-valued fish at the end market like Skipjack Tuna (*Katsuwonus pelamis*) and yellow-fin Tuna (*Thunnus albacares*) (NARA, 2017). Multi-day boats that are designed to store fish for up to a month while sailing in deep-sea waters belonging to the exclusive economic zone of Sri Lanka. Smaller one-day boats are designed for coastal fisheries. Multi-day fishing was steadily promoted since the end of the civil war in 2009, through government subsidies to improve deep-sea fishing fleets which led to the development of new ports to construct multi-day vessels to stabilize fishers' livelihood and improve the quality and safety of vessels (Bandara and Jonsson, 2013; Nadarajah *et al*., 2018).

Illegal fishing is widely seen in deep-sea fisheries as catch per day and species caught by fishers are not monitored properly. Illegal fishing has been an ongoing geopolitical issue in Sri Lankan waters where multi-day fishers from the north and eastern parts of Sri Lanka compete with Indian fishermen originating in Tamil Nadu in the Palk Bay and Gulf of Mannar (Ibrahim, 2020). The Demand for seafood has not changed over the years, as recent trends show Indian and Sri Lankan fishers moving to the south-west to the fringes of the free economic zone of India to exploit untapped fish stocks as both countries economic zones are experiencing fish stock depletion (Collins *et al*., 2021).

Brackish water/lagoon fishing and prawn farming are also prominent in Sri Lanka (NARA, 2018). Brackish water fishing involves the catching of edible crabs (*Portunus pelagicus* and *Scylla serrata*), shellfish (*Penaeus indicus and Penaeus monodon*), and finfish (*Nematalosa nasus*, *Pseudarius jella*, *Oreochromis niloticus* and *Liza dussumieri*) from areas where saltwater and freshwater is mixed, typically environments that are found closer to lagoons, estuaries, and saltmarshes (Attapattu and Nissanka, 2005). Fishers engaged in this field use a mix of safe and illegal methods such as gill nets, traps, and artisanal nets to extract shellfish which results in the destruction of nearby seagrass meadows due to human-induced sedimentation (Gunathilaka, 2019). Illegal fishing is continued by fishers lacking knowledge of the marine environment and emboldened by financial desperation. They fish in vulnerable marine habitats like seagrass meadows and coral reefs where there is no continual surveillance of marine or coastguard authorities. Jones *et a*l. (2022) report availability of fishing gear and proximity to habitats with chances of greater catch also determine fishers' willingness to utilise illegal methods to source fish/invertebrates from seagrass.

Fishing in Sri Lankan Seagrass Meadows

Only a limited number of sources have attempted to document the use of seagrass by Sri Lankan fishers' (BRT, 2018; Jones *et al*., 2022). Both Sri Lankan and Indonesian fishers have described seagrass meadows as reliable locations to catch fish, household income of fishers dictates their reliability to prefer seagrass meadows over other locations which require motorized fishing boats and expensive fishing gear to fish. In most cases, seagrass meadows and mangroves are destroyed in lagoon areas of the country in favour of shrimp/prawn farming. Lagoons attract fishers that do not have strong economical means to afford deep-sea fishing vessels and specialized fishing gear (Jones *et al*., 2022). Lagoons that have seagrass meadows like Puttalam, Negombo, Mundel, Rekawa consist of fishers that engage in all forms of seasonal fishing i.e., bivalves (*Crassostrea madrasensis*, *Saccostrea cucullate, Perna viridis, P. perna, Marcia opima, M.hiantina, Meretrix casta, Gafrarium tumidum, Anadara granosa, Pinctada vulgaris* and *P.margaritifera*), crustaceans (*Scylla serrata*, *Portunus sanguinolentus* and *Charybdis spp*.) and prawn farming (*Penaus monodon*) to sustain their livelihood (Munasinghe *et al*., 2010; Silva *et al*., 2013). However, lagoon fishing is unregulated, lacking surveillance and crucial monitoring of fish/invertebrates that have been overfished. Most of the fishers have caught non-target species or by-catch leading to declines inf local fish populations in the lagoons as the fishing gear is often abandoned after continuous use (Jones *et al*., 2018). In Sri Lankan seagrass meadows found in the northeastern parts of the island to Mannar are home to dugongs which are strongly dependent on seagrass meadow leaves for food. Certain fishers have hunted dugongs for the flesh and used destructive fishing methods such as explosive fishing, prawn trawling, drag netting and so on to extract marine resources and consequently kill dugongs as well as seagrass meadows (Prasad, 2018).

Restoration of Seagrass Meadows around the World

In Australia and New Zealand, seagrass meadows are restored using numerous transplantation methods suited for the local area (Tan *et al*., 2020). The most effective transplantation technique has been restoration via seeds whereby seagrass seeds or sometimes shoots are deposited to a degradable pot and left to grow in the designated restoration sites (Sinclair *et al*., 2021). The longest successful seagrass restoration program took 23 years to complete at Chesapeake Bay, USA with a total recovery of 3612 ha of seagrass meadows compared to the previous 213 ha of restoration plots (Orth *et al*., 2020). Some of the noticeable results of this long project were that the new seagrass growth significantly lowered seasonal turbidity, increased carbon, and nitrogen stocks to facilitate meadow self-recovery and increased the abundance of finfish and epifaunal communities. In addition to the successful restoration program, the natural dispersal of scallop larvae was also observed which is critical for the continuation of local clam aquaculture. It is worth noting that seagrass restoration does not mirror the same environmental drivers of the reference seagrass meadow and the natural recovery of the meadow is typically hard to quantify (Rezek *et al*., 2019). Seagrass restoration per unit ha would range from averages of 350k USD to 420k USD (accounted for 2010 inflation with the addition of total project costs) in a developed country however, the cost of restoring seagrasses in a developing country may be lower (Bayraktarov *et al*., 2015).

Restoration of Seagrass Meadows in Sri Lanka

Sri Lanka has recognised the ecological, commercial, and cultural value of seagrass meadows in the previous decade (Kallesøe *et al*., 2008) and has made attempts to prioritise the conservation of seagrass meadows as well as its fauna i.e., dugongs under several legislative acts which promises the establishment of marine national parks to protect seagrass meadows (Prasad, 2018). Recent seagrass restoration programs have been conducted in Kalpitiya and Puttalam lagoon resulting in a meadow recovery of 1012 m^2 (Munasinghe, 2018). There have been successful attempts in educating the public on the value of meadows to encourage conservation priorities for the benefit of the seagrass restoration practitioners and the local community (Munasinghe, 2018). Unlike temperate seagrass meadows where single species of seagrass meadows dominate an entire meadow for long distances (>1ha), tropical seagrass meadows contain a diverse population of different seagrass species which may require unique transplantation options (Tan et al., 2020). Transplanting of seagrass can be made using seagrass seeds, rhizomes, shoots and in some cases seagrass wrack. Different studies have shown the most effective transplant over another provided that more than 1000 transplants are used in the restoration trial (Katwijk *et al*., 2016). Continuous monitoring is important to ensure the newly established transplants have reached a stable threshold in the restoration site whereby the seagrass meadow is able to recover without much human intervention and can survive against external localised disturbances.

Challenges in Restoration of Seagrass Meadows in Sri Lanka

Sri Lanka is currently experiencing one of the worst political and economic crises in its history with foreign reserves emptying to a significant percentage compared to the previous years (Azmy, 2022). Several fishing communities around the country have been impacted by the scarcity of fuel like kerosene and diesel needed for their fishing boats. Multi-boat fishers are forced to spend shorter days because of the unavailability of enough fuel to return to landing sites. Almost 2.7 million people are engaged in fisheries in Sri Lanka usually diversifying their livelihood outside of fisheries (NARA, 2018). However, the current crisis has revealed there are no adequate safety nets and labour protection mechanisms to safeguard the country's fishers from inflation (Ibrahim, 2020).

Unlike other developed nations, there is not much recognition nor appreciation of seagrass meadows as opposed to recently popularised work in reef restoration thanks to the rise of social media and scientific communication to the general audience (Dahdouh-Guebas *et al*., 2020). Strong media coverage can assist in cultivating appreciation for lesser-known habitats all the while educating the public on the value of habitats for organisms as well as human beings. In the process, people become more informed and feel socially accountable to find solutions to protect threatened habitats over time. Alternatively, misinformation and uninformed societal perception can impact the way how certain habitats are managed, in the early parts of the 20th century, mangroves were cleared in large numbers due to their perception as vectors for spreading diseases and housing of animals that are inherently a danger to humans. A similar fate has been recorded in seagrasses meadows that are destroyed in pursuit of recreational amenities. While social media can be useful to educate the public on the importance of seagrasses, dissemination of educational content should be done with prior consultation of marine experts (UNEP, 2020).

The major criticism of seagrass restoration is that it is known to be very labour-intensive and expensive and requires professionals who are experienced in diving or swimming in hard-to-traverse areas of the intertidal/subtidal to transplant seagrass (Rogers *et al*., 2019; Tan *et al*., 2020). It also requires consistent monitoring and should not be limited to monitoring as soon as seagrass has successfully grown to its optimal height (typically in 12 months' time) in the restoration project period. Long-term planting performance needs to be evaluated despite small-scale disturbances that affect the health of newly restored meadows. Observation of localized disturbances can provide new experiences for seagrass managers to learn how to create future seagrass restoration trials whereby transplants are more resilient to local threats (Katwijk *et al*., 2016).

Seagrass transplantation requires donor transplants from a healthy meadow that is not subjected to degradation. To mass-produce seagrass transplants using limited resources from a pristine meadow free from destruction is a challenge on its own (Fonseca *et al*., 2000; Katwijk *et al*., 2016). As meadows are protected as NDCs, sourcing seagrass shoots to create transplants without timely preparation can affect their chances of growing in the seagrass restoration site. Seagrass seed transplants can be made with the establishment of seagrass aquaculture nurseries provided there is additional funding in restoration programs to set up aquaculture operations to cultivate seagrass using seeds. However, meeting the nutritional requirements for the seagrass substrates, determining the specific species to restore and the type of fauna that will inhabit these meadows are criteria that need to be addressed to avoid failure in restoration outcomes (Greening *et al*., 2011; Tan *et al*., 2020). In Sri Lanka, there is no cost-benefit analyses set for seagrass restoration alone. While countries such as Australia have set various committees to evaluate non-marketable values of seagrass restoration to the cost-benefit analysis equation (Rogers *et al*., 2019). This initiative can market ecologically significant outcomes of seagrass restoration like carbon sequestration and renewability of coastal fish stocks

Prospects in Seagrass Restoration for Sri Lankan Small-scale Fishers

When seagrass meadows are restored to an optimal level with increasing habitat cover and non-intervention propagation of seagrasses in subtidal depths, they can introduce finfish species that were once local to the area. The most obvious advantage seen for small-scale fishers is they have convenient fishing areas that do not require them to use fuel-run boats to access potential fishing grounds (Nordlund *et al*., 2018). There is also a prospect for stilt fishermen as well as recreational fishermen to fish in areas outside of lagoons if seagrass meadows are monitored by relevant authorities and not disturbed by mechanised boats using trawler nets and destructive fishing practices (Worm *et al*., 2009). Another avenue that may benefit small fishers is the development of scallop or bivalve farming. Scallop aquaculture is inducive if there is many restored seagrass meadows with self-propagating seagrasses to increase habitat cover for scallop larvae (Orth *et al.*, 2020).

Conclusions and Future Prospects

Seagrasses are a vital habitat for several marine organisms and are of significant for coastal fisheries around the world. Unfortunately, seagrass meadows are destroyed despite being extensively studied in the latter part of the 20th century and are slowly being recognized by countries around the world for their importance in providing several ecosystem services as well as improving the socio-economic conditions of many who are reliant on fisheries. Sri Lankan coastal fishing industry is not well monitored, and fishermen use destructive fishing practices to exploit marine resources during times of financial desperation and uncertainty. In the long run, such practices will destroy existing seagrass meadows and reduce their chances of achieving financial stability. Seagrass restoration is somewhat of a novel practice in Sri Lanka. Setting an incentive and promoting non-marketable values of seagrass restoration can attract potential stakeholders to invest in future restoration programs around the country. By expanding existing seagrass restoration programs to presently degraded lagoons across the country and providing a framework to engage small-scale fisher families in seagrass ecosystem recovery and ultimately allow fishermen to utilise restored meadows for fishing activities are important. The acquisition of knowledge in seagrass restoration is a continual process, restoration managers should be given financial resources as well as knowledge from successful seagrass restoration programs as a reference to develop financially feasible restoration projects in the country.

Conflict of Interest

Author has declared that no competing interests exist.

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CHAPTER
11

Circular Economy for Sustainable Agricultural Development in Sri Lanka

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Abstract Circular Economy (CE) and Circular Agriculture (CA) are being considered the new ways of approaching sustainable development with less resource extraction and waste disposal. Implementing CE in agriculture can bring many benefits to the sector and it aligns with sustainable agricultural development. This chapter discusses the concept of CE and CA, their benefits to the stakeholders and the ways and means of achieving sustainable development using them. It also looks at the strengths, weaknesses, opportunities and threats of CA approach in Sri Lankan context. Furthermore, this chapter explains the important challenges in implementing CA in Sri Lanka such as inadequate level of awareness and experiences, absence of properly directed policies, high level of labor-intensive farming practices, limited research and development, lack of introduction of the latest technologies to reduce input use, lack of innovation, small scale agricultural systems with less mechanization, lack of adequate fund to develop recycle economy and prominent backward organizational structure. Efficient CE implementation in agriculture demands interdisciplinary approaches involving agriculturists, engineers, designers, economists, behavioral scientists and sociologists, policymakers, and business and computer technologists to make a real transformation in the livelihoods of Sri Lankans. A single approach will not help to realize the huge benefits of CE.

Keywords: Agri-food, Circular agriculture, Circular economy, Sri Lanka, Sustainable development

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Introduction

Circular economy (CE) promotes sustainable production and consumption which underlines the 3R principles (i.e., Reduce, Reuse and Recycle).This approach reduces the extraction and disposal of resources by encouraging circular business models. Under CE, the existing resource usage is reduced, reused, recycled, and remanufactured in production, distribution, and consumption across various industries (Han *et al.*, 2020). Recently, CE has gained greater attention among researchers, practitioners and policymakers due to benefits accrued because of the efficient use of resources. However, existing literature reports that CE has not been sufficiently used in commercial agriculture to reap optimum benefits. Applications of CE concept in agriculture are, in general, known as 'circular agriculture' (CA). Adopting CE principles improves resource efficiency in agriculture and reuses the resources from the farm while reducing the use of harmful chemicals in Agriculture. According to Mehmood *et al*. (2021), CA has not been thoroughly explored to get optimum benefits, especially in developing countries. However, over the past decades, CE concept has received considerable attention as a solution to mitigate social, environmental and economic challenges in the agri-food industry (Segneanu *et al.*, 2018; Hamam *et al.*, 2021).Thus, it seems that CE has great potential to play a significant role to support the development of sustainable agriculture in a country (Nattassha *et al.*, 2020).

Given the resource scarcity for production purposes, implementing CE concept to manage resources and reduce waste, has become the paramount importance to both developed as well as emerging economies. This scarcity has been exacerbated by energy issues and climate change. Resource deficiency lowers productivity and lower efficiency in agri-food supply chains (Ulgen and Inan, 2022). Thus, developing nations face key challenges within their agri-food supply chains. These challenges range from resource scarcity for farming and post-harvest practices, animal feed and fodder production, soaring energy prices, global climate change, environmental degradation and increasing food demand etc. (Velasco-Muñoz *et al*., 2021). In addition to that, the agri-food sector can transfer the country into a low-carbon and climate-friendly country. Thus, CA has great potential in contributing to adaptation to climate change at the macro level and by providing sustainable healthy diets for households at the micro level (United Nations [UN], 2021).

In Sri Lankan scenario, the CE framework has not yet been well adapted to the agricultural sector (Velasco-Muñoz *et al*., 2021). There exist a dearth of research and critical reviews related to circularity in the agri-food system in Sri Lanka (Nattassha *et al.*, 2020). Given the current economic situation of Sri Lanka, it is important to aim for both profit maximization and minimizing resource utilization in all sectors of the economy. Much focus is on lesser resource utilization, as at the current prices, the purchase of inputs and food has become unbearable for the people (Gunasekara, 2021). CA would help, especially low-income households to minimize their expenses, and importantly it would help them to ensure to their households are food secure and to have a well-balanced healthy diet. CA applications at each stage of the value chain of agricultural commodities will have different benefits, also the synergistic effects of these benefits will smoothen the value chains and bring the most wanted foreign currencies to the country, especially through tropical fruit and vegetable-based exports. Thus, the implication of CA ranges from the farm to export destinations. In addition to this, the benefits of the regeneration of the agri-food systems and the benefits to the environment are unimaginable (Dandeniya & Caucci, 2020). At the time of a crisis, it is not only the man who is affected, but the environment is also heavily affected, and the rate of environmental destruction increases with the disasters, as humans find ways to survive the disaster (Gunasekara, 2021). A CA based approach would help to mitigate the damage that is about to happen to the ecosystem as well as to reduce the social and economic hardships the populace would be facing. Of course, CA would not be an immediate solution to the problems, but on the mid-to-long term, CA can indeed bring many benefits to the people, that are sustainable (UN, 2021).

The CA approach in the agri-food industry would help to target some of the serious repercussions of the current economic crisis, and thereby reducing the effects of the crisis on the populace. Hence, it is crucial to identify how the CA concept can be effectively used to face and mitigate the constraints faced by Sri Lankans, due to the present crisis. This chapter highlights the importance of CE concept and its application in CA. It explains the relevance of the CE concept to agriculture under the Sri Lankan context, and how it can contribute to the Sri Lankan economy to meet the sustainable development goals (SDG). Further, we identify operational principles for CA to be considered for Sri Lanka. The chapter explains how adopting a CA approach would ensure the benefits to the people and the ecosystem: food security, soil conservation, nutrient cycle regeneration, reduction in resource use and economic benefits to the households. It also stresses how CA can support women and children in overcoming food insecurity and providing access to a nutritional and balanced diet. Furthermore, this chapter proposes key strategies on how CA can be adopted in Sri Lanka, drawing experiences from other countries and recommend a bio-based economy approach on the CA principles.

Concept of Circular Economy

The concept of CA is not novel for Sri Lanka and its applications are being practiced for decades, even though they did not get the limelight. Most of the developed countries are utilizing CE and hence CA concepts are used to achieve sustainable development in their countries. But it was recently, that emerging countries including Sri Lanka have started to think on the line of CE and CA applications for sustainable agriculture. The term CE is described as an economy with closed material loops (Wautelet, 2018). Studies have considered CE as an emerging way of achieving sustainable development within nations of the world (Glnzalez, 2021). Based on Valavanidis(2018), CE is a concept that will utilize used goods to be a service or an input resource for others, achieved via closing the loops in the industrial sector, by reducing waste through sustainable means of reuse (Fig. 1).

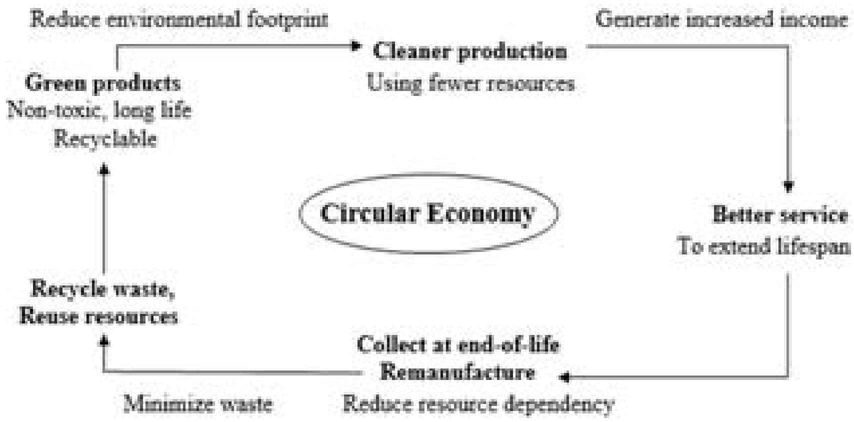

Figure 1. Model of a circular economy (Source: Glasco, 2019)

Circular economy means, moving away from the world's current and enormously wasteful economic models (linear economy) of 'take, make, throw away', in which resources are extracted, turned into products, used and discarded (Schröder *et al.*, 2021). In other words, CE is a system of utilization of resources in a sustainable manner through Reducing, Reusing and Recycling (3R principles) of resources, cutting down waste and recycling the rejected products without throwing them back to the environment(Valavanidis, 2018). During the past decades, both developed and developing nations have decided to transform their economies into an environment friendly industrial development and sustainable socio-technical systems (Valavanidis, 2018). Most of the natural systems in the world are cycles and thus they are sustainable: water cycle, carbon cycle and other nutrient cycles. The CE concept rejuvenates these cycles and closes the loops and creates the links hitherto which are broken in the environment and enhances biodiversity. Thus, through CE, the environment becomes a part of the economic systems. Hence, human will not just consider the environment as a place to 'dump' the waste.

Scope of the CE Framework in Agriculture

Implementation of CE within the agriculture sector can support enhancing the sustainability of livelihoods engaged in agriculture. Though CE has been related to the industrial economy, mainly to reduce resource usage and waste generation and to promote recycling, its adaptation in agriculture also has several merits which are worthy of discussion with special relevance to developing countries. Since CE consists of three major pillars: economy, society and environment, it can be closely related to sustainable development. Thus, CE in agriculture, i.e. CA can be seen as a way to achieve the SDG as well (Valavanidis, 2018; Ekins *et al.*, 2019). Hence, CE is interconnected with economic, social prosperity, and environmental protection. In addition to that, CE facilitate achieving food security of nations, and poverty reduction by improving health and wellbeing of nations, thereby enhancing social sustainability (Velenturf and Purnell, 2021).

CA can be defined as "the set of activities designed not only to ensure economic, environmental and social sustainability in agriculture through practices that pursue the efficient and effective use of resources in all phases of the value chain, but also guarantee the regeneration of biodiversity in agro-ecosystems and the surrounding ecosystems" (Velasco-Muñoz *et al*., 2021). There are some principles associated with the transition to CE (Taylor, 2020; Velasco-Muñoz *et al*., 2021). They are designing out (i) waste and pollution, (ii) keeping products and materials in use and (iii) regenerating natural systems.

(i). Designing Out Waste and Pollution

The first principle of the circular economy is about the differentiation of waste and pollution through identifying the ways of designing and innovations to reduce pollution for minimizing the negative externalities such as degradation of soil due to the inappropriate use and disposal of fertilizers, herbicides and pesticides (Taylor, 2020). Therefore, either the pollution can be reduced or the waste can be reused and remanufactured for some other purposes. Agriculture provides ample opportunities for such ventures. A waste of a one process can be an input for another process. For example, crop residues can be used as compost or as animal feed. Similarly, livestock waste can be used as a source of manure as well (Velasco-Muñoz *et al*., 2021).

(ii). Keeping Products and Materials in Use

This principle denotes the value of products and raw materials which are utilized in the production process, maximization of producing co-products and by-products within supply chains and value chains before referring to their permanent disposal (Velasco-Muñoz *et al*., 2021). This includes alternative uses in bio-energy production, soil amendments, bio-fertilizer and livestock feed.

(iii). Regenerating Natural Systems

This principle refers to the enhancement of ecosystems by replacing non-renewable resources with renewable resources (Velenturf and Purnell, 2021) and supports the implementation of regenerative agriculture (Batlles-dela Fuente *et al*., 2022). Regenerative cultivation methods support the reduction of greenhouse gas (GHG) emissions and decomposing of plant and animal debris to improve the structure of the soil (Rhodes, 2017). However, at present these principles have been utilized in the agriculture sector at a lower level in Sri Lanka. People don't pay much attention to these aspects and are not mindful of protecting the resources and the environment.

Circular Agriculture and its Importance

CA is defined as the fulfillment of farmers' needs to find solutions for the associative constraints by ensuring the maximization of raw material usage while completing their production process (Schouten, 2020). Recently, many studies have been started to pay attention on the concept of CA with reference to implementing the principles of CE to the agriculture sector. Traditional agricultural activities in emerging economies had followed CA principles for ages up to a larger level. After they transformed to commercial cultivations, those principles have been neglected by many people. Thus, CA is a timely and important concept for developing countries to enrich sustainable economic development and go back to the traditional principles in agriculture (Valavanidis, 2018; Velasco-Muñoz *et al.,* 2021). CA does not promote pure organic cultivation, but its principles are mainly based on 3R concept. CA focuses on using minimal amounts of external inputs, closing nutrient loops, regenerating soils, and minimizing the impact on the environment (UN, 2021). According to Janati *et al.*, (2021), the CA is an effective approach for the management of soil organic inputs that improves soil fertility and cropping system sustainability.

Generally, CA is practiced using minimum number of external inputs, higher recycling of residues and the optimum utilization of nutrients. Hence, external inputs are used sustainably without compromising the needs of the future generations to engage in environmental friendly agricultural practices (UN, 2021). Moreover, most of the bio-degradable materials help to regenerate the soil through the natural decomposing process. These, nutrient recycling processes enrich soil fertility and reduce the removal of nutrients from the soil. The concept of circular agriculture explores the maximum utilization of raw materials while performing their production process to reduce the impact on the environment (Schouten, 2020). Within the CA approach, reusing the materials in agriculture can also be done without disturbances. However, recycling residues is also a way to retain them within the natural cycling process to ensure sustainable production (Boer and Ittersum, 2018). Thus, the circular agriculture approach leads to reduce the usage of land, incorporating chemical fertilizers and waste materials to the soil, and minimize CO_2 emissions to the atmosphere. Moreover, circular agriculture plays an important role in social, economic and environmental perspectives as follows (Ellen MacArthur Foundation (EMF), 2016),

(i). Enhance Soil Health:

Reuse of crop and animal residues are practiced to the conversion of organic matter after decomposing them. Thus, it supports to enhance the microbial population in the soil. This leads to improve the fertility of the soil and its health (Gupta *et al.,* 2022).

(ii). Improve Biodiversity:
CA allows to improve biodiversity of the environmental systems by minimizing the release of residues to the surroundings and incorporating nutrients from the natural recycling process of the bio-degradable residues (Boer and Ittersum, 2018).

(iii). Reduce the Impact of Climate Change:
CA supports to minimize the CO_2 emissions to the atmosphere (EMF, 2016). CO_2 emissions led to a gradual increment of global temperature and indirectly causes fluctuations/variability in rainfall patterns (World Bank, 2021).

(iv). Minimize Utilization of Chemical Fertilizers and Pesticides:
CA approach consists 3R concept. Thus, crop and animal residues produce organic fertilizer due to the decomposing them. Previous research findings showed that, CA could reduce about 80 % of chemical fertilizer used in food systems (UN, 2021).

Circular Agriculture Model for Future

Arable lands are primarily used for food production as well as the organic manure are used to retain the fertility level of soil. According to the Fig. 2, crop and animal residues are releasing nutrients from natural recycling process to the soil to enhance the sustainably of feeding within the future population (Witjes and Lozano, 2016; Van Zanten *et al.,* 2019)**.** CA model shows a closed loop behavior of resources to enhance the optimum utilization. Both crops and livestock directly link with the suppliers' business model. Co-products are the desirable secondary goods that are obtained during the production process, and by-products generated from the residues within the production. Crop residues can be used for livestock farming as a source of animal feed. However, suppliers' business models usually add value before entering the producer's business model. In addition to that, producers' business model and suppliers' business model collaboratively act with the shared responsibility and technical and non-technical specifications throughout the value chain of agri-food system. Moreover, products of the producers' business model change into the suppliers' business model under the recovery process. Producers' business model releases waste into the surrounding environment and this waste are used to produce organic fertilizer by separating them into bio-degradable and non-biodegradable materials (Fig. 2). While bio-degradable waste utilizes for producing organic fertilizer and non-biodegradable waste is directed towards the recovery stage through the recycling procedure. Thus, the circular agricultural approach enriches the sustainability in the agricultural sector to develop the national economy in Sri Lanka. CA generate a considerable impact with the view of economic, social and environmental perspective of sustainability (UN, 2021). Fullerton *et al.,* (2022) discusses few potential circular business models, where they highlight the features of circular supply, resource recovery, sharing, product life and product services systems.

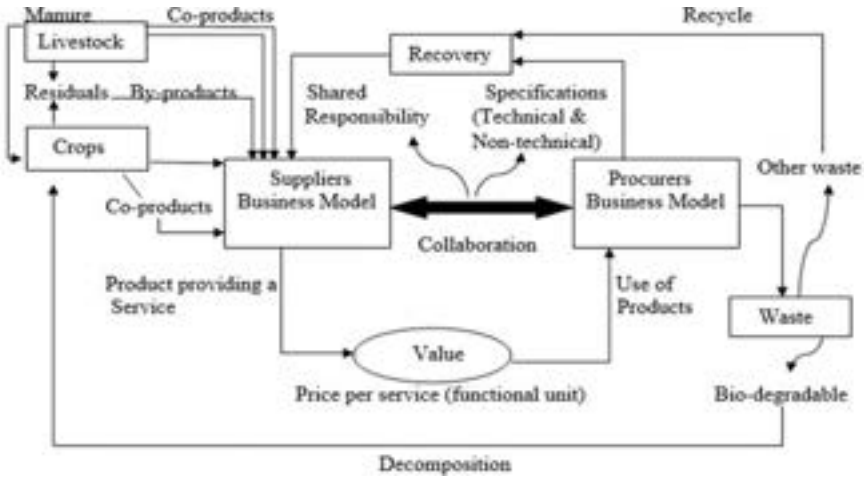

Figure 2. Circularity in agri-food systems (Source: Adapted from Witjes and Lozano, 2016; Van Zanten *et al.,* 2019).

Benefits of Circular Agriculture

Circular Agriculture leads to generate wide variety of benefits in economic, social and environmental aspects (Valavanidis, 2018; Ekins *et al*., 2019). According to the literature, the economic benefits of CA are: increased potential for the economic growth through facilitating sustainable rural development within the application of 3R concept for the agriculture sector (UN, 2021; Velenturf and Purnell, 2021). Moreover, CA concept recognizes the optimum utilization of agricultural inputs, co-products, by-products and their outputs in a sustainable manner (Boer and Ittersum, 2018). Furthermore, additional income earning capability could be obtained by implementing of CA approach to the improvements of production and product development (Hamam *et al.,* 2021). Fullerton *et al.* (2022) highlights the importance of the field of economics in CE in variety of ways. CE cannot serve only one discipline, and they stress that formal economic principles should be adopted in CE to quantify the benefits and costs involved in the process of CE.

CA involves demonstrating benefits from a social perspective: higher production and a wide variety of product development require more labor force. Thus, this generates more employment opportunities (Bouronikos, 2021). This concept engages with the regenerative food production that is directed towards the production of quality products while protecting the surrounding environment. Hence, it supports maintaining good health and eco-system balance (Oberč and Schnell, 2020). CA also ensures food security within agri-food supply chains through facilitating the availability, access, utilization, stability of foods and enhancing the innovative behavior of producers to improve the diversification of products (Wautelet, 2018: Velasco-Muñoz *et al*., 2021).

CA approach has an ability to reduce greenhouse gas emissions to the atmosphere (EMF, 2016). Moreover, CA leads to the natural decomposing process of crop and animal residues to improve the health and resilience of the soil. This improves the soil microbial population up to the optimum level (Gupta *et al.,* 2022). In addition, this approach consists of minimal usage of natural resources with the 3R concept being applied for agricultural resources and sustainable resource utilization to reduce environmental pollution (Ekins *et al.,* 2019; Bouronikos, 2021).

Present Status of Circular Agriculture in Sri Lanka

Circular Agriculture is not novel to Sri Lanka, although its applications remains at lower level (UN, 2021). Understanding the present status of CA is important to identify the challenges of implementing CA in the country. For some time, agricultural policies were directed towards organic agriculture (Voluntary National Review, 2018). Which happened during a short period of time without giving due recognition to the issues emanating from this decision. Organic agriculture transformation had variety of problems at the initial stage and policies are re-directed to the initiation of conventional farming systems recently (Tal, 2018). Currently, urban development programs are initiated to produce organic fertilizer through the utilization of bio-degradable urban waste materials to fulfill the organic fertilizer requirement of the country (Dandeniya and Caucci, 2020).

Integrated farming systems are being promoted within the rural households and farms to ensure optimum utilization of resources. In this method, both mix cropping and livestock farming practices are carried out within the same place (Sekaran *et al*., 2021). Mixed cropping type and integrated farming are considered as a circular strategy for the reduction of resource consumption, management of soil fertility, and improve crop resiliency to climate shocks. It can raise the crop yields in a sustainable way (Turan *et al*., 2022). Moreover, some of the small-scale agri-entrepreneurs in agro-forestry represents the circular nature through minimizing dependency on fertilizer and agrochemicals while cultivating crops and pastures (Sekaran *et al.,* 2021).

Recycling and reuse of irrigation water is a significant component of CA. At present context of Sri Lanka, most of the farmers in dry zone and intermediate zone reuse rainwater for irrigating their farmlands as a circular agricultural water management practice (Abeywardana *et al.,* 2019). Moreover, waste water recycling or reuse is also considered as the circular water management of farming. This reduces water pollution and ensure conservation of water. However, the waste water recycling is not a top priority in Sri Lankan agriculture sector, as farms emit very few waste water. However, industries with organic waste water could use them for irrigation purposes and waste from livestock can be also used for fertilizing the fields in solid or liquid formats. Special attention should also be taken to overcome input of hazardous chemicals in to the lands through a proper identification and treatment protocols.

SWOT Analysis of CA in Sri Lanka

Sri Lanka has a high potential to apply the CE concepts in to agriculture and can transform the linear agricultural production in to a CA successfully. SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis was conducted to recognize the key challenges of the CA in Sri Lanka (Table 1)

Table 1. SWOT analysis of circular agriculture in Sri Lanka

Strengths	Weaknesses
• Reduces environmental pollution	• Unavailability of adequate level of awareness and experiences by the farmers
• Creates additional income earning ability for the farmers	• Absence of proper policies for the circular agriculture
• Minimizes utilization of chemical fertilizers and pesticides	• Lower farmer adoption for the circular agricultural practices
• Enhances soil fertility and healthiness through increasing microbial population within the soil	• Lack of exchange of relevant information with other countries
• Helps for product development and diversification	• Labor-intensive farming practices
• Important for policy makers	• Limited research and development in circular agriculture.
• Helps for optimum utilization of resources	• Lack of government support
Opportunities	**Threats**
• Considerable global adoption for the circular agriculture	• Difficulties in entering into new markets through innovative products
• Potential of generating employment opportunities	• Difficult to do mechanization
• Protect biodiversity and improve the environment	• Lack of adequate fund to develop recycle economy.
• Large numbers of field experts	• Lack of motivation and negative attitudes of the government officers
• Enhance women empowerment	• Inadequate management & evaluation of circular agricultural process

Circular agriculture is a way towards the sustainable agriculture to enhance the development in most of the rural areas in Sri Lanka. CA leads to reduce environmental pollution due to the management of waste materials, co-products and by-products of a particular production process of the agri-foods. Thus, CA supports additional income earning ability within the agri-food supply chains. This approach reduces the utilization of chemical fertilizers and pesticides as they are substituted by organic fertilizer to a certain extent. Because of that, organic fertilizer produces through the natural decomposing process of bio-degradable waste materials and residues are highly useful. Thus, organic fertilizer enriches the microbial population of the soil to ensure the fertility and healthiness. CA approach facilitates product diversification due to optimum utilization of resources through the co-products and by-products within the agri-food chains. Therefore, an important policy implication is to motivate farmers to use organic fertilizer step by step. Then, the government can gradually reduce the importation of agrochemicals and chemical fertilizer and incentivize subsidies to farmers towards CA. A slower approach would not sabotage the country's food security. Thus, policy makers must emphasize the importance of institutional intervention to promote circular agriculture through its policies and periodic plans. Moreover, still Sri Lanka is not adequately directed to such endeavors. Thus, up-to-date agricultural policies, rules and regulations regarding the farming practices, production and trading of produced diversified products are needed to be formulated to overcome the issues arising from the critical condition of the economy of Sri Lanka.

When explore weaknesses in implementing circular agriculture concept in the country, some of the policy makers and extension authorities have lower level of awareness regarding the latest information and experiences of CA. This dilutes the rate of adequate information on CA within the information linkage of the extension authorities. Thus, still the concept of CA is less popular among collaborative institutions in Sri Lanka. This causes lower farmer adoption for the CA approach. Existing policies are not able to implement this concept in the country. Hence, CA based policies are needed to be formulated by directing both local and export market to overcome the current issues arising in agricultural markets. Research and development activities also limited in this aspect and it needs to be promoted with the public and private institutional collaboration to gain optimum benefits to the development of the circular agricultural sector. Brainstorming can support to overcome these circumstances through innovative ways and it could enhance the information dissemination of circular farming to each and every component of the sector involvements. In addition, lower level of introduction occurred regarding the latest technologies related to CA. Due to these reasons a multi-dimensional and multi-disciplinary approach towards CE and hence CA would be very practical (Fullerton *et al.,* 2022).

Increasing global adoption of CA is important to uplift the orientation into the export market by improving the formation of diversified agri-food products. When implementing CA, it generates employment opportunities for a wide variety of activities including pre-harvesting, harvesting and post-harvesting. Education and training of field experts to share timely updated information and experiences on CA is essential. Importantly, women play a significant role in CA. As these activities lead to empower women in economic and social point of view, those can be considered as important opportunities in implementing CA in the country.

According to the findings of the SWOT analysis, some threats have been identified (Table 1). There exist a threat to enter new markets through the innovative products as existing competitors exert an additional effort to remain in the market. So, the new entrant need to come up with unique products to have a competitive advantage over the existing. In Sri Lankan, small-scale agri-entrepreneurs and farmers are the prominent cohort as fragmentation of agricultural lands exacerbate. Therefore, these small-scale agri-entrepreneurs and farmers have fewer opportunities to engage in large-scales agricultural operations. In addition, shift towards green economy is associated with significant amount of initial capital requirement. So, it is difficult due to a critical financial situation in the country at present. Public and private institutional collaboration is important to uplift the circular agriculture sector while underling the various factors such as rules and regulations, legislations, well-directed action plans and risk management in formulating circular agricultural policies.

Strategies to Overcome the Challenges Associated with CA in Sri Lanka

Below listed are some ways and means to eliminate the challenges associated with CA in Sri Lanka,

- Conduct awareness programs to disseminate knowledge and improve farmers' skills and experiences on CA.
- Evidence based policies and strategies need to be timely update for the development of the circular agriculture.
- Organize extension programs to upward the farmer as well as the agri-entrepreneurs adoption to the CA.
- Facilitate foreign training opportunities to gain latest information about CA and outsourcing of experts to enrich with timely updated information with other countries.
- Introduce mechanized farming practices to overcome the labor shortage issues arising from labor intensive activities in farming.
- Conduct research and development activities to find out latest information regarding CA.
- Introduce modern technologies to upward the farmers and agri-entrepreneurs adoption for the CA based practices.
- Formulate and implement timely important regulations for the development of the export market of circular agricultural products.
- Introduce policies that are needed to overcome the threats for new entrants to the agri-food market.
- Invest more funds to develop recycle economy for the optimum utilization of resources.
- Facilitate more opportunities to improve merit base performance appraisals instead of backward organizational structure to emerge of young innovators.
- Formulate public institutions collaboration in order to implement the management and evaluation of CA based farming practices.

Circular Agriculture for the Sustainable Development in Sri Lanka

According to the literature findings, CA ensures the possibility of achieving 13 SDGs out of the 17 SDGs of UN for the developing countries (Schroeder *et al.,* 2019; Sutherland and Kouloumpi, 2022). Circularity within the agriculture sector engages with the optimum resource utilization based on 3R concept. Thus, product diversification and innovative product development support to earn additional income. In the context of CA, it is possible to rely on the sustainability of agriculture sector to achieve the optimum production of agri-foods (Boer and Ittersum, 2018). Organic farming is considered as the key circular agricultural practice within the sustainable agriculture systems (UN, 2021). Most of the CA based practices have higher women involvement due to labor intensive nature during the pre-harvesting, harvesting and post-harvesting activities. It improves the level of empowerment in social and economic perspectives (Sutherland and Kouloumpi, 2022). Generally, women empowerment is a critical aspect of enhancing gender equity to build up sustainability in the society (Rathnachandra and Malkanthi, 2022). Moreover, CA practices reduce utilization of agrochemicals in the farming systems (Velasco-Muñoz *et al.,* 2021). Hence, it minimizes the accumulation of excess chemical fertilizer and agrochemical in water sources. This could enhance the potential of retaining clean water in water sources and protect the aquatic plants and animals while generating better surrounding environment for them as the life below water (EPA, 2021). Livestock manure and other bio-degradable waste materials produce bio-energy with affordability rather than using non-renewable energy sources (Sobczak *et al.,* 2022). CA also supports innovation industries and infrastructure through the product diversification and development (Basso *et al.,* 2021). In addition to that, it leads to the way of sustainable cities and communities by performing sustainable agricultural practices. In the context of circularity, an economy can ensure optimize utilization of resources and protect those resources for the usage of future generation (Velenturf and Purnell, 2021). Generally CA associated with the regenerative cultivation methods and it supports reducing GHG emissions as the action on climate change (Rhodes, 2017). This support the protection of the microbial population of the soil because of improving the biological properties while protecting the life on land (Gupta *et al.,* 2022). CA can improve the institutional collaboration for enhancing the global partnership for achieving the sustainability within the agriculture sector in Sri Lanka.

Conclusions and Future Prospects

Sri Lanka has a great potential to formulate and implement circular agricultural practices as a key strategy for sustainable development. However, unavailability of adequate level of awareness and experience, absence of properly directed policies, lower farmer adoption for the CA based practices, Sri Lanka is still not exchange the latest information relevant to the CA with other countries. More labor intensive farming practices, limited research and development in CA, weaknesses in introducing latest technologies, threats to enter into the new markets through the innovative products, small-scale agricultural systems with less mechanization, lack of adequate fund to develop circular economy act as challenges for implementing CA activities in Sri Lanka. Thus, strategies to overcome the challenges towards successful implementation CA are; conducting awareness and training programs to disseminate knowledge and improve farmers experience on the CA, facilitating training opportunities to gain latest information about CA, introducing mechanized farming practices to overcome the labor shortage issues arising from labor-intensive activities in farming, conducting research and development activities, formulating and implementing timely important regulations for the development of the export market of circular agricultural products, formulating policies to overcome the threats for new entrepreneurs to the agri-food market, investing more funds to develop recycle economy for the optimum utilization of resources and strengthening the collaboration between related public/ private institution.

Conflict of Interest

Authors have declared that no competing interests exist.

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Effect of Air Pollution on Economic Crisis: Green Approach from Bioremediation

CHAPTER 12

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Abstract The most severe environmental risk nowadays is the air pollution which is caused by many anthropogenic sources like coal gasification, activities in petroleum refineries, and motor vehicle exhaust. The studies from the most recent Global Burden of Disease (GBD) evaluate that air pollution was the cause of millions of premature deaths globally. Further health consequences of air pollution are cardiovascular and respiratory diseases. Furthermore, it disturbs the environment and affects crop yields, with influencing ecosystems and biodiversity. Air pollutants deposited on crops appear in the long run through "yellowing", reduced growth, or premature crop death. The economists assume that the market impacts of air pollution, such as productivity of labor, expenses in health, and agricultural harvest yields, will lead to higher global economic expenditures. There is a wide range of literature related to economics that explores the relationship between human health and recessions, stating the importance of taking action against economic downturns to improve health outcomes. The consequences to the economy due to air pollution are considered by assigning a monetary value to every health aspect. Quantifying the exposure by adjusting the effect of economic tendencies on air pollution got relatively few studies available. Air pollution is a crucial focus that affects directly the economy in the world but this concern does not address appropriately in Sri Lanka as a country. In the nonappearance of supplementary and strict policies, increasing energy demand and economic activity without sustainable recovery in the environment will lead to a significant increase in global emissions of air pollutants and it will directly lead to an economic catastrophe. Bioremediation will be one of the most effective and eco-friendly approach to eliminate contaminants from the atmosphere. The aim of the chapter is to provide important evidence linking the effect of human health and agriculture-related problems created by air pollution on the economy of Sri Lanka.

Keywords: Biocontrol, Bioremediation, Eco-friendly, Economic downturns

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Introduction

Air pollution is one of the significant environmental concerns around the modern world, particularly in urban areas. Air pollutants are produced from a range of anthropogenic sources that includes the burning of fossil fuels in power generation, transport, manufacturing and households. The natural sources include windblown dust, volcanic explosions and emissions of volatile organic complexes from plants because of the huge level of manufacturing development. The release of such air pollutants in greater amounts help settling them over the surfaces. Levels of aromatic hydrocarbons present in the atmosphere are dependent on many variables, including local emission sources, temperature and metrological conditions and tend to rise during the winter months due to an increase in fossil fuel consumption (Crawford, 1996, Esen *et al*., 2010, Kumar *et al*., 2020). Air pollution is continuously destructing the whole ecological system and affecting the plants and animals (Kampa and Castanas, 2008). The emitted pollutants are circulated in the atmosphere and again deposited back onto ground level through dry deposition and wet deposition. When it occurs, the phyllosphere, water resources and soil surfaces get contaminated with pollutants. The depositions of pollutants on agricultural crops can affect quality and quantity of the crop yield. When those pollutants deposit on edible fresh crops, they disturb the growth of the crop and reduces the crop yield. Considering all these issues related to health and agriculture caused by toxic air pollutants, scientists have experimented an ecofriendly ways and means to overcome the problem. Bioremediation is suggested as one of the best options for removing contaminants from the environment by the scientific community.

Recent studies have focused on the environmentally friendly biological approach to remove polycyclic aromatic hydrocarbons (PAHs). Therefore, biological processes are limited due to the bio recalcitrant, toxic and low solubility of PAHs in water (Homem and Santos, 2011). Many microorganisms, including bacteria, yeast, oomycetes and fungi live on the phyllosphere, as do other biological surfaces. (Hardoim *et al*., 2015). Undugoda *et al*. (2016) recorded that 1-10% of the total heterotrophic phyllosphere inhabitants containing diverse bacterial species could degrade aromatic hydrocarbons. In another study, *Enterobacter ludwigii* confirmed 87 % polycyclic aromatic hydrocarbon (PAH) degradation, while *Bacillus cereus* and *Enterobacter* sp. evidenced 86% and 76% PAH degradation, respectively (Manage *et al*., 2015).

In a country, foremost contributor to the economic growth is the industrial sector and industries make a foundation for today's lifestyles. In the manufacturing sectors, the process of producing goods is mainly focused on how to convert natural raw resources into value-added essential goods (Carriazo, 2016). In relation to manufacturing industry, environmental pollution becomes a major issue that lays parallel to economic growth. Environmental sustainability has become the core of global economic policies over the past three decades. Undeniably, several measures were taken by environmental economists to slow down the alarming environmental pollution. However, these policymakers could not address all the environmentally destructive aspects completely. Notwithstanding the negative effects of industrial activity on the environment which described above are widely debated publicly at the present time since it becomes a major threat to economic growth as well as all living beings.

Increased pollutants level can directly affect air pollution and cause economic costs. It straightly affects the economic costs in numerous dimensions (Fig. 1). When it comes to the agricultural aspect, it affects air pollution in a serious indirect way such as necrotic lesions which can appear in a short time starting from injuries to foliage or slowly it turns into chlorosis or yellowing of the leaf. Reduction in the growth of various parts of a plant can also be occurred due to these pollutants. Likewise, there are numerous health effects of air contamination and those health circumstances direct the way to huge health expenditure and it straightly goes to the economic cost. Other than that those health conditions affect labor productivity, disutility of illness and mortality.

Figure 1. Phases of the economic significances of air pollution

According to Fig. 2, labor productivity, health expenditure, and agricultural yields can be considered a market cost and the disutility of illness and mortality can be listed under nonmarket cost component which will affect the economy directly by air pollution. According to the statistical data estimates, air pollution directly affects premature deaths. These mortality percentages really affect the health conditions in the country. Medical coverage and drug usage will be getting higher because of the high mortality percentage which indirectly affects the economic cost (Pervin *et al.*, 2008).

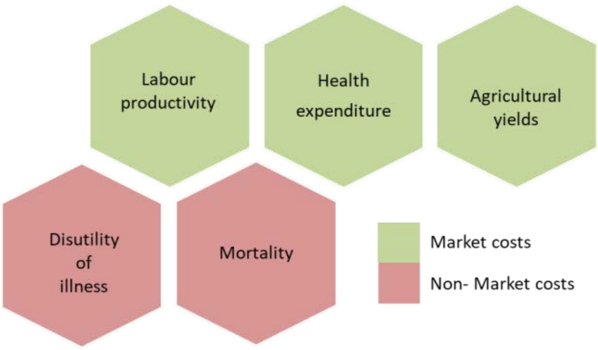

Figure 2. Market and non-market costs caused by air pollution (Source: OCDE, Economic consequences of outdoor air pollution. Organization for Economic Co-operation and Development)

Mainly air pollution can be divided into two groups; (i) indoor air pollution-pollution cause by non-industrial private or public places and (ii) outdoor air pollution-pollution caused by pollutants in metropolitan zones where these contaminants are mostly discharged from vehicles, power plants, aircraft, incinerators, petrochemical plants, industrial boilers and ships (Lee *et al.,* 2011, Koren and Bisesi, 2016).

Quantifying the exposure by adjusting the effect of economic tendencies on air pollution got relatively few studies available. Air pollution is a crucial focus that affects the economy directly in the world but this concern does not address appropriately in Sri Lanka as a country. Therefore, this chapter provides evidence linking the effect of human health and agriculture-related problems created by air pollution on the economy of Sri Lanka and Introduces novel technologies and innovative bio-controlling units for sustainable resource management leading to reducing the air pollution risk in Sri Lanka.

Anthropogenic Sources of Air Pollution in Sri Lanka

Conferring to the surveys carried out by University of Colombo indicated that the foremost sources of air pollution are vehicular emission and biomass burning (Fig. 3).

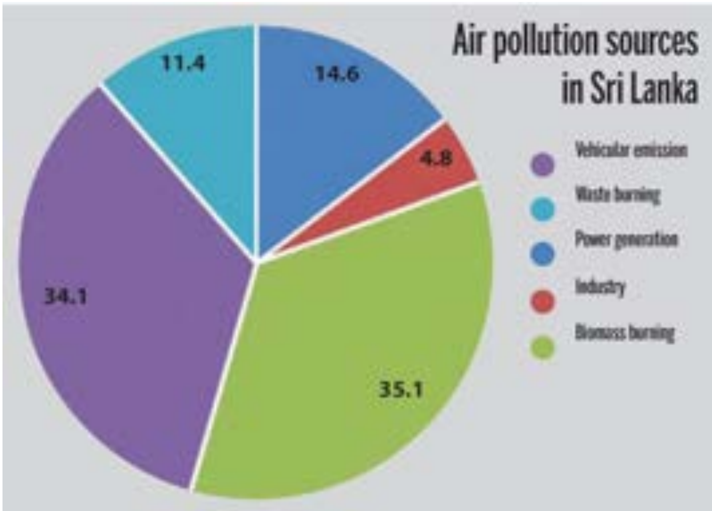

Figure 3. Air pollution sources in Sri Lanka, 2019 (Source: Department of Geography, Faculty of Arts, University of Colombo)

Sources of Outdoor Air Pollution: Vehicular Emission

In metropolitan surroundings, outdoor air pollution can be classified as mobile, stationary, or area sources. The vehicular emissions which contribute to over 60% of total emissions in Colombo is the main source of outdoor air pollution in Sri Lanka.

Automobile emission was recorded as 55-60% of contribution to air contamination in Sri Lanka, in 2011, while 20-25% was due to industries and 20% was from domestic sources (Annual Report-Ministry of Environment, 2012). The transport sector generates the most amount of air pollution which is due to the ever-increasing number of vehicles on the roads whereas the road system has not significantly improved. It is clear that the number of motor vehicles has increased considerably during the last two decades in the country. Currently, there are around 5 million motorcycles registered, a six fold increase since 2000. In addition, the number of cars has increased to around 896,885, which is a fivefold increase since 2000. As the number of motor vehicles has increased, traffic jams, pollution, and productivity loss have increased. The amount of soot, carbon monoxide, and unburnt hydrocarbons produced in traffic jams is greater than that produced by vehicles traveling uniformly at about 40 km/h. Motorcycles make up about 50% of the entire fleet, followed by three-wheelers with the next largest share. During the period 2015-2019, motorcycles increased by 290% and three-wheelers by 380% (Ileperuma *et al*., 2020). Because the most of these two categories of vehicles have two-stroke engines, they cause considerable air pollution by releasing PM_{10}/$PM_{2.5}$ and CO into the atmosphere (Konara *et al*., 2019). Vehicle proliferation will pose the greatest challenge in the future. Colombo's traffic congestion is estimated to result in an annual economic loss of around Rs.32 billion (Kumarage, 2013) and increased health care costs resulting from air pollution will pose an immense burden on the government.

Sources of Outdoor Air Pollution: Oil Refinery Process

One of the most significant anthropogenic source of outdoor air pollution is the oil refinery process in Sri Lanka. While Sri Lanka produced more than 95% of its power from hydropower as of 1993, that percentage has steadily decreased, and hydropower now accounts for only about 50% or less. In fact, a study by the Central Bank in 2018 showed that 5149 GWh were generated through hydro, 1886 GWh by thermal, and 4764 GWh by coal (Ekanayake *et al*., 2021, Herath and Ratnayake, 2004). This demonstrates that more power is generated through burning fossil fuels, leading to more pollution in the country. Further, furnace oil has a high percentage of about 3.5% sulphur (S) and furnace oil combustion generates more SO_2. Furthermore, more than half of all vehicles, 70% of industries and several thermal power plants are located in the Colombo metropolitan area (Pereira and Tiruchelvam, 1998). Those vehicles and power plants emits a huge quantity of air pollutants which could deposit back on to ground level by following dry and wet deposition methods.

Sources of Indoor Air Pollution

The concentration of pollutants inside a sealed indoor atmosphere can be high even if the emissions are relatively modest. During periods of moderate or high wind speed, indoor air pollution concentrations may match to those of outdoors. As a tropical country, Sri Lanka must have good indoor aeration, yet few previous research findings suggest that indoor air is significantly more contaminated than outdoor air. In households, air pollution is caused primarily by cooking fuel, while smoke from other sources, such as tobacco smoke, is also a factor. In Sri Lanka, Demographic Survey 2000/2007 and Health Survey 2006/2007 stated that firewood is the main fire source used in 78.3% and 78.5% of the households respectively. It is doubtful that a higher percentage of Sri Lankans will move to cleaner fuels in the upcoming future (Nandasena *et al*., 2012). Most of the traditional resident stoves have incomplete combustion of firewood which results in high contaminant discharges. Furthermore, poor ventilation leads to high levels of indoor pollution (Wickramasinghe *et al*., 2013).

Health Impact of Air Pollution

Annually, outdoor air pollution is attributed to an assessed 4.2 million premature deaths, strokes, primarily due to heart disease, lung cancer, acute respiratory infections in children and chronic obstructive pulmonary disease. Worldwide, 43% of deaths are caused from chronic obstructive pulmonary disease, 29% of deaths by ischemic heart disease as well as lung cancer (Ileperuma, 2020). The research of Nandasena *et al*. (2010) indicated that indoor and outdoor air contamination is a significant hazard to the country's public health. The relationship between exposure to outdoor or indoor air pollution and numerous health consequences, such as respiratory complaints, lung cancers and low birth weight was examined in several investigations. In all studies, there were significant correlations among air contamination and detrimental health outcomes. Public health is highly impacted by indoor pollutants emitted by firewood-burning stoves. According to WHO estimates, 4200 fatalities in Sri Lanka were attributed to indoor air pollution in 2004 (Nandasena *et al.,* 2012). Air pollutants like CO, small particles, and carcinogenic polyaromatic hydrocarbons like benzo(a)pyrene are found in particularly high concentrations in wood smoke (Ileperuma, 2020). Burning mosquito coils and incense sticks inside of homes are another major source of fine particles, in addition to firewood. According to Liu *et al*. (2003), burning a mosquito coil produces the same amount of $PM_{2.5}$ as smoking about 100 cigarettes and emits the same amount of formaldehyde as burning 50 cigarettes. Additionally, there are sufficient amounts of polyaromatic hydrocarbons which cause adverse health effects. According to United States Environmental Protection Agency (US EPA) 2017, there are six main health effects of outdoor air pollution (Fig. 4). Pregnant women, infants, adults, outdoor workers and individuals with –pre-existing health circumstances as the people who are at major risk related to outdoor air pollution.

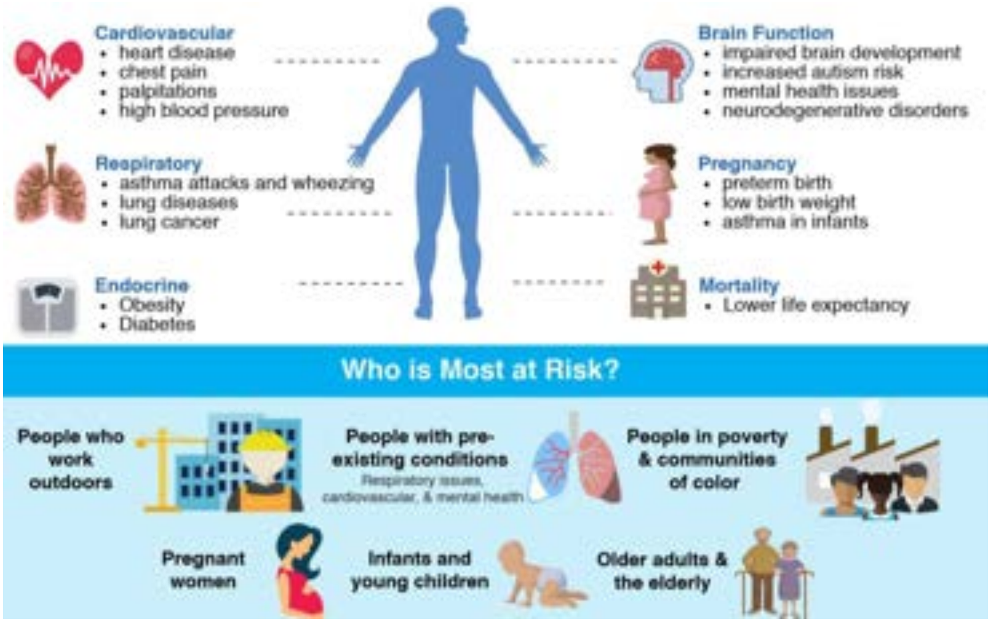

Figure 4. Infographic that shows the health effects of outdoor air pollution. Source: United States Environmental Protection Agency (US EPA), 2017.

Automobile emissions, which have increased dramatically along with the number of vehicles on the road and traffic congestion, are mostly responsible for outdoor air pollution (Ileperuma, 2020). Through vehicle emissions, contaminants such as polycyclic aromatic hydrocarbons (PAHs), nitrogen oxides, sulfur dioxide, carbon monoxide, particulate matter (PM), volatile organic complexes are released into the environment and could be harmful to human health. The WHO estimates that outdoor air pollution in Sri Lanka was responsible for 1,000 fatalities in 2004 (Nandasena *et al.,* 2012).

Agricultural Impact due to Air Pollution

Air pollution indirectly affects agriculture. These impacts can cause huge damage to the nation's economic stability and could be very significant, but these issues and their implications for agricultural policy and pollution control have not been recognized by many nations. Air pollution can affect agriculture in direct and indirect ways. Growth and yield are directly affected by air pollution. Crop yields are generally reduced with increasing exposure to pollutants, even in the absence of visible injury, scientists have proved it with a range of different contaminants (Manisalidis *et al*., 2020). When the pollutants are deposited onto the leaf surfaces, it causes a huge negative effect on the edible plants such as tea leaves and green leaves which consume in fresh form. The deposition of pollutants can damage the leaf growth and they also can decrease the nutritional value of the leaves (Desalme *et al*., 2013). Air pollution could also indirectly affects agriculture (Lemaire *et a*l., 2014). Air pollutants can cause a variety of subtle physiological, chemical or anatomical changes which will not lead to noticeable yield drops even at relatively low concentrations (Bell *et al.*, 1993). These agricultural impacts should be addressed with proper policies as a nation since these can affect the economy of the country directly and indirectly (Molajou *et al.*, 2021).

Approaches to Control Pollution

Physical and chemical methods are widely used as pollution controlling approaches but they can cause adverse side effects. Some strategies can reduce the pollution up to certail level (Fig. 5). Since the chemical and physical methods can cause adverse side effects to the environment, the scientists have experimented the bioremediation approaches to reduce air pollutants. The processes that use microorganisms or their enzymes to treat contaminated sites for recovering their original condition is defined as bioremediation (Glazer and Nikaido, 1996). There are two measures of applicable air emissions control. Source control involves reducing emissions over raw product substitution, reduction or recycling. However, these reduction mechanisms may decrease the quality of the product or may increase the costs. Secondary control contains treatment of the wastes after the production process. Although secondary control can be done through chemical treatments, it could generate diferent type of pollution (Flagan and Seinfeld, 1988), Meramo-Hurtado *et al.*, 2020). Consequently, instead of chemical treatments, bioremediation can be used to eradicate polycyclic aromatic hydrocarbon pollutants in the environment (Davie-Martin *et al.*, 2017, Devinny *et al.*, 2017; Gitipour *et al.*, 2018, Singh and Haritash, 2019).

Figure 5. Infographic that shows different approaches to reduce exposure. Source: United States Environmental Protection Agency (US EPA), 2017.

Bioremediation

Bioremediation uses microbes to decrease pollution through the biological degradation of contaminants into non-toxic matters (Rockne and Reddy, 2003). This can contain either aerobic or anaerobic microorganisms that frequently use this breakdown as an energy source (Vidali, 2001). There are three groups of bioremediation techniques: in situ land treatment for soil and groundwater; biofiltration of the air; and bioreactors which are predominantly involved in water treatment. While chemical scrubbing has been used to clean gases discharged from chimneys, the newer technique of 'biofiltration' is helping to clean industrial gases (Tyagi and Kumar, 2021). This technique involves passing contaminated air over a replaceable culture medium containing microorganisms that degrade pollutes into products such as carbon dioxide, water or salts. Biofiltration is the solitary biological practice currently existing to remediate airborne pollutants (Sinha *et al*., 2022).

The main advantages of bioremediation are, it a natural process with limited harm to the environment since this is an eco-friendly aproach. The public acceptancy level is also high, cost-effective to maintain, does not disturb the economical flow and little energy consumption is required for the process. For the reason that the bioremediation can fulfill the need for pollutant control, it proves to be eco-friendly and cost-effective. Use of alive organisms to transform toxic substances into nontoxic forms is the fundamental concept of bioremediation (Rahman *et al*., 2006, Mishra *et al*., 2019). Bacteria can convert polycyclic aromatic hydrocarbons entirely to biomass, CO_2, H_2O, and other pollutants into nontoxic levels. Microorganisms from a wide range of different bacteria and fungi are capable to assimilating a defined range of compounds entirely or showing an incomplete metabolism (Shuttleworth *et al*., 1995, Ning *et al*., 2012, Horel *et al*., 2020). Microorganisms such as bacteria, fungi, and microalgae perform a key role in pollutant elimination through bioremediation processes (Nikolova and Nenov, 2005, Kumar and Kundu, 2020). Biotechnological approaches could play a vital role in bioremediation. Biotechnological mechanisms are used to remove contaminants from the air and the microbes can be used in these mechanisms as consortiums or modified by genetic engineering which is more effective in degrading contaminants.

Introducing the biofilter units as a novel innovative pollutant controlling system has become a trend in the science community and the major importance of using biofilters is, they absorb contaminated air and the microbes degrade those chemicals into nontoxic levels with low investment and operational cost. The separation between the microorganisms and the treated air is the fact that biofiltration varies from other biological treatments. The microbial biomass is statically immobilized to the bedding material in the biofiltration, while the treated air is mobile and it transfers through the filter (Fig. 6).

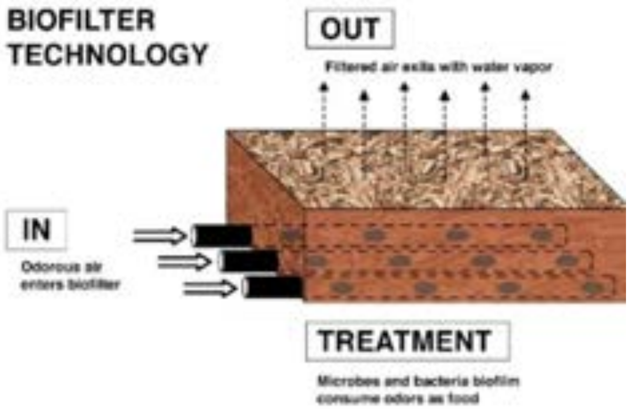

Figure 6. The concept of the biofilter immobilized with microbes in an optimized medium to increase the degradation of air pollutants (source: Biofilters For Air Pollution Control by Darshan Kr in 01 July 2021/ https://www.seminarstopics.com/seminar/8015/biofilters-for-air-pollution-control).

This structure forms a separation between the treated airflow and the microbial biomass (Cohen, 2001, Lebrero *et al*., 2011, Luengas *et al*., 2015, Zhang *et al*., 2018). There are two types of biofilter configurations. They are, openly designed biofilter units, installed outdoors since they need large spaces with ascending gas flows (Delhoménie and Heitz, 2005, Gopinath *et al*., 2018, Dhamodharan *et al*., 2019). The other type needs more restricted capacities than the open configuration, hence they are frequently installed in closed spaces, and can use ascending or descending gas flows and termed as "enclosed designed bio-filters" (Ottengraf, 1986). Flow rate, filter bed, pressure drop, moisture content, temperature, nutrients, pH and microorganisms are the most significant physical, chemical, and biological parameters influencing the effectiveness biofiltration process (Delhoménie and Heitz, 2005). Furthermore, immobilizing bacteria and fungi on matrices facilitated not just simply remediating a contaminated spot but also enhanced pollutant biodegradation capacity. Other than that immobilizing bacteria and fungi in to matrices can amplified bacterial and fungal enzyme activity, enhanced the durability of the immobilized strains, and enhanced their tolerance to high pollutant masses.

Conclusions and Future Prospects

There is a wide range of literature related to economics that explores the relationship between human health and recessions, stating the importance of taking action against economic downturns to improve health outcomes. The consequences to the economy due to air pollution are considered by assigning a monetary value to every health aspect. Quantifying the exposure by adjusting the effect of economic tendencies on air pollution got relatively few studies available. Air pollution is a crucial focus that affects the most economies directly in the world, but this concern has not addressed appropriately in Sri Lanka. The most effective way to eliminate contaminants from the environment in an eco-friendly approaches such as bioremediation. The public acceptance level of bioremediation is also high, cost-effective to maintain, does not disturb the economical flow and little energy consumption is required for the process. For the reason that the bioremediation can fulfill the need for pollutant control, it proves to be eco-friendly and cost-effective. Use of alive organisms to transform toxic substances into nontoxic forms is the fundamental concept of bioremediation. Sri Lanka as a country undergoing a major economic crisis nowadays could benefit from these ecofriendly and cost-effective approaches in reducing the air pollution in the country.

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Conflict of Interest

Authors have declared that no competing interests exist.

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CHAPTER 13

Supercapacitor-Assisted Converter Techniques for Implementing Highly Efficient and Self-sustained Off-grid Renewable Energy Systems

P.L.A.K. Piyumal[1]*, A.L.A.K. Ranaweera[1], S.R.D. Kalingamudali[1] and N. Kularatna[2]

Abstract The supercapacitor (SC) is a short-term energy storage device with a low energy density compared to electrochemical batteries such as lead-acid, nickel-metal, and lithium-ion batteries. SCs have several advantages over electrochemical batteries, including long cycle life, mechanical robustness, low internal resistance and high power density. Due to recent developments in SC technology, there is a possibility to use SCs as energy storage devices in renewable energy systems. However, when an empty capacitor is charged by an external source using a parallel charging configuration, it stores only half of the energy delivered by the source compared to that of an electrochemical battery. Therefore, it wastes 50% of useful energy. A portion of this wasted energy can be collected and utilised if a useful resistive load is connected in series to this capacitor charging loop. This method is known as the SC-assisted loss management technique. This theory is an extension of the typical resistor-capacitor (RC) circuit theory which uses the advantage of a large time constant when an SC is connected to an RC circuit. Based on this concept, several SC-assisted circuit topologies such as SC-assisted low dropout regulator (SCALDO), SC-assisted surge absorber (SCASA), SC-assisted LED lighting converter (SCALED), and SC-assisted hybrid photovoltaic (SCAHPV) system are currently being developed. This book chapter discusses the development of SC technologies and their uses as energy storage devices in off-grid renewable energy systems.

Keywords: Energy efficiency, Photovoltaic system, RC circuit theory, Solar energy, Supercapacitor

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Introduction

In the modern world, energy has become a critical part of humans' day-to-day life. In order to generate the required energy, humans have harnessed energy from various sources using different methods since the ancient times. During the past decade, burning fossil fuels has become the primary electricity generation tool after hydropower for a developing country like Sri Lanka. However, the emission of various kinds of toxic gases while burning fossil fuels has become a life-threatening act for all living creatures on the planet (Chowdhury *et al.*, 2013). Furthermore, the depletion of fossil fuels and increased demand for them has also increased their price, decelerating the country's economic development. This increased consumption and depletion of fossil fuels and the emission of toxic gases into the atmosphere have forced the world community to find a greener solution through renewable energy sources to supply the energy demand in the 21st century. Among many renewable energy sources, photovoltaic (PV) cells remain on top of the most popular devices that can harness solar energy and convert it to electricity (Chowdhury *et al.*, 2013).

The power from the sun intercepted by the earth is approximately $1 \cdot 8 \times 10^{11}$ MW which is far larger than global power generation from all other sources (Balat, 2005). We could easily satisfy our current energy requirement if we could harness even a tiny fraction of this energy and convert it to electricity. According to Fig. 1, there has been a massive decrease in the power generation cost of photovoltaics compared to the other energy sources during the last decade.

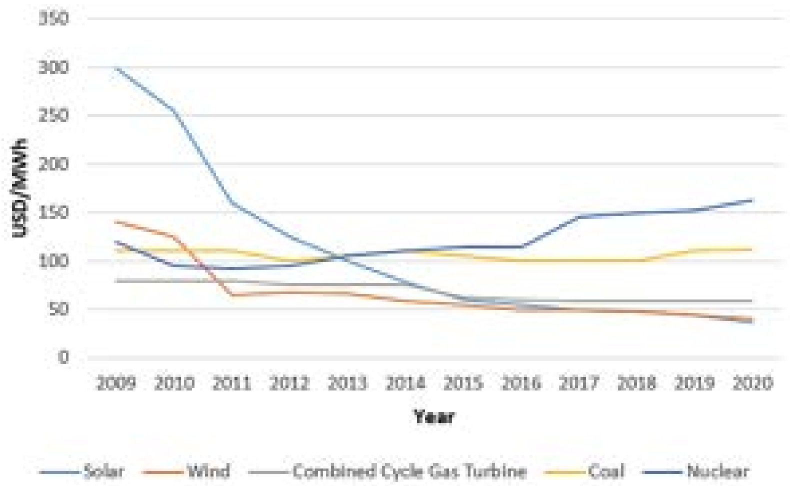


Figure 1. Comparison of power generation costs between photovoltaic and other power sources from 2009 to 2020 (Global Market Outlook for Solar Power, 2021)

Even though the development of solar PV technologies has many advantages, the efficiency of conventional solar panels lies on the low side compared to other energy generation methods. Recently developed photovoltaic technologies have demonstrated efficiencies of 20 to 28% (Green *et al.*, 2015). This is a huge disadvantage because it would require a large area of solar panels covering many grounds or rooftops to generate sufficient electrical energy to satisfy present energy needs. Furthermore, as shown in Fig. 2, most electrical consumer goods feature electronic modules powered by a cascade of converters, usually beginning with an AC-DC converter and continuing with a number of DC-DC converters. An AC-DC converter followed by additional DC-DC converters may have a system efficiency as low as 73% if the energy source is a 230 V AC, 50 Hz domestic power supply or from an inverter output of a PV system, assuming each of the three converters has reasonably high efficiencies of 90%. With the availability of DC outputs from renewable energy sources like photovoltaic solar cells, it is possible to eliminate a few converter stages, achieving a significant rise in system efficiency. Because of these reasons, it is essential to find a way to utilise the energy generated by solar panels in an effective manner.

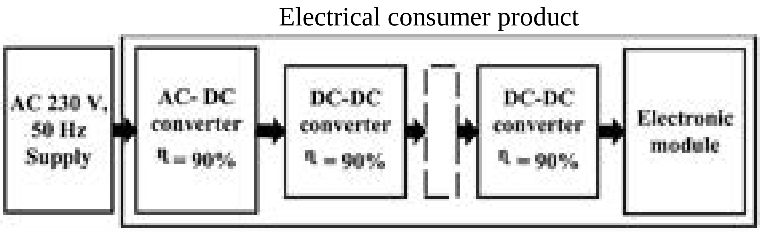


Figure 2. Energy flow within a typical electronic product or a system showing system efficiency of around 73% (Jayananda *et al.*, 2020)

Off-grid PV Systems

All solar PV systems work on the same basic principle. Solar panels in a PV system first convert solar energy into DC electricity. The DC power can then be stored in a battery or converted to AC power using a DC to AC inverter to power up household appliances. Excess solar energy can be delivered to the power grid or stored in various battery storage systems, depending on the type of installation. There are three main types of solar PV systems; (i) Grid-connected PV systems, (ii) Standalone (Off-grid) PV systems and (iii) Hybrid PV systems. Both off-grid and hybrid PV systems employ a battery bank with a charge controller. Grid-connected PV systems do not employ a battery bank as they are directly integrated with the utility grid. Off-grid PV systems can be used but are not limited to power buildings in remote areas where the national electrical grid is unavailable. Electrochemical rechargeable batteries are commonly used in off-grid PV systems to store energy in the daytime and produce power for the loads at night. Fig. 3 shows the block diagram of a typical off-grid PV system with DC and AC loads.

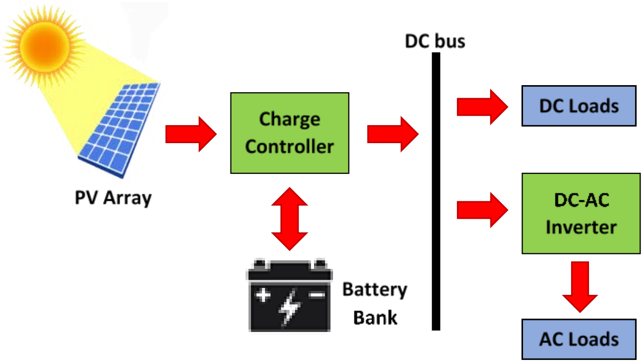


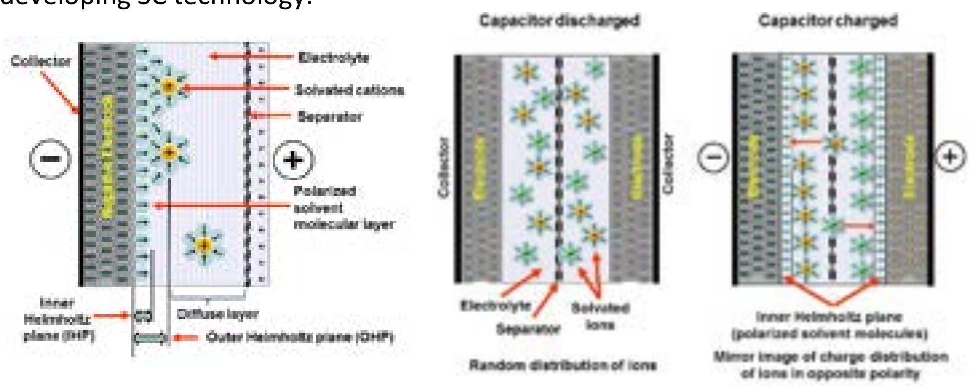
Figure 3. Block diagram of an off-grid PV system

Over the years, several types of standalone PV systems were introduced with novel power management and controlling strategies (Wu *et al.*, 2014; Mahmood *et al.*, 2015; Rosini *et al.*, 2021), although most of them have the same hardware. The battery charge controller is a crucial part of an off-grid PV system because it must extract, deliver and store the maximum energy from the PV array into the battery bank to optimise system efficiency. Furthermore, a charge controller is needed to manage the charging and discharging processes of the battery by switching "off" the PV modules when the batteries are fully charged and switching "off" the load when the batteries become discharged below a certain limit. Modern off-grid PV systems employ maximum power point tracking (MPPT) charge controllers, which have an efficiency of around 90% (Chowdhury and Mourshed, 2016). These MPPT charge controllers use switch mode DC-DC converters to match the load impedance to the instantaneous impedance of the PV array using a technique called impedance matching. This is done by varying the duty ratio of the DC-DC converter's control pulse width modulated (PWM) signal. The PWM signal is varied by tracing the PV array's maximum power point (MPP) using various MPPT algorithms (Esram and Chapman, 2007; Ram *et al.,* 2017; Badoud *et al.,* 2021).

Introduction to Supercapacitors

As the name implies, SCs can have a larger capacitance than conventional ones. SCs have a very large cyclic life but a lower energy density than electrochemical batteries. With the advancement of technology, SCs can now be used as short-term energy storage devices (ESDs) in electronic systems, with the benefits of low maintenance, longer life cycle and constant equivalent series resistance (ESR) with the depth of discharge (DOD). SCs were first developed in the range of a few Farads, with internal resistances ranging from fractional ohms to a few ohms (Kularatna, 2015), and were intended for basic applications such as buffering memory modules for a short term. With recent developments, SCs are available with capacitance ranging from hundreds to a few thousands of Farads (Linzen *et al.*, 2005; Li *et al.*, 2008). SCs can be hybridised with battery packs to take advantage of their higher power density than batteries. For example, SCs are already being employed as supplementary devices to store energy during braking and boost power during rapid accelerations in modern electric vehicles, which ultimately increases the power efficiency of the vehicle (Horn *et al.*, 2019). However, single-cell SCs have limited cell voltage, usually less than 5 V (Douglas and Pillay, 2005; Kularatna, 2015).

SCs work on the same basic principles as electrostatic capacitors, with larger area plates and shorter spacing between plates resulting in higher effective capacitance. SCs are formally known as electric double-layer capacitors (EDLCs) since these devices generate an electrical double layer next to a wide area electrode and an electrolyte. An SC comprises two electrodes connected to current collectors and separated by a separator soaked in electrolyte. Each electrode's inner surface is not smooth but rather padded with activated porous carbon, resulting in a surface area 100,000 times that of a conventional electrostatic capacitor (Bakhoum, 2009). Double-layer capacitance is one of the essential properties of an electrical double layer created at the interface between a conductive electrode and the liquid electrolyte. When an external electric field is applied to the two electrodes, they are electrically charged, and ions in the electrolyte migrate toward the electrode with the opposite charge (Linzen *et al.*, 2005; Jayalakshmi and Balasubramanian, 2008; Kularatna, 2015; Jayananda *et al.,* 2020). As shown in Fig. 4(a), electrons in the electrode and ions in the electrolyte are separated by a single layer of solvent molecules. Those molecules adhere to the surface of the electrode and act as a dielectric in a conventional capacitor (Jayananda *et al.,* 2020). Fig. 4(b) shows the anions and cations arrangement of EDLC capacitors at charged and discharged states. At the charged state, the anions and cations are positioned in the electrolyte near the electrode, balancing the excess charge on the electrically conducting side of the phase boundary. As a result, there will be two layers of excess charge of opposite polarity across each phase boundary. Therefore, the interface of the electrode and electrolyte acts as a capacitor, and the complete cell can be represented as two capacitors connected in series. This effect is the key to developing SC technology.



(a) (b)

Figure 4. Formation of EDLC capacitor: (a) Conceptual electrochemical capacitor, and (b) Arrangement of Anions and Cations at charged and discharged states (Jayananda, 2020)

During the last decade, SC manufacturers have introduced several variants of SCs. Symmetrical EDLCs, hybrid SCs and CAPA batteries are the most common SC families. Table 1 compares the parameters of commercially available SC families. The CAPA battery type SCs, introduced recently, have a higher energy density and capacitance. Despite having a lower cycle life and power density than more mature EDLC families, they have a far higher cycle life and power density than lead-acid batteries.

Table 1. Comparison of commercially available single-cell supercapacitors

Parameter	EDLCs	Hybrid SCs	CAPAbatteries
Energy density (WhL^{-1})	5-8	10-14	50-120
Power density (WL^{-1})	8,000	2,500-4,000	1,600-3,200
Cycle life	1,000,000	40,000-50,000	15,000-20,000
Rated voltage (V)	2·7	2·7	2·8
Capacitance (F)	1-3,000	200-7,500	1,000-70,000

(Source: ESD-SCAP Catalogue, SAMWHA Capacitor Co.,Ltd., 2018)

The internal resistance of a conventional electrochemical battery increases with the DOD (Kularatna, 2015). However, an SC's ESR will remain constant throughout the charging and discharging phases (Kularatna, 2015). Therefore, the cell's energy loss and power density are higher than the electrochemical battery. Furthermore, the cyclic life of SCs is a few thousand times larger than conventional battery technologies. Therefore, SC banks could be utilised to replace hazardous electrochemical battery packs in energy storage applications. Table 2 shows a comparison of the properties of SCs, electrochemical batteries, and conventional capacitors. As discussed above, most of the time, the performance of different ESDs is compared using their energy density and power density. Electrochemical batteries are ideal for long-term energy storage applications due to their high energy density, while SCs are useful in short-term energy storage applications due to their medium energy density. With a very high power density of SCs, they can be used in applications where burst currants are required, which an electrochemical battery can never achieve.

Typical Applications of Supercapacitors

In the early days, SCs came with only a few farads of capacitance. Therefore, their applications were limited to powering memory modules as a short-term backup (Saha *et al.,* 2021). After the development of new SC families with capacitance over thousands of farads, they are used to hybridise with electrochemical batteries because of SCs' high power density. Furthermore, SCs have a large cyclic life compared with typical rechargeable batteries. Depending on these two different characteristics, applications of SCs can be discussed in two application domains; (i) low-power applications where the batteries could be used, but with SCs, maintenance and lifetime problems can be addressed, and (ii) high-power applications where the use of batteries is limited. The following text describes some of the state of art applications of SCs that utilises unique characteristics of SCs.

Table 2. A comparison of energy storage technologies (Source: Gunawardane and Kularatna, 2018)

Parameter	Batteries	SCs	Conventional capacitors
Charge time	1-5 hours	1-60 minutes	10^{-6} to 10^{-3} s
Discharge time	0·3-3 hours	0·1-30 minutes	10^{-6} to 10^{-3} s
Energy density (Whkg^{-1})	20-100	1-20	< 0·1
Power density (Wkg^{-1})	50-200	10,000	< 10,000
Cycle time	500-2000	50,000-1,000,000	> 106
Charge/discharge efficiency	70-85%	near 100%	near 100%
Internal resistance or ESR	50 mΩ to few Ω (increases with DOD)	fractional mΩ to several m Ω (constant with DOD)	fractional Ω to several Ω
Capacitance (F)	N/A	fraction of a Farad to thousands of Farads	pF to a fraction of a Farad

(i). Engine Starter

Currently, the energy required to crank and start an engine is stored in either Pb-acid or NiCd batteries. Due to their high internal resistance, the initial peak current required to start an engine is limited. Because of this reason, they have to be oversized. Also, the cold environmental temperature and fast discharging nature of batteries further limit their performance. However, SCs have a better operating temperature range (Kularatna, 2015) and low ESR value, making them a better option to substitute batteries and use as engine starters.

(ii). Electric and Hybrid Vehicles

SCs are used as energy storage for starter motors in modern vehicles. However, due to their low energy density, they are not suitable for primary energy storage for automotive applications such as electric vehicles (EVs) and hybrid electric vehicles (HEVs). Nevertheless, due to their high power density, SCs are ideal to be used for capturing and storing energy from regenerative braking employed in modern vehicles. Later, the stored energy in SCs can provide short-term power boosts for sudden accelerations. Because of this added advantage, the size of the battery of an electric vehicle can be reduced. However, SCs are connected in parallel with EV's batteries in typical systems. Thus, their upper and lower threshold voltage levels are determined by the fully charged and fully discharged battery voltage levels, respectively. Therefore, a considerable amount of energy in the SCs left unused (Burke *et al.,* 2014).

(iii). Uninterruptable Power Supply (UPS)

SCs are used in UPS systems to back up the system for short-term peak power requirements. By combining SCs with a typical battery-based UPS system, batteries can be used as a long-term energy backup, while SCs can be used as a short-term, high-power energy backup, extending the battery's lifetime. Which also aids in employing smaller batteries in UPS systems.

(iv). Portable Electronic Devices

Similar to the UPS systems, SCs can be combined with batteries in portable electronic devices such as mobile phones and laptops to improve the lifetime and battery run-time. Studies show that an increase in run-time of 4-12% is achievable (Palma *et al.,* 2003).

(v). Renewable Energy Applications

Benyahia *et al.*, (2013) discussed a grid-connected PV system consisting of an SC bank connected to the main DC link of the system through a bi-directional DC-DC converter. The DC link is then connected with a DC-AC inverter like a typical grid-connected PV system. The SC bank in this study is used to smooth out the DC link voltage by buffering the energy fluctuations. The invention by Wei (2012) describes a method to manage a Pb-acid battery's charging and discharging processes in a photovoltaic system, while the invention by Fang *et al.* (2011) describes a grid-connected system that consists of a PV array, wind turbine and commercial power interface where an SC is connected to the system to buffer the energy fluctuations. However, recent developments in SC technologies have provided the ability to use them in non-traditional applications. Most of them are based on the supercapacitor-assisted loss management (SCALOM) concept discussed in the literature (Ariyarathna *et al.*, 2017). The following section discusses the basics of this theory.

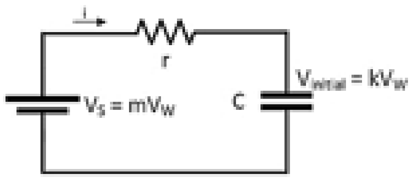
Supercapacitor-Assisted Loss Management Concept

SCALOM concept is an extension of the typical resistor-capacitor (RC) circuit theory. This concept explains how to enhance the efficiency of a system using an SC charging loop consisting of a useful resistive load. This technique uses the advantage of a large time constant when an SC is connected to an RC circuit. Based on this concept, several SC-assisted circuit topologies such as SC-assisted low dropout regulator (SCALDO) (Gunawardane and Kularatna, 2018; Kularatna *et al.*, 2021), SC-assisted surge absorber (SCASA) (Fernando *et al.*, 2014; Fernando, 2016), SC-assisted light-emitting diodes (SCALED) (Jayananda, 2020; Jayananda *et al.,* 2020; Kularatna *et al.*, 2021) and SC-assisted hybrid photovoltaic (SCAHPV) system (Piyumal *et al.*, 2021, 2022) are currently being developed.

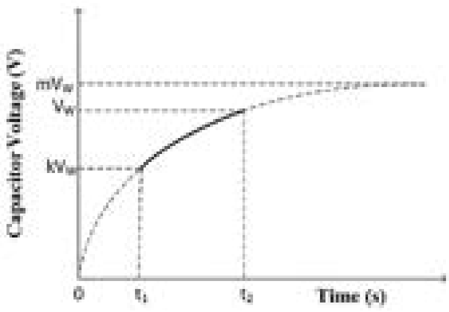
When an empty capacitor is charged to a voltage of V by supplying charge Q, the capacitor stores $\frac{1}{2}QV$ of energy while wasting the same amount of energy in the entire loop resistance, regardless of its value (Ariyarathna *et al.*, 2017). Compared to an electrochemical battery, which stores an energy amount of QV, the capacitor charging loop wastes 50% of supplied energy. This is a basic observation of electrical fundamentals. According to the SCALOM theory presented in the literature

(Ariyarathna *et al.*, 2017), if a non-empty SC bank is charged while a useful load is connected to the loop in a series configuration, the total system efficiency can be improved. This is because the energy consumed by the useful load is doing useful work before being dissipated.

Fig. 5 (a) shows a simple RC circuit with an over-rated DC voltage source and a pre-charged capacitor. Fig. 5(b) shows the typical capacitor charging circuit where we focus on the energy efficiency for partial charging of capacitor from kV_W to V_W. The source voltage is over-rated by a factor of m with respect to the final DC voltage of the capacitor V_W. The initial voltage of the capacitor is set to kV_W. k $(0 \leq k \leq 1)$ and m (≥ 1) are defined as the pre-charged factor and power supply over-voltage factor, respectively (Ariyarathna *et al.*, 2017). When $k \rightarrow 1$, SC bank reaches its pre-defined final voltage. In Fig. 5(a), C is the capacitance of the capacitor, V_s is source voltage and r represents the total resistance of the charging loop, which includes the source internal resistance, ESR of the capacitor, and loop parasitic resistance.



(a)



(b)

Figure 5. (a) Charging circuit of a pre-charged capacitor and (b) Capacitor charging curve

The efficiency of the capacitor charging process (η) can be written as,

$$\eta = \frac{E_C}{E_C + E_r} \times 100\% \tag{1}$$

where, E_C is the total energy stored in the capacitor and E_r is the energy dissipation through the loop resistance r. Using the extended theory discussed by Ariyarathna *et al.*, (2017), η can be expressed as a function of k and m as follows.

$$\eta = \frac{1 + k}{2m} \times 100\%\,. \tag{2}$$

As seen from equation (2), it is clear that the charging efficiency of the capacitor can be varied by choosing different values for k and m. When $k \rightarrow 0$ and $m \rightarrow 1$ where there is no initial charge in the capacitor and no power supply over-rated factor, the charging efficiency $\eta \rightarrow 50\%$. Which is the basic observation of the capacitor charging circuit as discussed above. Therefore, it is evident that charging efficiency is enhanced if the capacitor is pre-charged. Practically, this means that when using a capacitor as energy storage, the efficiency can be enhanced if the capacitor is not allowed to be fully discharged during a cycle. However, if we increase the value of m to minimise the charging time, the efficiency will be reduced since $\eta \propto \frac{1}{m}$ as seen from equation (2). The 100% efficiency is reached when $k \to 1$ and $m \to 1$. This is practically an impossible scenario where the initial voltage of both source and capacitor equal to V_W if $k \to 1$ and $m \to 1$ so that no charging can occur. The variation of the capacitor charging efficiency vs. k and m is depicted in Fig. 6.

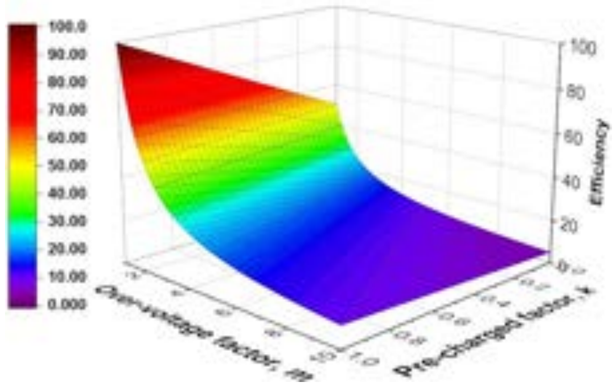
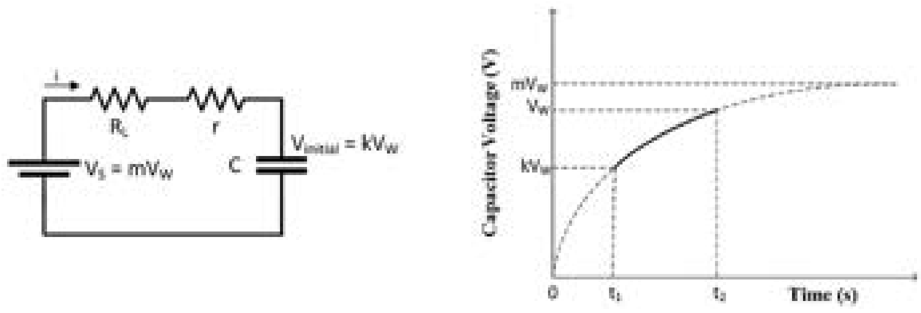


Figure 6. Variation of charging efficiency of a pre-charge capacitor vs. k and m

Now consider a case as shown in Fig. 7 where a useful resistive load, R_L has been inserted into the capacitor charging loop. For this case, dissipated energy through the useful resistive load $\left(E_{R_L}\right)$ and loop resistance (E_r) can be written as a fraction of the energy loss (E_{Loss}) of the typical capacitor charging loop as follows.



(a) (b)

Figure 7. (a) Capacitor charging circuit with useful resistive load, and (b) Capacitor charging curve

$$E_{R_L} = \left(\frac{R_L}{r + R_L}\right) E_{Loss} \tag{3}$$

$$E_r = \left(\frac{r}{r + R_L}\right) E_{Loss} \tag{4}$$

Expressions (3) and (4) conclude that when a useful resistive load R_L is inserted into the capacitor charging loop, it is effectively utilising the portion of wasted energy. This results in a minimised energy loss because the energy consumed by R_L does useful work before being dissipated, enhancing the efficiency of the system. Therefore, this allows redefining the efficiency expression (1) as follows.

$$\eta = \frac{E_C + E_{R_L}}{E_C + E_r + E_{R_L}} \times 100\% \tag{5}$$

Using the extended theory by Ariyarathna *et al.* (2017), η can be expressed as,

$$\eta = \frac{1}{1 + P}\left(P + \frac{1 + k}{2m}\right) \times 100\% \,. \tag{6}$$

where, $P = \frac{R_L}{r}$ and $P \geq 0$.. When $P \to 0$ (i.e. when $R_L \to 0$), equation (6) is reduced to equation (2). Equation (6) shows that if the capacitor is not allowed to discharge fully in a cycle (when $k \neq 0$), system efficiency can be improved. As seen from equation (6), η can be enhanced by selecting proper values for k and m. Nevertheless, when P increases, the efficiency advantage increases significantly. Therefore, the effects of k and m on efficiency are minimised. This trend is shown in Fig. 8, which illustrates the variation η vs. k and m for different selected values for P. These trends clearly show that the efficiency of an RC circuit can be enhanced by inserting a useful resistive load and a pre-charged SC into the RC circuit, as in Fig. 7(a).

Furthermore, as seen from equation (6), the system's efficiency does not depend on the capacitance of the capacitor. Therefore, extending the loss circumvention theory mentioned above is possible to a loop consisting of an SC or SC bank. Commercial SCs have lower ESR than electrolyte capacitors, making SCs less dissipative. Therefore, the dissipative voltage across a series-connected SC could be negligibly small. The potential difference, ΔV, across an SC bank can be large and only varying slowly because ΔV is inversely proportional to the capacitance. For a case of constant current (I_C) charging, ΔV can be written as follows (Jayananda *et al.,* 2018),

$$\Delta V = \frac{I_C \, \Delta t}{C} \tag{7}$$

where Δt is the time elapsed to increase the potential difference across the capacitor in ΔV volts and C is the capacitance of the capacitor. Furthermore, the rated voltage of an SC is smaller than that of an electrolytic capacitor. Therefore, with a usage of an over-rated voltage source, the SC may be over-charged. However, since the capacitance of the SC is very high, the RC circuit will have a longer time constant. Therefore, a voltage detection system can be used to monitor the voltage of the SC bank to disconnect the loop to prevent overcharging of the SC bank in the case of the usage of over-rated DC source. Consequently, this concept is applied to develop novel circuit topologies with enhanced system efficiency. The following section discusses the development of several novel SC-assisted circuit topologies.

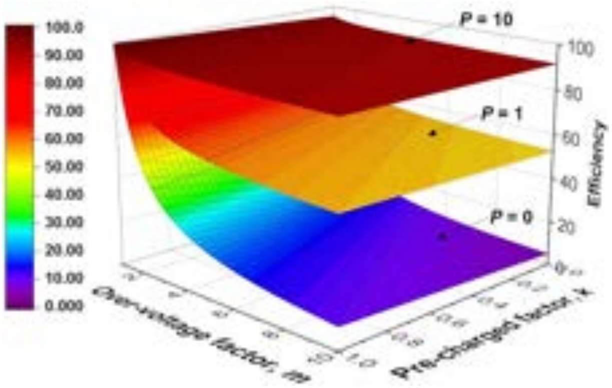


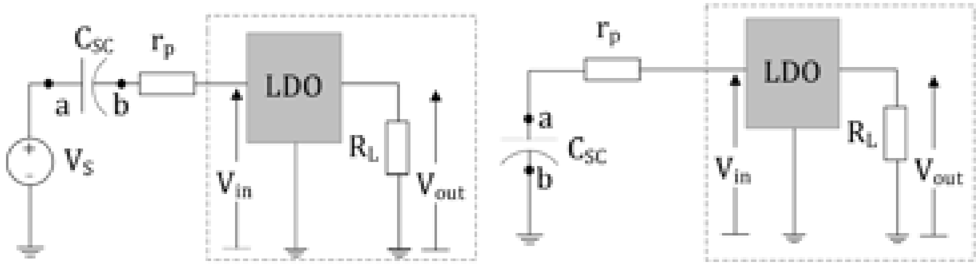
Figure 8. Efficiency variation of the modified RC circuit vs. k and m

Practical Applications of the SCALOM Theory

(i). Supercapacitor-Assisted Low Dropout (SCALDO) Regulator

Switch-mode DC-DC converters and switched-capacitor type converters are commonly used in applications requiring DC-DC conversion. However, common switch-mode DC-DC converters use inductor-based switching at the power stage, raising the issue of electromagnetic interference (EMI). Moreover, both switch-mode DC-DC converters and switched capacitor converters carry a high complexity in their designs due to high-frequency control operation. However, linear converters offer high-quality DC output voltage levels with very low noise. Nevertheless, due to their low efficiency, the applications of linear regulators may be limited to low-current applications. A low dropout regulator (LDO) is a linear regulator with low input-to-output dropout voltage. Combining a switch-mode DC-DC converter with an LDO is possible in cases where high efficiency and lower noise are required. However, because of their design complexity, high cost, and size, they also have limited applications.

The SCALDO regulator was the first patented circuit topology which is based on the SCALOM theory (Kularatna and Fernando, 2011). In this topology, the LDO-load combination is inserted into the capacitor charging circuit in place of R_L of Fig. 7(a) discussed in above section. Fig. 9 shows an illustration of the SCALOM theory applied in the context of the SCALDO regulator. The power supply, SC and LDO-load combination is connected in series in the charging mode of the converter. Because of this series connection, the SC act as a lossless voltage dropper and aids in enhancing the system efficiency by storing a portion of wasted energy. In this topology, as the SC charges in the 1st phase, the input voltage of the LDO regulator, V_{in} decreases. The converter is operated under this mode until V_{in} falls to the LDO regulator's minimum operating voltage. At this point, the converter is switched to the discharging phase, as shown in Fig. 9(b), where the SC is allowed to discharge until V_{in} falls to the LDO regulator's minimum operating voltage again. After that the converter is switched back to the charge phase and cycle repeats while maintaining the charge balance of the SC (Kularatna *et al.*, 2021). Unlike typical LDO regulator operation, the SCALDO regulator uses the input power supply only when the converter is operating in the charge phase.



(a) (b)

Figure 9. The SCALOM concept in the SCALDO technique: (a) SCALDO charge phase, and (b) SCALDO discharging phase (Kularatna *et al.*, 2021)

To change the operating mode of the SCALDO converter, a MOSFET-based switching network is utilised. This is a very low frequency and low noise approach compared to switch mode DC-DC converters and a highly efficient technique compared to typical linear regulators. For example, a typical 12 – 5 V LDO regulator has a maximum efficiency of around 45%. However, the SCALDO regulator with the same specifications can reach up to 83% efficiency (Kularatna *et al.*, 2021). Recent studies show that the theoretical efficiency of the SCALDO regulator can be as high as 88% (Jayasekara *et al.*, 2020). More information on SCALDO regulators can be obtained from Subasinghage *et al.* (2017), Gunawardane *et al.* (2018) and Kularatna and Jayananda, (2020).

(ii). Supercapacitor-Assisted Surge Absorber (SCASA)

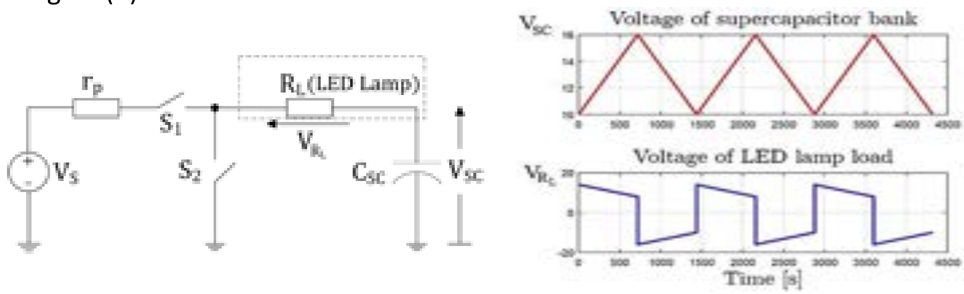
As discussed above, the SCALOM theory shows that when the capacitor is charging, most of the energy is wasted during the initial stage, and energy waste reduces with the capacitor's increasing state of charge (SOC). Replacing the capacitor using an SC can increase the RC time constant up to the range of seconds to several minutes. However, the duration of a typical transient surge voltage induced on the AC line voltage is around or less than 100 microseconds. Therefore, the voltage increment of the SC due to a surge can be in the range of millivolts, and most of the surge energy will be dissipated through loop resistance. This concept is being used in

SCASA, where this has become a standard surge absorber in Australia. Fig. 10 shows the commercialised product of SCASA. More details on SCASA circuit topology can be found in (Kularatna *et al.*, 2011; Fernando, 2016).

Figure 10. SCASA commercialised product (*STViQ/2 SMART TViQ | Thor Technologies*, 2021)

(iii). Supercapacitor-Assisted LED (SCALED) Lighting System

In the context of achieving energy security and implementing self-sustained renewable energy systems, the SCALED lighting system could be a very useful option. Lighting is one of the primary developments when considering street lighting and modern buildings lighting. Driving LED lamps using the conventional AC line would be inefficient due to the several power conversion stages employed in converters. Therefore, worldwide interest is in powering LED lamps through a DC microgrid. SCALED is a concept where the SCALOM theory is being utilised to drive LED lamps through a DC microgrid (Jayananda *et al.,* 2020). In the SCALED concept, the LED lamp is used as the useful resistive load R_L of Fig. 7(a). As the primary power source, the SCALED system uses a PV array and operates on the constant current region. Fig. 11(a) shows SCALED circuit topology. Similar to the SCALDO converter, the SCALED topology has two operating modes. In the 1st phase, the switch S_1 is closed, and S_2 is open so that the power source, the LED lamp, and the SC bank will connect in series configuration, allowing the SC bank to charge while driving the LED lamp load. When the SC bank reaches its predefined maximum voltage, as shown in Fig. 11(b), switch S1 is opened, S_2 is closed, and the DC source is disconnected. Therefore, the LED lamp load is entirely driven by the SC bank and the cycle repeats. The corresponding voltage waveforms across the LED lamp and SC bank are shown in Fig. 11(b).



(a) (b)

Figure 11. SCALED converter: (a) modified RC charging loop with LED lamp; (b) simulated voltage waveforms for LED lamp load and SC bank (Jayananda *et al.,* 2020; Kularatna *et al.*, 2021)

In real word, the applications of the SCALED lighting system, a solar PV array replaces the DC power supply with an open-circuit voltage, V_{OC} higher than the nominal voltage of the SC bank and LED lamp. For example, to drive a nominal 12 V LED lamp, a nominal 12 V SC bank is necessary. And the V_{OC} of the PV array must be higher than 24 V. It is interesting to see that recent advances in LED lighting technologies have introduced LED lamps operating under a wide range of DC voltages while achieving constant brightness (Jayananda *et al.,* 2019). This is very useful for the SCALED lighting system because the voltage across the LED lamp will vary during the charging and discharging phases of the system. Table 3 summarises the characteristics of some commercially available LED lamps.

Table 3. Characteristics of some commercially available LED lamps operating in constant brightness regions (Jayananda *et al.,* 2019)

Manufacturer and Model	Operating voltage range (V)	Operating current range (A)
Philips 5·5 W	10 to 30	0·6 to 0·2
Philips 7 W	10 to 17	0·7 to 0·4
TCP 5 W	10 to 30	0·5 to 0·2
TCP 4 W	10 to 25	0·4 to 0·2
PRO ELEC 5·4 W	10 to 20	0·4 to 0·3

Similar to the SCALDO regulator, the SC bank in the SCALED system not only acts as energy storage but also acts as a lossless voltage dropper. Since the charging time of the SC bank is very large, the switching operation of the semiconductor switches is easy compared with high-frequency converters and has minimum losses (Jayananda, 2020). Although this system does not track the PV array's maximum power point (MPP), the source-to-load efficiency of driving LED lamps is high compared to driving LED lamps using the AC grid. The efficiency of the SCALED lighting converter typically lies in the range of 90% to 94% (Jayananda, 2020). This system is already being practised at the Port of Auckland, New Zealand (Jayananda, 2020). More details on the SCALED lighting system can be found in Jayananda (2020) and Jayananda *et al.* (2020).

(iv). Supercapacitor-Assisted Hybrid Photovoltaic (SCAHPV) System

Fig. 12 shows a block diagram of the SCAHPV System, an off-grid PV system consisting of SC-battery hybrid energy storage. In the context of implementing a self-sustained and low-maintenance system, this is also an excellent option. This system is also an extension of the SCALOM theory discussed above. As shown in Fig. 12, the system has three two-way electronic switches, K1, K2 and K3. They are switched to P_1, P_2, P_3, P_4, P_5 and P_6 positions based on the voltage of the SC bank, PV array, and battery bank. An LED lamp load is introduced to the system through a DC microgrid as a useful way to utilise the energy stored in the SC bank. Based on the position of each switch, the system is designed to have three operational modes, as detailed in the text below (Piyumal *et al.*, 2021).

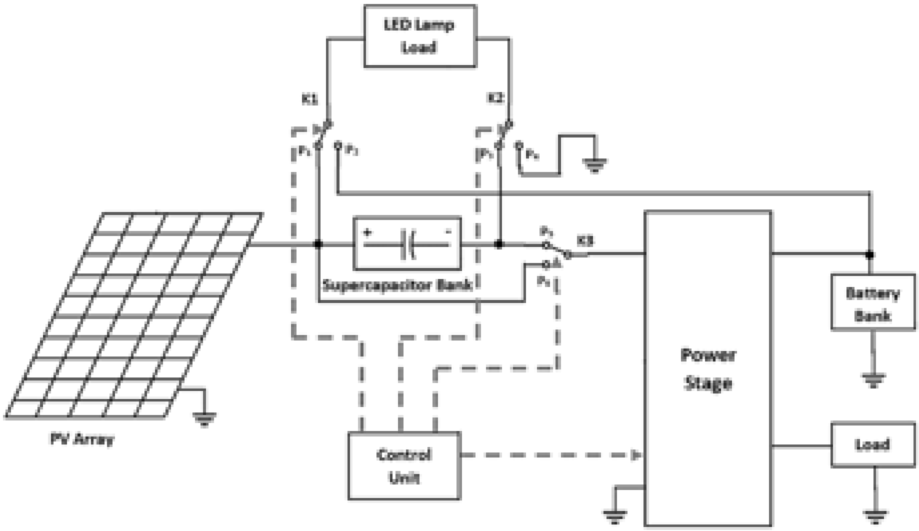


Figure 12. Block diagram of the SCAHPV System (Piyumal *et al.*, 2022)

- Neutral Mode

In this mode, the switches K1, K2, and K3 will be switched to P_1, P_3, and P_5 positions, respectively. This will connect the LED lamp load in parallel with the SC bank while the SC bank is connected in series with the PV array and power stage. The LED lamp load will be driven directly by the PV array if the current output from the PV array is sufficient, while the surplus current will flow through the SC bank, allowing the SC bank to charge. The current will then pass through the power stage, which will charge the battery bank. If there is insufficient current to drive the LED lamp load, the SC bank will buffer the extra current, causing the SC bank to discharge slowly.

- SC Charge Recovery Mode

While the system is in neutral mode, the SC bank voltage can be decreased to its pre-defined minimum voltage due to lower input power. Hence, the LED lamp load will be connected to the battery bank by switching K1 and K2 into P_2 and P_4 positions, respectively, while keeping K3 in the same position. Therefore, the LED lamp load will be disconnected from the SC bank. As a result, the SC bank regains its charge, and the system is switched back into neutral working mode once it reaches its pre-defined maximum voltage.

- SC Bypass Mode

While the system is in neutral mode, if the SC bank reaches its pre-defined maximum voltage, the switch K3 is switched into the P_6 position. The other switches will remain in the same position. This will connect the PV array to the power stage and the battery bank in a parallel configuration, similar to typical systems bypassing the SC bank. The LED lamp load is now entirely powered by the SC bank, causing the SC bank to discharge rapidly. The system is switched back into neutral working mode when the SC bank is depleted to its pre-defined minimum voltage. Table 4 summarises the position of each switch at each operating mode of the system.

Table 4. The position of each witch under each mode of operation of the SCAHPV system (Piyumal, 2022)

Operating Mode	**Position of Each Electronic Switch**		
	Switch K1	**Switch K2**	**Switch K3**
Neutral	P_1	P_3	P_5
SC Charge Recovery	P_2	P_4	P_5
SC Bypass	P_1	P_3	P_6

The system has been assumed to be operational during the daytime in all modes discussed above. However, the SC bank can be totally discharged because the PV array is not generating electricity at night. As a result, all the system loads will be connected to the battery bank, similar to typical systems. Unlike the SCALED system, this system is capable of tracking the MPP of the PV array. Therefore, the maximum available power generated by the PV array at a given moment will be usefully utilised (Piyumal, 2022). According to the literature (Piyumal *et al.*, 2021; Piyumal, 2022), this system has reached 98% average conversion efficiency. This is an 8% efficiency enhancement compared with typical off-grid PV systems (Rezk and Eltamaly, 2015; Chowdhury and Mourshed, 2016; Rokonuzzaman *et al.*, 2020).

The DC load attached to this system is driven directly by the power generated by the PV array and the SC bank buffers the excess energy only if required. Therefore, no additional switching is required for this operation. Furthermore, the source-to-load efficiency will be very high. Also, similar to the typical off-grid PV systems, a DC-AC power inverter can be connected to the battery of the proposed system to drive typical electrical appliances. Utilising these unique advantages, the SCAHPV system can be implemented into any building replacing the old off-grid PV system by installing only a few more additional components to the system. This system is very suitable for office buildings and warehouses because they have LED lighting systems operating throughout the day. Therefore, the system's SC-assisted DC microgrid can be used to drive the LED lighting while the other heavy loads can be driven by the battery bank, similar to the typical systems. Because of the added advantage of this system's enhanced efficiency, the size of the PV array of a particular system can be reduced. Also, since the SC bank is added as additional energy storage, the battery bank size can be reduced, and the life cycle of the battery bank is improved (Piyumal, 2022). More information on the development of the SCAHPV system can be obtained from the literature (Piyumal *et al.*, 2019, 2020, 2021, 2022).

Suggestions for Future Policy Formulation

The National Energy Policy and Strategies of Sri Lanka (2019) aims to ensure energy security through supplies that are cleaner, secure, economical and reliable, to provide convenient, affordable energy services to support socially equitable development of Sri Lanka (The gazette of the democratic socialist republic of Sri Lanka, No. 2135/61 - August 09, 2019). On the other hand, Sri Lanka as a country is currently facing the worst energy crisis in its recent history. Therefore, the directing countries energy mix towards renewable additions as much as possible is a necessity while making the energy policy of the country renewable friendly as much as possible. Solar PV technology is one of the most rapidly growing renewable energy generation methods globally (Fig. 13). During 2020 alone, the net global increase in capacity for solar PV is 138 GW, the highest among the other energy generation methods.

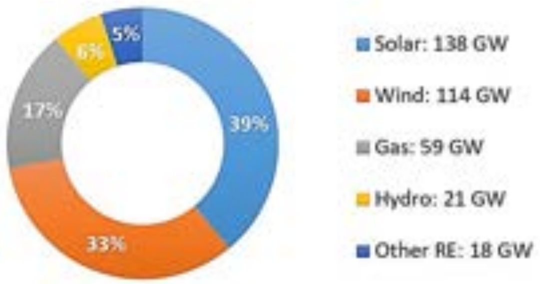


Figure 13. Net global increase in capacity in electric energy generation during 2020 (Global Market Outlook for Solar Power, 2021)

As per the sustainable development goals (SDGs) set up by United Nations (UN), there is a necessity to ensure access to affordable, reliable, sustainable and modern energy for all humans on the globe by the year 2030. To achieve this goal, it is necessary to reduce the cost of power generation and, most importantly, increase the efficiency of power generation techniques. Typical battery-based energy storage techniques in renewable energy systems have very low efficiency and short lifetime. In Contrast, SC-based energy storage systems have very high efficiency and a long lifetime. However, these systems are still being developed. Therefore, the government's policy of expanding solar PV should not be limited to the typical grid-connected systems but provide support for implementing off-grid or hybrid systems consisting of SC energy storage since the developed countries are already adapting this technology for their solar PV systems. Therefore, as an initial step, it would be a great idea to allocate some annual budget to implement the existing SC-based PV systems as pilot projects in different provinces in the country, which will help the developers to understand the real nature of these systems under challenging operating conditions. Providing funding for the research and development activities for this fast-growing technology will also play a significant role in achieving energy sustainability in the country.

Conclusions and Future Prospects

This book chapter discusses the development of SC technologies and their non-traditional applications based on the SCALOM theory. An SC is a short-term energy storage device with a very high-power density and medium energy density compared with electrochemical battery technologies. These unique characteristics of the SCs, together with their very large capacitances, are the basis of developing the SCALOM theory. The SCALOM theory is an extension of the well-known RC circuit theory. As per the fundamentals of electric circuits, a typical RC loop is only 50% efficient. The SCALOM theory discusses a technique to attach a useful load in series with a non-empty SC to enhance the system's overall efficiency. This concept developed novel circuit topologies such as the SCALDO regulator, SCASA, SCALED lighting system, and SCAHPV system. These systems are highly efficient as compared with their respective typical systems. Therefore, these novel SC-assisted systems will be the key to developing highly efficient, self-sustained and low-maintenance renewable energy systems in the country to achieve energy security.

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Conflict of Interest

Authors have declared that no competing interests exist.

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Graphene: Material of the 21st Century for the Development of Renewable Energy Sources in Sri Lanka

CHAPTER 14

W.P.R.T. Perera

Abstract Owing to the depletion of conventional energy sources and augmenting the energy demand, an energy crisis is appearing in most countries in the world including Sri Lanka. Graphene is gaining popularity for the development of renewable energy sources due to its excellent properties such as high charge mobility, thermal conductivity, visible light absorption, strong mechanical strength, and high specific surface area depending on the synthesis techniques. Meanwhile, graphite mining has occurred in Sri Lanka since the country's Dutch occupation. It is the world's only country that produces the purest form of graphite (purity of 99.99%). Value-added products of graphite such as graphene and graphene-based composites are being developed for various kinds of applications such as solar cells, fuel cells, electro-catalysis, and lithium-ion batteries. Recent research studies have highly focused on the utilization of graphene for renewable energy sources. Hence, Sri Lanka has a great potential for developing more value-added products of the graphite to face and overcome the energy crisis. This chapter intends to understand and cover graphene's background, including its properties for better use of graphene in its applications for the development of renewable energy sources.

Keywords: Fuel cells, Graphene, Graphene-composites, Renewable energy, Solar cells

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Introduction

Because of the rapidly increasing demand for energy and the depletion of conventional energy sources, an energy crisis is now one of the most serious issues confronting the world (Sahoo *et al*., 2012). Sri Lanka also facing a huge crisis in energy demand and attention has been on renewable energy sources for fuel as well as electricity. In third-world countries like Sri Lanka, there is a clear correlation between the generation of electricity and fuel consumption. Most of the cases, electricity is generated via the burning of fossil fuels such as petroleum, coal, and natural gases. The combustion of fossil fuels emits massive amounts of poisonous gases and other toxicants such as sulfur dioxide, nitrogen oxides, particulate matter, carbon monoxide and mercury, which pollute the air. More importantly, fossil fuels are non-renewable, with reserves depleting much faster than new ones are discovered or created. This will be a critical situation for energy consumption for third-world countries concerned less with renewable energy sources (Kamat *et al*., 2010; Sahoo *et al*., 2012; Yang *et al*., 2016). Meanwhile, huge attention has focused on graphene for different modern applications such as applications in the renewable energy field and it has been introduced as the material of the 21st century by scientists. Graphene, a single or few layers of two-dimensional (2D) sp 2-bonded carbon sheets, has piqued the interest of many scientists in recent years due to its unique structure and exceptional physical properties, including high electrical and thermal conductivities, mechanical flexibility, charge transport mobility, large specific surface area, good chemical stability and optical transparency (Geim *et al*., 2010; Seabra *et al*., 2014). Graphite mining has occurred in Sri Lanka since the country's Dutch occupation. It is the world's only country that produces the purest form of graphite (purity of 99.99%). The development of value-added products from graphite that contributes to renewable energy sources will be very beneficial to Sri Lanka, particularly to overcome the economic crisis in the country (Bohm *et al*., 2021). The main intention of this chapter is to explore the novel applications of graphene for renewable energy approaches such as the development of solar cells, fuel cells, electro-catalysis, and lithium-ion batteries and to discuss the ways to utilize and development of value-added products from the Ceylon graphite for the expansion of the renewable energy sources.

Energy Crisis and Depletion of Non-renewable Energy

The energy crisis has been a hot topic for the last few decades due to dependency on non-renewable energy sources. Energy is essential for a country's economic development. A dependable source of energy is needed to improve people's living standards. Industrial progress is essential to the growth of any country and industrial progress is dependent on a reliable supply of electricity. In Sri Lanka, people are facing a huge crisis because of the lack of a reliable supply of electricity. Prices of fossil fuel and other energy sources are highly dependent on the world's political status, environmental factors and various pandemic situations. Therefore, to have a stable supply of energy according to the demand, all countries should focus on getting the maximum out of renewable energy sources. The beginning of 2022 was marked by a global energy crisis, which impacted economies all over the world. This crisis is the result of interaction of several forces. Following the drop in global energy consumption in the early months of the COVID-19 pandemic, the speed and magnitude of the economic recovery have created a mismatch between energy demand and supply. Meanwhile, the energy sector has been afflicted by persistent underinvestment and lax market regulation as a result of severe weather events as well as insufficient buffers (Berahab *et al*., 2022).

Causes of Energy Crisis since 2021

Even though the past few years' energy crises have been limited to oil, now it is influenced by the natural gas supply as well (Fig. 1).

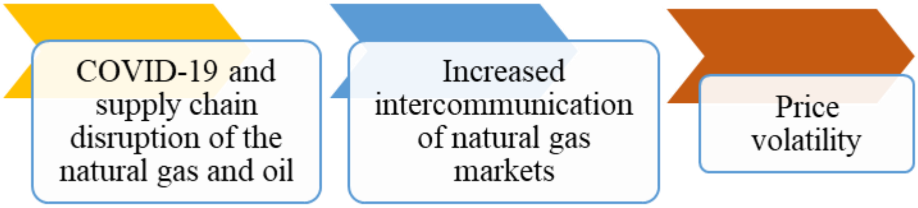

Figure 1. Key reasons for the energy crisis since 2021

The magnitude of the impact of the early 2020 energy market disruptions on the current crisis is undeniable. Many fuel prices fell dramatically in the early months of the COVID-19 crisis, and global energy consumption fell significantly. However, energy prices quickly recovered due to an unusually rapid global economic recovery (Gilbert *et al*., 2021). However, most governments including the Sri Lankan government have not pursued strong enough policies to develop alternative energy sources and rapidly deploy new clean energy infrastructure, which could bridge the potential gap created by the suspension of hydrocarbon investments. As a result, this situation reveals the energy trilemma that many countries are currently facing in terms of economy, environment and security (Fernandez Alvarez *et al*., 2021). Most countries including Sri Lanka highly depend on non-renewable energy sources such as fossil fuels, natural gas and coal due to they are energy-rich and relatively cheap to process. However, they are finite sources, and the rapid increase of the population and the expansion of the economies of the country further accelerate energy requirements.

Graphite and Energy Conversion

Owing to the depletion of traditional energy sources, there is a growing demand for renewable energy and energy-efficient devices. Graphene, a novel 2D nanomaterial with unique properties, has piqued the interest of researchers and is a promising material for applications in energy conversion and storage devices. The variation of graphite's crystal structure is the key identification of the graphite to utilize as an energy conversion material. Polycrystalline graphite, for example, can have crystallites that are aligned, as in highly ordered pyrolytic graphite, or that are more or less randomly oriented, as in some nuclear-grade materials. Apart from that, the electrical conductivity of properties of the graphite is also critical for some applications related to energy conversion (Walker *et al*., 1987). Graphite is a wonder material that bears amazing properties and can be used for applications in renewable energy innovations. Graphene has properties that are distinct from graphite. Although graphite is frequently used to reinforce steel, its sheer planes prevent it from being used as a structural material on its own. Graphene is just one atomic layer of graphite, which is a layer of sp2-bonded carbon atoms arranged in a hexagonal or honeycomb lattice (Geim, 2009).

Properties of Graphene

Owing to its amazing qualities; graphene has exciting properties such as high charge mobility (230,000 cm^2 /Vs) with visible light absorption up to 2.3%, thermal conductivity (3000 W/mK), high strength (130 GPa) and high theoretical specific surface area (2600 m2 /g) appearing in the graphene, more attention has focused on developing the value-added modified products from the graphene for the renewable energy applications (Partoens *et al*., 2010). To utilize graphene and modifications of graphene, four basic properties can be considered especially for renewable energy applications. This has piqued the interest of the research community, who are eager to learn more about graphene's applications. As a result, in fuel cells and batteries, a thorough understanding of the applied graphene's physical, chemical, mechanical and electrochemical properties is required. Fig. 2 explains the amazing properties of graphene in detail.

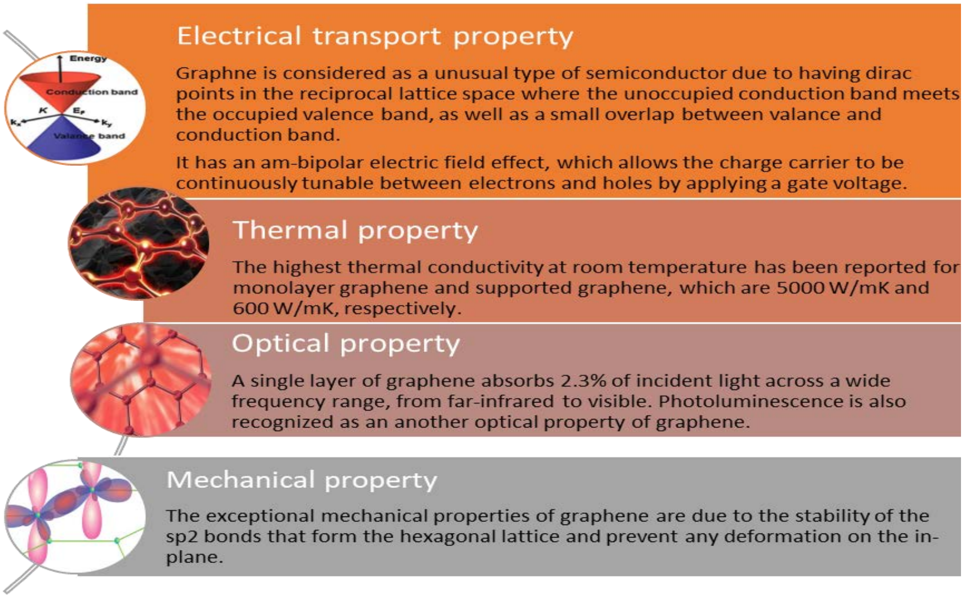

Figure 2. Major properties of graphene that focused on the applications of renewable energy sources (Hossain *et al*., 2022).

Synthesis of Graphene and Graphite Oxide

Various low-cost and recent methods have been developed to synthesize graphene from graphite. In 2004, graphene was first mechanically exfoliated from graphite. Novoselov *et al*. (2004) explained the electronic measurements on single and few-layer graphene. In their study, graphene was obtained by repeatedly employing a technique known as micromechanical cleavage, also known as the scotch tape method (Novoselov *et al*., 2004). The micromechanical method is simple and does not require any specialized equipment. A piece of adhesive tape is applied to and then peeled off the surface of a graphite sample (Dresselhaus *et al*., 2002). The most popular accepted method is the liquid phase mechanical exfoliation for the synthesis of graphene. Graphene researchers have used liquid-phase approaches to exfoliate individual sheets of graphene from bulk graphite. In some previous studies, graphite powder was sonicated in N-methyl pyrrolidone and centrifuged the resulting dispersion to remove large un-exfoliated graphite pieces. It was possible to create suspensions of few-layer graphene with concentrations as high as 1% by weight (Hernandez *et al*., 2008). Another well-established technique is surfactant-assisted graphene exfoliation, which uses a variety of surfactants (*Lotya et al., 2009*).

The first experiment on the chemical reactivity of graphite was conducted in 1859 (Brodie, 1859). The study discovered that by repeatedly exposing graphite to a solution of nitric acid and potassium chlorate for several days, it could be extensively oxidized Graphite oxide (GO), like graphite, has a lamellar structure and is mostly carbonaceous. The graphite basal plane is riddled with oxygen-bearing functional groups such as hydroxides and epoxides as a result of oxidation, while the layers are rimmed with carboxyl, carbonyl, and phenol functionalities (Dreyer *et al*., 2010). GO is the oxidized form of graphene that is typically produced by oxidizing natural graphite powder in acidic media. Graphene, on the other hand, has emerged as the most exciting material in recent years due to its amazing and unique physical properties such as excellent mechanical strength, thermal stability, and high electronic conductivity (Zhu *et al*., 2010).

Applications/ Modifications of the Graphene for Solar and Fuel Cells

(i). Applications of Graphene for Solar Cells

In order to grab solar energy and convert it directly into electrical energy, solar cells/ photovoltaic cells are being developed. Owing to the corresponding properties of graphene on the development of solar cells, various value-added products have been developed from graphite. Because of this, graphene-based materials have sparked intense interest in their potential applications in solar cells due to specific properties (Fig. 3).

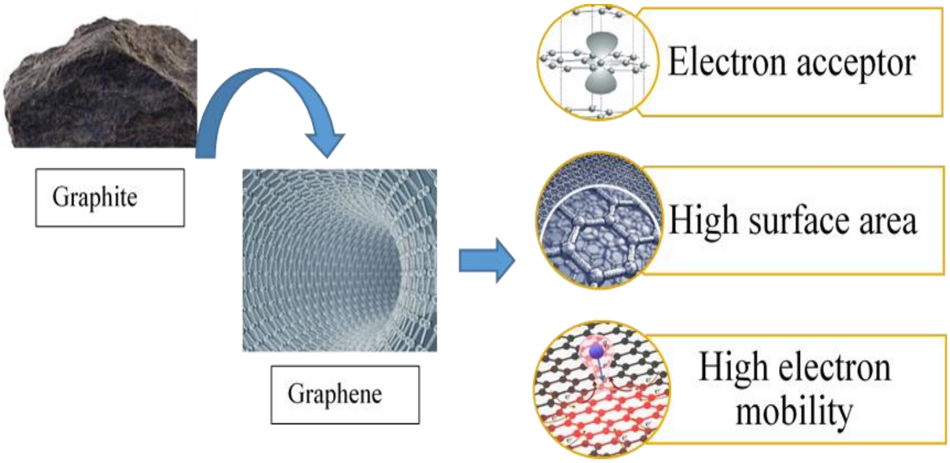

Figure 3. Specific beneficial properties of graphene for the development of solar cells

Graphene is mainly used for organic photovoltaic solar cells (OPV) and dye-sensitized solar cells due to the above-mentioned properties. Owing to the light weight of the graphene, organic photovoltaic cells are being developed as a better replacement for inorganic solar cells. Apart from that, manufacturing simplicity, compatibility with flexible substrates and low-cost materials are other advantages of the OPV. However, the power efficiency of OPV devices still remains lower than that of conventional inorganic devices (Helgesen *et al*., 2010). As mentioned above, due to graphene bearing high electron acceptance quality and mobility, the majority of research on renewable energy focuses on replacing or collaborating with fullerene derivative 6,6-phenyl C 60 butyric acid methyl ester (PCBM) in polymer-based OPVs, and its energy level can be easily tuned by controlling its size, layers, and functionalization. After the functionalization of graphene, it is readily dispersed in organic solvents and as a result, the graphene/polymer bulk heterojunction nanocomposites can be prepared using a solution process (Nair *et al*., 2008). There are several applications of the graphene/derivatives of graphene for the application of OPVs which are listed below (Sun *et al*., 2011; Yu *et al*., 2011).

- Reduced graphene oxide (r-GO) and graphene oxide (pr-GO) reduced by p-toluenesulfonyl hydrazide were used as the Hole Transfer Layer for high-performance solar cells.
- Graphene thin films' growth from chemical vapor deposition is also thought to be a promising electrode material for solar cells because of their transparency, electrical conductivity and flexibility.
- Fullerene grafted graphene is used as an electron acceptor in OPV.
- Chemically modified reduced GO, Graphene: poly (3-octylthiophene) (P3OT) is used as an electron acceptor in OPV.

Having large surface areas, high optical transmission and good electro-catalytically properties, graphene is being developed as a substitute material for the counter-electrodes in dye-sensitized solar cells. For example, chemically reduced GO, thermally reduced GO and carbon nano-tubes like graphene-based materials are being applied to counter electrodes dye-sensitized solar cells providing a new method for producing low-cost, high-performance dye-sensitized solar cells using graphene's unique properties, particularly its large surface area, and experimenting with combinations with other materials such as Pt, shows promise in developing high-efficiency cells (Kavan *et al*., 2011).

(ii). Applications of Graphene for Fuel Cells

Developing clean, renewable and sustainable energy is critical in dealing with environmental concerns because it helps to reduce global warming, pollution and reliance on fossil fuels for energy. Many people are interested in studies on energy conversion (such as fuel cells) and storage. Fuel cells are electrochemical devices that convert chemical energy into electrical energy (Abu-Saied *et al*., 2020). The purpose of using graphene in the applications of fuel cells is basically as low-cost electrocatalysis. In fuel cells, reactions occur at the cathode and anode, with the cathode typically involving the reduction of oxygen from the air, while the anode is associated with the oxidation of fuels. Nobel metals such as Pt, Ru, Au, Ni, and Pd as well as their alloys are applying for the catalyze the reaction at the anode and the cathode of the fuel cell. Pt is the most commonly used catalyst for electrode reactions, particularly in low-temperature fuel cells. However, these noble metals are expensive, have a limited supply on Earth, poor reaction kinetics, and have a low tolerance for carbon monoxide poisoning (Ma *et a*l., 2022; Yu *et al*., 2022). Hence, catalytic support is being introduced in fuel cells. Graphene with a large surface area can support and diffuse catalysts evenly, preventing inter-particle accumulation and increasing electroactive site exposure. Topographic defects and residual functional groups (such as epoxy, carboxyl and hydroxyl) are commonly present in GO-derived graphene materials and these provide an excellent substrate for catalyst growth and immobilization with excellent structural stability and interactions (Yung *et al*., 2019).

(iii). Modification of Graphene as an Electro-catalyst and its Benefits

Many studies have been conducted, particularly on Pt catalyst hybrids with graphene. It was reported that catalytic activity was improved due to the higher implementation and activation of Pt on graphene sheets which associate with better dispersion of Pt on graphene sheets by virtue of graphene sheets larger specific surface area (Iqbal *et al*., 2011). Due to the GO having outstanding properties such as a large surface area, good mechanical strength, thermal stability, proton conductivity, and a wide operating temperature range, it can be used as an alternative proton exchange membrane to Nafion (Xu *et al*., 2021). Furthermore, Graphene Nafion/GO composite membrane has higher proton conductivity due to the increased GO content (Li *et al*., 2018) and GO/ polybenzimidazole has higher chemical stability due to the presence of hydrogen bonding between GO and BuIPBI, allowing for greater absorption with a lower swelling degree (Xue *et al*., 2014). Modified Sulfonated GO (SGO) is created by adding sulfur to graphene. SGO has significantly improved the performance of alternative proton exchange membranes (Heo *et al.*, 2013).

(iv). Application of Graphene in Lithium-ion Batteries

In the 90th century, Lithium-ion batteries (LiB) were developed and have been successful. LiB is an important electrochemical energy storage material for a wide range of electronic applications. Several studies have recently been conducted to develop substitute electrodes for LiB. Graphene has been recognized as a suitable replacement material for anodes. This is due to graphene's excellent properties, which include a large surface area, a wide electrochemical window, and excellent electrical conductivity (Pei *et al.*, 2012).

Table 1. Development of graphene and graphene composite materials for the different applications in lithium-ion batteries

Application	Type of graphene material	Beneficial qualities of the batteries	Reference
Graphene as anode	Pristine GO, hydrazine reduced GO, pyrolytic GO and electron beam reduced GO	Significant defective graphene showed great reversible capacities and good cyclic stability	Pan *et al.*, 2009
	Defect-introduced graphene sheets	Great reversible capacities and high charge/discharge properties	Hu *et al.*, 2016
Alloying graphene for anode	Si/graphene nanocomposites	high capacity, excellent cycle-ability and high rate capability	Hu *et al.*, 2014
	Tin/graphene nano-sheet composites	Presence of edge-type sites, nano-cavities, or defects GNS active sites result in high lithium storage capacity	Chen *et al.*, 2012
	Germanium/graphene and Ge/carbon nanotubes composites	High rate performance and high structural stability	Gao *et al.*, 2017
Doped graphene	Beryllium doped graphene	Drastically improved storage capacity	Ullah *et al.*, 2017
	N and S co-doped graphene	Drastically improved storage capacity	Cai *et al.*, 2017

Despite the fact that many researchers have tested graphene in fuel cells and lithium-ion batteries (Table 1), more research is encouraged in order to meet the challenge of finding renewable, clean and sustainable energy.

Conclusions and Future Prospects

Alternative renewable energy sources must be investigated to reduce our reliance on fossil fuels. The contribution of graphene to the development of renewable energy approaches has gained attention for novel research studies. Because graphene has been identified as a remarkable substance, with a plethora of astounding properties that have earned it the moniker "wonder material". Fortunately, the land of Sri Lanka bears the world's best graphite species, and unfortunately due to the lack of technology, research, and development approach, a fewer number of value-added products are developing in Sri Lanka. Introducing graphene to various applications is one approach to achieving the goal and its excellent properties have attracted numerous studies. Thus, graphene synthesis is important in determining suitable applications for its properties and characteristics because different synthesis procedures such as mechanical exfoliation, reduction of graphene oxide, chemical vapor deposition (CVD) and graphene epitaxial growth, will produce graphene characteristics and properties. Graphene could use as a high-potential material for producing clean, renewable and sustainable energy. Further, more research approaches need to be initiated for the development of value-added products of graphite inside Sri Lanka to contribute actively to novel renewable energy sources. This would pave the path in developing renewable energy devices/sources to mitigate the energy crisis to some extent.

Conflict of Interest

Author has declared that no competing interests exist.

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Biodiesel and Its Importance as an Alternative Energy Source for the Fuel Crisis

CHAPTER 15

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Abstract Upsurging of the population throughout the world has given a negative effect on daily energy consumption. Fossil fuel reserves are decreasing gradually due to the energy demand and the need of finding alternatives is growing. Biodiesel is such an alternative that derived from crops and animals. It is also contributing to the green environment as it does not emit carbon dioxides, carbon monoxides, hydrocarbons and particulate matter comparative to petroleum diesel. There are several types of oils and fats that are used in deriving biodiesel such as edible oil and non-edible oils. Palm oil, jatropha oil, soybean oil, castor oil, algae and animal fats are some of the feedstocks used in producing biodiesel. Waste cooking oil is an economical alternative for the sources of biodiesel. The triglycerides of oils and fats are used to produce alcohols and esters which could be result from catalytic or non-catalytic reactions. Biodiesel is composed of mono-alkyl esters of long-chain fatty acids and is synthesized mainly by pyrolysis, microemulsion and transesterification. The transesterification is the most common and widely used method of manufacturing biodiesel. Acid catalyzed transesterification, alkali catalyzed transesterification, enzyme catalyzed transesterification and non-catalytic esterification are broadly used in the transesterification process. Properties, such as, cetane number, cloud and pour point, density and viscosity have an enormous impact on the quality of biodiesel. This chapter provides an overview of the manufacturing process and characteristics of biodiesel.

Keywords: Alternatives, Biodiesel, Edible and non-edible oils, Transesterification

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Introduction

Energy is the most indispensable resource for existence. With the industrial upheaval in the 18th and 19th centuries, energy has become a vital factor for the human beings. Transportation has become a key important sector in energy consumption. It plays a crucial role in the world's economy and the development of any country. The demand for the primary energy supply is fulfilled with fossil fuels such as natural gases, petroleum and coal. By the end of 2050, global energy consumption will increase by 50%, due to the population growth and development of new technologies (Shahid and Jamal, 2011). During the past years, transportation has an enormous growth due to the upsurge of number of vehicles used all over the world. Hence, many statistical estimations have pointed out a rise in energy consumption by 1.8% each year (Atabani *et al.*, 2012). The largest energy consumption is from the industrial and transportation sector. Transportation is responsible for 30% of the energy consumption around the world, of which more than 80% is due to the road transportation. Currently, transportation is responsible for nearly 60% of the oil demand, having 97% of the energy consumption from oils and very little volume of natural gases (Atabani *et al.*, 2012).

With high energy consumption, large amount of carbon dioxide (CO_2) is released to the atmosphere over the years, thereby increasing the environmental pollution and global climate change. The major contributor for the release of these air pollutants are vehicle engines. Despite of pollution caused from ozone and smog, diesel exhaust also contains, carbon monoxides, oxides of nitrogen, hydrocarbon toxic contaminants and diesel particulate matter (Chincholkar *et al.*, 2005). Hresearchers are prompt to find alternative sources to cater to the increasing demand of energy and reduce environmental pollution. Biodiesel is an excellent alternative, as it contains numerous advantages, such as, biodegradable, contains low amount of sulfur and aromatic compounds, sustainable, non-toxic and efficient. It is a very economical and promising source of alternative fuel, as it reduces the reliance of imported petroleum fuels. Biodiesel has an incredible potential for its usage of versatile feedstocks and decisive characteristics (Lyu *et al.*, 2021). In developing countries including South Asian countries, such as Sri Lanka and India, high amount of energy is needed in order to provide a standard living. Sri Lanka, due to economical imbalance and inflation is experiencing a massive fuel crisis for the past few months. Therefore, to overcome the ill-effect of economic crises and global warming, biodiesel would be an excellent alternative.

Biodiesel

Biodiesel is a green alternative for diesel derived from fossil fuels. It is environmentally friendly, low toxic and has non-emission of hydrocarbons. Biodiesel is chemically classified as a combination of mono-alkyl esters of fatty acids and long chain fatty acids (Zhang *et al.*, 2016). Palmitic oil, soyabean oil, stearic oil, rapeseed oil, palm oil, canola oil and sunflower oil are some of the organic oils used in producing biodiesel. Other than that, catalysts are also used in manufacturing biodiesel. Biodiesel is defined according to ASTM D 6751 (American Society for Testing and Materials), as a fuel composed of mono-alkyl esters of long chain fatty acids of natural oils and fats (Zhang *et al.*, 2003). Oils and fats are mainly composed of triglycerides containing long chain fatty acids bound with a glycerol backbone (Fukuda *et al*., 2001). Oils and fats cannot be used directly as a fuel because of free fatty acid (FFA), acid composition, gum formation due to oxidation and polymerization, high viscosity and carbon deposits. The major problems associated with the substitution of triglycerides as diesel are high viscosity, poly unsaturated character and low volatility (Mishra and Goswami, 2018). There are three main processes to overcome these drawbacks, such as transesterification, pyrolysis and micro-emulsion. Among those processes, the most commonly used method is transesterification. Triglycerides react with short chain monohydric alcohols in the presence of a catalyst such as acid catalysts, alkali catalysts and enzyme at high temperatures in order to obtain fatty-acid alkali esters (FAAE) and glycerol (Fukuda *et al*., 2001). Transesterification is one of the most efficient and cost-effective methods that can be used in producing biodiesel.

Having a similar viscosity as petro-diesel, biodiesel is observed as amber-yellow liquid. Biodiesel manufacturing is a costly procedure compared to petro-diesel, which seems to be the major drawback. Operational weaknesses of biodiesel are low engine power, small engine power and difficulty of prolong storing due to degradation. Higher cloud and pour point, lower energy capacity, low speed, high emission of nitrogen oxides are some of the physical drawbacks that biodiesel possesses (Graboski and McCormick, 1998).

Feedstock of Biodiesel

Sources of biodiesel can be ranged from oils and fats to algae, microalgae and fungi. Most of the feedstocks are from plant-based oils and animal fats. However, waste cooking oil and non-edible vegetable oils are also highly economical sources of raw materials that can be used in manufacturing biodiesel in large scale. Edible oils are produced from vegetable sources mostly used for human consumption. It does not need any chemical process for the oil extraction. It is economically expensive to produce biodiesel from edible oils due to high demand and limited supply (Bhuiya *et al.*, 2014). The most common edible oil feedstocks are palm oil, sunflower oil, rapeseed oil, soybean oil and peanut oil. Palm oil is one of the most important oils to produce biodiesel due to its high productivity. Usually, 1.25 L of palm oil could produce 1 L of biodiesel (Ishola *et al.*, 2020). Due to its many health benefits, soybean oil is highly beneficial and used for human consumption. To produce 1 L of biodiesel, 1.3 L of soybean oil is needed. Soybean oils are mostly harvested in USA, Brazil and East Asia (Colombo *et al.*, 2019). Another highly productive oil is rapeseed or canola oil which is mainly harvested in Europe and Canada. Rapeseed oil produces 1 L of biodiesel from 1.1 L of oil (Qiu *et al.*, 2011).

Non-edible oils are mainly applied for industrial use such as for soaps, detergents and the paint industry. Mostly used non-edible oils are jojoba oil, animal tallow castor, jatropha oil and waste cooking oil (Atabani *et al.*, 2013). Although, non-edible oil is economically preferable in producing biodiesel, the yield is low compared to edible oils. This happens due to higher amount of FFAs contained in non-edible oils. Hence, FFAs content should be lowered before it is used in manufacturing biodiesel (El-Gharbawy *et al.*, 2021). Jatropha is cultivated in elevated temperatures like in Egypt and is also the main source of feedstock in Asian and African countries as well. Jatropha seeds have nearly 30-35% of oil. Hence, the seeds could be used to produce a considerable amount of biodiesel (Juan *et al.*, 2011). Castor oil is another non-edible vegetable oil, which is highly viscous but biodiesel made from castor oil has extremely low pour and cloud points. Therefore, it is preferable in winter conditions (Keera *et al*., 2018). Waste cooking oil is a very promising alternative to produce biodiesel as it has a very low price. Other than that, it is renewable, easy to assemble, widely available and also reduces the need of land for crop cultivation. Waste cooking oil contains a higher amount of FFAs, which hinders the reaction of transesterification and produces significantly low yield (Degfie *et al.*, 2019). Biodiesel production through algae is highly economical and easy process as it contains 20-80% of oil which is converted to fuel (Tharusha and Ratnatilleke, 2021). Some of the algae species such as Ulothrix, Euglena and Tribonema are highly productive in producing biodiesel (Khan *et al.*, 2017). Cyanobacteria and microalgae are considered as the latest feedstock for gaining biodiesel. Modifying of these microorganisms genetically, cultivating them to attain different fuel characteristics are seems to be very much productive.

Fatty Acid Composition of Crop Edible and Non-edible Oils and Its Contribution to Biodiesel Production.

Fatty acid is an important aspect in any sources of biodiesel production. The fatty acid content of a source/crop is highly dependent on the quality and the geographical conditions of which it is cultivated. Some of the available fatty acids contain in oils are palmitic acid, oleic acid, linoleic acid, stearic acid, myristic acid, lauric acid (Hellier *et al*., 2015; Alves *et al.*, 2019). These fatty acids and alcohols in oils may have a considerable influence on the properties of biodiesel such as cetane number, melting point, cloud point, cold flow, lubricity and viscosity. The impact in these properties is affected by individual unsaturated fat methyl ester in biodiesel. These properties also enhance with an upsurge of chain length and diminishes with the increase of unsaturation. Even though, the upsurge of the degree of unsaturation helps increment of the behavior of biodiesel at low temperatures, certainly there are obstacles such as lowering of cetane number and deprived oxidation stability (Hellier *et al*., 2015).

Biodiesel Production Technologies

In order to produce biodiesel, oil extraction is an essential step in which seeds and kernels are used. Mechanical extraction, enzymatic extraction and solvent extraction are the three main methods of extracting oils (Aransiola *et al.*, 2019). The most conventional method of extracting oils is mechanical extraction. In this method, 60-80% yield can be extracted from seeds (Subroto *et al.*, 2015). Solvent extraction is another technique, which the oils are extracted with the use of a liquid solvent (Razal *et al.*, 2012). Soxhlet extraction, hot water extraction and ultrasonication are used in solvent extraction methods (Luque-Garcia and Castro, 2004). Enzymatic oil extraction is one of the most promising methods of extracting oils (Solanki *et al.*, 2020). There are many obstacles in processing vegetable oils or any other oils to get the approximate values of biodiesel such as low volatility, higher viscosity and polyunsaturated conditions (Balat and Öz, 2008). Hence, to overcome these hindrances and produce biodiesel, Three main methods are used; (i) pyrolysis, (ii) microemulsion and (iii) transesterification (Mishra and Goswami, 2018).

(i). Pyrolysis

Pyrolysis is also known as thermal cracking or decomposition of organic matters or change in chemical composition in the presence of a catalyst due to the application of thermal energy and in the absence of air (Higman *et al.*, 1973). Vegetable oils, animal fats and natural fatty acids are used as substrates for pyrolysis technique. The biodiesel produced through pyrolysis is considered as suitable for use in diesel engines for its properties such as lower viscosity, pour and flash point. The pyrolyzed vegetable oils contains a lower cetane number, acceptable levels of sulfur and water content (Parawira, 2010). Alkanes, alkadines, alkenes, carboxylic acids and aromatics are produced due to the thermal cracking process (Hsu, 2012). There are three types of pyrolysis namely slow pyrolysis, fast pyrolysis and flash pyrolysis. These types of pyrolysis differ from one another by the rate of heating, particle size, processing temperature and residence time. During pyrolysis, thermal cracking or degradation of organic matter of the feedstocks occurs at temperatures of 300 – 500 °C and ends at 700 - 800 °C. Under these temperatures, breakdown of long-chain carbon, oxygens and hydrogens into smaller molecules occurs (Patel *et al*., 2020).

(ii). Microemulsion

Microemulsions are known as colloidal dispersion of optically isotropic fluid having dimensions of not more than 1-150 nm (Zare *et al*., 2020). It is a transparent and a stable colloidal dispersion and is formed from two immiscible liquid and ionic amphipathic. Microemulsions are made from solvents like ethanol, methanol, butanol and hexanol. These types of microemulsions are excellent in owning maximum viscosity necessities, which is significant in biodiesels. They also can improve the spray characteristics of biodiesel by vaporizing all the low boiling components of the micelles (Schwab *et al*., 1987).

(ii). Transesterification

Transesterification is considered as the most promising, common and frequently used method of synthesizing biodiesel. Triglycerides react with alcohols, therefore it is also known as “alcoholysis”. The process involves few reversible and consecutive steps (Fabiano *et al.*, 2012). Transesterification is a stepwise reaction which comprises of 1 mole of triglyceride to produce 3 moles of fatty acids. Glycerol is the main by-product of biodiesel synthesis which is used in many industries including pharmaceutical and cosmetics. There are two different methods used in transesterification namely, catalyzed transesterification and non-catalytic transesterification (Fukuda *et al.*, 2001). Three equations below (Eq.1-3) indicate the conventional steps of biodiesel manufacturing (Perez *et al.*, 2014). The block diagram of biodiesel manufacturing plant is shown in Fig. 1 (Walpita *et al.*, 2012).

$$TRIGLYCERIDE\ (TG) + ROH \leftrightarrow DIGLYCERIDES\ (DG) + RCOOR1 \quad (1)$$
$$DIGLYCERIDES + ROH \leftrightarrow MONOGLYCERIDES\ (MG) + RCOOR2 \quad (2)$$
$$MONOGLYCERIDES + ROH \leftrightarrow GLYCEROL + RCOOR3 \quad (3)$$

Catalytic method is the most prominently used transesterification method as it has a higher yield. The use of catalyst is very much vital as it upsurge the rate of reaction, because solubility rate of alcohols is somewhat lower. Catalysts such as, alkali catalyst, acid catalyst and enzyme catalysts increase the rate of alcohol solubilizing with oils and fats (Juan *et al.*, 2011; Thangaraj *et al.*, 2018). Alkaline catalytic transesterification is known as the most promising, fastest, economical, productive and the most evanescent method of producing biodiesel. Catalysts such as NaOH, KOH, K_2CO_3, $KOCH_3$, NaOCH and NaMeO are used increasing the rate of biodiesel synthesis. NaOH and KOH are most commonly used catalysts as they are cost effective (Trejo-Zárraga *et al.*, 2018). However, in order to use these alkaline catalysts, the FFA content of the oils should be lower than 0.5%. Beyond these limits, soap formation will occur and the yield will decrease. Though, use of alkaline catalysts is best to uses, various obstacles are also found, for example, glycerol recovery is difficult, alkaline wastewater should be treated prior to dumping, catalysts should be removed and it is energy intensive (Nasreen, 2018). Strong acids like H_2SO_4, HCl, H_3PO_4, ferric sulphate and sulphonic acids are the main types of catalysts used in acid catalyzed transesterification. Compared to alkaline catalytic transesterification, acid catalysts are more tolerant to FFAs and water. It gives an excellent yield but the process is time consuming. However, acid catalyzed transesterification is widely used all over the world for its excellent conversion efficiencies, tremendous yield, and low energy use (Thiruvengadaravi *et al.*, 2012). Enzymatic catalytic esterification known as a trouble-free process to produce biodiesel. Lipase enzymes are used as the catalyst for the triglyceride and alcohol reactions. It conveys the best tolerance for the FFA content in oil feedstocks. Furthermore, it also has a tendency to react with long-chain alcohols compared to short-chain alcohols. Hence, reaction with ethanol is much likened than to methanol. With the use of enzyme catalysts, recovery of glycerol and eradication of soap and catalysts are no longer needed. Even though, enzyme catalytic process is much trouble-free and easy to handle and it is uneconomical (Szczęsna Antczak *et al.*, 2009). Non-catalytic transesterification includes supercritical methanol transesterification. This method involves high temperature and pressures. It is very efficient in time and uses low energy for producing biodiesel. Hence, it is also an environmental-friendly process. Nevertheless, supercritical methanol transesterification is highly expensive and has a higher methanol consumption compared to catalytic transesterification (Demirbas, 2008).

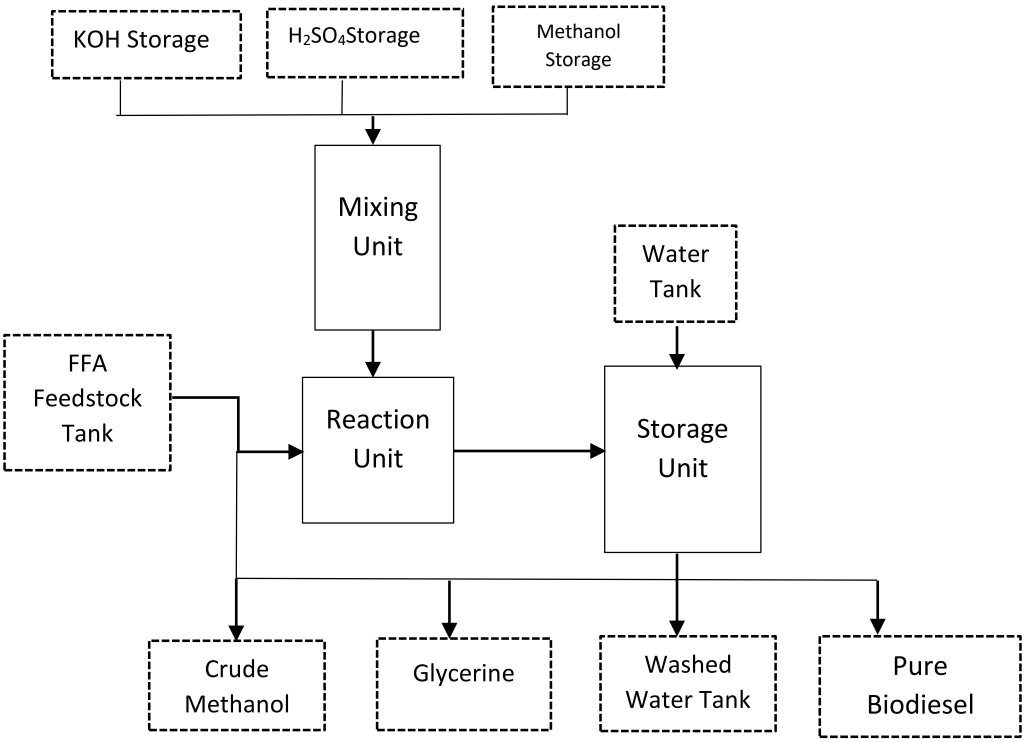

Figure 1. Block diagram of a biodiesel plant

Characterization of Biodiesel

The characterization of the properties such as density, flash point, cetane number, pour point and cloud point, viscosity, oxidation stability and calorific value interpret the quality of the fuel. Density of any fuel is directly link with the engine performance. It also has an effect on cetane number, viscosity and combustion quality. When the density increases, the size of the fuel droplets increases and the rate of emission will upsurge as density is also relates with output of engine. Furthermore, the efficiency of the atomization expands with lower density. Density of biodiesel is measured with ASTM standards D1298 (Pratas *et al.*, 2011). Flash point is known as the temperature which the fuel will ignite. It indicates the flammability of the fuel. Generally, the flash point of biodiesel is much higher compared to petroleum diesel as it has a flash point of 150 °C, which is considered to be safe to handle, store and transport (Gülüm and Bilgin, 2015). Cetane number determines ability of auto ignition. Higher the cetane number gives the quicker ignition, indicating rapid startup of the engines and smooth and noiseless running. Biodiesel has the highest cetane number comparable to convectional diesel. The cetane number is directly proportional to saturation and fatty acid chain length. Higher the fatty acid chain lengths and saturation could result in higher cetane number (Sivaramakrishnan and Ravikumar, 2012). Pour point and cloud point are very significant properties of fuels to evaluate their performance at low temperatures. During winter weather conditions, solidification of fuel may block and damage the engines due to poor lubrication. Biodiesel has cloud and pour point higher than the petroleum diesel. Hence, a blend of biodiesel and normal convectional diesel will be a better substitute during the winter and cold conditions (Kannan *et al*., 2018; Ogami *et al.*, 2018).

Viscosity is another highly significant parameter for biodiesel as it relates with the combustion of the engine. It indicates the ability of a liquid to flow and affects the fluidity of the fuel (Tesfa *et al.*, 2010). Due to the larger molecular structure, biodiesel has a viscosity much higher than the normal convection diesel. Hence, at low temperature weather conditions, the viscosity of biodiesel becomes much thicker. Greater viscosity deteriorates the combustion quality and increase the emission (Ramírez Verduzco, 2013). Oxidation stability of biodiesel is a measure of its reactivity with air and oxidation. The presence of unsaturated fatty acids and double bonds makes the biodiesel more prone to react with atmospheric oxygen. Hence, antioxidants are needed in preventing the oxidation. Due to the molecular structure of biodiesel, it has lower oxidation stability comparative to diesel derived from fossil fuels (Pullen and Saeed, 2012). Calorific value is a vital property determining the quality of biodiesel. The output of an engine is dependent on the calorific value. The greater the value gives higher the heat in combustion, thereby enlightening the performance of the combustion. Biodiesel contain much lower calorific value than petroleum diesel (Ozcanli *et al*., 2013).

Biodiesel as an Alternative Energy for Fuel Crisis

The Sri Lankan fuel and economic crises hit the nation in the month of June 2022, making long queues for days. Sri Lanka is currently experiencing the worst economic crises, upsurging of the dollar rates day by day, which put the government in a place that they could no longer afford the high demand. Hence, it pushes Sri Lanka to think about new alternative methods to beat up the high demand and the upsurging of prices. Biodiesel is one simple option at least could give a partial solution to fulfil the energy demand. The main feedstocks for biodiesel are plant seeds. Seeds like, Kithul, Avocado, Mee, Domba, Rubber seed, Endaru, Palmyra, Mango, Tamarind, Kaneru, Jack seed, Rambutan, sugarcane are the most abundant plants that grow within the country. Other than that, algae and bacteria such as, cyanobacteria, also possess high yields when producing biodiesel. Sri Lanka is well-known as a tourist kingdom.

Hence, it also possesses huge number of hotels and restaurants, where they throw out the waste cooking oils, which is also known to be an economical and cost-effective method of synthesizing biodiesel. Waste cooking oil also can be found in every house residing in Sri Lanka. Hence, it will be a source of income for everyone, during this economic crisis.

Conclusions and Future Prospects

Energy has become the major requirement to maintain a better behavioral and living standards of the world. Due to the increase in population, the fossil fuel derivatives are being finite and the need of alternative energy sources is upsurging. Transportation sector is one of the largest energy consumers in the world. Petroleum diesel has many disadvantages including the environmental damage caused from the emission of gases such as CO_2, carbon monoxide and sand particulate matter. Hence, scientists and researchers around the world are motived to investigate new sources of alternative and renewable energy. Biodiesel is the most attractive and commonly used alternative to the petroleum diesel, possessing enormous environmental and natural benefits. Oils derived from crops such as palm, soybean, jatropha, sunflower and animal fats are the main sources of feedstocks used to produce biodiesel. Other than that, waste cooking oil from hotels and restaurants and oils derived from algae are some of the economical feedstocks for manufacturing biodiesel. Hence, the selection of best feedstock that could produce higher yield with minimum cost is vital. The technologies such as thermal cracking (pyrolysis), microemulsion and transesterification are used in manufacturing biodiesel. Transesterification is the most commonly used method. Characterization of properties of biodiesel are essential to maintain the quality of biodiesel. Those include density, flash point, cetane number, pour point and cloud point, viscosity, oxidation stability and calorific value. At the current state, biodiesel is economically less productive and much investigations are needed to make it competitive compared to the convectional diesel. Providing funds to continue research and financial aid for those who are capable of manufacturing biodiesel will be worthwhile.

Conflict of Interest

Authors have declared that no competing interests exist.

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Detection of Suspicious Objects in Unconstrained Environments to Effectively Manage a Security System in Sri Lanka

CHAPTER 16

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Abstract Computer vision-based security surveillance using automated CCTV cameras could help identifying criminals and reduce the crime rate. It has been widely used in defence, transportation, and public terminals such as airports, harbours, and bus stands. Object detection in unconstrained environments is essential for providing proper real-time security surveillance in high-security zones. Unconstrained environments in computer vision are backgrounds with virtually any artefact where object detection does not consider any assumption. Adequate security measures and enhancing access to the public terminals without fear are necessary for the nation's economic success. Besides this, tourism is a major contributor to the country's primary revenue. Proper security surveillance definitely minimises the fluctuation of the tourism industry. This chapter proposes a method to detect weapons such as knives, swords, and sticks from real-time security surveillance in an unconstrained environment. The proposed method uses a "You Only Look Once" (YOLO) object detection framework. All the fully connected dense layers of the YOLO model were trained with a newly created dataset with different images captured in environments where tear gas is present and contains dangerous objects. The proposed model achieved a prediction of knives at 80%, swords at 88%, and sticks at 95%. Considering the challenges of identifying dangerous objects, the developed model shows higher accuracy in real-time detection in an unconstrained environment. The information presented in the chapter would be a guide for providing real-time security surveillance in an unconstrained environment using computer vision to effectively manage the security system in Sri Lanka. The synthesis that is presented here can be used to enhance safe access to public terminals and contribute to the country's economic success through the stability of the tourism industry, which is a significant source of country's revenue.

Keywords: Computer vision, Deep learning, Object detection, Unconstrained environment, YOLO

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Introduction to Computer Vision-based Security Surveillance in Sri Lanka

Digital security surveillance systems are essential for providing proper security to every part of the world. The world faced several security surveillance issues in past several years. From 2006 to 2022, the world and Sri Lanka faced several terrorist attacks and public protests. These incidents recorded significantly higher public deaths. It is primarily affecting the economic growth of the countries. Because of several episodes, many government authorities discussed developing automated detection mechanisms. Most of the time, the current methods fail to detect unauthorised materials, especially during protests and looting times. In this situation, the environment was mostly unconstrained, created by tear gas and water cannon. Therefore, it is beneficial to have a real-time security surveillance system that automatically identifies unauthorised materials or persons in an unconstrained environment using well-trained datasets. It helps to improve the security surveillance system of the nation. This chapter discusses an effort that efficiently provides security in public places such as airports, harbours, shopping malls, and religious and tourist areas. Well-provided security could play a vital role in the country's economic development (Sun *et al*.. 2013; Girshick *et al*., 2014; Liu *et al*. 2018).

In practice, security surveillance systems in public places have to deal with constrained and unconstrained environments. Digital security surveillance focuses on detecting suspicious objects and behaviours in public roads, airports, harbours, shopping malls, and religious and tourist places in real time. Existing security surveillance systems use computer vision-based detection methods developed for constrained environments (Ghiass *et al*., 2013; Gidaris and Komodakis, 2015; Khajuria *et al*., 2019). In Fig. 1, an existing object detection method is applied to predict people in an unconstrained environment containing heavy smog zone. Low detection rates shown in Fig. 1 indicate that the detection algorithm has failed to predict the objects due to the heavy smog zone made by tear gases.

The primary object detection environments can be divided into two categories such as less-challenging and more-challenging. The images obtained from constrained environments are of good quality without many artefacts. In unconstrained environments, input images are low-quality and have many artefacts. The images captured in smog zones (high, medium, and low density), water cannon and tear gas used zones, blurred areas, rainy and cloudy regions and low backgrounds are typical examples of unconstrained environments. Fig. 1 shows an unconstrained environment created due to smog. Therefore, detection in unconstrained environments usually faces several challenges in detecting objects. According to recent studies, object detection rates in unconstrained environments are much lower compared to constrained environments. Situations such as protests which can bring unlawful disturbances to a country, can be easily controlled using automated surveillance methods. It significantly contributes to the protection of the public and their property. Various technologies are available but are not accurate when tear gases and water cannons create an unconstrained environment. The YOLO-based object detection technology can overcome the drawbacks found in the existing technology.

Sri Lanka faced several computer vision-based security surveillance issues with suspicious object prediction and detection in unconstrained environments. The main objective of this chapter is to overcome the problems mentioned above and develop a suitable object detection method for unconstrained environments to predict suspicious objects and provide a proper security surveillance system. Furthermore, chapter aims to design a model to detect suspicious objects in unconstrained environments with modern deep learning-based and computer vision-based object detection methods (Hu and Ni, 2018).

Figure 1. An example of an unconstrained environment created by a smog zone made by tear gas (left) and low detection rates of people (right)

The rest of the chapter explores the importance of security surveillance in the tourism industry and the role of object detection in intelligent security systems. In the section on the impact of security surveillance on the tourism industry, the importance of providing a safe and secure environment for tourists is emphasised, and the potential consequences of failure in this regard are discussed. The overview of object detection in intelligent security surveillance section provides a brief history of object detection and an overview of traditional and deep learning-based approaches. The section on why technological approaches are needed for security surveillance highlights the limitations of physical surveillance and the benefits of semi-automatic and automatic surveillance. It also discusses the trends and challenges in developing and deploying these technologies. Finally, the section on the significant challenges of identifying unauthorised materials in an unconstrained environment indicates the substantial challenges and benefits of using object detection for security surveillance in such environments. This includes considerations such as accuracy, efficiency, adaptability, and cost.

Impact of Security Surveillance on the Tourism Industry

In Sri Lanka, tourism has been one of the significant contributors of the economy during the past several years except during the COVID-19 pandemic. Safety and security are vital to provide quality tourism. More than any other economic activity, a tourist destination's success or failure depends on providing visitors with a safe and secure environment. The existing digital security surveillance systems failed to provide proper surveillance during the Easter attack in 2019. Bombs ripped through churches and luxury hotels; these incidents highly affect tourist arrivals in Sri Lanka.

Numerous studies have shown that perceptions of security and the control of risk, safety, and security significantly impact tourists' destinations. The absence of safety and security in tourist areas is shown to have resulted in significant drops in worldwide travel. Fig. 2 shows the number of foreign tourist arrivals in Sri Lanka in the last ten years. There was a massive drop in 2019 due to the easter bomb attack and after April 2022 public protests. These two incidents mainly affected country's economy before and after the COVID-19 pandemic. With the prevention of both these events by using computerised object detection technology, we could have quickly recovered from the economic fluctuation after the COVID-19 pandemic. A security camera is a crucial tool that plays a significant role in surveillance system to accomplish the safety management of travellers. Security is essential for tourism because it is vital in ensuring the safety and well-being of tourists and visitors. Security is often a top priority in the tourism industry, as tourists often travel to unfamiliar places and may be vulnerable to various risks and threats.

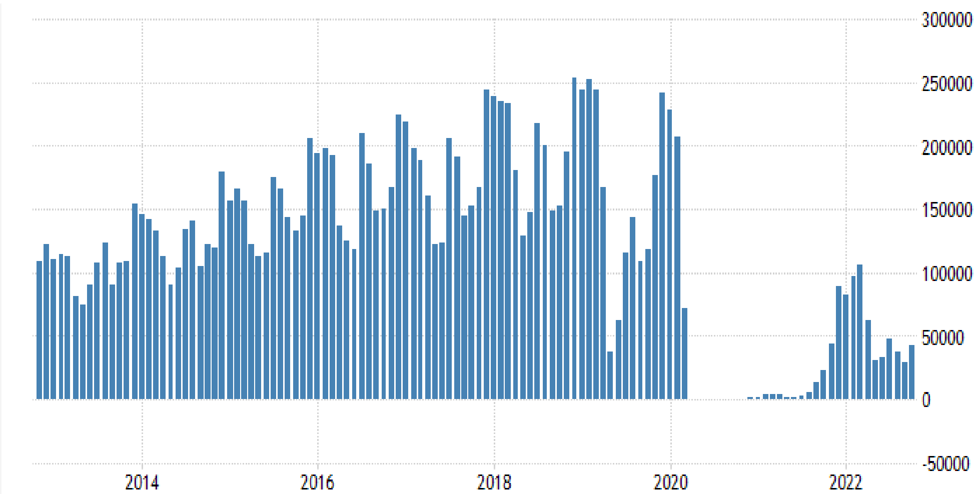

Figure 2. The number of foreign tourist arrivals in Sri Lanka during last ten years (Source: Sri Lankan Tourism Research and Statistics)

Reasons that Security Plays an Essential Role in Tourism

(i). Safety
Ensuring the safety of tourists is critical for maintaining a positive reputation and attracting visitors to a destination. Tourists are more likely to return and recommend a travel destination perceived as safe and secure.

(ii). Crime Prevention
Tourists are often targeted by criminals, who may take advantage of their unfamiliarity with the local area and culture. Adequate security measures can help preventing crime and protect tourists from harm.

(iii). Emergency Response
Security measures can also help to ensure that tourists receive timely and practical assistance in an event of some emergency, such as a natural disaster, medical emergency, bomb blasting, terrorist attack, and protest or looting.

(iv). Risk Management
Security measures can also help to mitigate other types of risks, such as health risks, environmental risks, and logistical risks, which can impact the overall quality of the tourist experience.

Overview of Object Detection in Intelligent Security Surveillance

Object detection and recognition are not new subjects in the digital era. This technology has a long history. Object detection based on template matching techniques and a simple image part base module was introduced in 1973. The object detection mechanisms were developed based on statistical classifiers such as Neural Networks, Support Vector Machines (SVM), Adaboost, and Bayes (Cheng *et al*., 2014; Wai *et al*., 2016). There are many areas where object detection and recognition systems play significant roles, such as robotic intelligence systems, automatic security surveillance, compression of videos, online communication, online traffic monitoring, vehicle navigation, and human-computer interaction (Najibi *et al*., 2018; Rekha *et al*., 2020).

Computer vision object detection and recognition generally fall into two categories, (1) traditional computer vision approaches and (2) deep learning-based computer vision approaches. Main traditional computer vision approaches for object detection include the Viola-Jones object detection framework based on Haar features (Grega *et al*., 2016; Dwivedi, 2017), Scale-Invariant Feature Transform (SIFT), and Histogram of Oriented Gradients (HOG) features. The deep learning methods use end-to-end object detection without precisely defining features such as Region Proposals (R-CNN, Fast R-CNN, Faster R-CNN, and cascade R-CNN) (Chellappa *et al*., 1995; Pita *et al*., 2009; Najibi *et al*., 2018; Zou, 2019), Single Shot MultiBox Detector (SSD) (Huang *et al*., 2018), YOLO (Luo and Chen, 2020), Single-

Shot Refinement Neural Network for Object Detection (RefineDet), Retina-Net, Deformable convolutional networks and many others (Ouyang *et al.*, 2017; Sun *et al.*, 2018; Lee *et al.*, 2019; Athira and Khan, 2020). Object detection using computer vision is not as novel as it first appeared. Object detection has changed tremendously during the past 20 years (Gunasekar *et al.*, 2014; Liao *et al.*, 2017; Luo and Chen, 2020) and its progress is often separated into two main historical periods before and after the arrival of deep learning, as shown in Fig. 3.

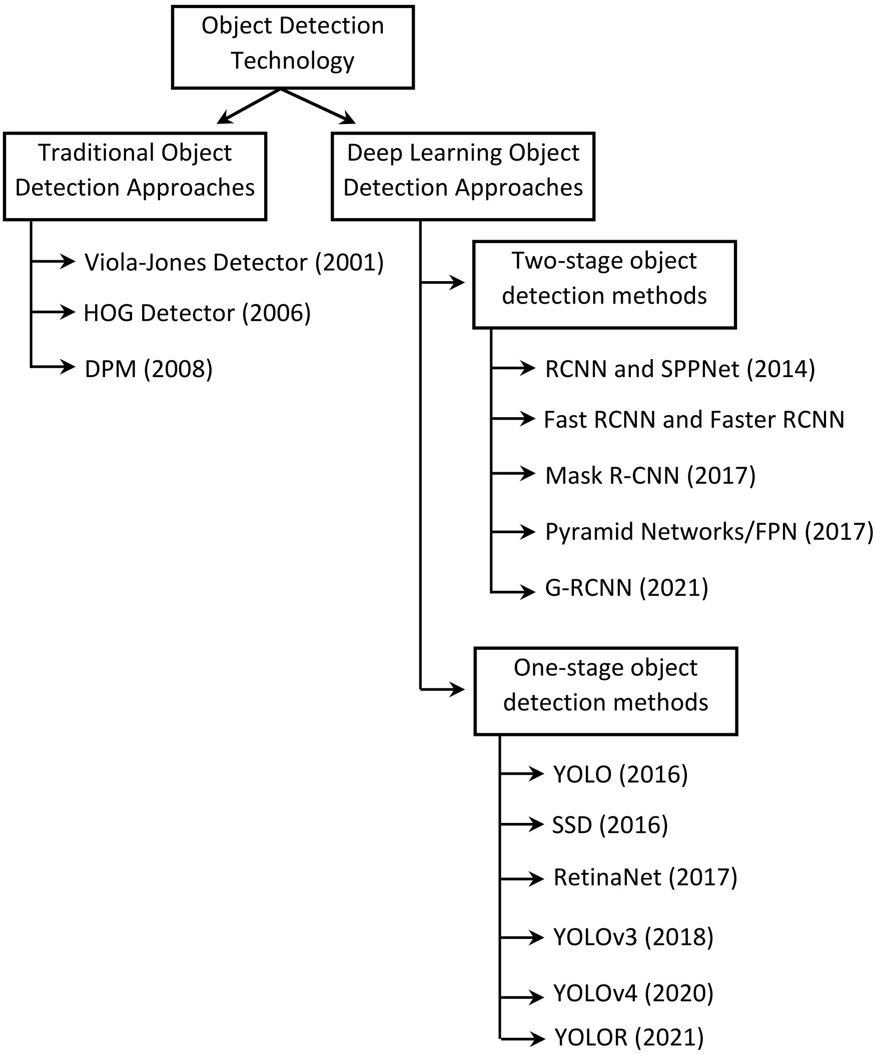

Figure 3. Current trends of object detection

Need for Technological Approaches

Monitoring a specific region or enclosed location is surveillance in terms of safety and protection. This surveillance prevents unlawful or criminal activity and protects property and the public. Modern surveillance systems come with excellent recording features that can be helpful for the investigation process. For the following reasons, managing security surveillance in public commercials using traditional approaches is becoming more difficult now than ever.

(i). Physical Surveillance Method
The most basic type of surveillance is person physically watching a location. This method is a typical example that may be observed daily, including stores, homes, communities, and entry control points in public and private institutions. Usually, inadequate security staff members may fail to detect criminals or weapons in public places.

(ii). Semi-automatic Surveillance Method
Another popular form of surveillance is having a conservative view of live video feeds from security cameras. Additionally, it failed to detect weaponry in public.

(iii). Automatic Surveillance Method
Live, automated video monitoring is one of the most common types of surveillance technology in public places. This is one of the surveillance methods that usually operates on a daily schedule where on location, no human guards monitor the system during active hours. These technologies also need to detect objects accurately in an unconstrained environment.

In security surveillance, despite using drones and CCTV cameras as surveillance tools, ambiguous regions are where it is challenging to identify whether one or several objects are in the visual. The detecting complexity increases as the lighting, perspective, and viewpoint vary during the protests and looting (Sarda *et al*., 2021). Therefore, the identification and implementation of publicly affordable, cost-effective, and sustainable modern technologies are needed to transform the country's security system from the traditional security surveillance system towards intelligent security surveillance that can also operate in unconstrained environments (Malhotra and Garg, 2020; Shi, 2021).

Significant Challenges of Locating Unauthorised Materials in an Unconstrained Environment.

(i). Minimal-quality images: Smog or water mainly covers the environment, so the system receives minimal-quality images.

(ii). Quickly change the objects' appearance: A person has materials with different angles. Usually, protests and looting situations quickly change the objects' appearance.

(iii). Physical challenges: Minimal differences in the physical appearance of the materials, and some parts of the objects only appear, and the rest is hidden.

(iv). Imaging challenges: Motion capturing, blurry images, partly captured, illumination variations, complicated backgrounds, pose occlusions.

(v). Locating objects: In unconstrained environments, mostly covered with smog zones, it is usually similar to the background of the target tracking material and then the problem arises in locating objects.

Object detection and recognition are renowned research areas in computer vision technology. Recognising an object is an easy task for human beings. One can quickly identify an item from its physical appearances, but vision-recognizing materials are one of the most challenging tasks for the computer. Therefore, highly developed detection and recognition methods are available in constrained environments to improve security surveillance in the unconstrained environment (Tianjiao and Hong, 2020). The benefit of this study is improving security surveillance in public places and enhancing the detection and efficacy level of recognition mechanisms.

YOLO-based Object Detection

The YOLO-based object detection uses a single neural network as a real-time object detection system. It allows the user to train the model with the most recent version of ImageAI, v2.1.0, to recognise any kind and quantity of objects. Convolutional neural networks are examples of classifier-based systems that apply the detection model to an image at several scales and locations using repurposed classifiers or localisers. The final identification occurs in zones resembling the provided training images (Chandan *et al*., 2018; Wu and Zhang, 2018; Lu *et al*., 2019; Kuna, 2020; Menaka *et al*., 2020). YOLO is much faster than most convolutional neural networks since it conducts classification and bounding box regression in a single step as a single-stage detector. For instance, YOLO object detection is 100 times quicker than Fast R-CNN and more than 1000 times faster than R-CNN (Girshick, 2015). In addition, YOLO offers more immediate inference, recognition of small or distant objects, little missing objects, little to no overlapping boxes, and effective object detection in crowded areas.

Architecture of YOLO

The YOLO is an object detection algorithm using a Convolutional Neural Network (CNN) to directly predict the object bounding boxes and class probabilities from whole images. YOLO uses several layers that process the input image and produce the output predictions. The layers of a YOLO CNN can be broadly divided into several types.

(i). Feature Extraction Layers

These layers process the input image and extract features such as edges, corners, and textures. The features are then passed to the following layers of the network, which in turn makes more abstract and composite representations of the image content. Feature extraction layers are a type of layer in a neural network used to extract features or patterns from the input data. These layers are typically used in the early layers of the network before the fully connected layers. They are designed to identify and extract input data's most relevant and informative features. Many different types of feature extraction layers can be used, depending on the specific characteristics of the input data and the desired features. Some common types of feature extraction layers include,

1. Convolutional layers are the feature extraction layers commonly used in image processing tasks. They apply filters to the input data to extract features such as edges, corners, and patterns.
2. Pooling layers are used to downsample the feature maps produced by the convolutional layers. They reduce the spatial dimensions of the feature maps, which can help reduce the computational cost and improve the model's generalisation.
3. Recurrent layers are feature extraction layers commonly used in sequence processing tasks, such as natural language processing or speech recognition. They apply a set of weights to the input data at different time steps, allowing the model to capture temporal dependencies and patterns.
4. Attention layers are feature extraction layers used to focus the model on specific parts of the input data. They can be used to weigh the importance of different input features and improve the model's accuracy.

Moreover, feature extraction layers are an essential part of many neural networks, as they help to extract the most related and informative features from the input data and feed them into the downstream layers for further processing.

(ii). Prediction Layers

These layers use the features extracted by the feature extraction layers to make predictions about the objects in the image. In YOLO, the prediction layers include several fully connected layers that predict the object bounding boxes and class probabilities. The specific architecture of a YOLO network depends on the version of YOLO being used. For example, YOLOv3 uses a more complex network architecture with 53 layers, while YOLOv2 uses a simpler network with 19 layers. These layers are typically located at the end of the network after the feature extraction and are responsible for producing the final output. Depending on the network's specific task and output format, many different types of prediction layers can be used. Some common types of prediction layers include,

1. Classification layers predict a discrete class label for the input data. They are often used in image classification or natural language processing tasks, where the goal is to predict a similar class of an input image or text.
2. Regression layers predict a continuous numerical value for the input data. They are often used in forecasting or time series prediction tasks, where the goal is to predict a numerical value for a given input.
3. Sequence prediction layers are used to predict a sequence of values for the input data. They are often used in tasks such as machine translation or speech recognition, where the goal is to predict a sequence of words or phonemes for a given input.
4. Generative layers are used to generate new data samples based on the input data. They are often used in tasks such as image synthesis or text generation, where the goal is to generate new samples similar to the input data.

Moreover, prediction layers are an essential part of many neural networks, as they produce the network's final output and make predictions based on the input data. YOLO is a repurposed classifier that can be used to perform detections in unconstrained environment security surveillance. The end-to-end neural network YOLO proposes simultaneous bounding boxes and class probabilities prediction. YOLO has the natural advantage of speed, better intersection over union in bounding boxes and improved prediction accuracy compared to the real-time object detectors. Furthermore, it only requires one iteration. The methods that use region proposal networks must do numerous iterations on the same image (Nishiyama *et al*., 2011; Hua *et al*., 2012; Sehgal *et al*., 2020; Yoo *et al*., 2015).

Proposed YOLO-based Security Surveillance System in an Unconstrained Environment

The current digital era needs more improvement in object detection in unconstrained environments to produce proper security surveillance during public protests, robberies, looting, and terrorist attacks. Because these environments are fully covered with smog zones created by tear gas bombing and cloudy zones created by water cannons, these situations also require more progress in higher-level motion object detection (Lee *et al*., 1999; Chen *et al*., 2011; Tychsen-Smith and Petersson, 2017). In unconstrained environments, the system receives minimal image quality because of various artefacts. For instance, persons with materials appearing from different angles in protests or looting situations will have occluded and overlapping objects in complex backgrounds. Light variations, motion capturing, blurred images, pose, acquisition geometry challenges, dataset availability, and quality of datasets are noted challenges (Tathe *et al*., 2017; Jiao *et al*., 2019; Fan and Gao, 2020).

This chapter proposes a method to improve security surveillance in an unconstrained environment with the surroundings covered by tear gas in protests and riots. The technique can detect public violations of weapons such as knives, swords and sticks using well-trained YOLO model. Fig. 4 shows a graphical summary of the proposed method, including several steps. The dataset was newly developed for model training, containing images captured in surroundings covered by tear gas with public violation objects such as knives, swords and sticks, as given in Table 1. These images were captured from different viewpoints and angles. Then the images are labelled with the relevant classes and object boundaries. Image augmentation techniques such as flip, rotation, grayscale, blur, and noise were applied to develop a larger healthy dataset.

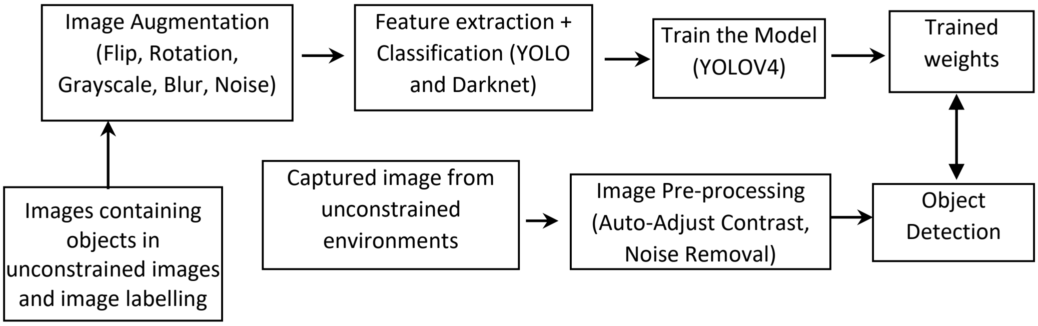

Figure 4. The proposed YOLOv4 based system to detect objects that can cause public violations.

Table 1. Dataset created with weapons found in unconstrained Environments

Class	Number of images
Knife	520
Sword	258
Stick	410

The most relevant features are extracted using the DarkNet convolutional neural network backbone of the YOLOv4 and classification is performed using the YOLO dense layers. Finally, the model weights are obtained to predict knife, sword, and stick objects. The real-time application detection model enters the trained pipeline when an image is captured from a public security surveillance system based on CCTV cameras. Then, the features of the image are extracted and classified with YOLO and Darknet. Finally, a few in-built image pre-processing mechanisms are used to improve the image quality to predict suspicious objects in the tear gas environment to maintain higher accuracy. Some sample predictions of the existing methods of unconstrained environment security surveillance detections are shown in Fig. 5. Most of the time, it fails to detect the weapons while predicting the objects. The system predicts only the persons and bags.

The developed YOLO model effectively predict the offence-able objects such as knives, swords and sticks as shown in Fig. 6. Most photographs include numerous artefacts with cluttered, messy backgrounds and partially visible objects due to the unconstrained environment. The suggested approach, however, overcomes them and exhibits a better prediction rate. As a result, the proposed method can enhance digital security surveillance in situations involving protests and looting.

Figure 5. An example of experimental results an existing model of SSD

Figure 6. An example of experimental results of the proposed model

As given in Fig. 6, the model can accurately detect batons on the hands in an unconstrained environment, which is challenging due to the smog artefact, a wide range of poses, lighting, and background variations. This demonstrates the effectiveness of the proposed methodology for security surveillance in such environments. One of the key benefits of using the proposed methodology for security surveillance is its ability to operate in real-time, allowing it to continuously monitor area and alert security personnel or authorities in the event of suspicious or unusual activity. Additionally, deep learning techniques enable the model to learn from data and adapt to new scenarios, further improving its performance and accuracy over time. Therefore, proposed object detection model represents a significant advancement in security surveillance, offering a reliable and efficient solution for detecting objects of interest in an unconstrained environment. Its real-time performance and adaptability make it a valuable tool for enhancing the security and safety of many settings. Fig. 7 shows how the detection accuracy varies with epoch values during training. The developed model was tested in several real-time unconstrained environments. The resulting model's performance is shown in Fig. 8 in terms of detection accuracy.

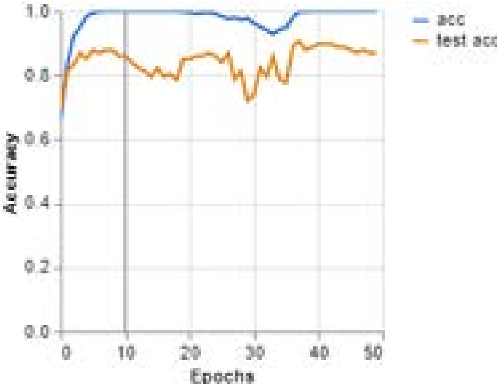

Figure 7. Average training (acc) and test accuracy (test acc) of the proposed model

Accuracy per class

CLASS	ACCURACY
Knife	0.80
Sword	0.88
Stick	0.95

Figure 8. Detection accuracy of each class

Further, to assess the model's efficacy, we used a variety of metrics, such as precision, recall, and detection accuracy per class. According to the combination of the ground truth and the prediction, the samples for a classification task can be categorised as true positives (TP), false positives (FP), true negatives (TN), and false negatives (FN). Formula (1) and (2), respectively, show how precision and recall are calculated. F1-score is defined as the harmonic mean of precision and recall. Table 2 shows the precision, recall and F1-score for knife, sword and stick classes. From Table 2, it can be seen that the proposed method has achieved higher precision, recall and F1-score values.

$$P = \frac{TP}{TP + FP} 100\% \quad (1)$$

$$R = \frac{TP}{TP + FN} 100\% \quad (2)$$

Table 2. Precision, recall, and f1-score of each class

Performance Measure	Knife	Sword	Stick
Precision	91.05%	88.37%	98.92%
Recall	83.50%	76.00%	92.00%
F-score	87.09%	81.72%	95.34%

Conclusions and Future Prospects

The most countries need help with computer vision-based security surveillance as a real-time application. Nowadays, object detection in unconstrained environments is highlighted as a significant issue in security surveillance due to public protests and terrorist attacks. Surveillance cameras failed to detect suspicious objects when water cannons and tear gases are used to control the demonstrations and protests. This erroneous surveillance environment makes the protesters involved in more violations. This chapter analyses the issues and the limitations found in the existing object detection algorithms in unconstrained environments and proposes the YOLOv4 object detection algorithm as the baseline model with the detection rate of knives at 80%, swords at 88%, and sticks at 95%. This real-time detection rate helps overcome the issues in object detection in unconstrained environments. The proposed YOLO single-stage object detection model would improve security surveillance in the country. This system can help reducing public violations that will support improving tourism, a significant contributor to economy of Sri Lanka. The model can be improved further by training for more classes (i.e., more kinds of suspicious objects), adding additional challenging environments like clouds, water, and smoke, and also testing with various YOLO versions like OYOLO and Tiny YOLO to increase detection accuracy.

Conflict of Interest

Authors have declared that no competing interests exist.

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