In commemoration of the 25th Anniversary of the Faculty of Agriculture and Plantation Management

RISING WITH AGRICULTURE: Challenges and New Perspectives

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Rising With Agriculture: Challenges and New Perspectives

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Forward

In the ever-evolving landscape of agriculture, this edited book titled 'Rising with Agriculture: Challenges and New Perspectives' represents a significant contribution, offering fresh perspectives and in-depth analyses on various aspects in the field of agriculture such as agricultural economy, crop production, agri-tourism, floriculture, climate change, food security, biotechnology, hybrid seed production, *etc*. It is with great pleasure that I write this foreword, not only because of the book's scholarly merit but also due to my deep respect for the editors and contributors who are the senior academics of the Faculty of Agriculture and Plantation Management at Wayamba University of Sri Lanka. This book represents the culmination of rigorous scholarship, thoughtful reflection, and a deep commitment to advance our understanding in the field of agriculture. They have worked meticulously to bring this task to fruition to commemorate the 25th Anniversary of the Faculty of Agriculture and Plantation Management.

As a Senior Academic, I have witnessed firsthand the dedication and passion that Prof Jagath Edirisinghe, Prof Chandana Abeysinghe, Dr Erandi Wijesinghe, Dr Priyanwada Warakagoda, and Dr Surantha Salgado have poured into this task as editors of the book. They are well renowned for their expertise in the field of Agriculture and their meticulous curation of the chapters reflects their deep understanding of the subject matter. Their thoughtful organization of contributions from fellow academics ensures that this book is not only comprehensive but also accessible.

In an era characterized by unprecedented agricultural advancements and complex global challenges, this collection of articles offers a timely and comprehensive examination of key issues and emerging trends across various disciplines in Agriculture. Each article within this book is a testament to the dynamic nature of scientific inquiry and the relentless pursuit of knowledge that defines our era. The authors of the articles in this book are leading academics who have graciously shared their insights and research findings. They explore a range of topics—from the economic aspects of Sri Lankan Agriculture to the ethical implications of biotechnology, and from the nuances of climate change to the innovations to face the climate changes. Each chapter delves into complex issues with clarity and rigor, offering new angles and practical solutions that are both thought-provoking and actionable. Their work not only enhances our comprehension of these fields but also highlights the interconnectedness of scientific endeavors and their broader societal impacts.

As the research in the field of agriculture continues to evolve, so too must our approach to understanding and addressing the challenges we face. The articles published in this book reflect the diversity of thought and the spirit of collaboration that are essential for advancing research in agriculture and solving the pressing issues of our time. Authors of the articles in this book invite readers to engage with new ideas, question established paradigms and envision the future of agricultural research progress.

I am confident that this book will not only serve as a critical reference but also inspire ongoing dialogue and exploration. This book is an essential addition to the literature and a testament to the collaborative efforts of its distinguished contributors. I extend my deepest gratitude to the contributors for their dedication and expertise, and to the editorial team for their tireless efforts in bringing this collection to fruition. I am confident that readers will find this volume both enlightening and inspiring, as it captures the essence of agricultural research and its profound impact on our world. May this book serve as a catalyst for further inquiry and a reminder of the boundless potential that lies at the intersection of knowledge and imagination.

I encourage readers to engage deeply with the ideas presented in this book. The discussions within these pages are not just academic; they have real-world implications that can inspire change and foster understanding in the field of agriculture.

In closing, I would like to congratulate editors and all the contributors for their remarkable efforts in bringing this important work to fruition. I am confident that ‘Rising with Agriculture: Challenges and New Perspectives’ will be a valuable resource for scholars, practitioners, and anyone interested in the field of agriculture.

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Chapter One

A Glimpse into the Agriculture Economy in the Crisis Year

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Abstract

Sri Lanka's agriculture sector has faced significant challenges in recent years, including the impact of the COVID-19 pandemic, economic crises, and climate change. The pandemic disrupted supply chains and led to labor shortages, while the economic crisis and the ban on chemical fertilizers severely affected crop yields. Climate change has also posed challenges, with more frequent and intense droughts and floods affecting crop production. Despite these challenges, there are valuable lessons to be learned for the future of Sri Lanka's agriculture sector. One key lesson is the importance of diversifying crops to reduce vulnerability to market fluctuations. Promoting a wider range of crops can enhance food security and reduce risks. Sri Lanka should also explore new markets and export opportunities to mitigate the risks associated with relying on a few major export destinations. Becoming more climate-resilient is another crucial lesson. This involves investing in irrigation systems, promoting drought-tolerant crop varieties, and developing early warning systems for extreme weather events. Sustainable agriculture practices, such as agroecology and organic farming, should be promoted to improve resilience and enhance product quality. Developing value chains in agriculture is essential for enhancing competitiveness, sustainability, and profitability. Farmer cooperatives and associations can help farmers access resources, share knowledge, and negotiate better prices. Public-private partnerships can strengthen rural

infrastructure and improve post-harvest handling and transportation. Empowering women farmers is crucial for improving productivity and food security. Women play a vital role in agriculture but often lack access to resources and opportunities. Empowering them can lead to better food choices and improved nutrition for their families. Investing in youth is also important for the future of agriculture. Training and education programs can ensure that the sector has the workforce it needs to succeed. Embracing innovation, such as precision farming and IoT-based solutions, can significantly boost productivity and reduce costs. Comprehensive policy reforms are needed to address the challenges faced by the agriculture sector. These reforms should include fiscal measures to support farmers, improve access to credit, and streamline regulatory processes. By embracing these strategies, Sri Lanka can ensure the continued growth and prosperity of its agriculture sector, while building resilience in the face of future uncertainties.

Keywords: Agriculture sector, COVID-19, Crisis, Economic development

1. Overview of Sri Lanka's Agriculture Sector

Sri Lanka, affectionately known as the "*Pearl of the Indian Ocean*," is an island covering an area of 65,000 square kilometers, surrounded by pristine, turquoise waters. The country enjoys a moderate climate year-round, abundant fertile soil, easily accessible groundwater, a well-distributed river network in most regions, and two monsoon seasons that bring rainfall for the two main agricultural seasons. These environmental factors are essential to Sri Lanka's agriculture.

Benefiting from these favorable conditions, the agricultural sector has consistently served as a significant economic driver in Sri Lanka, making substantial contributions to the national economy, ensuring food security, and providing employment opportunities. Additionally, agriculture serves as the primary source of livelihood for the majority of the rural population, playing a crucial role in poverty reduction.

2. Composition of the Agriculture Sector

Sri Lanka's agriculture sector is characterized by an impressive array of crops. At its heart lies rice, the staple food of the nation and a cultural symbol deeply woven into Sri Lankan identity. Beyond rice, the sector is enriched with a host of plantation crops and minor export agricultural crops that bring foreign revenue to the country. The plantation sector comprises of the "traditional triples" – tea, rubber, and coconut, along with other plantation crops, including sugarcane, oil palm, cashew, and palmyrah.

Tea is recognized as the jewel in Sri Lanka's agricultural crown. Renowned globally for its quality, Sri Lankan tea is a significant export commodity. The country is also a key player in the global rubber market, with vast plantations dotting the landscape. Coconut, another vital crop, yields a range of products, from oil to coir, contributing to both domestic consumption and exports. In addition to these plantation crops, the country is renowned for its minor export agricultural crops, including Sri Lankan spice crops; cinnamon, cardamom, nutmeg, pepper, cloves, and beverage crops; coffee, cocoa, and other crops such as betel and arecanut. Similar to plantation crops, Sri Lanka's spices are also well-known around the world for their aroma and flavor.

Moreover, the country cultivates an abundance of tropical fruits, such as mangoes, bananas, and papayas, along with various types of vegetables like gourds, roots and tubers, legumes and grains, bulbs and stem vegetables, and leafy vegetables adding to its agricultural diversity. Apart from these various types of crops, the agriculture sector is also associated with the livestock and fisheries sub-sectors that fulfill the protein requirement of the population and also bring a considerable amount of foreign exchange earnings to the country. Around 70% of farmers solely practice crop production while the rest have integrated crops with livestock and in a few instances, only livestock rearing can be seen.

Regardless of the type of crop that is being cultivated, the agriculture sector displays a broad spectrum of farm sizes and ownership models. The majority of farms in Sri Lanka are small-scale and family-owned, sustaining subsistence-level agriculture. These smallholders can be seen in all sub-sectors of agriculture including, paddy, plantation crops (tea, rubber, coconut), minor plantation crops, fruit, and vegetables, and in the livestock sub-sector. The crops cultivated by these smallholders primarily cater to local consumption and bolster domestic food security. In contrast, larger commercial plantations are more concentrated on exportation, making them pivotal players in foreign exchange earnings and the country's overall economy. This coexistence of smallholder and commercial agriculture is emblematic of Sri Lanka's agricultural landscape, where tradition and modernity intersect.

3. Climate and Agriculture

Sri Lanka a tropical country in which the temperature remains relatively consistent at specific elevations, and there are two distinct monsoon seasons referred to as the "*Maha*" Season (from November to February) and the "*Yala*" season (from May to September). These monsoons are driven by the distribution of rainfall across the country. Consequently, the country is categorized into three distinct climatic regions, i.e.: (1) Wet Zone; (2) Intermediate Zone, and (3) Dry Zone (**Figure 1.1**).

The Wet Zone receives over 2500mm of mean annual rainfall covering the South-West regions including central hill countries, whereas the Dry Zone covers the Northern and Eastern parts of the country with a mean annual rainfall of less than 1750 mm. The Intermediate Zone is located between these two zones receiving a mean annual rainfall ranging from 1750 mm to 2500 mm. In addition, the country has been classified into 24 agro-ecological zones based on the rainfall, soil characteristics, forestry, and the land use manner and with the advancement of navel technology, these 24 agro-ecological zones have further been divided into 46 sub-regions (Premarathne & Premalal, 2006).

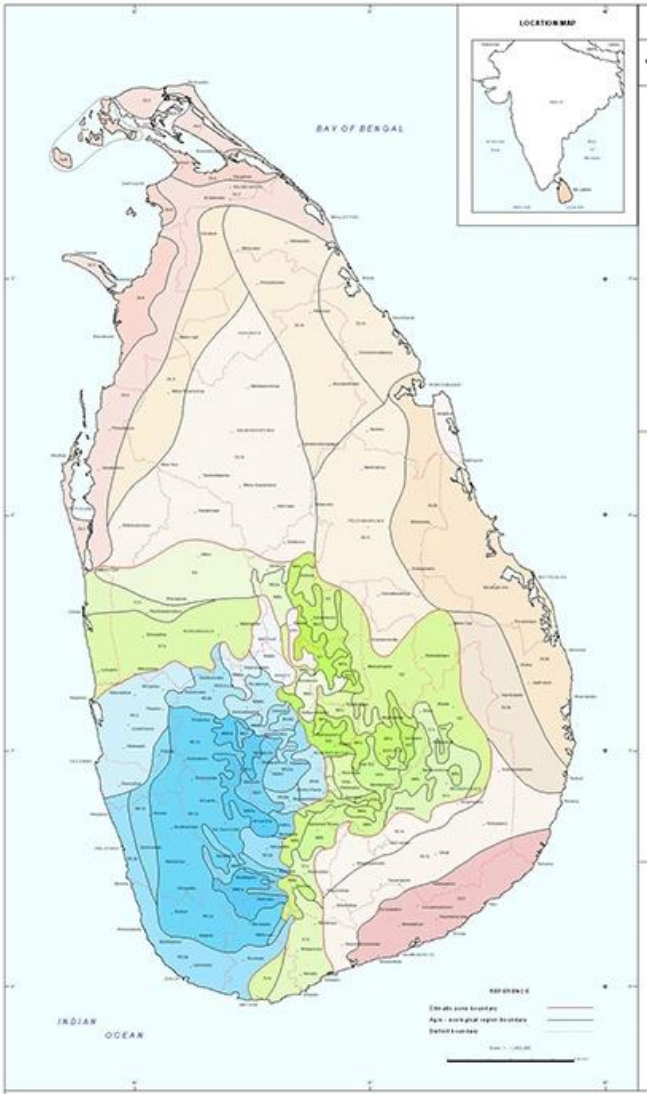

Figure 1.1: Agro-ecological zones in Sri Lanka
(***Source:*** *Department of Agriculture*)

Sri Lanka boasts a consistently moderate climate, featuring optimal temperatures and well-distributed rainfall throughout the year. The country is further distinguished by an extensive freshwater network, comprising artificial reservoirs, rivers, and other freshwater sources, alongside fertile adjacent soil. Due to these favorable resource advantages, Sri Lanka has earned its reputation as the 'Pearl of the Indian Ocean.' Consequently, the agricultural sector plays a pivotal role in the nation's economy, providing essential contributions in terms of food security, employment opportunities, and poverty reduction within rural communities.

4. Role of the Agriculture Sector in the Sri Lankan Economy

Sri Lanka's agriculture sector is a highly dynamic sector characterized by diverse crops, a myriad of agri-ecological zones, and a spectrum of farm sizes. While its relative contribution to GDP has witnessed a gradual decline, it continues to play a critical role in employment generation, economic stability, and food security of the country.

The agriculture sector has long been a cornerstone of the Sri Lankan economy, playing a pivotal role in providing livelihoods, ensuring food security, and contributing significantly to the nation's GDP. The agriculture sector is contributing approximately 7.9% to the GDP in 2023, with sub-sectors like fisheries and livestock adding around 1.3% and 0.9%, respectively.

It provides livelihoods for about 27% of the workforce, ensuring food security with paddy production estimated at 4.5 million metric tons in 2023, sufficient for domestic demand for about 13 months. Additionally, agriculture plays a crucial role in foreign exchange earnings, with tea being a significant export commodity despite a 7.4% decline in production in 2024 due to climate impacts (Central Bank of Sri Lanka, 2023).

While the relative contribution of Sri Lanka's agriculture sector to GDP has experienced a gradual decline due to the growth of other sectors, it remains a critical component of the nation's economic fabric. **Figure 1.2** highlights the contribution of three key sectors; agriculture, industry, and service, and shows the declining trend in the contribution of the agriculture sector due to the improved contribution of other sectors. **Figure 1.3**, highlights that the contribution of the agriculture sector stayed relatively stable in the short term and the declining trend of **Figure 1.2** was mainly evident due to the significant growth of the other two sectors.

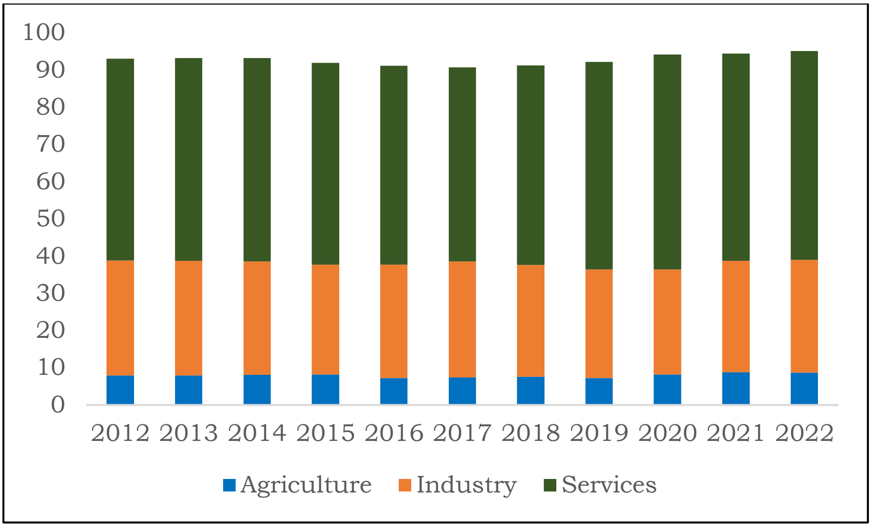

Figure 1.2: Contribution of Sectors for GDP (2012-2022)
[***Source:*** *Central Bank Annual Report (Multiple Years)*]

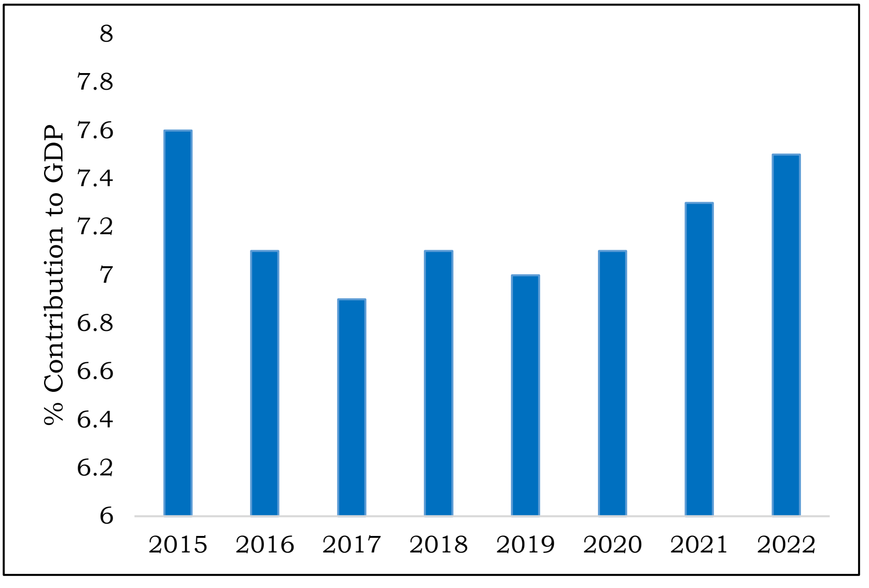

Figure 1.3: Contribution of the agriculture sector to the GDP (2015 – 2022)
[***Source:*** *Central Bank Annual Report (Multiple Years)*]

Agriculture contributes directly through the value of agricultural production and indirectly by bolstering associated industries, including agro-processing and exports. The sector's value-added activities, such as food processing and manufacturing, further amplify its economic impact. The intricate interplay between agriculture and these sectors underscores the agriculture sector's substantial role in driving economic growth and stability.

5. Employment Generation

One of the most important impacts of Sri Lanka's agriculture sector is its contribution to employment generation. It provides livelihoods for a significant portion of the population, especially in rural areas where the majority of farms are situated. The labor-intensive nature of agriculture ensures a consistent demand for agricultural workers, encompassing a wide spectrum of activities, including crop cultivation, harvesting, post-harvest processing, and distribution. Smallholder farmers, in particular, rely heavily on agriculture as their primary source of income, making it a crucial social safety net that mitigates poverty and unemployment challenges.

6. Food Security

The cultivation of staple crops like rice guarantees a stable supply of food for the population. Sri Lanka's self-sufficiency in rice production is instrumental in stabilizing prices and reducing the nation's dependence on rice imports. Beyond rice, the diversity of crops grown in different agri-ecological zones contributes to dietary variety and improved nutritional outcomes. This diversity is particularly valuable for maintaining balanced diets and reducing vulnerability to crop failures caused by climatic fluctuations. Nevertheless, the agriculture sector faces ongoing challenges linked to climate change, land use alterations, and market dynamics, necessitating sustained efforts to enhance and safeguard food security for the nation.

With this brief overview of the Sri Lankan agriculture sector, the next section of this chapter explores the nature of the crisis Sri Lanka has experienced during the last couple of years. The section will cover the nature of the crisis, the challenges faced by various sub-sectors in the sector including paddy and other crops, and livestock and fisheries sub-sectors. It further discusses how the crisis has affected the prices of agricultural commodities and the food security of the country creating nutritional concerns for the Sri

Lankan community. This is particularly evident when examining the four pillars of food security: availability, access, utilization, and stability. Crises can disrupt the availability of food by affecting production and supply chains, limit access due to increased prices and reduced purchasing power, impair utilization by impacting the quality and safety of food, and undermine stability by causing fluctuations in food supply and prices, thereby exacerbating nutritional concerns.

7. Nature of the Crisis

During the years 2020 to 2022, Sri Lanka had to face a global crisis in the form of COVID-19 and the resulting economic crisis. This was coupled with another crisis, especially related to agriculture and many termed it as a 'man-made,' the ban on chemical fertilizer. Let us look at these in detail and its impact on agriculture.

The COVID-19 pandemic or the Coronavirus pandemic was first reported in Wuhan, a Chinese city, in December 2019. It spread very quickly and was a worldwide pandemic by the year 2020. By September 2023, around 6.9 million deaths worldwide from 770 million reported cases. Hence, it was declared as one of the deadliest epidemics in the history of mankind.

The global healthcare system was put to test by this unforeseen pandemic and no country could respond effectively to the rapid spread of the virus. Vaccines were only available as late as December 2020, about a year later, when the pandemic broke out. Hence, the major control measures were travel restrictions, contact tracing of the infected, lockdowns, mask mandates, business restrictions and closures, workplace hazard controls, quarantines, and testing systems. This has led to an economic disruption leading to what is now known as the COVID-19 recession. This is the second-largest global recession in history. The first case of COVID-19 was reported in Sri Lanka in January 2020. The reported COVID-19 cases in Sri Lanka was 672,579 while the fatalities were 16,882 (Epidemiology Unit, 2023). There was a sharp increase in reported cases from March 2021 (WHO, 2023). Being already hit with poor economic performance, the lockdown due to the pandemic significantly affected Sri Lanka's development effort and the GDP growth rate dropped to negative values.

The economic crisis in Sri Lanka heightened after the Covid pandemic. The mismanagement of the economy by successive governments led to the final explosion, where Sri Lanka self-declared that it was a bankrupt nation in April 2022. The government attempted to manage the dwindling foreign exchange levels with the gradual banning of imports, which resulted in a situation where imports came to a standstill. This created a shortage of inputs to agriculture as well as unprecedented price hikes in both inputs and output. The inflation rate shot up to over 70% in certain months in 2022 (Central Bank of Sri Lanka, 2023).

There were queues for many consumer goods including fuel, which made farming much difficult as machinery such as tractors could not be operated during this time. To make matters worse, the government in May 2021 decided to ban the importation of chemical fertilizer and other agrochemicals in a bid to turn the country to fully organic in the wake of a lack of foreign exchange to import fertilizer. Although the government lifted the ban to allow the private sector to import fertilizer and agrochemicals in November 2021, the required volume could not be imported due to the shortage of foreign exchange because of the economic crisis the country was already in.

8. Challenges Faced by Paddy and Other Crop Sectors

The agriculture sector was heavily affected first, due to the disruption of the supply chains due to COVID-19 and then due to the ban on fertilizers and the import restriction. The agricultural sector was mostly affected not by the pandemic itself, but by the mitigation strategies adopted. These are the closure of rural markets, low demand for farm produce, shortages of agricultural inputs, and problems of labor availability for farm activities. Of the farmers in rural areas, small-scale horticulture and livestock farmers were the hardest hit due to COVID-19 (Talukder *et al.*, 2021; Adhikari *et al.,* 2021).

Table 1.1 presents the percentage annual growth in various economic activities related to agriculture to assess the impact of the crises that prevailed during the period

2020-2022. Paddy cultivation, one of the major livelihoods of the rural population was severely affected during the crisis years. Although there was a growth in 2020, it showed a negative 6.7% growth in 2021. This can be because of the impact of COVID-19 as well as the fertilizer ban. From **Table 1.1** it is clear that many economic activities in agriculture started to feel the impact from the year 2021 and continued through 2022.

Table 1.1: Percentage growth of economic activities related to agriculture (2018 – 2022)

Category	2018	2019	2020	2021	2022
Growing of cereals (except rice)	2.0	-9.5	44.8	9.7	-21.6
Growing of rice	44.7	-0.3	7.0	-6.7	-13.0
Growing of vegetables	4.0	1.5	7.6	-2.5	-8.4
Growing of sugar cane, tobacco and other non-perennial crops	-10.9	8.4	19.3	-7.4	1.8
Growing of fruits	11.4	8.5	6.2	-7.8	0.5
Growing of oleaginous fruits (coconut, king coconut, oil palm)	7.1	18.2	-10.4	11.2	8.6
Growing of tea (green leaves)	0.4	-1.3	-7.1	7.4	-15.9
Growing of other beverage crops (coffee, cocoa, *etc.*)	25.6	-23.4	21.7	-15.6	-9.1
Growing of spices, aromatic, drug and pharmaceutical crops	5.9	-1.0	3.3	4.5	3.3
Growing of rubber	-0.3	-9.5	4.6	-1.7	-6.7

Growing of other perennial crops	-2.5	-0.3	1.6	-4.8	2.0
Animal production	8.0	3.2	-2.8	9.7	-12.9
Plant propagation and support activities to agriculture	0.2	-6.3	-0.4	10.6	
Plant propagation	-	-	-	-	8.3
Agricultural supporting activities	-	-	-	-	14.7
Forestry and logging	-0.8	-4.8	-7.9	5.1	16.1
Fishing	0.2	-4.3	-16.6	1.4	-10.5

*(**Source:** Central Bank Annual Reports, 2019, 2020, 2021, 2022)*

It is reported that 53% of the paddy production in the 2021 Maha season was reduced because of the fertilizer ban. In addition, the yield of potato cultivation has dropped by 52%, maize by 68%, big onion by 52%, and Chillie by 43%. Furthermore, vegetable cultivation declined by 57%. Sadly, 86% of flower growers were also reported to have left the floriculture sector (Ministry of Agriculture, 2023). With the reduction of the yield levels, the incomes of farmers dropped, making matters worse.

The floriculture industry which is a major agribusiness sector in Sri Lanka which gained popularity in recent years has been termed as a rapidly growing industry with an annual growth potential of 25-30% which is close to 30 times of cereal or any other agricultural product (Pal *et al.*, 2014). At the rural levels, this sector is dominated by women, and hence, floriculture is seen as a tool for empowering women. It is reported that during the 2021 Maha season, about 86% of flower growers have left the floriculture sector because of a lack of fertilizer. A report published by the Hector Kobbekaduwa Agrarian Research and Training Institute (HARTI) shows that 86% of farmers have reduced the scale of farming operations in floriculture, while 92% had quality concerns with available fertilizer and agrochemicals and 41%

of households that conducted floriculture are moderately or severely affected (HARTI, 2022).

Farmers, especially in rural areas, faced shocks from the supply side, demand side, and logistics. Initially, there was panic buying due to the fear of lockdowns, demand went skyrocketing, however, mostly for dry rations. The demand for products such as rice, various cereals, etc., increased. However, due to the lockdown, logistics came to a standstill, with farmers unable to move the product from the farm gate to consumer markets. Although the government intervened by using armed forces and special passes for transporters of essential items, the produce from rural areas found it difficult to find the markets in towns.

About 56% of the farmers found it difficult to sell because of low demand. On the supply side, the usual cultivation and harvesting were adversely affected due to being advised to stay home (Singh *et al.*, 2021). It further revealed that 41% of farmers were adversely affected because of this. Making matters worse, the main shock on the supply side emerged, the ban on fertilizer. This aggravated farmers' problems, who are already severely affected by COVID-19, as production decreased in greater amounts, as discussed previously. Increases in the cost of living lead the way for the demand to reduce, creating further inroads into farmer income. Most farmers contemplated giving up farming; however, it is not easy for them to shift away from farming activities due to the low-performing economy where employment opportunities dwindled.

9. Impact on Livestock and Fisheries Sectors

Apart from the supply chain disruptions and labor shortages that were faced by all the agricultural sectors, the livestock and fisheries sector had several unique issues. For example, in some cases, there was reduced demand for poultry products due to misconceptions about the virus spreading through chicken and eggs. This led to a temporary decline in prices for poultry products. On the other hand, on a positive note, the increased time spent at home during lockdowns led to a higher home consumption of dairy and poultry products, as people cooked more at home. This provided a modest boost to the demand for certain livestock products.

The pandemic disrupted global seafood supply chains, affecting Sri Lanka's seafood exports. Reduced demand in key export markets and logistical challenges led to a decline in seafood exports. For example, edible fish exports in 2019 which were US$ 262.45 million reduced to US$ 189.81 million in 2020 (Export Development Board, 2023). The demand for seafood in the domestic market saw fluctuations. Initially, there was a reduction in demand due to consumer concerns, but later, demand rebounded as people sought alternative protein sources to replace meat. Lockdowns, movement restrictions, and especially, the shortage of fuel due to the economic crisis affected the ability of fishermen to go out to sea. This had a direct impact on fish catch and income for fishermen.

Fuel shortages caused reduced fishing activity, increased fishing costs, reduced catch volumes, and delayed transportation, all of which created supply shocks in the market. All these have led to a substantive increase in the market prices, at times to very unrealistic prices. In addition, fish processing plants faced difficulties due to COVID-19 outbreaks among workers, leading to temporary closures. Export-oriented seafood processing units were particularly affected. Therefore, the impacts of COVID-19 on the livestock and fisheries subsectors in Sri Lanka were multifaceted, with challenges related to supply chain disruptions, labour shortages, and export market disruptions. At the same time, some opportunities resulted from increased domestic consumption and government support measures.

10. Market dynamics and price fluctuations in agricultural commodities

The impact of COVID-19 on the fluctuation of farm prices in Sri Lanka, as in many other countries, has been complex and multifaceted. The pandemic affected various aspects of the agricultural sector, leading to positive and negative consequences on farm prices. Key impacts include:

- *Supply Chain Disruptions*: The lockdowns and movement restrictions imposed to curb the spread of COVID-19 disrupted supply chains, making it difficult for farmers to access inputs such as seeds, fertilizers, and pesticides. This disruption in the supply chain led to reduced agricultural production, which in turn, affected farm prices.

- *Labor Shortages*: COVID-19 also caused labor shortages in the agriculture sector, as many migrant workers returned to their home villages due to job losses and concerns about the virus. The shortage of labor resulted in delays in planting, harvesting, and other agricultural activities, affecting the supply of agricultural products and causing price fluctuations.

- *Export and Import Restrictions*: Export and import restrictions imposed by various countries during the pandemic disrupted international trade. For Sri Lanka, this could affect the export of agricultural products and the import of essential inputs, which had implications for both supply and demand in the domestic market, influencing farm prices.

- *Shift in Consumer Behavior*: Changes in consumer behavior during the pandemic, such as increased demand for certain food products (e.g., staples such as rice) and decreased demand for others (e.g., luxury fruits and vegetables), have led to changes in the demand for agricultural products, affecting their prices.

- *Government Interventions*: To mitigate the impact of COVID-19 on the agriculture sector, the Sri Lankan government has implemented various policies and interventions, such as price controls, subsidies, and support for farmers. These measures influenced farm prices either by stabilizing them or distorting market dynamics.

- *Economic Impact*: The broader economic impact of COVID-19, such as reduced consumer purchasing power and economic uncertainty, affected agricultural product demand and subsequently farm prices.

The COVID-19 pandemic and the resulting economic crisis have had a significant impact on inflation in Sri Lanka, creating many hardships for consumers and the poor.

Initially, at the onset of the pandemic, lockdowns and movement restrictions led to a sharp drop in consumer demand, especially for non-essential goods and services. This led to a decrease in demand exerting downward pressure on prices, leading to lower inflation.

People were spending less due to income uncertainties, job losses, and restrictions on movement. However, COVID-19 disrupted global and local supply chains, making it difficult for Sri Lanka to import essential goods and raw materials. Supply chain disruptions led to shortages and increased production costs, which, in turn, increased prices for some goods, contributing to inflation. To counter the economic impact of the pandemic, the Central Bank of Sri Lanka, often implemented expansionary monetary policies. These policies included lowering interest rates and increasing money supply. These measures also contributed to inflation.

Inflation reached its highest during September 2022, after the Covid had ended in the country (**Figure 1.4**). This shows the impact and the severity of the economic crisis in Sri Lanka.

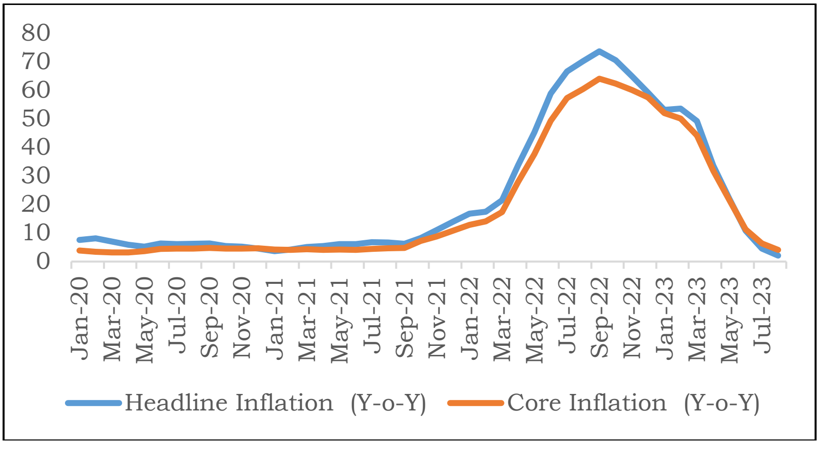

Figure 1.4: Change in consumer price inflation (2020 – 2023)
*(**Source:** Central Bank of Sri Lanka, 2023)*

Government fiscal stimulus measures, such as increased government spending or tax cuts, to support the economy during a crisis boosted demand and contributed to inflation. Currency devaluation or depreciation occurred during an economic crisis, making imported goods more expensive. Sri Lanka faced challenges in managing its exchange rate, and fluctuations in the exchange rate contributed to imported inflation.

Inflation in Sri Lanka can be particularly sensitive to food and energy prices. Global food and energy price fluctuations affected domestic prices, contributing to inflation. Disruptions in the production and distribution of these commodities also affected their prices. Uncertainty about the duration and severity of the economic crisis can influence consumer and business behavior. Businesses may have adjusted pricing strategies, and consumers may have changed their spending habits, both of which can impact inflation.

Furthermore, Sri Lanka's inflation dynamics can also be influenced by structural issues in the economy, such as high government debt levels, fiscal deficits, and supply-side constraints. These issues exacerbated inflationary pressures during the crisis.

11. Food Security and Nutrition Concerns During the Crisis

Sri Lanka’s food security issues heightened, not during the pandemic itself, but during the years when prices started soaring up because of the economic crisis.

Food availability was reduced due to supply shocks created by the import ban of fertilizers and other agrochemicals, and general import restrictions. For example, the import ban created a shortage of milk powder during the period and local manufacturers were unable to meet the total demand. Thus, there were long queues to buy these items. This affected the required nutrition intake in general and the nutrition of infants and children was clearly affected.

Production volumes declined and import restrictions made food items more scarce creating a price hike, making food inaccessible to most Sri Lankans. In certain times, food inflation increased by more than 90% making it very difficult for the poor to afford (**Figure 1.5**). Thus, the reduction in supply (availability) and reduced accessibility due to the high inflation of food prices created food insecurity and hunger in recent years. This hike in prices coupled with job losses and reduced incomes have made many Sri Lankans unable to afford an adequate and nutritious diet. This has led to increased food insecurity, with households struggling to access sufficient food.

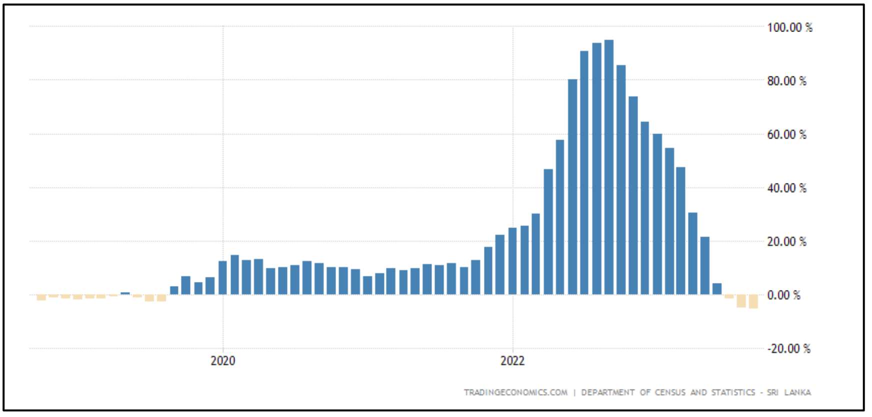

Figure 1.5: Inflation in food prices in Sri Lanka

This means the number of people who are food insecure increased from 1,900,000 to 2,400,000 in this period. The crisis has turned into food-based coping strategies such as eating less food, skipping meals, or reducing portion size. All these have led to a reduced nutrition intake, and this will especially affect children. When the required nutritional levels are not available, there can be poor growth in children, making the future workforce weaker.

Figure 1.6 shows that the percentage of people who are moderately or severely food insecure increased from 8.9% to 10.9% from 2018–2020 to 2020-2022.

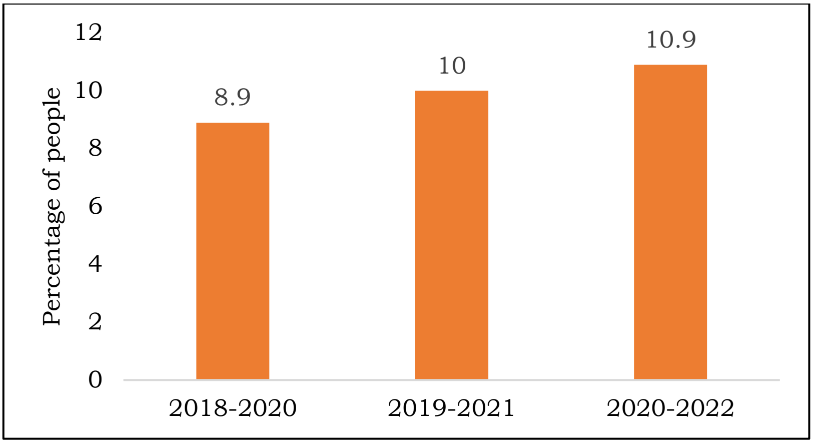

Figure 1.6: Prevalence of severe food insecurity
*(**Source**: FAOSTAT, 2023)*

Child malnutrition has worsened nationwide from 2021 to 2022 where percentage of underweight children under five years increased from 12.2% to 15.3%, percentage of stunting in children increased from 7.4% to 9.2%, while wasting in children has increased from 8.2% to 10.1% during the same period. Nuwara Eliya district had the highest percentage of stunting and underweight children recorded at 22.8% and 23.9% respectively (Central Bank of Sri Lanka, 2019-2023).

It's important to note that the impact of the crisis on food security and nutrition can vary across different regions and population groups within Sri Lanka. Vulnerable populations, including those living in poverty or in conflict-affected areas, are particularly at risk.

So far, the chapter has focused on giving the reader a general overview of the Sri Lankan agriculture sector followed by the impacts of recent crises encountered by the country. The COVID-19 pandemic has affected several sub-sectors in the Sri Lankan agriculture sector including paddy and other crop production, livestock and fisheries, and food and nutritional security. Upon identification of those affected areas and the nature of the impact, the next section of this section explores the lessons learned out of these challenges and management strategies along with how Sri Lanka should be looking forward to the development of the agriculture sector and in turn the economic development of the country.

12. Lessons Learned and Future Outlook for Sri Lanka's Agriculture Sector

Sri Lanka's agriculture sector has long been the backbone of its economy, contributing significantly to both its GDP and employment. However, in recent years, the sector has faced numerous challenges exacerbated by economic crises, climate change, and the ongoing COVID-19 pandemic.

The pandemic disrupted both domestic and international supply chains, affecting the availability of agricultural inputs and markets for produce. Lockdowns and movement restrictions led to labor shortages during crucial planting and harvesting seasons, resulting in crop losses. The economic crisis, which began in 2021, has had a devastating impact on the agriculture sector. Further, the government's ad-hoc decision to ban the import of chemical fertilizers in April 2021, to promote organic farming, led to a sharp decline in crop yields. This, in turn, led to a rise in food prices and food shortages.

Climate change is another challenge for the agriculture sector in Sri Lanka. The country is already experiencing climate change, such as more frequent and intense droughts and floods. These extreme weather events can damage crops and reduce yields, making it difficult for farmers to make a living. As a result, many unprecedented challenges have emerged within the agriculture sector threatening its prosperity.

Sri Lanka's agriculture sector relies heavily on imports, including fertilizers and machinery. The country's recent foreign exchange crisis has severely affected the sector's ability to access these essential inputs, leading to decreased productivity and increased costs. The country's high debt levels and unsustainable fiscal policies have limited the government's ability to provide adequate support to the agriculture sector, hindering its growth and development.

Urbanization and deforestation have led to the loss of valuable agricultural land, further decreasing the sector's capacity to meet growing demands. Considering this, it is important to explore the lessons learned from these challenges and a possible future outlook for Sri Lanka's agriculture sector, emphasizing the need for sustainable practices, technological advancements, and policy reforms to ensure resilience and growth.

One of the key lessons learned from the challenges faced by Sri Lanka's agriculture sector is the importance of diversifying crops. Overreliance on a few cash crops, such as tea and rubber, has made the sector vulnerable to price fluctuations and market uncertainties. Promoting the cultivation of a wider range of crops can help reduce risks and enhance food security. Further, Sri Lanka's agriculture sector must explore new markets and export opportunities.

Reducing dependence on a few major export destinations can help mitigate the risks associated with market fluctuations and global economic crises. Efforts should be made to diversify export markets and value-added agricultural products. This can be achieved through trade agreements, market research, and quality control measures. One such example is the rising coconut export industry in the country. A total of 37 coconut-based products are being exported annually to more than 90 countries around the globe covering Eastern Europe, Europe, Africa, the Middle East, Asia, and the American continent (Coconut Development Authority, 2018).

It's important to note that the success of the coconut export industry in Sri Lanka depends on factors such as high product quality, emerging international market demand, flexible trade policies, product diversification, and unique competitive advantage over other coconut-producing countries.

Sri Lanka's agriculture sector needs to become more climate-resilient to shocks and stresses, such as economic crises, pandemics, and climate change. This involves investing in irrigation systems, promoting drought-tolerant crop varieties, and developing early warning systems for extreme weather events. Sustainable agriculture should be at the forefront of the sector's outlook. This involves promoting agroecology, reducing chemical input use, and supporting organic farming practices systematically.

Government incentives and certification programs can encourage farmers to adopt these practices. Sustainable agriculture not only improves resilience but also enhances the quality of agricultural products. Collaborative efforts with international organizations and climate adaptation programs can also help build resilience. The agriculture sector is a global issue, and no country can address it alone. Sri Lanka needs to work with other countries to share knowledge and resources and to develop solutions that are sustainable and equitable.

Developing value chains in the agriculture sector is essential for Sri Lanka to enhance the competitiveness, sustainability, and profitability of its agricultural industry. Value chains in agriculture encompass the entire process from production to consumption, including input supply, production, post-harvest handling, processing, marketing, and distribution. One such ideal way to implement this is to encourage the formation and strengthening of farmer cooperatives and associations. These groups can collectively access resources, share knowledge, negotiate better prices, and have a stronger voice in policy discussions.

Public-private partnerships should be formed to strengthen the rural infrastructure, including roads, storage facilities, and irrigation systems, to reduce post-harvest losses and enable efficient transportation of agricultural products. Further, this is a pathway to amalgamate expertise, investment, and technology in agriculture. Combined efforts may always generate the required synergy in the sector. In addition, there should be a formal and reliable mechanism to ensure that farmers and agribusinesses have access to affordable credit and financial services to invest in their operations and value addition activities. Hence, workable value-chain financing is critical.

Empowering women farmers is another important aspect. Women play a vital role in agriculture, but they often lack access to resources and opportunities. Empowering women farmers can help to improve productivity and food security. Women are often responsible for household nutrition. Empowering them in agriculture can lead to better food choices and improved nutrition for their families. This has long-term benefits for the health and well-being of communities. They gain a stronger voice in decision-making processes at the household, community, and national levels.

Empowering women in agriculture helps challenge traditional gender roles and stereotypes, promoting equal access to resources and opportunities. This, in turn, can lead to broader social and cultural changes toward gender equity.

In addition, investing in youth should be done in parallel. The youth are the future of agriculture. Investing in youth training and education can help to ensure that the sector has the workforce it needs to succeed. Entrepreneurship is the best catalyst to bind youth in agriculture. Further, the agriculture sector must embrace innovation to remain competitive. This includes developing new technologies and practices that can improve productivity and sustainability.

The adoption of modern agricultural practices and technology, such as precision farming, IoT-based solutions, and farm mechanization, can significantly boost productivity and reduce production costs. The country's agriculture sector should prioritize technology adoption. This includes providing training to farmers on modern farming practices, encouraging the use of agricultural apps and digital platforms, and facilitating access to affordable and efficient farming equipment. This could be implemented through investing in research and development to adapt existing technologies to local conditions and develop new solutions that address specific challenges faced by Sri Lankan farmers.

Further, it is recommended to implement pilot projects and demonstration farms to showcase the benefits of technology adoption. Farmers can learn from these practical examples and see the results firsthand. Providing financial support, subsidies, or incentives to help farmers acquire and adopt technology is essential to up and run this mechanism. This can include grants or low-interest loans for purchasing equipment or implementing new practices.

Most importantly, the establishment of platforms or information centers where farmers can access information about modern farming practices, weather forecasts, market prices, and technological advancements is also vital. Mobile apps and community-based knowledge sharing can be effective tools for this purpose.

There should be a strong and well-focused facilitating environment which affects the sustainability of these strategies. Hence, the government must implement comprehensive policy reforms to address the challenges faced by the agriculture sector. These reforms should include fiscal measures to support farmers, improve access to credit, and streamline regulatory processes.

Additionally, policies should encourage private-sector investment in agriculture and promote research and development. However, the lessons learned from these challenges provide a roadmap for a more resilient and sustainable future. Policy reforms, technological advancements, sustainable practices, and market diversification are essential components of the sector's outlook. By embracing these strategies, Sri Lanka can ensure the continued growth and prosperity of its agriculture sector while mitigating risks and building resilience in the face of future uncertainties.

13. Conclusions

The agriculture sector in Sri Lanka has faced unprecedented challenges in recent years, including the impacts of the COVID-19 pandemic, economic crises, and climate change. These challenges have highlighted the vulnerabilities of the sector and the urgent need for strategic interventions to ensure its resilience and sustainability.

The COVID-19 pandemic disrupted both domestic and international supply chains, leading to labor shortages and crop losses. The economic crisis further exacerbated these challenges, particularly with the ban on chemical fertilizers, which significantly affected crop yields and food security. Climate change has added another layer of complexity, with extreme weather events threatening crop production and livelihoods.

Despite these challenges, there are valuable lessons to be learned. Diversifying crops and exploring new markets can help reduce vulnerability to market fluctuations. Investing in climate-resilient practices, such as irrigation systems and drought-tolerant crop varieties, is essential for adapting to changing environmental conditions. Sustainable agriculture practices, including agroecology and organic farming, can improve resilience and enhance product quality.

Developing value chains in agriculture is crucial for enhancing competitiveness and profitability. Farmer cooperatives and associations can play a key role in this process, helping farmers access resources, share knowledge, and negotiate better prices. Empowering women farmers and investing in youth is also important for the future of agriculture in Sri Lanka. Comprehensive policy reforms are needed to address the challenges faced by the sector. These reforms should include fiscal measures to support farmers, improve access to credit, and streamline regulatory processes. By embracing these strategies, Sri Lanka can ensure the continued growth and prosperity of its agriculture sector while building resilience in the face of future uncertainties.

In conclusion, while the challenges facing Sri Lanka's agriculture sector are significant, there are opportunities for growth and development. By learning from past experiences and implementing strategic interventions, Sri Lanka can build a more resilient and sustainable agriculture sector that can thrive in the face of future challenges.

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Chapter Two

Prospects in the Vegetable Industry in Sri Lanka: Ending Hunger

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Abstract

Vegetable cultivation in Sri Lanka has been recorded since ancient times. The unique climatic condition in various altitudes creates a favorable environment to cultivate vegetables all year round with a broad range including leaf, root and all other vegetables. The monsoon rain pattern (*Yala and Maha*) is the main factor that determines the crop cultivation in Sri Lanka. Annual crop production is just sufficient to fulfill the local food demand. Significant changes in the climate over the past few decades have disrupted the food supply chain and negatively impacted farmers' livelihoods. COVID-19 pandemic and the ongoing national economic crisis caused a shortage of inorganic fertilizer, pesticides and imported hybrid seeds, and lack of other agricultural inputs severely affected the routing of vegetable production throughout the country. Due to the continuous usage of inorganic fertilizer and chemical pesticides, soil in arable lands is deteriorated, and therefore, unable to expect a quality yield. It is essential to take remedial actions to improve vegetable production in the country to meet the national demand and upgrade farmers' livelihood. Independence of agriculture is the key to sustainability. Novel technologies of water management and climate smart agriculture techniques ensure continuous vegetable supply and protect crops from natural hazards and pests and diseases. Further, it is essential to unitize locally available eco-friendly fertilizer amendments to sustain soil health. Introducing bio-controls and pest repellent leads to minimizing chemical usage for pest control. Training farmers

to use smart agriculture and be aware of market information is mandatory to optimize farmer income.

Keywords: Farmer income, Sustainability, Vegetable production

1. Introduction

Sri Lanka is blessed with a tropical climate and geography favorable for a variety of vegetable crop cultivation. In addition to climatic advantage, the fertile soils, extensive stretches of arable land and the conventional knowledge transferred from one generation to another, a highly improved irrigation network that comprises both natural inland water resources and man-made reservoirs or tanks, and rainfall distribution patterns are quite conducive to vegetable cultivation. Good agricultural practices improved for centuries, and the immense support given by the government further strengthened vegetable cultivation in Sri Lanka.

Vegetable production is very important for food security in the country, and it plays a leading role in Sri Lanka. After paddy, the vegetable sub-sector is the most prominent in the local agricultural sector. Several vegetable crops are grown for local consumption and export market. The annual vegetable and fruit production is around 900,000 mt. Approximately, 40 different species of vegetables are grown in diverse agro-climatic zones by independent clusters of farmers in the country (de LW Samarasinha *et al.*, 2020). The low temperature (14 °C) of the central hill region is ideal for temperate crops such as carrot, bean, cabbage, leek, beet, salad leaves, cauliflower, salad cucumbers, and bell pepper while the low country with its dry and humid clime is favorable to a variety of tropical vegetables such as pumpkin, cucumber, bitter gourd, snake gourd, chilli, long yard bean, red onion, okra, luffa, brinjal, *etc*.

Leafy vegetables such as *gotukola*, *kangkong*, *mukunuvenna,* spinach, and *Thampala* are well-grown in the intermediate zone. Besides ordinary vegetables, Sri Lanka has various endogenous root and tuber crops such as *Xanthasoma sagittifolium*, under-water tender stems of water lilies (*Nymphea lotus* and *Lasia spinosa*) which are mostly cultivated in the *Maha* season. Immature fruits and pods of perennial tree crops such as jackfruit, June plum (*ambarella)*, breadfruit, and moringa (drumstick) have captured the attention of both local and international consumers. Various research on vegetable cultivation is carried out in Sri Lanka and the research division of the Department of Agriculture (DOA) is the main responsible institution for vegetable research. Agriculture faculties of leading universities, and private sector organizations also contribute towards research and development of vegetable cultivation. The private sector is showing growing interest in engaging in vegetable production, with a broader focus ranging from breeding to improve planting materials to post-harvest adaptations aimed at minimizing waste of fresh produce.

2. Vegetable Cultivation in Sri Lanka

The wide variety of plant components found in vegetable crops helps to provide the essential nutritional needs of the human diet. Vegetables can be eaten raw (in salads), cooked (in curries), or partially processed (in steamed dishes). They can also be served fresh or value-added (dehydrated, canned, pickled, *etc*.). In addition to providing people with essential vitamins (A and C), dietary fiber, potassium, and folic acid, vegetables are also the most affordable and healthiest food option for those who are concerned about their health as well as for communities or areas that are at risk of food insecurity worldwide. Due to the high rates of malnutrition in South Asian and African nations, vegetables are now an essential part of their daily diets. Constant production of vegetables ensures a year-round supply to satisfy the expanding market demand. Vegetable production should be continuously improved with novel technologies and value chains to be assessed and managed for fair trading. Continuous monitoring and adaptation of the novel technology resolve the existing limitations in the production, postharvest handling, and marketing of vegetables.

In the Sri Lankan economy, the contribution of the vegetable subsector is significant. Approximately, 70% of the farmer community depends on vegetable cultivation (Weerakkody and Mawalagedera, 2020). The vegetable sector contributes to enhancing the national income and export revenue, it generates income for farms and provides nutrition to the public. Same as other industries, vegetable production should be increased to meet the needs of the growing population, enhance farmer income, and increase the revenue from exports and the tourism industry. Consumers tend to buy healthy, and quality foods when they receive high income, thus boosting expenses on vegetable consumption. Although the varied agro-climatic conditions prevalent in Sri Lanka allow for the cultivation of a wide variety of vegetables, year-round in different parts of the country, the per capita consumption of vegetables is much lower than the recommended nutritional requirement (200 g/day) (Wanasinghe and Sachitra, 2022). Therefore, it is essential to at least double vegetable production to meet the growing demand and achieve the recommended quantities of vegetables per capita. A comparison of vegetable cultivation area, production, and productivity status is given in **Table 2.1**.

Table 2.1: Comparative statistics on vegetable production in Sri Lanka and certain selected countries with the global average (based on statistics from 2012 to 2016)

Country	**Area (ha x 10^6)**	**% Area Global share**	**Production**		**Productivity (MT/ha)**
			Million MT	**% Global share**	
China	22.700	41.00	513.70	0.10	23.0
USA	10.200	1.80	34.40	3.35	33.6
India	8.260	14.90	119.00	11.60	14.4
Bangladesh	5.330	0.96	4.50	0.40	8.4
Japan	0.380	0.68	9.90	0.96	26.4
Sri Lanka	0.081	0.15	0.92	0.10	11.4
World	55.400	100.00	1026.70	100	18.6

*(**Source:** FAOSTAT, 2017)*

The productivity of vegetable cultivation in Sri Lanka, India and leading countries in the world is given in **Table 2.2**. This information reveals the necessity of further improvements in the vegetable sector to hold the market share at least within the South-Asian countries. The differences in average vegetable productivity between countries areappeared due to various reasons including agronomic and socioeconomic factors. For instance, implementing an irrigation system is essential for achieving high yields. However, agroecological conditions favour vegetable growth and the quality parameters of the same crop grown in different countries.

Table 2.2: Average yield of main vegetable crops cultivated in Sri Lanka

Crop	**Average yield**			**Potential productivity (MT/ha)**	**Maximum productivity reported (MT/ha)**
	Sri Lanka	**India**	**World**		
Tomato	18.9	20.7	33.8	60 – 80	70.5 (USA)
Eggplant	12.8	18.6	26.5	40 – 50	34.7 (Japan)
Okra	11.1	12.0	7.8	15 – 20	17.8 (Jordan)
Cabbage	25.0	22.9	29.4	30 - 40	42.6 (Japan)

*(**Source:** IASRI, 2018)*

In recent decades, arable lands have been declining due to other developments for the growing population, hence the carrying capacity of limited land resources has been exceeded (Gunawardana and Somaratne, 2011). A large variety of vegetables are cultivated in Sri Lanka; however, it is essential to use land without exhausting its capacities. Intensified cropping systems should be determined within the environmental boundaries for efficient utilization of resources such as agricultural inputs, labour, or natural resources (sunlight, soil, and water *etc.*). Identifying crops with their environmental necessities and grouping them to develop cropping systems is required to increase the output of individual crops per land area. For selecting a cropping system, space pre-required by each crop, root system, leave area and antagonistic behaviour of the plant to be taken into account.

Various research and surveys have been conducted in the country by research institutes and universities in the last decades, and by analyzing those data, it would be possible to generate information related to the technological gaps in the vegetable sector which can be bridged through future improvement projects.

3. Vegetable Cultivation Zones

Sri Lanka is divided into three main climatic zones as dry, intermediate, and wet zone. Based on the micro climatic condition these zones are further divided into 46 Aro-ecological regions. All these zones are suitable for growing certain types of vegetables (**Figure 2.1**).

Various types of up-country vegetables are grown in Nuwara-Eliya and Badulla districts. Among them, in Nuwara Eliya, two-thirds of agricultural operations take place while the rest are in Badulla district. Vegetables are grown in these districts throughout the year, with several growing cycles per year. **Figure 2.2** shows the distribution of vegetable growing operations during *Maha* season of 2017.

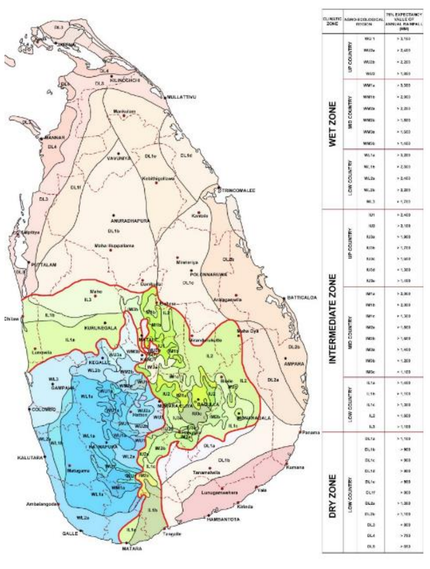

Figure 2.1: Agroecological regions in Sri Lanka
*(**Source:** doa.gov.lk)*

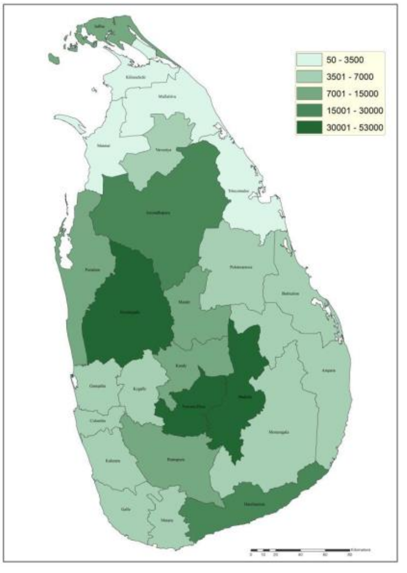

Figure 2.2: Vegetable operations by district
*(**Source:** doa.gov.lk)*

3.1. Vegetable Cropping System

Various vegetable cropping systems exist in different locations in the country; in ancient Sri Lanka, vegetables were produced through mixed cropping systems, cultivated around the house (Home gardening), *Ovita* cultivation, '*Koratuwa*' gardens and chena cultivations, in which vegetables were produced for domestic consumption or exchanged with neighbours. However, these traditional cropping systems were changed into market-oriented production systems during the colonial era when livelihoods expanded, and they were quickly diversified during the 20th century. In Sri Lanka, conventional farming techniques are currently becoming less common, and commercial croplands produce most of the the country's vegetables.

The following discusses some vegetable cultivation strategies, the considerably large-scale vegetable crop cultivation for commercial purposes, (a) continuous cultivation in the up-country with rainfed or irrigated systems and (b) rice-based seasonal vegetable cultivations mostly in the low country, which is again segregated based on the water supply as Mahaweli main irrigation, regional main reservoir irrigation, rainfed or agro-well cultivation. Both up country and low-country vegetable cultivation are exhausted at present due to the high cost of production and lack of labour, and the soil health is deteriorating of vegetable lands with high usage of agrochemicals. Even though traditional vegetable cropping shows low productivity, commercial or "conventional" cultivation is unsustainable in the long run, despite their yield volumes and yield quality advantages (Weerakkody *et al.*, 2000; Suriyagoda *et al.*, 2012).

3.2. Open-field Intensive Commercial Vegetable Cultivation

There are two main methods for cultivating vegetables in Sri Lanka: (a) seasonally growing rice-based vegetables at lower elevations; and (b) continuous vegetable production on muddy terrain at high altitudes (Nuwara Eliya and Badulla districts) (Perera, 1990). Together, these two systems, which are found in the Uva Province (UP) and Central Province (CP), produce 45% of the vegetables produced in the country.

Leek (*Allium ampeloprasum*), cabbage (*Brassica oleracea*), carrot (*Daucus carota*), beet (*Beta vulgaris*), radish (*Raphanus raphanistrum* subsp. sativus), knol khol (*Brassica oleracea* var. gongylodes), and lettuce (*Lactuca sativa*) are the most grown vegetables in upcountry regions. These are not native crops, but they yield a lot. Therefore, each year, synthetic chemical fertilizers, and insecticides, as well as hybrid seeds, must be imported. Continuous uses of synthetic agriculture chemicals cause higher environmental risk. Furthermore, the application of heavy dosages of pesticides with a high frequency expecting overprotection for the crop and increasing the profit-making yields which lead to relentless deterioration of soil in the cropping lands. Farming in small land extents (0.2–0.4 ha) in hilly areas under year-round cultivation tends to soil erosion by rain and wind, causing intimidation to water availability. Thus, the primary challenge in Sri Lankan vegetable farming is the economic viability of traditional cropping patterns (Suriyagoda *et al.*, 2012).

In rice-based vegetable cultivation, paddy is cultivated in the *Maha* season from October to February and vegetables are cultivated during the *Yala* season from March to September. Based on the water availability, such cropping system is mostly practiced by the large-scale growers in the dry and intermediate climatic zones. Most of the tropical vegetables are cultivated during the *Yala* season (Weerakkody *et al.*, 2000).

This is the second largest vegetable cultivation in the country and comparatively less usage of agro-inputs, income and productivity is lower than upcountry vegetable cultivation. In addition, a unique vegetable cropping system at Kalpitiya area in Puttalam district, the Northwestern Province similar to the intensive commercial cultivation in up-country and heavily depends on external inputs. In Kalpitiya, supply year-round production with groundwater supply from shallow wells scattered in the area. However, safety measures should be taken to prevent any environmental issues that may occur due to the over-utilization of groundwater in this area (Aheeyar *et al.,* 2016).

3.3. Home Gardening

Home gardens make an extensive contribution to the national vegetable production in Sri Lanka. Approximately, 1.42 million home gardens are present with a land extent of around 76,483 ha (Weerakkody and Mawalagedera, 2020). Home gardens play a crucial role in maintaining a range of crop types and genetic resources of vegetables while beautifying the environment.

Home gardening is an ideal system to provide fresh and uncontaminated vegetables to the kitchen at home. Most of the home gardens practice eco-friendly farming without using inorganic fertilizers or agrochemicals, hence the yield is healthy and safe. Further, household wastes and gardening wastes are used for home gardening as fertilizer which minimizes the cost of production. Home gardening comprises a broad range of crops such as seasonal, biannual, and perennial, which further expands as big trees, bushes, shrubs, creepers, and ground cover crops based on the space availability and climatic conditions. For example, jackfruit (*Artocarpus heterophyllus*), *ambarella* (*spondias dulcis*) and breadfruit (*Artocarpus altilis*) are mostly found in the Wet Zone (WZ) or/and Intermediate Zone (IZ). Drumstick (*Moringa olifera*), mango (*Mangifera indica*), ash plantain (*Musa* sp.) and *kathuru-murunga (Sesbania glandiflora*) are commonly grown in the Dry Zone (DZ).

Home garden is not considered the main income of the household; crops are selected based on the time availability of the family. Traditional vegetable varieties are inherently adapted to adversarial environmental conditions, and they are resistant to pests and diseases thus, are favorable to be cultivated. Vegetable production from the home garden fulfills the household needs and the surplus is sold or shared among neighbours. Apart from, providing a balanced diet, home gardens beautify the microenvironment while providing a therapeutic feeling to the people around them and conserve indigenous vegetable crop varieties. There is a huge potential to improve the home gardening systems in the country using smart agriculture tools such as polytunnels, irrigation systems, effective recycling of home and garden wastes and solar energy. Further, space utilization can be expanded via vertical gardening, rooftop cultivation and indoor gardening.

3.4. Peri-Urban Vegetable Cultivation

Peri-urban vegetable cultivation is practiced when the space is very limited, and utilize alternative spaces such as plots, balconies, rooftop and containers. Mostly, poor, and landless city dwellers are engaged with urban cultivation, intensive cultivation in small size plots makes effective use of limited resources such as water and land.

Peri-urban describes the farmland units near the town area, which produce mostly leafy vegetables called (*keerakotu*), operating as semi or fully commercial units to provide fresh leaves to the urban and semi-urban consumers. The shelf life of leafy vegetables is very short due to continuous dehydration and loose acceptability. As peri-urban cultivation is close to the market it helps reduce post-harvest losses while maintaining consumer preference.

3.5. Organic Vegetable Cultivation

There is a growing demand for foodstuffs free from pesticide residues. According to available records in 2006, there were a total of 3,301 registered organic farms in Sri Lanka (Weerakkody and Mawalagedera, 2020). Vegetables are also considered one of the main food products under organic cultivation in the country. Many people are willing to buy vegetables cultivated with low use of agrochemicals. This method is described as organic or environmentally friendly farming in which neither chemical pesticides nor inorganic fertilizers are allowed to be used, this system is culturally sensitive, and sustainable but an efficient management system is required to make it economically viable and maintain productivity.

During the past decades, experienced farmers in the country have established organic farmer associations, particularly in the Wet Zone, to obtain the benefits of supplying organic vegetable products to the export market. In addition to that, various other farmer groups and individuals practice organic vegetable cultivation. Most of the organic vegetable production is exported to Europe and other countries. Even though organic vegetable farming's productivity is comparatively low, farmers gain a high income due to the low cost of production and premier market price for organic vegetables.

3.6. Protected Culture and Soil-less Culture

Protected cultures and soil-less cultures were introduced to the Sri Lakan vegetable sector in the 1990s. It has gradually become popular among farmers throughout the country. About 62% of vegetable-growing protected culture units are single span, small (100–200 m^2), these culture houses are made of soft plastic tunnels with an insect-proof net cover to protect from insects, and ventilation is controlled naturally or by air fans.

Protected culture units found in Sri Lanka, are mostly manual or semi-automated, and only a few units are available with fully automated. However, basic greenhouse technologies such as water supply (drip or sprinkles), media (soil culture, hydroponics or aeroponic), panting materials (hybrid local or imported), and complete fertilizers (fertigation), practices are almost similar among growers within the country. Due to the intensive care of protected culture, yield is higher, and less exposure to pests and diseases leads to improved vegetable quality than outdoor cropping systems. Therefore, these products capture premium prices in local and export markets (Weerakkody, 2004).

Although local vegetable productivity per unit area is comparatively lower than the global main producers (150–450 MT/ha) such as Mexico, USA, and Canada, (Padilla-Bernal *et al.*, 2010) still there is a niche for Sri Lankan vegetables in the world market. Protected culture is practiced in Kandy, Matale, Nuwara Eliya, and Badulla districts, spreading among other areas for vegetable cultivation. A range of vegetables are cultivated in closed houses such as bell pepper, scotch bonnet, hot pepper (Muria F1), salad/green cucumber (*Cucumis sativus*) and tomato, meanwhile, lettuce is cultivated in circulation-type hydroponics without solid media. There are various economic benefits associated with this method. In addition to vegetable production, the closed house is used for vegetable seed production (Kumara *et al.*, 2015).

4. Vegetable Production and Consumption

4.1. Annual Vegetable Production

In Sri Lanka, vegetable cultivation covered 61,000 ha and yielded 705,000 mt. The vegetables categories that are cultivated in the country are given in **Table 2.3**. Sri Lanka has indigenous yam varieties which can be categorized under vegetables, that are underutilized and well-grown in mid and dry zones. These crops are well adapted to local weather conditions, easily grown with the least input and care, even under harsh conditions and resistance against pests and diseases is higher than other crops. Local yams carry other benefits than nutritional value such as medicinal value, functional properties *etc.* Demand for these yam types is higher in local and international markets, hence farmers gain higher profit with the least investment. Department of Agriculture and universities pay special research attention to indigenous yams these days due to their unique economic benefits and trying to popularize traditional yam varieties and encouraging farmers for large-scale yam cultivation in Sri Lanka.

Table 2.3: Categorization of the vegetables grown in Sri Lanka

Category	Examples
Root and Tubers	Beetroot, Carrot, Kohila, Manioc, Potato, Radish, Sweet potato, and Lotus roots
Fruity Vegetables	Ash plantain, Breadfruit, Jackfruit, Tender jackfruit, and Tomato
Leafy Vegetables	Agati Leaves, Amaranth Leaves, Cabbage, *Gotukola*, *Kangkung* / Water Spinach, Lettuce, Mint, Spinach
Bulb and Stem	Garlic, Knol kohl, Leeks, Lemongrass, Onion
Legumes and Grains	Beans, Black gram, Chickpeas, Corn, Drumstick, Fenugreek, Green grams (Mung beans), Yard long beans (*Mae karal)*, Lentils, Okra, Soybean
Gourds	Ash pumpkin, Bitter gourd, Bottle gourd, Brinjal, Cucumber, Ridge Gourd, Pumpkin, Snake gourd, Thai Eggplant
Chilies	Capsicum, Chillies, Green chillies, Red chillies, Bird chilli (locally known as *Kochchi*), Bell Pepper
Edible Fungi, flowers, and nuts which are considered as vegetables	Artichoke, Cauliflower, Mushroom, Peanut, Banana blossom

*(**Source:** doa.gov.lk)*

Yam varieties in Sri Lanka show higher nutritional values and unique taste, some are even considered superfoods. Currently, more than 55 indigenous yam varieties are grown in various locations in Sri Lanka. Table 2.4 lists examples of the most popular underutilized root and tubers, including yams, among farmers and consumers.

Table 2.4: Indigenous root and tubers cultivated in Sri Lanka

Botanical Name	Local Name
Dioscorea pentaphylla	*Katuala*
Dioscorea alata	*Rajala* and *Angili ala*
Dioscorea esculenta	*Kukulala*
Canna edulis	*Buthsarana*
Amorphophallus campanulatus	*Kidharam*
Maranta arundinacea	*Heen ala* or Arrowroot
Xanthosoma sagittifolium	*Kiri ala*

4.2. Vegetable Market and Consumption

4.2.1. Local consumption

Local vegetable consumption is reported as 180.55 g/day/person; however, it varies in different societies, in urban areas people consume more vegetable (165.89 g/day/person) than rural areas (108.38 g/day/person) (Udari *et al.*, 2021). Vegetable intake is confined along with three meals in a day (Jayawardena *et al.*, 2020). A study revealed that the young community in Sri Lanka consumes vegetable in very low qualities, the mean vegetable consumption per day was 267 g which is far below the recommended quantity for the age group (Perera and Madhujith, 2012).

4.2.2. Exportation

The vegetable exportation is gradually increasing due to high demand worldwide for fresh and processed vegetables. Sri Lanka exports vegetables to the main commercial hubs in the world; among them, 65% of fresh products are exported to the Middle East and Maldives (Dissanayake et al., 2022). Nearly 90% of processed vegetable products are moving to European countries. United Arab Emirates, Maldives, Saudi Arabia, Qatar, India, Germany, the United Kingdom, Kuwait, and Pakistan are the top vegetable importing countries from Sri Lanka (EDB, 2019). Exporters ensure high-quality vegetables are obtained in our country by adhering to Good Agriculture Practices (GAP). In crops cultivated in polytunnels, pests and diseases are well controlled, and post-harvest handling and sophisticated packaging, and international standard transportation methods are practiced.

According to the United Nations COMTRADE database on international trade, Sri Lanka imported edible vegetables, certain roots, and tubers with a value of USD 351.91 million in 2023. Sri Lanka plays a leading role in the Maldives' vegetable import market holding nearly 20% of the market share (Syed, 2015).

5. Challenges

Vegetable cultivation faces multiple challenges regardless of the size of the cultivation and the type of crop as shown in **Figure 2.3**. A holistic approach with the participation of the Government and private sector, farmers and vegetable processors, traders, and exporters are required to mitigate those issues (Nuskiya, 2019).

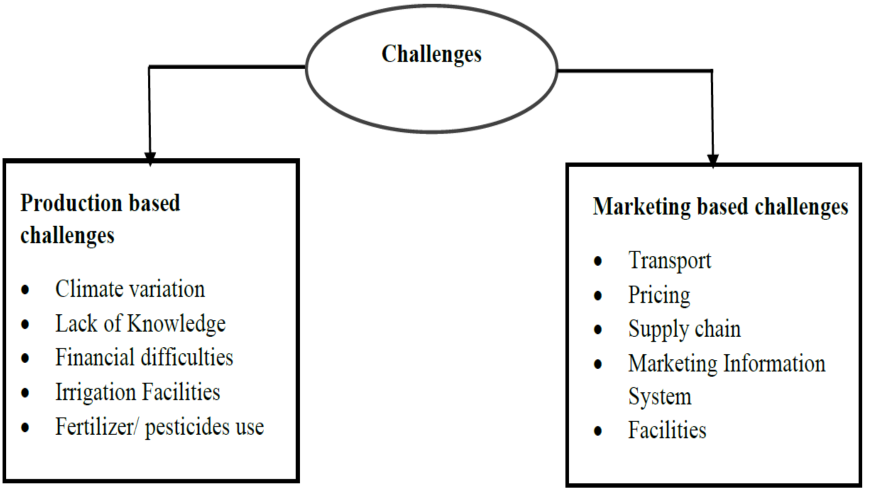

Figure 2.3: Challenges in vegetable production and marketing

4.3. Challenges in Vegetable Production

5.1.1. Climate Change

Climate change has become a serious threat to global crop cultivation including Sri Lanka. Consequently, both the intensity and the frequency of natural disasters have increased in recent years. Common natural disasters that affect agriculture are drought, heat, flood, pest and disease infestation, and cyclones. According to the national statistics in 2010 – 2014, most of the *Grama Seva* divisions (GS division) in the country have undergone natural disasters (**Table 2.5**). Out of total GS divisions, drought in 5517, flood in 4503, pest and diseases in 748, Cyclone in 1496 and wildlife attacks in 3607 were recorded. Hence, extreme weather conditions negatively influence vegetable production, productivity, and the farmers' livelihood in the country.

Table 2.5: Natural disasters occurred in Sri Lanka

District	Drought	Flood	Pest	Cyclone	Wild animals	Others
Colombo	10	181	13	32	62	43
Gampaha	42	353	28	72	62	41
Kalutara	80	379	33	124	46	125
Kandy	327	45	35	55	505	272
Matale	232	89	40	29	197	111
Nuwara Eliya	112	65	19	108	137	168
Galle	212	303	13	245	130	40
Matara	112	150	51	193	188	85
Hambantota	325	182	123	79	270	29
Jaffna	249	98	14	43	24	28
Mana	117	102	6	8	28	5
Vavuniya	97	84	1	17	41	0
Mullaitivu	116	98	3	9	35	9
Kilinochchi	78	51	2	1	6	7
Batticaloa	224	329	14	14	63	4
Ampara	259	379	42	27	142	15
Trincomalee	156	154	9	24	64	4
Kurunegala	1015	346	95	69	404	69
Puttalam	253	208	31	51	73	23
Anuradhapura	583	425	39	47	299	13
Polonnaruwa	207	183	27	25	143	8
Badulla	269	50	60	84	320	194
Monaragala	248	25	20	57	109	8
Rathnapura	104	158	12	59	93	80
Kegalle	90	66	18	24	166	89
Total	5517	4503	748	1496	3607	1470

*(**Source:** Dananjaya & Wijeratne, 2017)*

5.1.2. Scarcity of Agricultural Inputs

COVID-19 pandemic critically affected global trading and limited the importation of main agricultural inputs for vegetable production such as agrochemicals (fertilizer, pesticides, insecticides, growth promoters *etc*.), planting materials and other equipment (irrigation kits and closed-house equipment). Farmers engage in vegetable cultivation with severe uncertainty due to the unavailability of inputs under local scenario. Agrochemicals and vegetable seeds are supplied through importation. The importation was affected by the COVID-19 pandemic situation followed by the economic crisis of the country which affected crop production. Consequently, the poor growth of the crops finally affected crop production, productivity, and the farmers' income.

Financial Problems

Uncertainty in the agriculture sector persists due to bad weather conditions, pest and disease infestations, and market price fluctuations. These factors can reduce farmers' income, and in some cases, farmers may struggle to repay bank loans and face numerous problems.

Shortage of Work Force

Most of the farm operations such as land preparation, weeding, fertilizer and pesticide application and harvesting are done by human labour. Timely manpower is essential in vegetable cultivation; shortages of workers can significantly impact daily operations. The availability of skilled workers is gradually decreasing, while the demand for daily wages is increasing. The younger generation is not interested in working in agriculture fields. Consequently, the daily wage rates are Rs. 1,200–1,500 for men and Rs. 800–900 for women. (Samaraweera *et al.,* 2022). Lack experienced workers reduces productivity and the quality of the harvest.

Lack of New Technology

Introduction and adaptation of novel technology is the main drive that influences the productivity of vegetable cultivation. Modern technologies are not adequately used for tilling, cultivating, and harvesting. These time-consuming activities are mostly done by workers. However, many new technologies are used for water management in the field established crops nowadays. Field-level techniques to evaluate water availability and water requirements are yet to be introduced, hence, currently water management is ineffective. Traditional farmers who lack knowledge are often reluctant to use new methods for vegetable cultivation, which could significantly impact crop production. Land area per farmer is comparatively small; therefore, using machinery or equipment does not significantly influence productivity and profit. Additionally, they often cultivate on sloppy or uneven land where machinery cannot be easily used.

5.1.3. Poor Farmer Education

According to the agriculture household survey in 2017, the estimated number of households engaged in agriculture is 2.1 million, and the estimated population is 8.1 million. Among these farmers, 4% did not attend school at all. The majority (46%) of farmers attended school up to grade 10. Farmers who passed O/L and A/L were 17% and 12%, respectively. Degree or above level education was obtained only by 3% of farmers (Mahindarathne and Min, 2019) (**Figure 2.4**).

Farmer education has a huge influence in terms of agriculture modernization. Introducing novel techniques, machineries, and procedures is essential for improving productivity. With the majority of uneducated farmers, it is very difficult to change their cultivation pattern and understand the technical aspects of soil health, environmental safety, postharvest practices, and good agriculture practices (GAP). Hence, they are following low-productive traditional farming methods.

5.2. Challenges in Vegetable Marketing

5.2.1. Price Fluctuation and Trading

The cost of agricultural inputs is gradually rising, which influences the farmgate price of vegetables. However, farmers have very limited bargaining power due to various factors, such as the perishable nature of produce, poor transport facilities, lack of market knowledge, and the large number of farmers cultivating the same crop at the same time. The quality of products is determined by the health of the crop; well-grown crops produce better quality vegetables and gain higher market prices. On the other hand, unhealthy crop produces comparatively low-quality vegetables which will be marketed at a lower rate. The quality of the product influences the price fluctuation in the vegetable market.

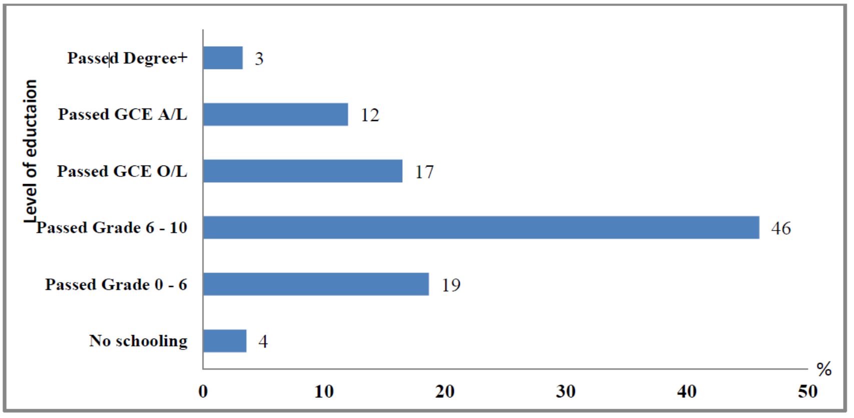

Figure 2.4: Percentage distribution of agriculture household population by level of education
*(**Source:** www.statistics.gov.lk)*

5.2.2. Poor Transport and Storage Facilities

Mode of transport, transport duration and exposure to harsh conditions during transport directly influence the quality, shelf life and consumer preference of fresh vegetables. Farmlands are located far from the road, and farmers must manually carry vegetables in bags to the roadside for transportation to commercial hubs. This results in high labor costs and excessive handling of vegetables. Especially in the upcountry, vegetables are cultivated on steep slopes, making it difficult to use vehicles for transportation. Fresh produce trading occurs in regional economic hubs such as Dambulla, Nuwara Eliya, and Kalpitiya. However, the transportation of vegetables to these centers by lorries or other means is not standardized to protect them from heat, sunlight, and physical damage. Therefore, the average estimated postharvest loss ranges from 30% to 40%.

5.2.3. Supply Chain

There is a significant difference among farmgate, wholesale, and retail prices. If the market information reaches all parties engaged in the value chain (growers, traders, and consumers) in time, vegetable prices will be controlled. Facilitating to approach market information would be helpful to minimize the price games in the supply chain. In addition, farmers face various other issues such as,

- the absence of competition in terms of collecting vegetables in remote areas results in the dominance of the private collectors and determines the vegetable price.
- due to poor financial support, farmers are heavily indebted to private vegetable collectors, hence farmers face difficulties in seeking alternative markets.

5. Recommendations and Way Forward

The agriculture system in the country is dependent on imported agro-inputs (inorganic fertilizer, chemical pesticides, and most of the seeding materials), hence agriculture productivity and total operations are severely influenced by the dollar rate and global economic and political crisis. It is essential to implement a holistic approach to the development of the vegetable sector in the country, with affordable and local technologies to be developed in seed/planting materials production, plant nutrients management, crop protection and water management.

5.1. Seed and/or Planting Materials

Up-country vegetable cultivation is heavily dependent on imported seeds, especially for cool-season vegetable species, as on average, 90% of the seeds of up-country vegetables are imported. In 2017, 197,348 kg of seed were imported (SCS (2018). Among up-country vegetables, beans, radish, and tomato seeds are produced locally. About 62, 200 kg of seeds for low-country vegetables were imported in 2017, accounting for 66% of the total seed requirement of the low-country (SCS (2018). Breeders face difficulties in developing upcountry vegetable seeds due to lack of favorable climatic conditions such as long days and/or low-temperature conditions, which are essential for the seed production of cabbage carrot, lettuce, leek, and beet.

Attention should be given to the seed production of these crops under the modified atmospheric conditions to gain independence for vegetable cultivation. Research evidence is available for stimulating flower induction of these crop species using plant growth regulators (hormones), under specific environmental conditions, however, research efforts to experience such techniques are not adequate locally. Only a few research has achieved successful results in local research stations such as flower induction in beet; (Kumuduni *et al.*, 2013), extended pollination period for seed production (Fonseka *et al.*, 2010), improved seed quality by fruit thinning and canopy management *etc.* (Fonseka *et al.*, 2013; Sooriyapathirana *et al.*, 2013.

Simultaneously, seed production, packaging materials, storage facilities and testing technologies are to be developed to maintain viability. Farmers are reluctant to buy locally produced seeds due to various quality issues, such as poor germination, damaged seeds, and lack of uniformity. Therefore, the seed system needs to be strengthened.

5.2. Field-Level Water Management

Vegetable cultivation requires comparatively more water and a continuous water supply to minimize drought stress. However, due to a lack of awareness, farmers apply more water than required, leading to significant water wastage. Currently, well-developed irrigation methods are available in the world, boom, center pivot irrigation, sprinkler and drip irrigation are some of them, and used in closed houses and open fields. In addition, plastic mulching (reusable or biodegradable) is used to reduce water evaporation from the soil surface.

Establishing an intensive irrigation system is cost-effective hence, the farmer should be trained to use field-level low-cost water conservation techniques such as mulching, cover cropping etc. Drain water systems are to be implemented simultaneously to protect crops from excess water due to unexpected rain. Hydroponics is a successful alternative strategy for vegetable cultivation in fast-diminishing arable lands in the country where vegetables can be grown without soil, plant nutrient is well managed, and precision agriculture can be employed for promising output.

Recommendations for hydroponics conditions such as fertilizer dosage, pH, and electrical conductivity (EC) are given only for several crops such as tomato, bell peppers, green cucumber, and lettuce. Hydroponic systems can be employed for many other crops and optimize the yield hence it is necessary to develop guidelines through research.

5.3. Plant Nutrition

Synthetic fertilizer is heavily used in vegetable fields to increase crop productivity. However, long-term usage of synthetic fertilizer causes deterioration of soil, damages the ecosystem, and contaminates water bodies. Therefore, most countries such as Europe, China, Korea, and Japan, reduced the usage of synthetic fertilizer per unit cropping area. To mitigate such harmful effects of plant nutrients, novel innovations are to be introduced such as pellets, granulated fertilizer formulation, and slow-release or controlled-release formulation. Integrated plant nutrient systems (IPNS), crop-specific and site-specific fertilizer application methods, and eco-friendly or sustainable fertilizer management are novel-approaches in vegetable cultivation.

Local and international demand for organic vegetables has gradually increased. Due to the limited developments and numerous problems, organic farming is not popular among the farmers. A few research have been conducted on the use of green manure to produce compost, biochar, and bio-fertilizers, (Egodawatta *et al.*, 2012; Herath *et al.*, 2015; Rajapakse *et al.*, 2016). However, there is no sufficient research outcomes to deliver a full solution for the agricultural system in the country. It is necessary to introduce a hybrid mode to use a combination of inorganic and organic materials to provide plant nutrients.

As a result, various organic fertilizer amendments and some products have reached the commercial level. Fish tonic, fruit tonic and vermicompost are examples of comparatively high-efficacy organic fertilizer formulations. Apart from that, there are organic agriculture practices introduced by other countries such as bokashi in Japan, and nature farming in Korea. National agriculture extension service to be strengthened to introduce such viable techniques for local vegetable cultivation. With a strong policy framework, the private sector should be encouraged to engage with eco-friendly fertilizer production locally. Exhibitions, demonstration plots and model vegetable gardens should be established for training purposes through which farmers will build confidence and interest in eco-friendly farming. Commercial-scale indoor vegetable production systems in the polytunnels and partially controlled greenhouses are emerging due to various advantages in high-valued vegetable production among which the protection of the crop from pests and diseases, and wild animals.

5.4. Plant Protection

Hybrid or improved vegetable varieties are highly susceptible to pests and diseases. Genetic improvement of crops concerned the yield quality and productivity, resulting in the varieties showing less resistance to pests and diseases. Even though, user recommendations have been given based on scientific studies, overuse, and misuse of chemical pesticides by farmers have extensively been informed in vegetable lands in Sri Lanka, which leads to environmental and human health hazards. Several studies in rice-based vegetable cultivation in the dry zone reported that up to 23.4 kg/ha of pesticides were used, which is much higher than the recommendation (Jayakody & Munkittrick 2011).

In vegetable cultivation, predominantly (85.5%) use fungicides (Hadji *et al.*, 2017). Even though environmentally friendly pest and disease control strategies such as natural enemies, integrated pest management (IPM), insect traps, and crop rotation, are popular in the world however, local farmers are not well adapted to them (Jayasooriya and Aheeyar 2016; Dharmasena *et al.*, 2017).

Many studies have proven the damage caused by chemical pesticides to the environment and public health, leading to increased attention to alternative plant protection techniques, such as green plant protection. Various integrated pest management techniques are used in global agriculture. Introducing such techniques to local farmers brings advantages. Introducing natural enemies is another alternative for pest control which is commercially practiced in China. There is a range of natural enemies that have been identified in Sri Lanka. Conducting more research on those insects and their pest control efficacy will provide information on low-cost pest control methods. Various research has been conducted on bio-pest control around the world and discovered successful applications. Leaf extracts are promising pest repellants and various products are introduced to the market, countries such as India and Korea commercially produce for crop protection.

5.5. Value Addition and Product Development

Due to the monsoon agriculture pattern in Sri Lanka, high vegetable volumes reach the market in the peak season, which creates a price reduction and completion on preference, as perishable products, vegetables should be sold out before losing commercial value. Therefore, producers and trading arms face a high risk in the vegetable business. During the off-peak period, low volumes of vegetables reach the market, leading to higher prices. This scenario started from farmgate to end-retail sellers in town and difficult to control price fluctuations. As a solution, encourage small and medium-sized enterprises (SMEs) to focus on product development using excess vegetables from the peak season. For example, pumpkins can be used to produce infant food and spreads, while cassava can be used for sago production.

6. Conclusions

The extension service should organize continuous community training programs and awareness programs among the farmers to uplift the knowledge on proper fertilizing methods and pesticide usage. Department of Agriculture, universities and private sector institutes are to be encouraged to plan and conduct long, medium, and short-term research at the field level which leads to understanding the actual problem in the field and buildup farmer confidence in novel innovation. Agro-input companies allocate large budgets for product promotion and dealer conventions, companies should be encouraged to invest in farmer training for the safe use of agro-chemicals and fertilizer. Mass media and TV programmes should broadcast the effective use of agro-chemicals to aware farmers continuously. Make research investments and policy changes that emphasize the development of pesticides and application technologies that reduce health risks and are compatible with ecologically based pest management. Universities and research stations, and private organizations together could organize seminars/ conferences to disseminate knowledge among scientists and the farmer community.

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Chapter Three

Agritourism for Rural Empowerment

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Abstract

Agritourism has emerged as a vital strategy for fostering rural development in Sri Lanka, providing sustainable means to address economic and social challenges in rural communities. This chapter explores the potential of agritourism as a tool for rural empowerment by integrating agriculture with tourism, thereby generating alternative income streams and opportunities for communities, and promoting environmental conservation. It discussed how agritourism initiatives enhance rural livelihoods, preserve cultural heritage, and promote sustainable agricultural practices. It also highlights the key challenges, including inadequate infrastructure, marketing limitations, and lack of policy support, which hinder the sector's growth. The chapter concludes with recommendations for fostering agritourism as a driver of rural development, calling for collaborative efforts from the government, private sector, and local communities with appropriate policy interventions. Agritourism holds immense potential to revitalize Sri Lanka's rural economy, empowering local communities, particularly women, and contributing to long-term sustainable development on par with Sri Lanka's development goals.

Keywords: Agritourism, Development, Empowerment, Rural

1. Introduction to Agritourism

Agritourism, also known as agrotourism, although has no accepted definition, is a form of tourism that involves visitors participating in agricultural activities or experiencing rural life. It is a blend of agriculture and tourism, where tourists visit farms, ranches, vineyards, or rural areas to learn about and engage in various agricultural activities. Rural tourism and farm-tourism are often used interchangeably with agritourism (Roberts and Hall, 2001). Agritourism offers visitors a chance to experience and understand agricultural practices, traditions, and rural culture first-hand. It provides an opportunity to connect with nature, learn about sustainable farming methods, and appreciate the food production process. The activities offered in agritourism can vary depending on the location and type of agricultural operations involved. Sznajder and Przezbórska (2004) categorize agritourism products and services as; Farm accommodation, Farm catering, Participatory agritourism, Farm retailing, Therapy at the farm, Holidaying in a farm and Farm entertainment.

Common Agritourism activities include:

- *Farm tours:* Visitors can explore working farms, observe farming operations, and learn about different crops, livestock, and agricultural techniques.
- *Harvesting and picking:* Tourists can participate in activities such as fruit picking, and vegetable harvesting depending on the season and location.
- *Animal interactions:* Visitors may have the chance to interact with farm animals, such as feeding, milking cows, herding sheep, and cattle.
- *Food-related experiences:* Agritourism often includes experiences like cooking classes, food tastings, cheese and curd making, or baking using farm-fresh ingredients.
- *Farm stays:* Some agritourism destinations offer accommodation on working farms, allowing visitors to experience rural life by staying overnight or for a few days.
- *Festivals and events:* Agricultural festivals, fairs, and events are organized to showcase local traditions, celebrate harvests, or highlight specific agricultural products.

Agritourism not only benefits tourists by providing educational and recreational experiences but also supports local economies, promotes sustainable agriculture, and helps preserve rural communities and traditions. It allows farmers to diversify their income sources by opening their farms to visitors and selling farm products directly to consumers. Additionally, agritourism can contribute to raising awareness about sustainable farming practices, local food systems, and environmental conservation. Agritourism includes a wide range of activities such as on-farm sales of agricultural products, education to entertainment (Schilling *et al.*, 2012).

2. Agritourism potentials in rural Sri Lanka

Agritourism in Sri Lanka is gaining popularity as the country's agricultural sector is a significant part of its economy and cultural heritage. Sri Lanka's diverse climate and fertile land allow for a wide range of agricultural activities and experiences that attract tourists. There are diverse range of agritourism opportunities in Sri Lanka. Sri Lanka is famous for its tea production, and visiting tea plantations is a popular agritourism activity. The central highlands, particularly Nuwara Eliya and Ella, offer breath taking landscapes dotted with tea estates. Visitors can tour the plantations, learn about the tea-making process, and even participate in tea plucking and processing. Spice gardens are also a trending Agritourism opportunity within the country. Sri Lanka is known as the "Spice Island" due to its abundant spice production. Many spice gardens across the country, such as in Kandy and Matale could offer tours where visitors can explore the gardens, learn about various spices like cinnamon, cardamom, and cloves, and understand their cultivation and medicinal properties. It can also offer an educational and sensory experience for local and foreign tourists, providing insights into Sri Lanka's spice heritage, cultural traditions, and medicinal practices. Exploring these gardens allows visitors to appreciate the country's diverse flora and gain a deeper understanding of the importance of spices in Sri Lankan cuisine and traditional medicine.

Considering the fruit orchards, Sri Lanka boasts a wide variety of tropical fruits, including mangoes, pineapples, papayas, and bananas. Agritourism activities often include visits to fruit orchards where visitors can taste fresh fruits, learn about cultivation techniques, and sometimes even participate in fruit picking. The Jaffna district in the

Northern part of Sri Lanka is famous for its mango orchards. The region's warm climate is ideal for mango cultivation, and visitors can explore mango farms, learn about different mango varieties, and enjoy the unique flavors of Jaffna mangoes.

Strawberry farms in Nuwara Eliya are popular destinations where visitors can explore strawberry farms and enjoy strawberry picking experiences. These farms also cultivate other fruits such as blueberries and raspberries.

Paddy farming can be enhanced as an agritourism opportunity in rural Sri Lanka since rice is the staple food in Sri Lanka, and visiting paddy fields provides a unique opportunity to learn about paddy cultivation. Some Agritourism initiatives allow visitors to experience the process of traditional paddy farming, from planting to harvesting, and gain insights into the importance of rice in Sri Lankan cuisine. Central, Uva and Sothern provinces are popular locations for agritourism in the country.

In addition, there are several organic farms in Sri Lanka that promote sustainable agriculture practices. Visitors can explore these farms, learn about organic farming techniques, and even participate in activities like composting, planting, and harvesting organic produce. It's a chance to understand the importance of sustainable agriculture and taste fresh, chemical-free food. Tourists can also participate in activities like garden walks, nature photography, and farm-to-table dining experiences.

Sri Lanka has a growing dairy industry, and some farms in Nuwaraeliya District already offer agritourism experiences related to milk production. Visitors can learn about dairy farming practices, witness milking processes, and sometimes even participate in activities like feeding and taking care of cows. These are just a few examples of agritourism experiences available in Sri Lanka. The country's rich agricultural heritage, coupled with its scenic beauty, makes it an ideal destination for those seeking a closer connection to nature and rural life.

3. Agritourism and Local Economic Development

3.1. Opportunities and Reversing Rural Outmigration

Agritourism can play a significant role in local economic development by providing opportunities for rural communities to diversify their income sources to generate additional income. Sri Lankan rural setting should consider more deeply on agricultural festivals that celebrate the local farming culture, harvest seasons, or specific crops. These festivals can feature activities like agricultural exhibits, live demonstrations, traditional music and dance performances, and local food stalls. They offer a festive atmosphere and a chance for visitors to immerse themselves in rural traditions. Rural crafts and artisanal products are also a significant way to generate income through creating new livelihoods for the rural young generation. Showcase traditional crafts and artisanal products that are unique to rural areas could create a better market among foreign visitors. This can include pottery, weaving, basket making, woodworking, and other handicrafts. Visitors can observe artisans at work, try their hand at creating crafts, and purchase locally made products. Developing educational programs and workshops that educate visitors about sustainable farming practices, conservation efforts, and environmental stewardship is another opportunity to uplift the rural economy based on agritourism. This can include workshops on composting, beekeeping, or sustainable agriculture techniques. These programs promote knowledge sharing and create awareness about responsible farming practices. This will lead to food security in rural areas due to the sustainable agricultural practices in villages along with additional income through tourism.

To maximize the potential of agritourism in reversing rural outmigration, it is essential to invest in supportive policies, infrastructure, marketing efforts, and training programs. Collaboration between local governments, tourism agencies, community organizations, and farmers is crucial to create a sustainable agritourism ecosystem that benefits both visitors and rural residents. Reversing rural outmigration through agritourism requires strategic planning and implementation of various measures. Address any challenges related to agritourism, such as environmental sustainability, preservation of natural resources, and the potential impact on local communities.

Develop guidelines and regulations to ensure responsible and sustainable tourism practices. Encourage the adoption of sustainable farming methods and educate visitors about the importance of preserving the rural environment and culture. Continuously monitor and evaluate the impact of agritourism initiatives on reversing rural outmigration is essential. Assess the economic, social, and environmental benefits and make necessary adjustments to optimize the outcomes. Collect feedback from visitors and residents to improve the quality of the agritourism experience and address any concerns. Outmigration can be reduced by enhancing community involvement and providing ownership. Involve local communities in the planning, development, and management of agritourism initiatives is crucial.

Encourage community ownership of tourism projects, fostering a sense of pride and responsibility. Engaging communities ensures that tourism benefits are distributed more equitably and that residents have a stake in the success of the industry. By implementing these steps, rural areas can leverage the potential of agritourism to attract visitors, create economic opportunities, and reverse the trend of outmigration by offering a compelling and sustainable rural lifestyle.

3.2. Community Involvement and Development

Community involvement is essential for the successful development of agritourism. Engaging the local community ensures that the tourism initiatives are sustainable, culturally sensitive, and economically beneficial to the residents. There are many ways to involve the community in agritourism development. Community consultation is a major focus during this process. It initiates open and inclusive dialogue with the local community to understand their needs, aspirations, and concerns regarding agritourism development. Hold community meetings, workshops, or surveys to gather input and involve community members in decision-making processes.

Capacity-building is also crucial since it provides training and capacity-building programs to empower community members with the skills and knowledge needed to participate in and benefit from agritourism. This can include training in hospitality, customer service, marketing, entrepreneurship, sustainable farming practices, and cultural preservation. Encouraging and supporting local entrepreneurship by helping community members establish their own agritourism businesses is a key step in rural economic development. Provide assistance with business planning, marketing, access to finance, and other resources necessary for successful entrepreneurship. This enables community members to take ownership of tourism activities and create livelihood opportunities.

Cultural preservation is essential when doing modifications with agritourism in rural settings which involve showcasing their cultural heritages to the visitors. It should encourage the participation of local artisans, performers, and cultural organizations in providing authentic cultural experiences to visitors. This promotes cultural pride, preserves traditions, and generates income for local artists. Developing community-based tourism initiatives that directly involve the income generation of local community is also an important aspect in here. This can include homestays, community-managed accommodations, guided tours led by community members, and the sale of locally produced crafts and products. Revenue generated from these activities should flow back into the community, supporting local development and improving quality of life. Engaging the community in environmental conservation efforts related to agritourism is known as environmental stewardship in agritourism.

Promoting sustainable farming practices, waste management, energy efficiency, and biodiversity conservation are considered here. Encourage the community to take responsibility for preserving the natural resources that attract tourists and contribute to the long-term sustainability of agritourism and the rural economy. Encourage community members to share their knowledge, stories, and personal experiences related to local agriculture and heritage. This can be done through guided tours, storytelling sessions, or interpretive signage. Engaging the community as storytellers enriches the visitor experience and deepens their understanding of the local culture.

Collaborative networks facilitate collaboration and networking among community members, tourism organizations, local government, and other stakeholders. This can include forming community-based tourism associations, cooperatives, or committees to collectively address challenges, share resources, and promote the tourism destination. Collaboration strengthens the community's voice, improves coordination, and fosters mutual support. Involving the community in agritourism development can create a sense of ownership and pride, ensure the preservation of cultural and environmental assets, and generate economic benefits that directly benefit the local community. It is crucial to foster ongoing communication and engagement, allowing the community to have a meaningful role in shaping and benefiting from the agritourism initiatives.

4. Farmer Motivation for Agritourism

Agritourism has gained popularity in recent years as people seek more authentic and immersive experiences related to food production, rural lifestyles, and sustainable farming practices. Farmer motivation for engaging in agritourism can be attributed to several key factors as described below.

Agritourism provides farmers with an additional stream of income, helping to stabilize their financial situation. By opening their farms to tourists, farmers can generate revenue through various activities such as farm tours, farm stays, workshops, and on-site sales of farm products. Many farmers have a strong attachment to their land, its history, and the traditional ways of farming. Engaging in agritourism allows them to share their knowledge, skills, and cultural heritage with visitors, promoting a sense of pride and preserving the rural way of life. It also helps to create awareness about the importance of sustainable agricultural practices and the challenges faced by farmers.

Agritourism provides a platform for farmers to educate the public, particularly urban dwellers, about the agricultural industry, food production processes, and the challenges faced by farmers. Through interactive experiences such as picking fruits, milking cows, or participating in hands-on workshops, visitors gain a deeper understanding of where their food comes from, the hard work involved, and the importance of supporting local agriculture.

Agritourism activities often attract residents as well as tourists. By opening their farms to the public, farmers create opportunities for social interaction, fostering a sense of community. This can lead to strong relationships between farmers and visitors and collaborations with local businesses, tourism organizations, and other farmers, strengthening the rural economy. Further, agritourism offers farmers the chance to directly market their products to consumers. By showcasing the quality and freshness of their produce, farmers can establish a loyal customer base, increase brand recognition, and potentially create value-added products. This direct connection with customers can also lead to valuable feedback and insights into consumer preferences, helping farmers adapt their farming practices to meet market demands.

For many farmers, agritourism is a way to share their passion for farming with others. It allows them to connect with people who appreciate and value the hard work and dedication required to sustain a successful farm. The positive feedback and appreciation received from visitors can be personally fulfilling and reinforce their commitment to farming.

5. Developing an Agritourism Product, Marketing and Promotion

Developing an agritourism product involves creating a unique and attractive experience for visitors that showcases the agricultural aspects of a farm or rural area. Marketing and promotion play a crucial role in attracting potential tourists and creating awareness about the agritourism offering. First, we should identify the farm's strengths, resources, and activities that the farm can offer to visitors. This could include agricultural practices, farm animals, crops, natural landscapes, or specific cultural aspects. For example, a farm known for its organic vegetable production could develop a farm-to-table experience where visitors learn about sustainable farming and enjoy freshly harvested meals.

Then it is important to define the target audience or the specific group of people you want to attract to your agritourism products. This could be families, school groups, nature enthusiasts, or food lovers. Understanding the target audience will help tailor the experience and promotional efforts accordingly. For instance, a farm with extensive trails and wildlife habitats might target outdoor enthusiasts and nature lovers. Next, it is vital to create an agritourism experience that aligns with the farm's strengths and target audience. This could include farm tours, workshops, pick-your-own experiences, or seasonal events like harvest festivals. The goal is to offer an immersive and educational experience that connects visitors to the farm's agricultural heritage.

Then we should identify the most effective marketing channels and tactics to reach the target audience. This could involve a combination of online and offline strategies. Utilize digital marketing tools like a social media platform, and online travel platforms (i.e., YouTube Channel) to showcase the agritourism products. Offline strategies could include partnerships with local tourism organizations, distributing brochures at visitor centers, or participating in agricultural fairs and events. It also needs to understand the importance of developing visually appealing brochures, flyers, videos, and photographs that highlight the unique experiences and attractions of the agritourism products.

We can use storytelling techniques to convey the farm's history, values, and the benefits of visiting. High-quality visuals showcasing farm activities, scenic landscapes, and happy visitors can attract attention and generate interest. It is also can be considered to incorporate testimonials and reviews from previous visitors to build credibility while engaging with the community through local businesses, tourism organizations, and community groups to create synergistic partnerships. This can include cross-promotions, joint events, or offering special packages that combine agritourism experiences with other local attractions.

Further special promotions and packages can be offered as incentives to attract visitors, such as discounted rates for groups, seasonal offers, or package deals that combine multiple activities. This encourages visitors to stay longer, participate in more activities, and increases the perceived value of the agritourism experience. For instance, a farm offering farm stays might offer a discounted rate for families staying for a week during the summer.

In the end, successful marketing and promotion of an agritourism product require continuous feedback from visitors through reviews and surveys to identify areas of improvement and implement necessary changes. This helps in maintaining visitor satisfaction and enhancing the overall experience.

6. Challenges and Effective Approaches to Agritourism Implementation and Development

Implementing and developing agritourism can present certain challenges that need to be addressed to ensure its successful implementation. Many farms may lack the necessary infrastructure and facilities to accommodate tourists. This could include amenities such as visitor centers, restrooms, parking areas, or accommodation options. Effective approaches to address this challenge involve identifying the specific needs of visitors and gradually developing the required infrastructure based on priority. Collaboration with local authorities, tourism organizations, or seeking funding opportunities can help in improving the farm's infrastructure.

Agritourism activities may involve compliance with various regulations and permits related to health and safety, land use, food handling, and insurance. It is essential to thoroughly understand the legal requirements and ensure compliance. Engaging with local authorities, consulting legal experts, and establishing proper risk management strategies can help navigate the regulatory landscape. Promoting and marketing agritourism products can be challenging, particularly for small-scale farmers with limited resources and marketing expertise. Effective approaches include utilizing digital marketing tools such as websites, social media, and online travel platforms to reach a wider audience. Collaborating with local tourism organizations, participating in agricultural fairs and events, and developing partnerships with other local businesses can also enhance marketing efforts.

Some farms may face challenges related to seasonality, with peak tourist seasons and low periods. This can impact revenue generation and operational sustainability. Effective approaches involve diversifying the agritourism offerings to include activities that can be conducted year-round, such as indoor workshops or farm-to-table dining experiences. Additionally, implementing sustainable practices, such as minimizing environmental impact, promoting local culture and heritage, and involving the local community, can enhance the long-term sustainability of agritourism. Providing an engaging and educational visitor experience is crucial for the success of agritourism. Challenges may include maintaining visitor interest, managing large crowds, and ensuring the quality and authenticity of the experience. Effective approaches include offering interactive activities, guided tours, and hands-on workshops that allow visitors to actively participate and learn. Training staff members to deliver informative and engaging presentations, and incorporating visitor feedback into improving the experience, can help enhance the overall visitor satisfaction.

Establishing and maintaining agritourism operations can require significant investments in terms of infrastructure development, marketing, staff training, and maintenance. It is essential to carefully assess the financial viability of agritourism ventures and develop a robust business plan. Conducting market research, identifying potential revenue streams, and seeking financial support through grants, loans, or partnerships can help ensure a positive return on investment. Building positive relationships with the local community is crucial for the long-term success of agritourism. However, some communities may have concerns about increased traffic, noise, or environmental impact. Effective approaches involve open and transparent communication with the local community, addressing their concerns, and actively involving them in the development and promotion of agritourism. Engaging in community events, supporting local businesses, and sharing economic benefits with the community can foster support and collaboration.

By addressing these challenges and implementing effective approaches, agritourism can be successfully developed and implemented, providing economic opportunities for farmers, preserving rural heritage, educating visitors, and creating memorable experiences.

7. Agritourism and Capacity Building

Agritourism gives producers an opportunity to generate additional income and an avenue for direct marketing to tourist consumers. It enhances the tourism industry by increasing the volume of visitors to an area and the length of their stay.

Particularly in rural regions, tourism could amplify the voices of women. A country can profit economically, socially, and environmentally from tourism. In marketing and media initiatives related to tourism development, men are frequently given an advantage (Bungau *et al.,* 2015). Men frequently took control when women began tourism firms, reducing women's responsibilities and participation over time. Traditional gender norms and expectations have been reinforced by tourism, particularly those that pertain to women performing household duties while taking care of visitors. Tourism is still regarded as a little step toward empowering women (Muresan *et al.,* 2016). Women who would not otherwise be able to work outside the home are given employment opportunities by tourism, which enables them to support their families financially and lessens their reliance on men.

The growth of tourism encourages the empowerment of women, which raises their self-esteem, independence, and capacity to make decisions for their households in areas where conventional gender roles still exist, such as rural or indigenous ones (Calina, 2017). It is essential because women manage household finances more effectively than men do, meeting the needs of every family member.

Women can profit from tourism, and it encourages women's empowerment and change their roles in households and communities. The empowerment of women and their new positions might result in new behaviors that can have both beneficial and harmful effects too.

Economic empowerment relates to a community member’s ability to be employed and generate income and to ensure that the income comes from reliable sources.

Additional considerations are related to the distribution of economic benefits across the community given that power structures may constrain benefit distribution. Psychological empowerment refers to community members' perception and attitudinal aspects. For instance, a psychologically empowered individual is self-reliant and independent, whereas a psychologically disempowered individual is apathetic and submissive. In some communities, tourism facilitates the creation of social development through projects which strengthen community unity.

8. Agricultural Production and Improving Productivity Through Agritourism

Creating a connection between agriculture and tourism could be a huge opportunity for the development of the nation. Agritourism is a viable solution for many development issues, including low agricultural productivity, high food imports, lost tourism income, bad public health, and youth unemployment.

Sri Lankans rely on agriculture for a large portion of their income. At the moment, Sri Lanka is experiencing a severe foreign currency crisis. When tourists visit, a sizable percentage of the money they bring in is immediately spent on buying goods, food, and beverages from the local market. During their visit to the country, tourists spend a major portion of their money on lodging, with food and drink coming in second. By selling some agricultural products to visitors in addition to the aforementioned items, local farmers may have a great chance of improving the living standards of their communities.

Visitors would prefer to eat foods they are accustomed to. Food items purchased from local farmers' farms can be cooked by locals during homestays or by teaching innovatively thinking chefs for how to make regional specialties for hotel menus. By connecting an app to farmers and chefs, a digital solution has been applied in Haiti State. Even in Sri Lanka, tourism should be developed to connect farm gates and chefs to create delectable meals for visitors.

Quality and certification are additional concerns for farmers who want to sell their products to the tourist industry. By adhering to food standards and receiving certification, the European Union supports the growth of farmers' ability to connect to value chains. So that our farmers' output can be enhanced to reach quality requirements to satisfy tourist demand. Then, by inviting visitors to their farms, farmers can interact with the tourist market directly. Tourists are eager to spend more for authentic local cuisine, fresh produce, and sustainability.

Investing in agritourism can have a positive impact beyond the economic stimulus from interacting directly with tourists. Linking agriculture and tourism is the best way to overcome rural poverty (Harvey, 2010). In addition, the tourism element creates new jobs on farms in tour-guiding, social media linking, and business development, calling on young people's online and language skills.

Agritourism's potential contribution to health, jobs, and local economies and environment is clear. But how do we get there? Government intervention in tourism development is essential. Private public partnering in tourism development should be encouraged and linking rural communities to the tourism industry should be guided by the partnership.

9. Entrepreneurship Development and Empowering Local Community

Agritourism creates a win-win situation for the local community and visitors. Tourists have all the fun and benefits of natural foods and pristine nature for very little money, chemical-free diets, and a quiet break from their jobs. Farmers can supplement their primary income by working part-time and using readily available local resources. Through various activities, other local groups will be able to supplement their income, tour operators will gain access to new locations and customers, and unidentified farmers and villagers will gain recognition for their vocation and village.

Further, it has the potential to generate employment, reduce dependence on agriculture as the primary source of employment, provide an alternative to the primary income as well as the alternate market for local produce, and empower women. In such ways, agritourism generates value additions for rural lives.

Agritourism supports local people to learn in many ways. It may be formal learning as well as informal learning opportunities through socialization. Agritourism is a diversification in the economic activity that takes place when travel is linked by people with agricultural products, services, or experiences. Social developments will occur due to socialization through tourist activities.

Agritourism creates a good opportunity for farmers to operate agritourism as a niche market. Further, it has been found that the social skills of farm-based entrepreneurs, farm aesthetics, and proximity of farms to urban centers are enhanced via Agritourism.

Twenty-four districts in Sri Lanka experience various climatic conditions. It has a variety of agro-climatic conditions suited for raising various kinds of animals and crops. Agriculture dominates Sri Lanka's economy because it is a predominantly agricultural nation. Agritourism can be developed using a variety of crops, mostly plantation crops like tea, rubber and coconut plantations and horticultural farms. In the upcountry, where tea is grown, the climate is particularly hospitable, with low temperatures and stunning scenery. Its stunning natural surroundings are the main draw for travelers. These are Sri Lanka's agritourism destinations.

Sri Lanka has a long history of success in the tourism and hospitality sectors. By fusing the nation's tourism and agriculture sectors, there is a significant opportunity for the growth of the agritourism sector (Malkanthi, 2013). The success of such endeavors should need the combined efforts of all stakeholders, including farmers, local villagers and district administrations, the agriculture department, and the tourism department. Simple access, a comfortable stay, cleanliness, good food, security, and medical services are just a few requirements for any tourism business to be appealing. Therefore, Sri Lanka is rich in these untouched natural areas and natural beauty that can draw tourists for the benefit of the nation. It has not yet attained its real value.

10. Infrastructure and Policies in The Agritourism Industry

Policy development is necessary to improve Sri Lanka's agritourism sector. To ensure that tourists have a positive experience when visiting our nation, there should be clear norms and regulations that are adhered to. In order to provide them with tranquil, secure, and comfortable rural amenities, strong national restrictions are necessary. Providing them with a secure and safe place to stay while visiting the nation and the neighborhood should be guaranteed to boost tourism.

When dealing with tourists, it's crucial to practice diplomacy and ethical principles. Our infrastructure amenities need to be adequate and kept up to draw more tourists from other destinations. Infrastructure is crucial to this industry because tourists have busy schedules in their visits.

11. Conclusion

Agritourism has emerged as a dynamic and promising avenue for advancing rural development in Sri Lanka. Agritourism empowers communities through creation of new economic opportunities while preserving the cultural and environmental assets of rural Sri Lanka. Agritourism enables farmers to diversify their income sources, reducing dependence on conventional farming alone, which is often subject to market and climate risks. This diversification fosters economic resilience and enhances livelihoods in rural areas, particularly in areas where agricultural profitability has declined.

However, the potential of agritourism in Sri Lanka is yet to be fully realized. While some regions have embraced the concept, others face challenges such as lack of infrastructure, insufficient marketing strategies, and limited access to resources. Addressing these issues requires a multi-stakeholder approach that includes government support, private investment, and community participation. Policies that promote agritourism through training, financial incentives, and marketing initiatives are key in unlocking the full potential of this sector.

In conclusion, agritourism can act as a catalyst for rural empowerment in Sri Lanka by creating employment, preserving culture, environmental conservation and fostering sustainable agricultural practices in par with Sri Lanka's development goals. With appropriate policy interventions, infrastructure development, and capacity-building efforts, agritourism can transform rural areas into vibrant economic hubs while ensuring the well-being and empowerment of local communities.

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Chapter Four

Revitalizing the Floriculture Sector in Sri Lanka

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Abstract

Sri Lanka entered the international floriculture market several decades ago. However, the floricultural sector has experienced stagnation due to the negative effects of the COVID-19 pandemic, followed by the economic crisis, the influence of import restrictions, and the policy decision banning the use of agrochemicals. Despite these challenges, floriculture exports are now showing an overall growth trend. This sector has the potential to become a significant income-generating venture for Sri Lanka. In this chapter, we review the status of the floriculture industry in Sri Lanka, considering its strengths, weaknesses, challenges, and potential. We aim to compile and provide essential information to help revitalize the sector. For years, foreign exchange earned through the foliage sector has dominated the globally prominent cut flower sector in Sri Lanka. However, new sectors such as floriculture seeds and aquatic plants have emerged as potential areas for further development, showing continuous growth over cut flowers. The future of Sri Lanka's floriculture industry could be shaped by embracing innovation, sustainability, market expansion, and diversification, particularly through global collaboration and trade. Establishing an authority solely responsible for floriculture research, development, and marketing is a timely necessity. Establishing an authority solely responsible for floriculture research, development, and marketing is a timely necessity. By focusing on these strategies, the floriculture industry could be revitalized to

achieve sustainable growth, resilience, and continued success.

Keywords: Cut flowers, Export, Floriculture industry, Foliage

1. Introduction

Floriculture, a branch of horticulture, is a dynamic and diverse sector that encompasses various components, from production to marketing to design. It includes the cultivation of flowering and ornamental plants for the floral industry, gardens, and raw materials for industries. Further, it offers entrepreneurial opportunities for small, medium, and large-scale farmers to earn additional income and foreign exchange. The floriculture sector serves multiple markets and plays a significant role in enhancing environmental beauty and economic growth.

The floriculture industry is considered one of the highest-growing industries worldwide, hence a high-income generating agribusiness with the potential to activate self-employment among low and middle-income farmers and earn the essential foreign exchange, particularly in developing countries (Devrani *et al.*, 2023). The global floriculture market was worth around USD 59.25 billion in 2023 and is predicted to grow around USD 107.32 billion by 2032, with a compound annual growth rate (CAGR) of about 6.82% between 2024 and 2032 (Arnold, 2024).

Whereas Sri Lanka's floriculture sector generated USD 15.01 million in export earnings in 2023. Across the globe, the demand for cut flowers is flourishing and holds the largest market share. However, in Sri Lanka, the decorative foliage sector dominates in export earnings.

In this chapter, we review the status of the floriculture industry in Sri Lanka, considering its strengths, drawbacks, challenges, and potential. Our aim is to compile and provide important information to revitalize the floriculture sector following the worldwide COVID-19 pandemic, during which the first case was confirmed in Sri Lanka in 2020. Since then, gradual progress has been made over the past three years. We also make several recommendations to boost the industry in a socially and environmentally responsible manner in the future.

1.1. Components of the Floriculture Sector

The floriculture sector is a diverse and multifaceted industry that encompasses various components. Understanding these components is crucial for improving the industry. The key components of the export-oriented floriculture sector are given below.

- *Cut Flowers:* These are flowers or flower buds that have been cut from the plant for decorative use. Most of the exports are from the temperate cut flowers category, which uses imported hybrid mother plants to produce flowers such as Carnations, Roses, Chrysanthemums, and Lilies. Whereas tropical cut flowers, such as Anthuriums, Orchids, Heliconias, and Ginger, are exported in small quantities.

- *Cut Foliage:* These are obtained from plants grown primarily for their decorative leaves rather than flowers. They are commonly used in interior landscapes, including homes and offices. Tropical foliage includes Ferns, Palms, Dracaenas, Philodendrons, and Cordylines, while temperate foliage includes Conifers, Camellias, and Rhododendrons and include plants such as *Dracaena, Cordyline and Aglaonema.*

- *Potted Plants:* These plants are often sold in pots and can be used for indoor decoration or garden planting such as *Philodendron*, *Dracaena sanderiana*, *Livistona*, *Codiaeum*, *Polyscias*, *Cordyline,* and *Pleomele.*

- *Bedding Plants:* These are young flowering plants sold for planting in flower beds, borders, and some instances in containers, such as Anthurium, Marigold, Begonia, Poinsettia and Christmas cactus.

- *Seeds, Bulbs and Cuttings:* This includes planting material; F1 hybrid flower seeds (Pansy, Marigold, and Begonia) and open-pollinated flower seeds (Scarlet sage, Cockscomb, and Gobe amaranth); bulbs (Lilies, *Agapanthus,* and *Crenum*) and cuttings (*Codiaeum*, *Dracaena,* and *Pleomele*).

- *Tissue-Cultured Plants:* This technique has become popular worldwide as a rapid multiplication technique for valuable genotypes, expeditious release of improved varieties, production of disease-free quality planting materials, and round-the-year production. In Sri Lanka, terrestrial plants (*Epipremnum*, *Excoecaria*, *Gloriosa,* and *Syngonium*) and aquatic plants (*Echinodorus* and *Anubias*) are popularly propagated using tissue culture technique.

- *Aquatic Plants:* Aquatic plants are a rising segment in the floriculture industry in Sri Lanka. Different species of exotic aquatic plants, such as *Echinodorus*, *Anubias*, *Cabomba,* and a few native species such as *Cryptocoryne*, *Lagenandra*, and *Aponogeton*, are propagated and exported.

- *Edible Flowers:* These are blossoms that can be safely consumed and used to add sensory properties to food and to decorate dishes such as Blue butterfly peas, Roses, and *Hibiscus*. This category gained popularity in recent years in Sri Lanka.

1.2. Benefits of Floriculture

Floriculture offers numerous benefits that span economic, cultural, health and environmental dimensions. **Table 4.1** gives some key benefits.

Table 4.1: Benefits of the floriculture industry

Economic benefits	**Health benefits**
• Contributes to the economy through export revenues. • Provides employment opportunities. • Development of related industries: The floriculture industry supports ancillary	• Emotional and psychological well-being: Flowers have a positive impact on mental health, reducing stress, anxiety, and depression. • Enhance feelings of happiness and life satisfaction.

industries such as horticultural equipment, fertilizers, pesticides, and packaging.	• Therapeutic value: Flowers and plants are used in therapeutic practices, including horticultural therapy.
Environmental Benefits • Enhance the beauty of indoor spaces through interior designs. • Improve aesthetics of outdoor landscapes • Promotes urban and rural greening, which enhances air quality, reduces pollution, and supports pollinators and biodiversity.	**Social and Cultural Significance** • As an integral part of many cultural and religious ceremonies, celebrations, and rituals • Community engagement: Flower shows, botanical gardens, *etc.* foster social interaction and community bonding. • Use of floriculture products in traditional medicine.

2. Present Status of the Floriculture Industry in Sri Lanka

The export-oriented floriculture industry started in the 1970s in Sri Lanka (Dhanasekera, 1998). Sri Lanka is currently producing both tropical and temperate flora which have economic importance as cut flowers and foliage for the export market. Moreover, potted plant industry is also having a greater demand both in local and foreign markets. The Netherlands, Japan, the United Arab Emirates, and the United States of America (USA) represent the highest export markets in Europe, Asia, the Middle East, and North America, respectively. Apart from traditional floricultural products such as cut flowers and foliage plants, the seed sector, aquatic plants, and edible flowers have emerged as new components in the sector in recent years.

The Western, Northwestern, and Central provinces in Sri Lanka majorly contribute to the production of cut flowers and foliage for the export industry. The central highlands produce temperate cut flowers, which are highly export-oriented productions, whereas other cut flowers contribute to local requirements as well. The tropical cut flowers and foliage are grown in the Western and Northwestern provinces in Sri Lanka.

Green houses, polytunnels, and net houses are the major protected structures constructed for cultivation of cut flowers and foliage. However, the materials used for the cultivation depend on different categories in the production sector in Sri Lanka, including, small, medium, and large scales. The number of large-scale producers is very few when compared to small and medium-scale producers. Large-scale producers highly contribute to the export market using advanced technology, while medium-scale growers serve to the local and international markets. Small-scale growers usually cater to either one of these two markets, where the contribution to export is comparably low.

Several other regions can offer various opportunities for expanding floricultural production, leveraging Sri Lanka's favourable climatic conditions, soil diversity, and increasing global demand for cut flowers and foliage. Investments in infrastructure, technology, and training for growers can further enhance the country's floricultural sector in Sabaragamuwa, Uva, and Southern provinces.

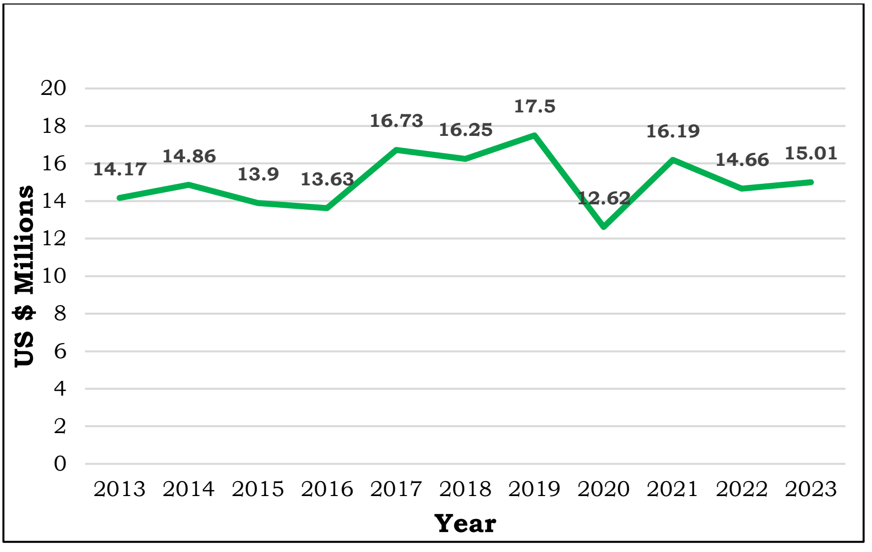

Figure 4.1: Export statistics of floricultural products from 2013 – 2023 (in US $ millions)
*(**Source:** Export Development Board of Sri Lanka, 2023)*

The Export Development Board of Sri Lanka maintains years of data on the export of floricultural products from Sri Lanka, and **Figure 4.1** shows the quantity of production and the earnings through the exportation of floricultural products including foliage, flower seeds, aquatic plants, and cut flowers for the period from 2013 to 2023.

2.1. Export Statistics of Floricultural Products

This data indicates notable fluctuations in export values with a notable drop in 2020; however, the overall trend is slightly positive. In 2013, the export value was $14.17 million, which increased in 2014, indicating growth. However, this was followed by a decline towards 2016. In 2017, there was a significant increase to $16.73 million, suggesting a strong recovery, due to the implementation of effective export strategies or favourable market conditions.

The exports continued to rise, reaching $16.25 million in 2018, and peaking at $17.5 million in 2019, indicating a period of successful market expansion. However, in 2020, the export value plummeted to $12.62 million, influenced by the global economic downturn caused by the COVID-19 pandemic. Following the drop in 2020, a remarkable increase of $16.19 million has been achieved in 2021, reflecting a recovery in the floriculture market. During this period, imports of the product groups that include potted plants have grown, especially those coming directly from developing countries (UN Comtrade, 2023). This global trend could be due to the prolonged lockdown periods extended up to 2021, which drew increased focus towards the potted indoor plants. The value then slightly decreased to $14.66 million in 2022, due to the banning of imports, the economic crisis, and the policy decision of the government in 2021 to completely ban agrochemicals. After the reversal of this policy in 2022, the earnings have increased to $15.01 million in 2023, marking an effort to stabilize the sector while facing challenges. Therefore, floriculture exports show an overall stable pattern despite the negative effects of the pandemic. When considering the contributions of different floricultural products to the exports in 2023, a remarkably high foliage production (92%) was reported (**Figure 4.2**), indicating the potential for expanding foliage production in the country.

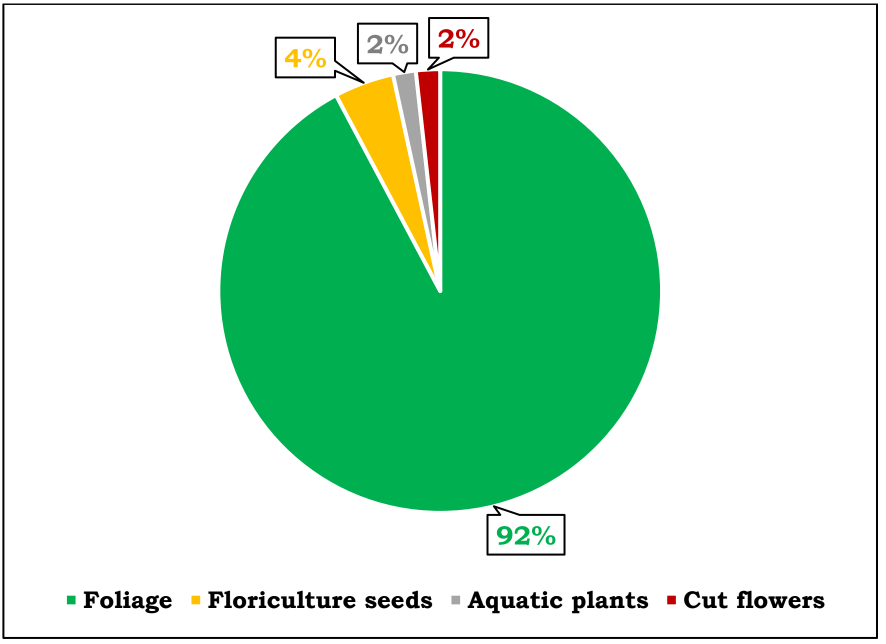

Figure 4.2: Sri Lanka export statistics on quantity of production of major floricultural products in 2023
*(**Source:** Export Development Board of Sri Lanka, 2023)*

The contributions from seed production, aquatic plants, and cut flowers were only 8% of the total production in 2023 (**Figure 4.2**). It is mandatory to enhance the production of other floricultural product categories to diversify the avenues to enhance profits through foreign exchange. **Figure 4.3** shows the contributions of different floricultural products for foreign exchange earned in 2023.

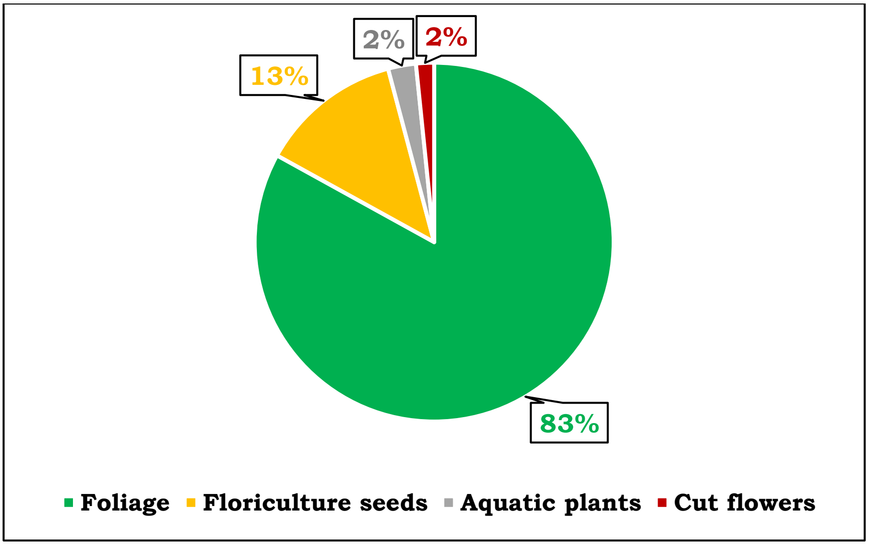

Figure 4.3: Sri Lanka export statistics on foreign exchange earned through floricultural products in 2023
*(**Source:** Export Development Board of Sri Lanka, 2023)*

The highest foreign exchange earned from the exportation was from foliage production, which accounts for 83%, whereas the earnings from aquatic plants and cut flowers were remarkably less (2% from each). The potential for forming a business venture in flower seed production is successful, as it has contributed 13% of the foreign exchange earned in the same year. Some of the reasons for foliage production to be the highest among the other categories are the lower necessity of intensive cultivation practices and high technology during postharvest handling, as well as the involvement of many small and medium-scale growers in foliage production.

In this context, while considering the expansion of other productions, it is essential to find ways to further strengthen the foliage production sector in the country to maintain sustainable production and exportation, ensuring the livelihoods of many stakeholders. Presentation of value-added products from the raw products is another major concern in the floriculture industry. The value-added products can be priced higher, which may help make more profits in return.

2.2. Export Destinations of Floricultural Products

The quality of the products of Sri Lanka has been well-known for years in the global market. There is a strong supply base in Sri Lanka for exporting floricultural products to about 77 different countries including, the USA, Netherlands, Germany, Saudi Arabia, United Kingdom, United Arab Emirates, Kuwait, Qatar, France, Maldives, Australia, and Japan (**Figure 4.4**; Export Development Board, 2024).

Figure 4.4: Export destinations of Sri Lanka for floricultural products
*(**Source:** Export Development Board of Sri Lanka, 2024)*

According to Sri Lanka's export statistics on floricultural products in 2023, the Netherlands is the main importer of foliage products from Sri Lanka, followed by Saudi Arabia and Japan. The Netherlands accounts for the highest importation of cut flowers as well followed by Oman and Japan. Further, Sri Lanka exports aquatic plants to Singapore, Maldives, and the United States, in high quantities. Moreover, large quantities of flower seeds are exported to the United Arab Emirates, Maldives, and the Netherlands (Export Development Board, 2024).

3. Stakeholders of the Floriculture Sector

Many parties contribute to and gain benefits from the floriculture sector in Sri Lanka. Growers, suppliers, retailers, event organizers, florists, exporters, the Department of National Botanic Gardens, the National Plant Quarantine Service, industrial organizations, universities, the tourism industry, and customers are the major stakeholders of the floriculture sector in Sri Lanka **(Figure 4.5)**.

Growers

Growers, as the main type of stakeholders, cultivate floricultural plants, and are responsible for meeting the market demand while maintaining the quality of products. Both the local and export markets are targeted by many growers. They have been engaged in this sector for many years and have found this sector economically profitable. Not only individuals, but small, medium, and large-scale companies have also entered the floriculture industry with well-known products.

Suppliers

Suppliers provide the growers with a better environment to work on by supplying planting materials, especially seeds, fertilizers, pesticides, tools, equipment, and machinery.

Retailers

The marketable products focused towards local distribution are then focused on domestic retailers. They showcase the products in retail outlets and can be easily accessible whenever needed by the people nearby, and purchase orders are also available for occasions such as weddings, religious functions, and many other events.

Event Organisers

The production segmented for local distribution is utilized by event organizers, who organize events as per the requirements of their clients, who need access to both local and international production.

Florists

The requirement of cut flowers and foliage is a necessity for florists as they direct funeral services apart from weddings and other functions. Therefore, there is a need for a continuous supply of cut flowers and foliage for florists, and it creates a promising business venture with them.

Exporters

Most of the products from large-scale and a considerable number of medium-scale growers will supply their products to the international markets where they access the exporters. Logistic facilities are supplied by the exporters along with the facilities for storage of the perishable products. The exporters are involved in exports and imports in the supply chain. They certainly connect the Sri Lankan floriculture industry to the foreign markets. Many growers are involved in direct exportation of their products and have been successful in their businesses.

Earnings through exportations are vital for the country under the context of a challenging economy. Transportation and logistics companies are closely linked to these imports and exports where they provide efficient and safe delivery to different parts of the island in the domestic market and to different destinations across the globe in the international market.

The Department of National Botanic Gardens

The Department of National Botanic Gardens provides the growers with knowledge on cultivation and conducts awareness programmes, workshops, training programmes, and coordinates fairs for the growers to collaborate with each other and facilitates the establishment of grower organizations. Further, they conduct research on agronomy, variety development, and postharvest handling of cut flowers and foliage. The national floriculture development programme 'Suwahas Mal' was initiated in 2005 with the objective of empowering the grower community island-wide. Since then, small-scale growers have been provided with expertise, knowledge, and infrastructure facilities to boost their production (Department of National Botanic Gardens, n.d.).

The National Plant Quarantine Service (NPQS)

The National Plant Quarantine Service provides guidelines for exportation and importation of consignments. By setting the standards for export quality and conducting quarantine activities, they ensure that the products are following local and international regulations.

Export Development Board (EDB)

The Export Development Board of Sri Lanka is a key government institute that facilitates the exportation of floricultural products to various parts of the world. They provide exporters with updated information on exportation, making them an essential resource for growers looking to expand their market reach. The strategic importance of this institution is its significant contribution to boosting the country's economic growth through export earnings.

Sri Lanka Council for Agricultural Research Policy (SLCARP)

SLCARP has established a national committee in the floriculture sector and contributes to funding for research and other programmes and promoting scientific research linkages. An annual symposium is organized by the SLCARP providing a forum to discuss floriculture research.

Industrial Organizations

Industry associations and trade groups are other important parties that provide networking opportunities for industry participants.

Universities

Universities conduct timely research activities related to the floriculture industry where new knowledge is generated to be applied in the practical context in Sri Lanka.

The Tourism Industry

The tourism industry is another major stakeholder that strengthens the Sri Lankan economy with a vast number of floricultural applications such as decorations and events in the hotel industry and setting up tourist attractions which include gardens.

Customers

Customers, as a pivotal group of stakeholders, make the floriculture industry more fruitful by purchasing the end products, including fresh products and value-added products.

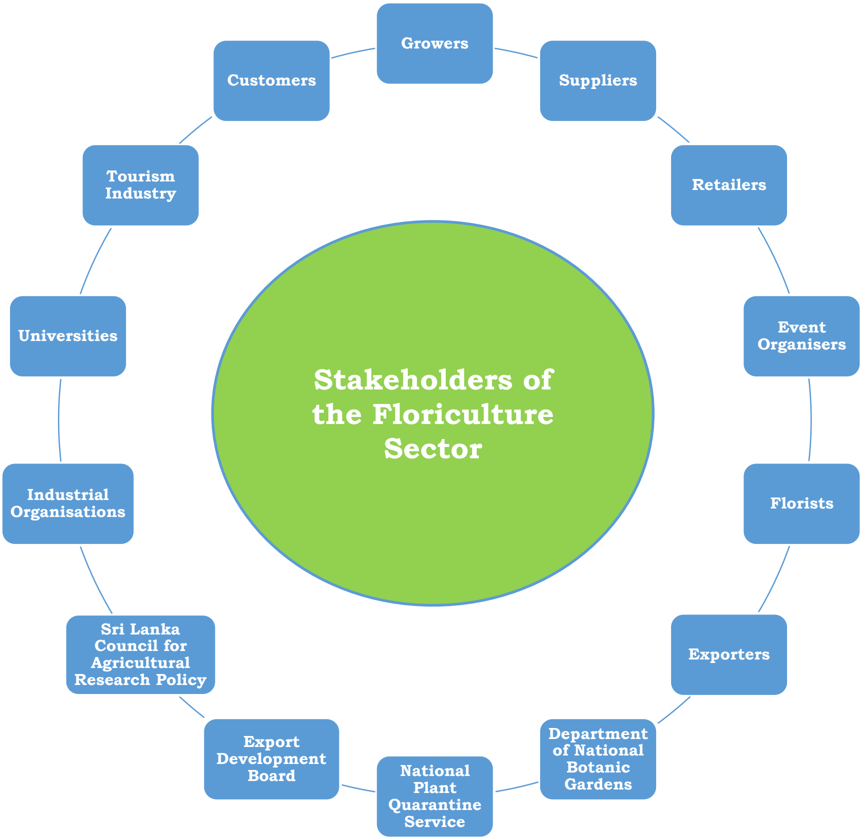

Figure 4.5: Stakeholders of the floriculture sector in Sri Lanka
*(**Source:** Export Development Board of Sri Lanka, 2023)*

4. Strengths of the Industry

The Sri Lankan floriculture industry is striving to move forward amidst many challenges; however, it also has several strengths that can be used in further developing the industry.

Climate

The prevalence of different climatic conditions of the country has been a treasure to the year-round cultivation with a diverse production including temperate to tropical.

Geographical Location

The geographical location of the country on the world map is another great advantage for strengthening the floriculture industry, especially in the international arena. The presence of well-established port facilities in Colombo and other coastal cities, and airports with air cargo facilities support efficient exportation, facilitating the timely delivery to international markets Hence, Sri Lanka has created a gateway to many international markets, such as Europe, the Middle East, and other Asian countries. Efficient distribution of products, cost-effective processes and less transit times are some of its advantages (Export Development Board, 2024).

Quality Certifications

Many growers employ a combination of traditional practices and modern technologies to ensure high-quality production (Fernando, 2021). Moreover, apart from large-scale entrepreneurs, most medium-scale entrepreneurs adopt quality standards so that they can approach European markets. It has captured many buyers from all over the globe for many generations since 1979. Fairtrade certification and Global Good Agricultural Practices (Global GAP) are some of those standards that ensure the quality of products.

Increasing Demand

The trade of Sri Lankan floricultural products has not been underestimated in the international market. The demand for the products has increased ever since not only for the fresh products but also for value additions. Furthermore, the industry is enriched with a diverse variety of flora species, both indigenous and exotic. The Sri Lankan government has also identified the importance of improving and strengthening the floriculture industry and, thereby, has introduced many infrastructure facilities, financial benefits via the bank system, and technical assistance to foster growth and competitiveness (Central Bank of Sri Lanka, 2022).

Value Additions

Floricultural produce is not only for fresh productions but for many other value-added commodities, which can earn more profits per unit of production. The floral petals are used to extract their unique scents which are highly beneficial in perfumery. High-end cosmetic products, including perfumes, lotions, body sprays, serums, and toners are some of the products made from infusion of floral extracts. Many of these extracts are known for their benefits in therapeutic use, especially in Ayurveda. The extraction of essential oils from flower petals is another practice that has many therapeutic advantages including aromatherapy. The food and beverage industry also benefits from garnishing and the production of syrups from floral extracts. Medicinal and herbal products are also produced out of floral resources. Dried flowers are used to create crafts and decorations such as pressed flower art.

Institutional Support

The Department of National Botanic Gardens of Sri Lanka is the pivotal institution for the development of the floriculture industry, which should be recognized as one of the greatest strengths of the industry. Moreover, the Sri Lanka Council for Agriculture Research Policy functions under the purview of the Ministry of Agriculture, Export Development Board of Sri Lanka, Department of Agriculture, National Plant Quarantine Service, and Sri Lanka Customs are some other institutes directly involved in the floriculture industry. These institutes perform a wide range of functions, such as coordination of research activities, policy formulation, providing funds and grants, conducting capacity building activities, dissemination of knowledge and collaborating with international institutions. These institutions play a pivotal role in sustaining and accelerating the growth of Sri Lanka's floriculture industry fostering continuous expansion and increased economic contribution.

5. Drawbacks of the Floriculture Industry

Even though Sri Lanka is identified internationally as a high-quality floriculture production center, the industry's growth has been stagnant due to several constraints and drawbacks.

5.1. Financial Constraints

The major constraint that the growers face is the lack of financial facilities. In Sri Lanka, the farmers involved in the floriculture industry get lesser recognition than those connected to the other sectors of agriculture. As a result, farmers find it difficult to obtain loans and other credit facilities from financial institutions such as banks for the development of floriculture production. This financial constraint has limited the number of farmers entering the industry and forced many to confine their production to the home garden level, which, in turn, negatively impacts the scale of production. However, there is a preference for importing countries for large-scale operations which exacerbates this issue. Floriculture also demands high initial investments in infrastructure, land, and quality plant material, along with advanced technology like automation, which small and medium-scale growers struggle to afford.

5.2. Lack of Novel Products

The floriculture industry is continually changing and developing, relying heavily on new products. However, Sri Lanka has been producing the same plant varieties for many years, diverting the attraction of importing countries to other exporters (Beneragama & Peiris, 2016). Therefore, it is essential to produce novel products to keep up with the ever-evolving global floriculture industry. Currently, Sri Lankans do not hold patent rights for floricultural crops with commercial value in the export market. Addressing this issue through policy reforms and aligning with international intellectual property standards can create a more conducive environment for innovation, investment, and market expansion in the floriculture sector.

5.3. Absence of a Separate Institute for Floriculture

There is a great demand for more research and development of floriculture products. According to the growers, the lack of a separate institute for floriculture research in the country is a major constraint they face. Growers are currently seeking the assistance of universities to handle their problems related to pest and disease management, issues in germination, *etc.*, and they prefer to have a separate institute dedicated to floriculture research (Padmini & Kodagoda, 2017). This also causes the lack of development of new plant varieties via breeding programs. The giants in the floriculture trade, including the Netherlands, Japan, Germany, and Kenya, have achieved sustained success over the years due to their well-structured research and development plans (Rikken, 2011). Although there are several institutions which are supported by the government in the research and development of floricultural products, there is no governmental body to overlook the sales and marketing, except the Export Development Board, which suggests the establishment of a flower council (Beneragama & Peiris, 2016).

5.4. Lack of Studies on Market Analysis

Research on the production channel and marketing is also important to sustain in this competitive industry. The efficiency of the industry can be increased by studying and addressing every level in the production chain. Conducting market research is important to identify emerging trends, reduce the risks, be strategically competitive, and uncover new opportunities for growth.

5.5. Poor Postharvest Knowledge and Practices

Fresh floricultural products are perishable with a limited shelf life hence they must be sold within a short time frame after harvest, often aligning with peak demand periods otherwise delays or mismatches in timing can lead to significant losses. Another major drawback of the floriculture industry is poor post-harvest handling practices except in large and medium-scale businesses. Most farmers still do not use techniques like cool storage and pulsing procedures, which can reduce losses and extend vase life (Hansika *et al.*, 2022). This may be due to several reasons, such as lack of knowledge, limited access to proper facilities such as cold room storage, financial constraints to invest in advanced handling, transport, and storage technologies, and climate and environmental factors. As a result, many small businesses face higher rates of product spoilage and wastage, as well as lower product quality, reducing the market value and customer satisfaction, resulting in financial losses. These challenges make it difficult for small-scale growers to enter larger markets or establish long-term partnerships with customers.

5.6. Lack of Information and Statistics

The lack of availability of information and statistics on floriculture in Sri Lanka causes a competitive disadvantage for the growers due to poor decision-making, inability to identify trends, poor market understanding, and inefficient resource allocation due to lack of information.

5.7. Shortage of Labour

The floriculture industry in Sri Lanka, like in many other countries, faces challenges related to labour. The work in floriculture is physically demanding and involves the exposure of the labourers to harsh environmental conditions. Low wages, lack of job security for workers, seasonality of work, and migration of people to urban areas and foreign countries for better job opportunities, education, and living conditions are the major reasons for the labour shortage.

5.8. Insufficient Land and Negative Impact on the Environment

The expansion of floriculture can lead to conflicts over land use, especially in regions where agricultural land is converted into flower farms, impacting food security and the livelihoods of local communities. Large-scale floriculture ventures often demand significant amounts of water, pesticides, and fertilizers, leading to environmental deterioration such as soil erosion, water pollution, and depletion of natural resources. Excessive use of pesticides and fertilizers in flower cultivation can lead to soil degradation, water contamination, and health hazards for workers and nearby communities.

5.9. Seasonality and Market Fluctuations

The industry is subject to market fluctuations and seasonal demand, which can lead to unstable incomes for farmers and producers. Sri Lanka's floriculture industry heavily relies on export markets, making it vulnerable to international market dynamics, trade regulations, and currency fluctuations. Climate change poses a significant threat to floriculture, as extreme weather events like floods, droughts, and storms can damage crops and infrastructure, leading to production losses and economic instability.

6. Challenges Faced by the Floriculture Industry

High Price of Agrochemicals

This is a major challenge faced by the growers as global fertilizer prices have increased in recent years. The government's recent decision to ban agrochemicals has also caused a significant increase in their prices. Even though the government opted to retract this decision, the impact it left extends beyond the floriculture sector.

High Taxes

The floriculture sector is subjected to various taxes, including import duties on essential inputs like fertilizers and pesticides, as well as export taxes. These high tax rates increase the cost of production. Moving forward with the complex tax regulations can be challenging for growers, especially small and medium-scale enterprises. The corporate tax rate for many sectors, including exports, has been increased to 30% from the previous 14%. This change is part of the government's efforts to boost tax revenue under the International Monetary Fund (IMF) program. The increased tax rate is anticipated to affect the resilience and performance of the export of floriculture products, potentially impacting investments, jobs, and foreign exchange earnings.

Cost and Complexity in Obtaining Quality Certification

Certification systems, such as Global GAP and Fair Trade, are increasingly required to access premium markets such as those in Europe. However, achieving and maintaining these certifications can be challenging. The process of obtaining certification is often complex and costly, involving rigorous standards and regular audits (Niranjan & Gunasena, 2006). The cost of procuring certification has increased over time, which has particularly affected small-scale suppliers. Hence, they tend to target the Middle East markets, where they fetch a comparatively lower return. There is a need for greater awareness and education among growers about the benefits and requirements of certification systems.

Difficulties in Supplying Consistently

Maintaining a continuous and consistent supply of flowers for the export market is difficult due to factors like seasonal variations, weather conditions, and pest infestations. Inadequate infrastructure and logistical challenges can disrupt the supply chain, affecting the timely delivery of flowers to international markets. If the growers do not supply the requirements consistently, the buyers may move to other growers who are capable of continuous supply. In addition, growers find it difficult to manage the fluctuations in demand in the export market. Further, being competitive in the export markets can be challenging for Sri Lanka due to poor quality standards, phytosanitary regulations, and trade barriers.

Irregular Weather Patterns

Sri Lanka's floriculture industry is vulnerable to the effects of climate change, such as irregular rainfall patterns, prolonged droughts, and extreme weather events like floods. These factors can affect production, quality, and availability. However, issues such as water scarcity, soil degradation, and chemical runoff also challenge the industry's sustainability efforts.

Controlling Pests and Diseases

Controlling pests and diseases in flower cultivation is crucial for maintaining quality and quantity. However, the improper use of pesticides can lead to environmental pollution and health hazards. Finding sustainable and effective pest management strategies is a continuous challenge for the industry.

7. Potentials of the Floriculture Industry in Sri Lanka

Rich Biodiversity Enables the Introduction of New Varieties

Sri Lanka's rich biodiversity includes a variety of native flora that are highly adapted to the conditions on the island. These indigenous species can be cultivated and marketed as indigenous varieties, targeting both local and international markets. With increasing global demand for cut flowers and ornamental plants, Sri Lanka can grab competitive advantages in the floriculture industry to become a key player in the international market.

Aquatic Cut Flower Industry

There is an increasing potential for the aquatic cut flower industry in the country as there is an already established market for it locally as well as in Asia. Hence, this industry can be promoted globally by developing new products and varieties, adopting proper postharvest practices, and developing market channels (Yakandawala, 2016).

Government Support

The floriculture industry has been recognized by all recent governments in Sri Lanka as a priority sector for economic development and export promotion (Herath, 2018). Government agencies and research institutions in Sri Lanka are actively involved in studying and improving floriculture practices. This research helps develop new varieties and improve cultivation techniques. The government provides various incentives and support programs for the floriculture industry, including subsidies, training programs, and export facilitation (Atapattu *et al.*, 2023). Government initiatives to promote the floriculture industry through policies, incentives, and infrastructural development can stimulate investment and growth in the sector. The Government of Sri Lanka and non-government organizations provide support to start small and medium-sized businesses to reduce poverty (Padmini, 2016).

Adoption of Technology

Adoption of modern agricultural practices and technologies by the growers, such as greenhouse cultivation, hydroponics, and tissue culture, can enhance productivity, improve quality, and extend the shelf life of flowers enhancing the production as well as the quality of the products (Herath, 2018). Precision agriculture is being increasingly adopted by the floriculture industry, which allows farmers to experience many advantages such as less requirement of resources, increased quality of the products, and minimum human Intervention. Implementing sustainable farming practices, such as organic cultivation and eco-friendly packaging will attract environmentally conscious consumers. The floriculture industry can explore product diversification to create additional revenue streams and enhance competitiveness.

Popularization of Indoor Gardening

The rising popularity of indoor gardening has opened new avenues, especially for foliage and potted plants. The expanded opportunities in the market for foliage and potted plants are driven by urbanization, lifestyle changes, and a growing awareness of environmental sustainability. As more people live in apartments and small homes with limited outdoor space, the demand for indoor plants has increased, transforming them into desirable home decor items that enhance aesthetics and improve air quality. Social media trends and influencers promoting plant care have further fuelled this interest, making indoor gardening a popular hobby. Consequently, nurseries and garden centers have seen increased sales, while entrepreneurs are innovating new plant varieties, decorative pots, and smart gardening tools to cater to this burgeoning market.

Promotion of Floriculture Tourism

The tourism industry in Sri Lanka provides an additional market for the floriculture sector. Floriculture tourism, also known as flower tourism or floral tourism, involves traveling to destinations famous for flower cultivations, flower festivals, and floral displays. This offers a unique and enriching experience for travelers, combining the beauty of flowers with cultural, economic, and environmental benefits.

Flower shows, guided tours for tourists, and engagement of botanical gardens in promotions are some potential means of expanding the industry. This sector continues to grow globally though it is new to Sri Lanka. It provides opportunities for communities to showcase their floral heritage and contribute to sustainable tourism development. This niche tourism sector offers numerous benefits including revenue generation, job creation, and promotion of local products. Apart from flower shows at Nuwara Eliya, only the ‘Diyatha Uyana’ could be considered a major flower market.

7.1. The Way Forward

We are already four years from the onset of the COVID-19 outbreak in Sri Lanka, which caused massive disruption in the global floriculture industry, including Sri Lanka. However, the future of the floriculture industry can be shaped by embracing innovation, sustainability, and new market trends. Here are some key strategies and directions for the way forward to revitalize the floriculture industry.

7.2. Embracing Technology and Innovation

- *Precision agriculture*: Use of advanced technologies like sensors, and IoT to monitor crop health, media conditions, and optimize resource use. This also could address the shortage of skilled labour problem.

- *Genetic improvement*: Investing in breeding programs to develop new varieties with desirable traits and increased resilience, such as unique flower colours or fragrances, growth habits, disease resistance and longer shelf life to compete with the global market. This would pave the path to obtaining patent rights for the new varieties.

7.3. Sustainable Practices

Organic farming: Promoting organic cultivation methods to reduce the use of harmful chemicals and protect the environment.

- *Water, pest, and disease management strategies*: Implementing efficient irrigation systems (drip irrigation and rainwater harvesting) to conserve water and reduce labour. The adoption of integrated pest management and biological control methods to reduce reliance on chemical pesticides.

- *Renewable energy*: Using solar panels and other renewable energy sources to power floriculture operations.

- *Sustainable Certification*: Promoting certification programs for sustainably grown products to attract environmentally conscious markets.

7.4. Market Expansion and Diversification

- *Exploring new markets*: Identifying and targeting emerging

- markets with a growing demand for flowers and ornamental plants.

- *Value-added products*: Developing and marketing unique value-added products such as essential oils, dried flowers, and floral arrangements.

- *Online sales and e-commerce*: Globally, e-commerce in floriculture is growing rapidly, driven by technological advancements, changing consumer behaviours, and the demand for convenience. Hence, expanding online sales channels and e-commerce platforms to reach a wider customer base is important.

7.5. Policy and Support

- *Government Support*: Advocating for government policies that support the floriculture industry through subsidies, grants, microfinance, and research funding.

- *Increase the export of cut flowers*: The government should make efforts to increase the export of cut flowers, which has the highest share in the world market, to enhance global trade in the floricultural sector.

- *Training and education*: Providing training and conducting education programs for farmers and workers to adopt best practices and new technologies.

- *Infrastructure Development*: Improving infrastructure such as cold storage and transportation to facilitate efficient supply chains.

7.6. Global Collaboration and Trade

- *International Partnerships*: Forming partnerships with international floriculture companies and organizations to share knowledge, technology, and best practices.

- *Trade Agreements*: Negotiating favourable trade agreements to facilitate the export of flowers and ornamental plants.

- *Standardization*: Working towards standardizing quality and phytosanitary standards to ensure smooth international trade.

- *Sea freight as a viable alternative to air freight:* The resurgence in interest in sea freight can be considered as a viable alternative to air freight for specific floriculture products that can withstand extended shipping durations without compromising the market value.

- *Concentrating on a monocrop*: Many small and medium-scale companies are engaged in exporting assortments. For medium-scale companies, rather than diversification, concentrating on a single crop at a large scale or a few products could establish a brand name and be profitable, as it can meet the quality standards and continuity in supply.

The floriculture industry is currently grappling with rising costs across all levels due to inflationary pressures on logistics, shortage of freight capacity, and increased energy expenses. Over the past few years, the rise in market prices has not been adequate to offset these heightened costs, jeopardizing profitability and hindering continued investment. Hence, by focusing on the above strategies, the floriculture industry could be revitalized to achieve sustainable growth, resilience, and continued success in the future.

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Chapter Five

Path to Mitigate Climate Change Implications through Adoption of Sustainable Agriculture

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Abstract

Agriculture is most responsible for climate warming, especially in developing countries. Agriculture alone is significantly attributed to global climate change, accounting for about 24% of greenhouse gas (GHG) emissions, the second highest next to the energy sector. Carbon sequestration is a significantly important bio-physiological process as it serves multiple critical functions essential for the sustainability and productivity of agricultural systems. Carbon fixation plays a vital role in the global carbon cycle by removing CO_2 from the atmosphere and storing the carbon inside plant biomass. Considering the negative environmental impacts of commercial-level agriculture, there is a growing concern about practicing sustainable alternatives at the farm level, aiming to develop regenerative agricultural systems, especially to mitigate climate change. Such alternatives include the use of organic farming practices, soil fertility management through nature-based solutions (addition of soil amendments and organic manures), climate-smart agricultural practices, precision agricultural techniques for targeting resource conservation and optimum utilization of resources in correct quantities at the correct time, incorporating agroforestry practices and sustainable forest management within the agricultural land use systems. Adopting these innovative practices can promote sustainable management approaches and integrate climate considerations into land use planning; societies can connect the potential of these sectors to sequester carbon,

conserve biodiversity, minimize GHG emissions, and secure a sustainable future for the next generations.

Keywords: Carbon fixation, Regenerative agriculture, Agroforestry, Sustainable nutrient management

1. Introduction

Industrialization and modern development cause continued increases in greenhouse gas (GHG) emissions, which results in global warming (IPCC, 2007). The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC), the first and ongoing international agreement to stabilize the GHG concentration in the atmosphere, has identified both developed and developing countries have shared responsibility to reduce the CO_2 concentration in the atmosphere to at least 18% below the 1990 baseline year.

The global scenario explains that agriculture practices alone are significantly attributed to global climate change, accounting for about 24% compared with other sources of GHG emissions (Sejian *et al.*, 2015). Agriculture is a significant sector that is responsible for climate warming, especially in developing countries. Agriculture contributes about 25% of GHG emissions in Sri Lanka, equivalent to emissions of 4.7 -10.9 $MtCO_2e$ (Massey & Ulmer, 2008). Most of this is methane released from animal husbandry during enteric fermentation, and nitrogen oxide (NO) is released from nitrogen-based fertilizer application and handling in agriculture. Sri Lanka has a small economy; therefore, the global share of GHG emissions is comparatively lower, remaining at 0.08% at present with expectations of achieving 14.5% emission reduction targets by 2030, focusing on increasing forest cover by 30% and adopting to renewable energy alternatives by 70% (UNDP, 2022). There is also some counterbalance in agriculture that has resulted in increased CO_2 emissions due to LULCC activities. Land use conversions from forest areas to agricultural lands will enhance GHG emissions, while establishing forest plantations and agroforestry farms may hit the trend to vice versa. Therefore, agriculture can be improved into a transformative approach, offsetting carbon in numerous ways.

Agriculture is an essential sector that feeds the current population while coping with the new challenges addressing resource use efficiency, minimum GHG emission, increased water and land productivity, and eco-friendly practices to ensure long-term sustainability within our agri-food systems. Agricultural lands can be transformed into more regenerative agricultural systems, incorporating permaculture features to reduce GHG emissions and manage them as climate-friendly, sustainable land management units. This chapter discusses how our conventional agricultural systems shift into climate-friendly systems by incorporating good practices and eco-friendly farming techniques, increasing carbon storage within the systems, and adopting alternative farming strategies to optimize these concerns. Therefore, the next few sections of this chapter discuss mitigating GHG emissions and climate warming by fixing more carbon within the landscape, particularly the possible involvement of the agriculture and forest sectors in carbon fixation and management.

2. Carbon Sequestration in Agricultural Systems

Carbon sequestration is a significantly important bio-physiological process as it serves multiple critical functions essential for the sustainability and productivity of agricultural systems. Carbon sequestration refers to the process by which atmospheric CO_2 is converted into organic compounds by plants, trees, algae, and certain bacteria (Prajapati *et al.*, 2023). Photosynthesis is a fundamental plant physiological process that contributes to this carbon sequestration, where CO_2 is eventually converted into carbohydrates such as glucose and sucrose using energy from sunlight. Alternatively known as carbon fixation, this process plays a vital role in the global carbon cycle by removing CO_2 from the atmosphere and storing the carbon inside the tree or plant biomass (Satakhun *et al.*, 2019). Such biomass in the main stem, branches, leaves, and reproductive organs of trees will make up the above-ground carbon pool in the agricultural systems.

Moreover, some above-ground carbon partition enters the below-ground carbon reservoir, which exists as soil organic matter. The accumulation of organic matter in the soil occurs through decomposed plant residues and root exudates, helping to improve soil health and fertility (Kowalska *et al.*, 2020). For example, the organic layer or the humus content increases the below-ground carbon pool. Organic content in the soil will enhance soil structure, water retention capacity, and nutrient availability, fostering a conducive environment for plant growth (Chan *et al.*, 2010). This will increase biomass production within the plants and further enhance the above-ground carbon sink.

Agricultural systems have huge potential for carbon fixation and contribute to climate change mitigation efforts by sequestering atmospheric carbon dioxide in both above and below-ground components. This can be used as a carbon offset mechanism to compensate for anthropogenic carbon dioxide emissions. Thus, agri-food systems can be used to mitigate greenhouse gas emissions and mitigate the impacts of global warming. Additionally, carbon-smart agricultural practices that enhance carbon fixation, such as conservation agriculture and agroforestry, improve soil health, crop productivity, and promote resilience to climate change impacts, thereby ensuring the long-term sustainability of agricultural systems. The importance of carbon fixation in agriculture cannot be underestimated, as it underpins the productivity, resilience, and environmental sustainability of farming ecosystems (Udawatta and Jose, 2012).

Agriculture and forestry practices are linked to the carbon cycle via photosynthesis. Higher concentrations of CO_2 can potentially stimulate plant growth, at least under certain conditions, with the potential to increase crop yield. This is called CO_2 fertilization. Factors such as temperature, precipitation, and sunlight availability affect CO_2 fertilization. Land Use Land Cover Change (LULCC), anthropogenic nitrogen deposition, CO_2 fertilization and Net Primary Productivity (NPP) to Leaf Area Index (LAI) ratio drive the terrestrial carbon uptake and storage (Tharammal *et al.*, 2019). When considering agriculture, crop type, cropping system and level of disturbance when implementing agricultural areas also play crucial roles in determining carbon fixation potential in the systems. For example, crop rotation will enhance the quality and quantity of soil organic matter (Venter *et al.*, 2016). The next section explains climate-smart agricultural practices that can reduce GHG emissions on agricultural lands.

3. Climate-Smart Agriculture: Adapting to Climate Change through Good Practices in Agriculture

Conventional fertilizers have long been a staple in modern agriculture, boosting crop yields and ensuring food security for a growing global population. However, their use comes with significant environmental costs, impacting soil health, water quality, and contributing to greenhouse gas emissions (Timsina, 2018). In response to these challenges, adopting climate-smart practices offers significant economic benefits. Improving productivity, enhancing resource efficiency, and reducing climate-related risks help farmers increase crop yields while conserving water and enhancing soil health, leading to more sustainable operations. Additionally, climate-smart farming reduces reliance on conventional fertilizers, accesses green markets, attracts investments, and promotes long-term resilience, contributing to food security, rural livelihoods, and mitigating the financial impacts of climate change.

One of the major environmental concerns associated with conventional fertilizers is their effect on soil health. Continuous application of synthetic fertilizers can lead to soil degradation, reducing soil fertility and negative impacts on soil biology (Jote, 2023). This degradation is often attributed to the loss of soil organic matter content, essential for maintaining soil structure and nutrient cycling processes. Additionally, the overuse of fertilizers can lead to soil acidification, disrupting the balance of soil pH and further impairing its ability to support plant growth and development. Moreover, the production and use of conventional fertilizers are associated with significant greenhouse gas emissions, primarily in the form of nitrous oxide (N_2O) (Walling and Vaneeckhaute, 2020). Nitrous oxide is a potent greenhouse gas with a global warming potential much higher than CO_2. Nitrogen-based fertilizers contribute to N_2O emissions through processes such as nitrification and denitrification in soil. These emissions contribute to climate change and deplete the ozone layer, further exacerbating environmental concerns (Li *et al.*, 2015).

Another significant environmental impact of conventional fertilizers is their contribution to water pollution. When applied to fields, fertilizers can leach into groundwater or runoff into nearby water bodies, carrying excess nutrients such as nitrogen and phosphorus. These nutrients can lead to eutrophication, a process in which water bodies become overly enriched with nutrients, leading to algal blooms, oxygen depletion, and harm to aquatic ecosystems (Savci, 2012). This pollution affects the environment and poses risks to human health, as contaminated water sources can impact drinking water quality.

The above negative impacts can be easily alleviated by reducing the over-application of synthetic fertilizers. Site-specific fertilizer management is the best way to minimize the over-application of N-based fertilizers. Further, to address these issues, many farmers are turning to sustainable alternatives like organic manure, which improves soil health without harmful side effects. Manure management is a broader term than fertilizer management. Manure contains all types of organic, natural fertilizers obtained through the decomposition of plants and animals. The crucial point in manure management is ensuring aerobic conditions during decomposition. Anaerobic decomposition will produce methane (CH_4) and partially decompose the manure, which is economically undesirable. Compost generation is one of the ideal methods in manure management, and to be climate-friendly, the heaps need to be aerated by turning the heap from time to time and adhering to the correct shape of the compost collection heaps. While making compost, the other alternative is to collect the generated CH_4 into gas traps and use them as biogas for cooking or as an energy source at the household level.

Precision agricultural practices, including optimal quantities of fertilizer application for the crop type, which matches the existing soil fertility, the optimal time of application and split application of fertilizer, are all comprised of research work that needs to be developed as the management guidelines or recommendations for the farmers. On the other hand, disseminating knowledge is far more important to get the right outcome at the farm and country levels. To achieve that, the aforementioned recommendations should be reached at the farmer level via sensible language for the farmers using well-organized extension services.

3.1 Irrigation Management

Smart irrigation management practices are crucial in adapting to climate change by enhancing water use efficiency and resilience in agriculture. These practices, which include AI-based decision support systems, weather data, and automated irrigation systems, help to optimize water use and reduce water waste. By applying water precisely when and where needed, smart irrigation management minimizes water loss through evaporation and runoff, which is especially important in regions experiencing water scarcity due to climate change (Patle *et al.*, 2020). This approach improves crop yields and ensures sustainable water use, contributing to agricultural resilience in the face of changing climate conditions.

3.2 New Varieties

New crop varieties play a crucial role in adapting to climate change by offering traits such as drought tolerance, heat tolerance, and resistance to pests and diseases. These traits allow crops to thrive in challenging environmental conditions, helping ensure food security in a changing climate. For example, developing heat-tolerant wheat varieties has enabled farmers to maintain yields despite rising temperatures (Reynolds *et al.*, 2016). Additionally, new varieties with improved water use efficiency can help mitigate the impacts of water scarcity on crop production (Kumar *et al.*, 2014). Adopting new crop varieties enhances agricultural resilience and contributes to sustainable food production in the face of climate change. However, potential downsides or challenges in developing and adopting new crop varieties include high research and development costs, long breeding cycles, limited accessibility for smallholder farmers, and the risk of reduced genetic diversity. Adopting new crop varieties enhances agricultural resilience and contributes to sustainable food production in the face of climate change.

3.3 Crop Rotation

Crop rotation is a vital technique for adapting to climate change, involving the sequential planting of different crops over several seasons. This practice helps prevent soil fertility depletion and reduces the buildup of pests and diseases. Cover cropping, commonly used in organic farming, involves planting crops like clover or vetch between main crops to protect and enrich the soil. Organic farming also emphasizes natural pest control methods, such as introducing beneficial insects or using traps, rather than relying on chemical pesticides. These practices help maintain a balanced ecosystem, enhance soil health, and reduce the risks associated with chemical exposure (Gattinger *et al.*, 2012).

3.4 Minimize Harvesting Losses and Post-harvest Losses

Minimizing harvesting and post-harvest losses is crucial for adapting to climate change as it ensures food security and reduces waste. Climate change can lead to more frequent and severe weather events, disrupting harvests and increasing losses. By implementing efficient harvesting techniques and improving storage and processing facilities, farmers can reduce losses and maintain food availability. This is particularly important in regions where food insecurity is already a challenge. Studies have shown that reducing post-harvest losses can significantly increase food availability and reduce the need for additional agricultural production to meet demand (Parfitt *et al.*, 2010).

4. Carbon Sequestration in Agricultural Soils: Mitigating Climate Change through Soil Management

Soil is an essential resource for crop growing that can hold and preserve high amounts of carbon within the agricultural landscape. Considering environmental impacts, there is a growing need for sustainable alternatives and practices in agriculture. One such alternative is using organic fertilizers derived from natural sources such as compost, manure, and plant residues. Organic fertilizers provide essential nutrients to plants and improve soil health by increasing organic matter content and promoting microbial activity. Additionally, organic fertilizers are less likely to leach into water bodies, reducing the risk of water pollution.

Organic farming's emphasis on maintaining healthy soils is a key factor in mitigating climate change by sequestering carbon in the soil. This process involves capturing and storing atmospheric CO_2 in the soil, thereby reducing the amount of CO_2 in the atmosphere, a major greenhouse gas responsible for global warming. Organic farming promotes carbon sequestration and is increasing soil organic carbon levels. The carbon associated with soil organic matter is called soil organic carbon (SOC). Soil organic matter is decomposed plants, animal materials, and microorganisms, and soil carbon may be found in inorganic forms such as calcium carbonate (Chan *et al.*, 2010). The soil has sub-organic pools, namely the humus layer (old decomposed organic carbon), freshly decomposed or partially decomposed organic carbon, charcoal, and microbial biomass. Soils in the agricultural fields account for both carbon fixation and carbon emission and therefore, soil's role in carbon storage is a two-way process. In agriculture, soil carbon storage can be enhanced by increasing the application of organic fertilizer, mulching, use of cover crops, and implementing optimal crop rotations. This stored carbon can persist in the soil for extended periods, effectively removing CO_2 from the atmosphere. Enhancing soil organic carbon will automatically increase the chemical, physical, and biological fertility levels and buffering capacity of the soil.

Research has shown that organic farming can significantly increase SOC levels compared to conventional farming practices. For example, a study by Gattinger *et al.* (2012) found that organic farming systems had 28% higher average SOC levels than conventional systems. Similarly, a meta-analysis by Powlson *et al.* (2014) reported that organic farming increased SOC levels by an average of 0.45% per year, highlighting the potential of organic farming to sequester carbon in the soil.

Furthermore, healthy soils in organic farming systems support diverse microbial communities, which are crucial in carbon sequestration. Soil microbes decompose organic matter and create stable forms of soil organic carbon, effectively storing carbon in the soil. Studies have shown that organic farming enhances microbial biomass and activity, leading to increased carbon sequestration (Hartmann *et al.*, 2015; Wang *et al.*, 2011).

5. Soil Health and Fertility in Eco-Friendly Agriculture

Soil health and fertility are paramount in sustainable agriculture, influencing crop productivity, ecosystem health, and climate change mitigation. While conventional agriculture often relies on chemical inputs to boost yields, eco-friendly farming practices prioritize soil health through natural methods, ensuring long-term sustainability.

Practices such as minimal tillage, cover cropping, and crop rotation promote beneficial microbial communities, enhancing soil fertility and reducing the need for external inputs. Furthermore, soil organic matter (SOM) is crucial for soil health and fertility.

Healthy soil is teeming with diverse microbial life, contributing to nutrient cycling, disease suppression, and plant growth. Furthermore, soil organic matter is crucial for soil health and fertility. SOM improves soil structure, water retention, and nutrient availability (Osman, 2012). Eco-friendly practices like composting, mulching, and organic farming increase SOM levels, enriching the soil and promoting sustainable agriculture.

6. Sustainable Nutrient Management Practices

Sustainable soil fertility refers to maintaining soil conditions such as physical, chemical, and biological properties while ensuring the long-term productive potential of soil and maintaining their environmental functions (Silveira and Kohmann, 2020). The sustainable soil fertility management approach emphasizes adding soil amendments and organic manures, including pasture phases and leguminous crops, minimal tillage systems, and incorporation of crop residues on site. Soil fertility can be improved by nutrient cycling, increasing nitrogen fixation, and minimizing soil and nutrient losses by implementing the practices listed above (Defoer, 2002).

Integrated Soil Fertility Management (ISFM) is crucial for sustainable crop production. ISFM, as defined by FAO (1989), is "a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity". Organic inputs release nutrients gradually based on their properties, making them valuable for improving soil quality and reducing fertilizer use. Effective maintenance of organic inputs (compost, manure, crop residues) in degraded soils can help to enhance soil fertility and reduce soil erosion susceptibility by promoting soil aggregation stability, nutrients, and water retention ability, improving hydraulic conductivity, soil pH, and soil microbial activities (Lehmann *et al.*, 2003; Steiner *et al.*, 2008; Major *et al.*, 2010). These benefits can be further improved by applying biochar as a soil amendment or soil conditioner. The key practices of integrated soil fertility management are outlined briefly below.

6.1 Compost: Nature's Fertilizer for Sustainable Farming

Organic farming techniques offer a sustainable alternative to conventional fertilizers, promoting soil health, biodiversity, and environmental sustainability. Unlike chemical fertilizers, which can degrade soil quality over time, organic methods focus on building soil fertility naturally. One key practice in organic farming is the use of compost. Composting is the biological decomposition and stabilization of organic materials (bio waste, yard waste, faeces, manure) under aerobic conditions, which recovers a complex group of macromolecular organic compounds with high stability for safe use in agriculture (Boldrin *et al.*, 2009). Composting aims to degrade biogenous wastes rapidly but efficiently and convert them into stable humic substances (Binner, 2016). Composting is vital to closing the nutrient cycle and reducing waste in landfills. Therefore, composting is an important component of sustainable waste management. The use of uncontaminated feedstock materials, preparation of adequate feedstock mixtures, and maintenance of control conditions (the carbon-to-nitrogen (C/N) ratio, temperature, moisture content, pH, aeration, and oxygen supply) are critical to the composting process. These factors help maintain aerobic conditions, minimize odor, and reduce nutrient leachate, thereby ensuring efficient and environmentally sustainable compost production (Binner *et al.*, 2002). Composting has clear benefits for farmers in low-income countries where agriculture is the primary source of income, and it reduces municipal efforts and costs. Composting transforms various organic substances into simpler and easily available nutrients for plants. When compost is applied to the soil, it will enhance the soil's physical, chemical, and biological properties. The application of compost will enhance the long-term below-ground carbon pool and contribute to carbon fixation.

6.2 Biofertilizers: Harnessing Nature's Potential

Biofertilizers are natural fertilizers that contain living microorganisms, which, when applied to seeds, plant surfaces, or soil, stimulate plant growth by supplying essential nutrients such as nitrogen, phosphorus, and potassium. Unlike chemical fertilizers, biofertilizers are environmentally friendly and sustainable and help to improve soil fertility over time (Sahoo *et al.*, 2012). One of the key benefits of biofertilizers is their ability to fix atmospheric nitrogen through symbiotic or associative nitrogen fixation. For example, rhizobium bacteria form nodules on legume roots, converting nitrogen from the air into a form that plants can use, reducing the need for synthetic nitrogen fertilizers.

Another benefit is their role in enhancing nutrient availability in the soil. Mycorrhizal fungi form symbiotic relationships with plant roots, increasing the surface area available for nutrient absorption and improving plant resilience to environmental stresses. Biofertilizers also contribute to soil health by promoting beneficial soil microorganisms and suppressing harmful pathogens. They can help improve soil structure, water-holding capacity, and overall fertility, reducing the need for chemical inputs. In addition to their agronomic benefits, biofertilizers offer environmental advantages, such as reducing greenhouse gas emissions and minimizing nutrient leaching and runoff.

6.3 Biochar: A Sustainable Solution for Mitigating Climate Change in Agriculture

Biochar, a form of charcoal produced from biomass, is gaining recognition as a sustainable solution for mitigating climate change in agriculture. When added to soil, biochar sequesters carbon, locking it away in hundreds to thousands of years. Therefore, biochar can be a long-term carbon sink (Smith, 2016). Further, incorporating biochar into agricultural fields increases carbon sequestration and enhances water retention, soil fertility, and nutrient cycling. More importantly, this process helps reduce the concentration of greenhouse gases in the atmosphere, mitigating climate change.

Additionally, biochar enhances soil health and fertility. Its porous structure provides a habitat for beneficial soil microorganisms, improves soil structure, and increases water retention. These properties can lead to increased crop yields, especially in nutrient-poor soils. Biochar application has been shown to play an important role in improving the chemical properties of soil over time (Galinato *et al.*, 2011). Biochar can help regulate soil pH.

Moreover, biochar can reduce the need for chemical fertilizers by improving nutrient retention in the soil. This reduces greenhouse gas emissions associated with fertilizer production and decreases nutrient runoff, which can pollute waterways. Biochar offers a range of environmental benefits, making it a promising tool for sustainable agriculture and climate change mitigation. However, further research is needed to optimize its production, application, and long-term effects on soil health and crop productivity.

6.4 Cover Crops: Improving Soil Fertility and Reducing Fertilizer Dependency

Cover crops are an essential component of sustainable agriculture, offering a range of benefits that improve soil fertility and reduce the dependency on synthetic fertilizers. These crops, planted between main crops or during fallow periods, help prevent soil erosion, suppress weeds, and enhance soil health through various mechanisms. One key benefit of cover crops is their ability to fix nitrogen in the soil. Leguminous cover crops, such as clover, peas, and vetch, form symbiotic relationships with nitrogen-fixing bacteria, taking up atmospheric nitrogen and converting it into a form that plants can use. When the cover crop is incorporated into the soil, it releases this nitrogen, reducing the need for synthetic nitrogen fertilizers.

Cover crops also improve soil structure and fertility by adding organic matter. As cover crops decompose, they release nutrients like nitrogen, phosphorus, and potassium, making them available for subsequent crops. This organic matter improves soil structure, increasing water-holding capacity, aeration, and microbial activity. Furthermore, covering crops helps suppress weeds by competing for resources like light, water, and nutrients. This reduces the need for herbicides, promoting a more sustainable and environmentally friendly approach to weed management. Farmers can improve overall soil health, reduce erosion, and enhance crop productivity by integrating cover crops into crop rotations. This practice benefits the environment and contributes to more resilient and sustainable agricultural systems.

6.5 Conservation Farming

Soil conservation practices aim to reduce soil erosion and conserve soil resources within farmlands. Zero tillage, minimum tillage, cover cropping, crop rotations, and soil conservation hedges reduce soil disturbance, improve soil structure, reduce soil exposure to open environmental conditions, and improve organic content. Cover cropping, crop rotation, application of compost, bio-fertilizers, biochar, and conservation farming can help improve soil health, reduce erosion, and enhance nutrient cycling, reducing the need for conventional fertilizers. Moreover, these practices will enhance soil carbon sequestration and improve soil health and resilience.

7. Precision Agriculture: Efficient Fertilizer Use and Environmental Benefits

Precision agriculture is a modern farming practice that leverages technology to optimize crop production while minimizing environmental impact. Precision agriculture involves the integration of new technologies including Geographic Information Systems (GIS), Global Positioning Systems (GPS) and Remote Sensing (RS) technologies to allow farm producers to manage within field variability to maximize the cost-benefit ratio, rather than using the traditional whole-field approach. Further, it involves the precise application of inputs such as fertilizers, pesticides, and water based on the specific needs of crops and soil conditions.

Another important technology used in precision agriculture is sensors. These sensors can monitor real-time soil moisture levels, nutrient content, and crop health. By collecting data from these sensors, farmers can make informed decisions about when and where to apply fertilizers, ensuring that crops receive the right amount of nutrients at the right time. This improves crop yields and reduces the risk of nutrient runoff into waterways, which can lead to water pollution. Precision agriculture also helps reduce greenhouse gas emissions associated with agriculture. Farmers can reduce the amount of energy used to produce and apply fertilizers, pesticides, and water by optimizing inputs. This can help mitigate climate change by reducing the agricultural sector's carbon footprint. In addition to environmental benefits, precision agriculture can improve farming operations' economic viability. Farmers can reduce costs and improve yields by optimizing inputs, leading to higher profits. Numerous studies are underway to quantify the benefits of precision agriculture, and this approach enables farmers to make more informed decisions regarding crop selection and rotation, thereby improving the long-term sustainability and profitability of agricultural practices.

8. Alternative Management Aspects in Agricultural Systems to Develop Them as High Carbon Content Areas

Conventional farming systems tend to produce considerable GHGs, disturbing the balance of the atmospheric composition and interfering with the climate system. This section explains some alternative management aspects we can follow within our agricultural lands to reduce GHG emissions and strengthen the resilience of food production systems.

8.1 Agroforestry as a Climate-Smart Alternative Management for Monocultures

Agroforestry practices can significantly increase carbon sequestration rates, helping mitigate climate change. Agroforestry refers to integrating trees in agricultural fields to promote ecological, economic, and social values in the land management unit. Agroforestry directly helps diversify the crop systems, which increases total biomass and above-ground carbon fixation long-term (Abbas *et al.*, 2017). Integrating trees and shrubs into agricultural landscapes, from 3% - to 5%, offers multiple benefits, including increased carbon sequestration, biodiversity conservation, and enhanced resilience to climate change (Possu *et al.*, 2016). Therefore, agroforestry systems are considered as climate-smart agricultural practices.

Agroforestry systems increase overall productivity and input use efficiency (Nair, 2005), featuring some climate-smart applications in agricultural systems. Compared to conventional cropping systems, agroforestry systems have higher capacities to store above-ground and below-ground carbon (Montagnini and Nair 2004). Timber species and deep-rooted forest species store considerable carbon content in their biomass within the main stem and root system for the long term. Thus, these systems function as a long-term carbon sink compared to a monocropping system, which only consists of crops, annuals. Timber trees in the Taungya systems and farmers' woodlot areas can fix CO_2 from the atmosphere and form long-term carbon sinks, which can be considered by the carbon offsetting programs as stipulated by international climate actions such as the Kyoto Protocol.

The carbon sequestration potential of agroforestry systems varies based on species mix, soil quality, and climate (Lorenz and Lal, 2014). Carbon stored in both above- and below-ground biomass tends to be much higher in agroforestry systems compared to treeless land use (Nair *et al.*, 2009; Fialho and Zinn 2014). Where crops and trees grow together, agro-silvicultural systems function as net carbon sinks, while agro-silvipastoral systems may exist as net carbon sources (Montagnini and Nair 2004). However, the counterargument is that silvopastoral systems sequestered 36–60% more CO_2 than tree-only systems and 27–71% more than grasslands (Mangalassery *et al.,* 2014). Some studies indicated that systems combining trees and grasses sequestered more soil organic carbon than just trees or pasture. Agroforestry practices such as alley cropping, windbreaks, and silvopasture can significantly enhance carbon fixation while diversifying farm income streams. In the tropical regions, above-ground carbon fixation in agroforestry systems is estimated as 2.1×10^9 MgC Year^{-1} (Oelbermann *et al.*, 2004).

Agroforestry systems have a high potential to sequester soil organic carbon. Within agroforestry systems, soil organic matter is strengthened by enhancing the return of organic matter to the soil, particularly agroforestry systems like alley cropping, lands where a sloping agricultural land technology (SALT) system is adopted, and multipurpose tree gardens. Although such agroforestry systems significantly mitigate climate change, they are still not systematically considered for national carbon accounting procedures.

8.2 Plantation Agriculture – Coconut and Rubber Plantations

Some plantation crops are perennials, which can be easily developed as carbon fixation model farms. In the Sri Lankan scenario, coconut and rubber are ideal plantation crops. Coconut plantations can be managed to create a negative carbon system by integrating some timber trees, intercropping under the coconut overstory, and having some cover crops for the soil surface layers. Other than that, soil conservation measures such as mulching, coconut husk pits and composting will enhance the below-ground carbon pools within the coconut plantations. Coconut-based poly-cultural systems are the best example of nature-based agricultural systems, featuring a species mix, multi-layer tree arrangements in the vertical space, enhanced resource utilization and increased biodiversity within the system (Kumar and Kunhamu, 2022). Coconuts are different when storing carbon compared to dicot trees as they store more carbon in the flesh parts such as fruits, leaves, fronds, and litter, but not in the main stem (Roupsard, 2008). Therefore, the normal procedures to find carbon accumulation within the forest trees can't apply to the coconut plantations.

Rubber plantations are ideal for carbon accounting purposes. Rubber is a perennial and functions as a timber tree, so all silvicultural estimations apply to rubber trees when estimating carbon within the system. The annual CO_2 sequestration by rubber plantations varied between 28.0 to 43.1 tons of CO_2 per hectare per year (Satakhun *et al.*, 2019). Further, Satakthun *et al.* (2019) suggest that 2.95 million hectares of natural rubber plantations in Thailand could sequester around 108 million tons of CO_2 annually. About 24.9 kilograms of net CO_2 was sequestered for each kilogram of natural rubber latex produced. This substantial carbon sequestration potential linked with natural latex production holds significant implications for adopting an "environmentally friendly" marketing approach to boost the competitiveness of natural rubber, particularly when compared to synthetic rubber.

8.3 Forest Management for Increasing Carbon Sequestration

Forests are pivotal in climate change mitigation (FAO, 2020). Sustainable forest management practices can enhance carbon fixation while promoting biodiversity conservation and resilience. Forests are among the most effective natural carbon sinks, sequestering large amounts of carbon through photosynthesis and storing it in biomass and soil organic matter (Vashum & Jayakumar, 2012). Forests encompass approximately one-third of the Earth's surface and serve as vital habitats for many terrestrial species. As of 2020, global forests collectively contain 662 billion tons of carbon, distributed as follows: 44.5% in biomass (both above-ground and below-ground), 10.3% in dead wood and litter, and 45.2% in the soil (FAO, 2020).

Using reforestation and afforestation initiatives to plant trees on deforested or degraded lands can significantly increase carbon sequestration and restore ecosystem functions (Zanini *et al.*, 2021). Rehabilitating degraded forests through restoration interventions such as selective logging, invasive species control, and natural regeneration can enhance carbon fixation while restoring ecosystem services and improving livelihoods for local communities. Analog forestry is a revolutionary silvicultural strategy for replanting degraded land that aims to create trees structurally and ecologically comparable to the region's original climax or sub-climax vegetation (Veintimilla *et al.,* 2020). The establishment of analog forests is one of the potential solutions to offset atmospheric GHGs. In forests, carbon is stored in above-ground and below-ground pools. Maintaining a comparable system to forests is a useful strategy to remove excess CO_2 from the earth system. Tropical forest systems can hold a significant amount of carbon; for example, 62% of the world's carbon pool is in tropical forests (Reddy and Colin, 1999).

Protecting existing forests from deforestation and degradation is crucial for maintaining their carbon sequestration potential, especially in developing countries where now the most forest cover remains. Enhancing carbon fixation in agriculture, forestry, and land use is essential for mitigating climate change and building climate-resilient ecosystems. By adopting innovative practices, promoting sustainable management approaches, and integrating climate considerations into land use planning, societies can connect the potential of these sectors to sequester carbon, conserve biodiversity, and secure a sustainable future for the next generations. Implementing policies and incentives for sustainable forest management, reducing illegal logging, and promoting forest certification schemes can help conserve forests as valuable carbon sinks.

9. Conclusion

Agriculture alone is significantly attributed to global climate change, accounting for about 24% of GHG emissions compared with other sources. It is the sector most responsible for climate warming, especially in developing countries. International agreements and negotiations are in place to stabilize future GHG emissions worldwide, aiming to maintain less than 2°C warming of the climate system in the future. Sri Lanka has a small economy; therefore, the global share of GHG emissions is comparatively lower, remaining at 0.08% at present with expectations of achieving 14.5% emission reduction targets by 2030, focusing on increasing forest cover by 30% and adopting to renewable energy alternatives by 70% (UNDP). However, agriculture can be practiced as a transformative approach for offsetting carbon in numerous ways. Organic farming practices, soil fertility management through nature-based solutions (addition of soil amendments and organic manures), climate-smart agricultural practices, precision agricultural techniques for targeting resource conservation and optimum utilization of resources in correct quantities at the correct time, incorporating agroforestry practices and sustainable forest management within the agricultural land use systems are some of the avenues that the agriculture sector should look into and implement in future to stay in the path of climate change mitigation. Adopting these innovative practices can promote sustainable management approaches and integrate climate considerations into land use planning; societies can connect the potential of these sectors to sequester carbon, conserve biodiversity, minimize GHG emissions and secure a sustainable future for the next generations.

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Chapter Six

Diversity, Thrifty Plans, and Resilient Food Systems as a Solution to Food Price Spikes

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Abstract

Locally controlled food systems of high diversity show potency to absorb natural or anthropogenic shocks and reorganize quickly, thereby ensuring adequate food supply. There are many potential strategies to augment the resilience of food systems in Sri Lanka that flatten food price spikes. One of the most promising ones would be 'agricultural diversification' which encompasses genetic, species, and ecosystem diversity. Of course, diversity must be carefully planned since unplanned diversity may be well sensitive to external perturbations. In fact, the functional diversity will make the food systems build resilience leading to a low degree of price fluctuations. Local sourcing may be a thrifty plan for attenuating price spikes since this approach will provide jobs for the local workforce. Further, the reduction of food waste via efficacious postharvest or post-slaughter processing and preservation will lead to smoothing out of food price spikes. This chapter focuses on the diversification of cereal and pulse–based products, fruit and vegetable-

based products, algae-based products, and animal-based products. In summary, this chapter begins with a description of food price spikes in Sri Lanka and their impact on the consumers; next, some potential strategies or thrifty plans for developing food system resilience are discussed; this section is followed by probable methods for the food production diversity; then, challenges and future prospects faced along the pathway of building food system resilience are briefly deliberated; and the chapter ends with a concise conclusion.

Keywords: Algae-based products, Animal-based foods, Cereals and pulses, Fruit and vegetables, Resilient food systems

1. Introduction to the Food Price Spikes in Sri Lanka and Their Impact

Sri Lanka heavily depends on imported agricultural goods, both plant- and animal origin, particularly wheat, sugar, milk powder, pulses, nuts, meat, maize, onions, potatoes, dried fish, and rice. Factually, it presents significant challenges to the country's food security. Equally, although these imports are vital for meeting the dietary needs of the locals, fluctuations in global market prices create a substantial hit on local market prices, creating a serious threat to the country's economic stability. As Selliah *et al.* (2015) highlighted, a strong link between global food prices and domestic inflation provides the economic repercussions Sri Lanka has been facing over decades of reliance on external markets. This reliance on external markets not only imposes a profound financial burden on many Sri Lankan households, as they allocate a substantial portion of their income to purchasing imported food and beverages, but it also exacerbates economic pressures and causes distress among them. Of particular concern are commodities like wheat and maize, which account for about 22% of the average Sri Lankan household's caloric intake (Wijesinghe & Yogarajah, 2022), highlighting the vulnerability of the nation's food supply to external market dynamics. Thus, urgent, and comprehensive safety net programs are essential to mitigate immediate economic hardships for the country's vulnerable groups, particularly the rural population. In the long term, poverty-alleviating strategies should prioritize initiatives that boost domestic food production by investing in agricultural research and technology. In addition, by encouraging diversification in patterns of staple food consumption, the locals can enhance food security and the Sri Lankan economy's resilience to external food market shocks.

2. Potential Strategies for Building Food System Resilience in Sri Lanka

'Resilience' can be defined as "the ability to recover from or to adjust to change" and is an attribute desired in food systems to combat food insecurity and mitigate price spikes. The changes or disturbances that the food systems have had to absorb in Sri Lanka in the recent past were severe weather, pest outbreaks, unavailability of fertilizer, and consequences of the meager availability of foreign currency. Unfortunately, the insufficient resilience of the prevailing food systems has reduced food production. Food price spikes resulting primarily due to decreased production, increased food wastage, and suboptimal distribution of foods, have worsened the food insecurity in Sri Lanka indicating the need to build resilience of food systems. Plausible strategies discussed in this chapter for building food system resilience in Sri Lanka are 'increased agricultural diversity' and 'local sourcing' and efficacious postharvest/post-slaughter processing and preservation.

2.1. Increased Agricultural Diversity

Agricultural diversity has resulted in resilience to both natural and anthropogenic disturbances or disasters, contributing to food security while mitigating food price spikes. Agricultural diversity or food production diversity can be identified at three levels. They are (a) genetic diversity, (b) species diversity, and (c) ecosystem diversity. Genetic diversity is achieved by cultivating different cultivars suitable for producing relevant food. Species diversity can be achieved in simple terms by having multiple species on a farm. Ecosystem diversity is much broader and refers to "the diversity of production between farms and within the broader food system" (MacFall *et al.*, 2015).

Genetic diversity has shown high resilience in the food system. For instance, a farm consisting of cultivars that show resistance to pest attack and pathogens and cultivars that can withstand droughts along with high-yielding cultivars may exhibit better resilience on pest attacks or droughts than a farm consisting only of high-yielding cultivars. Also, the benefits of depending on the genetic diversity of animals or crops for food production have been portrayed in numerous instances. For example, Kong *et al.* (2023) reported the enhanced performance of mixed cropping of eight wheat cultivars compared to monocropping under drought and high-temperature conditions in the North China Plain in terms of crop yield. Hence, it will be advantageous to consider incorporating genetic diversity in food systems to increase resilience in food systems, especially since research on cultivars and breeds with favorable traits is abundant (Abdel-Banat *et al.*, 2023, Reichhardt *et al.*, 2023, Samarasinghe *et al.*, 2023).

Species diversity achieved via cultivating and/or rearing multiple species in one farm has, in numerous instances, exhibited increased resilience against natural or artificial perturbations. For instance, Isbell and coauthors provided evidence for agroecosystems showing increased "crop and forage yield, wood production, yield stability, pollinators, weed suppression, and pest suppression" due to plant diversity that if adopted may undoubtedly contribute to developing resilient food systems in Sri Lanka (Isbell *et al.*, 2017).

Ecosystem diversity has contributed to the resilience of food systems. In fact, an ecosystem showing functional redundancy of its segments will exhibit a better response to variable environmental conditions, thus contributing to a satisfactory food supply. Further, soil fertility and crop protection will be augmented via ecosystem diversity. It must be emphasized that functional diversity is desired in ecosystem diversity or genetic or species diversity. Simply put, the functional diversity of ecosystems will inevitably be an 'insurance' against any shortfalls in the performance of a segment of the ecosystem (MacFall *et al.*, 2015). Ecosystem diversity indeed may be developed as a means of building resilient food systems in Sri Lanka.

Agroecology, related to ecosystem diversity, has been identified as a transformative approach to addressing food crises, ecosystem degradation, and many more. In fact, practices such as "landscape and farm diversification, intercropping, crop and pasture rotation, adding organic amendments, cover crops, and minimizing or avoiding synthetic inputs" constitute agroecology contributing to resilient food systems. Also, the co-creation of knowledge with farmers and participatory progressions are examples of the social component of agroecology (Kerr *et al.*, 2023). To enhance the resilience of food systems, the components of agroecology are all doable in Sri Lanka.

2.2. Local Sourcing

The advantages of local sourcing, which refers to the distribution of foods to the consumers via a network of local food producers and entrepreneurs are manifold. The diversity among the networks will enable fast response and adaptation to the perturbations of the food supply (MacFall *et al.*, 2015). This was evident in a study carried out on the resilience of farms producing organic pigs in Europe where the authors highlighted the contributions of direct marketing towards the resilience of the farms. However, it must be acknowledged that direct marketing is associated with several drawbacks such as high labor requirements (Pfeifer *et al.*, 2022). However, in the Sri Lankan context, local sourcing will offer job opportunities to local people increasing their household income while contributing to the resilience of the farms, which in turn will build the resilience of the food systems extenuating food price hikes.

2.3. Efficacious Postharvest/Post-Slaughter Processing and Preservation

Following the pattern in the developing world, Sri Lanka experiences significant loss of crops after harvesting. These postharvest losses partially contribute to the increment of the prices of raw or processed foods. An easily thinkable solution to this problem would be to process and preserve foods lowering the extent of food waste and simultaneously offering consumers diverse foods at a reasonable cost. However, this is 'easier said than done.' Thrifty plans for the involvement of the resources and processes required for this purpose are mandatory.

3. Possible Approaches for Food Production Diversity

3.1. Cereals and Pulses

Humans are dependent on diverse food sources for different nutrients. However, among them, cereals are recognized to be the most significant for thousands of years, as they play one of the main roles in the human diet. Cereal and Pulses are cultivated throughout the world, and the main producers are India, Canada, China, Myanmar, and Nigeria among the top producers (Didinger & Thompson, 2021). Cereals and Pulses are famous for their high content of plant protein, calories, dietary fiber, a varied range of minerals, and bioactive substances. However, the nutritional value of those and the different ways of preparation, processing and utilization make a remarkable connection. However, there is a general opinion that pulses and legumes are the same, Codex Alimentarius Commission Food Standard defined the difference between them based on fat content (Gupta *et al.*, 2021).

Comparably, cereals can grow in contrary environments and even without good soil conditions while providing higher yields. Post-harvest practices and storage conditions may impact nutritional value. The most positive fact is cereals are stable food with low moisture content, which can be stored for a longer period without affecting the nutritional value (ISO/TC 34).

The most popular food grains include wheat and rice. However, many pulses and cereals are used by different countries. Especially, in South Asian countries, pulses are a crop that is a very important part of their diet. Especially for vegetarians' pulses serve as a protein source.

Cereals and pulses are now gradually being used to process ready-to-eat (RTE) food products. Due to rapid urbanization, unstable lifestyles, and working people have become used to searching for healthy foods. The difference between the demand for and supply of cereal and pulses is increasing with the global population increase. Based on the kind of cereal/pulses, numerous production procedures are used, such as flaked, puffed, shredded, and so on (Joshi *et al*, 2021).

The grain will be examined and cleaned once it arrives at the factory. Some varieties use entire grains, whereas others grind the grain into fine flour using crushed massive metal rollers to remove the outer layer of the bran. In a massive rotational pressure cooker, whole and partial grains will be combined with other ingredients. The type of grain used will influence the rotational speed, duration, and temperature employed during this operation. After the grain has been cooked, it will be dried in an oven. However, a specific quantity of water content in the cooked grain is important to be molded as desired (Joshi *et al.*, 2021).

3.2. Fruit and Vegetables

The Spike in the price of fruits and vegetables during the pandemic gained considerable attention in Sri Lanka during the past few years. The reported spikes in daily consumption of commodities such as fruits and vegetables gained considerable concern about the purchasing power of the consumer and triggered social unrest (Mango *et al.*, 2018). Therefore, the measures to address the price spikes of fruits and vegetables are highly essential.

Boosting fruit and vegetable production in the country ensures the supply of produce for the consumers' demand. Encouraging farmers to cultivate more vegetables by offering them incentives and support, as well as promoting urban and peri-urban agriculture are both effective strategies to boost local fruit and vegetable production. These measures can help address fruit and vegetable price control by increasing the supply of fresh produce.

As a result of the commercialization of a few vegetables and fruit crops, the entire country is dependent on a few crops, neglecting many crops with high nutritional and medicinal qualities, traditionally grown in the past, which are critically endangered and on the verge of rapid disappearance (Dahanayake, 2015). These underutilized fruits and vegetable crops need to be popularized by conducting research, awareness, and educational workshops on their medicinal, functional, and nutritional properties. Improved marketing and a reliable supply of end products are essential for developing the market potential for underutilized fruits and vegetables. To prevent sudden price increases resulting from shortages of supplies or price increases in a few specific crops, it is necessary to encourage the production of a variety of crops. This will reduce the country's reliance on a small number of crops.

Approximately 30% to 40% of the annual fruit harvest is lost in Sri Lanka during postharvest operations, translating to around 210,000 metric tons of fruits. In financial terms, these losses amount to approximately US$ 90 million (Leelananda *et al.*, 2021). During post-harvest operations, vegetables are lost by about three hundred thousand metric tons per year in Sri Lanka. This represents about 20% to 40% of the total harvest. Approximately 110 million dollars are involved in this matter (Leelananda *et al.*, 2021). Harvesting before the produce has reached the correct maturity, inadequate handling procedures during harvesting, incorrect packaging at various stages of the process, and unsuitable transportation and retail selling practices, inadequate storage and transportation facilities have resulted in a significant amount of fruit and vegetable loss, thus contributing to high prices. By improving storage facilities and transportation methods, these losses can be reduced, and more fruits and vegetables can reach the market as a result.

The production of most of the perishable food crops is seasonal. Hence during this short time, those are produced in greater quantity than the market can captivate, so the surplus of many of these crops must be processed and preserved to avoid wastage, maintain the sustainable supply, and reduce price spikes of the food and loss of income to the grower.

Recent methods of storage, processing, and preservation of food such as smart packing with artificial intelligence and fully automated robotic processing units without manual contamination, are commonly used in developed countries. However, these are rare in many developing countries, while they are still using various processing methods requiring only simple and inexpensive equipment with indigenous knowledge. Further demanding growth in the food industry is the use of fruit and vegetable uses for value-added products. The phenolics and other phytochemicals are present in the peels, pulp/pomace, and seeds of many fruits and vegetables, which are significantly higher than in their respective edible tissues, suggesting these wastes and residues to be the potential sources for isolating bio-active compounds (Wadhwa, 2015).

The most appropriate food preservation method for fresh fruits and vegetables is influenced by their degree of maturity and ripeness. To preserve the best quality fruits and vegetables, one needs to know the difference between maturity and ripeness. Maturity means the produce will ripen and become ready to eat after picking it. Ripeness occurs when the color, flavor, and texture are fully developed. Once it is fully ripe, fresh produce begins the inevitable and declining spoilage process (Kitinoja *et al.*, 2011).

Refrigerated pickles are the simplest way to be used to preserve fresh vegetables and even some fruits to extend their shelf life for a few days as a type of salad or pickle. Freezing vegetables for long-term storage requires tolerable packaging and a devoted freezer appliance such as a blast freezer. It is needed to take suitable control measures to avoid chilling injuries.

Salting is a simple and old-fashioned method for preserving vegetables such as salted cauliflower. Fermenting with salt uses low salt concentration to promote fermentation. Sauerkraut and kimchi are the most well-known examples, however, which can be applicable to many more varieties with more modifications such as water activity and pH balancing, etc.

Though drying vegetables is the easy and traditional method that can control the water activity with means to retard microbial growth, now it can be performed in the automated-electric oven or more sophisticated Electric food dehydrator appliances which are very sensitive to flavour and nutritional compounds of the food.

Canning requires a comparably high investment with high technology in equipment and skilled labours. High-acid foods include most fruits and fruit products. In addition, low-acid vegetables can be canned using tested recipes for pickles, relish, and tomato products, which contain added acid, usually vinegar. Pressure canning is suitable for low-acid foods such as plain vegetables. A pressure canner reaches 116 °C, which destroys heat-resistant organisms that can cause food poisoning, primarily botulism.

The heating of foods for preservation is known as processing. The processing time and temperature should be adequate to eliminate bacterial growth and preserve the important nutritional and sensory properties. Almost all fruits and added vegetables can be processed at 100 °C temperature. Several value-added products can be processed with different fruits and vegetables and preservation methods which attract various consumer groups. Fruits and vegetables can be developed in a wide range of value-added products like jam, jelly, source, ketchup, powder mixtures of pudding and soup, and chutney.

3.3. Algae-based Products

Considering Sri Lanka's coastal location and high levels of sunlight, algae-based food production holds great potential. Algae are rich sources of proteins, soluble fibers, and polysaccharides. In addition, algae are also high in lipids, polyunsaturated acids, pigments, and vitamins (Kitinoja *et al.*, 2011, Matos *et al.*, 2022). Lipids and proteins are higher in algae than in traditional plants, and low algae biomass produces high amounts of essential amino acids compared to traditional plants (Matos *et al.*, 2022).

Algae can be consumed in several ways. It can be processed in the form of fresh, fermented, frozen in its whole form, or ground into flakes, granules, or powder (Mouritsen *et al.*, 2019). In addition, algae can be incorporated into food products and value-added products are highly popular in European markets (Nova *et al.*, 2020). The way that algae are processed can impact the final product's nutritional content, texture, and flavor. By developing new processing techniques, or modifying existing ones, a broader range of algae-based products can be created with different textures, flavors, and nutritional profiles.

To increase the diversity of algae-based food production, there is a need for a multidisciplinary strategy, including research and development activities to find novel species, processing technologies, product formulations, and growth techniques. A sustainable and diversified food system can be achieved by leveraging advances in technology and collaborating across disciplines.

Agricultural practices and meat consumption have a significant environmental impact on land and water usage, and it contributes to the emission of significant amounts of greenhouse gases. Issues such as topsoil erosion, water resource depletion, and surface and groundwater contamination with excess nutrients exacerbate conventional agricultural practices. To uphold the environmental equilibrium of the planet, it is imperative to transit towards more efficient and sustainable food production systems. However, it is crucial to meet future nutritional requirements while not contributing to climate change. When envisioning designs for a novel, sustainable food source, careful consideration must be given to land utilization, freshwater consumption, and the potential impact on biodiversity. Algae emerges as a promising candidate to address these challenges, offering the prospect of addressing various environmental problems associated with food production in the future (Kumarasinghe *et al.*, 2022).

Overall, a multi-disciplinary approach that involves research and development efforts to identify new species, processing techniques, product formulations, and cultivation methods is required to increase the diversity of algae-based food production. By leveraging advances in technology and collaborating across different fields, the potential for algae-based foods to contribute to a sustainable and diversified food system can be realized.

3.4. Animal-based Products

Promoting food production diversity by enhancing animal-based products in the Sri Lankan market, where plant-based products dominate, involves strategic interventions to strengthen nutritional security and sustainable agricultural development. One crucial aspect is promoting diversified animal-based farming systems that integrate multiple species, such as dairy cattle, sheep, goats, poultry, and fish suited to different agro-climatic zones of the country. This approach improves resilience to climate variability and enhances dietary diversity by providing animal-based products to the local market such as meat, eggs, milk, and fish (Teufel *et al.*, 2010). Animal-based products are well-known primary sources of high-quality proteins containing essential amino acids, the building blocks of proteins that cannot be synthesized by the body adequately and must be supplied in food as they are critical for human growth and development (FAO, 2009). Additionally, these products are rich in essential vitamins like B12, B6, riboflavin, and niacin, and minerals such as zinc (Zn), phosphorus (P), and calcium (Ca), which are vital for various physiological functions, including immune function and bone health.

Moreover, animal-based products account for about $1/3^{rd}$ of the total calorie content (~36%) and $2/3^{rd}$ of the protein available (~68%) in the food supply. Also, the nutrients in animal-based foods are regarded as better quality as they are high in content and bioavailability (Layrisse *et al.*, 1990), thus readily absorbed into the human body, compared to the nutrients from other foods (e.g., vegetable-based products) and non-food sources. As a result, Sri Lanka can improve dietary diversity and address nutritional deficiencies in the first place among its locals through the enhancement of animal-based food product availability.

Another critical approach is adopting sustainable animal husbandry practices, which include promoting improved animal breeds, efficient feeding systems, and appropriate management practices to enhance productivity and optimize resource utilization. Sustainable animal husbandry practices contribute to increased production of animal-based foods and can mitigate environmental impacts associated with animal agriculture. For instance, promoting locally adapted and underutilized fodder crops can improve feed availability and reduce dependency on external feed sources, thus enhancing the sustainability of livestock production systems while decreasing the cost of production. Similarly, diversification of local nutrient availability and production of more food sources through animal-based product development, in developing countries, is recommended to ensure food security and resilience and sustenance of transferring income sources away from a single source and direct toward an increasing number of sectors and marketplaces (Scanes, 2018). Adopting climate-smart animal husbandry practices helps further buffer against climate change impacts and ensures the resilience of animal-based food production systems in Sri Lanka.

Value addition and market development for animal-based products are crucial in promoting food production diversity and enhancing economic opportunities for locals, particularly for rural communities. By supporting the processing and marketing of value-added products such as dairy, meat, and processed fish, Sri Lanka can create and explore the potential of such products along the food chain (Vithanage *et al.*, 2013). Primarily, value addition increases the marketability of animal-based products and contributes to locals' income generation and job creation. Additionally, enhancing market linkages and improving cold storage and transportation facilities can reduce post-harvest losses and ensure the availability of best-quality animal-based foods in domestic and export markets (Teufel *et al.*, 2010). Consequently, by strengthening value addition and market development, Sri Lanka can maximize the economic potential of its animal husbandry sector and promote food production diversity, assuring food security and economic stability, achieving sustainable agricultural development with resilience, and improving the health and well-being of its locals. Nevertheless, it should be noted that it requires continuous investment in research, technology introduction and information extrapolation toward appropriate guidelines and recommendations if the expected outcomes are realized within the country.

4. Challenges and Future Prospects

The challenges of building resilient food systems for mitigating price spikes of foods are multifaceted, and a few important issues along with the prospects are mentioned herein. Most farmers lack the knowledge and know-how to bring about agricultural diversity scientifically to their farms. The large number of agriculture graduates produced annually from the universities may be channeled easily to work as advisors or consultants of the farms to buttress resilience in food systems via agricultural diversity. Another issue is that agricultural diversity in small-scale farmers' farms is usually discouraged since they must meet the minimum quantities of food required for sale to large-scale collectors. However, local farming will enable small-scale farmers to reach local consumers giving room to bring diversity to their farms, strengthening resilience in food systems. While encouraging agricultural diversity at the farm level, a master plan for bringing in agricultural diversity at the national level will be undoubtedly beneficial to develop resilient food systems in the country. The underutilized agricultural expertise in the country may be directed to make thrifty plans to serve this purpose. Finding the capital needed by the farmers to transform their farms into ones with agricultural diversity will be a major challenge. While encouraging gradual transformations, providing capital via bank loans, preferably with low-interest rates may be beneficial directly to the farmers and indirectly to the entire population of the country.

5. Summary

Frequent food price spikes have been detrimental to the household and country's economy. The main cause of price spikes is the susceptibility of the food systems to external conditions. Thus, it is mandatory to develop resilient food systems in the country. The most sustainable approach to build resilient food systems is by incorporating agricultural diversity, comprising genetic, species, and ecosystem diversity in the country's food systems. Local sourcing may also contribute significantly to the resilience of food systems. Reducing postharvest/post-slaughter losses via product diversification using appropriate food processing and preservation methods would be another way to weaken the food price spikes effectively. Lastly, thrifty plans at the national level are essential for building resilient food systems in the country.

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Chapter Seven

Unleashing Nature's Power: Phyto-protection by Bioactive Compounds

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Abstract

Exploration of antioxidants and their effects across diverse domains, from food science to medical and pharmaceutical fields, garners significant interest. The proven ability of antioxidants to neutralize oxidative damage caused by free radical reactive oxygen species (ROS) contributes to mitigating Non-communicable Diseases (NCDs) significantly. It is widely accepted that the organism's inherent defense mechanism is specifically geared towards countering these oxidative stresses by quenching free radical ROS (oxidant), often in conjunction with the complementary effects of dietary antioxidants. Hence, the bio-delivery of antioxidants is crucial as it assures the equilibrium between oxidants and antioxidants, thereby preventing oxidative stress and reducing the risk of NCDs. Out of the natural dietary antioxidants, plant-derived bioactive compounds (secondary metabolites): phenolic compounds, carotenoids, alkaloids, vitamins, and nitrogen-containing compounds play vital roles in plant reproduction, growth, and defense system, and more specifically, in the coloration of flowers and fruits. Significantly, these compounds are widely acknowledged for offering protection against oxidative stress. Therefore, in quantifying the capacity of antioxidants to counteract oxidative stress by quenching free radicals, quantitative assessment methods; electron transfer (ET) reactions, and hydrogen atom transfer (HAT), are involved in the field of research in biochemistry. This chapter reviewed the quantitative assessment methods that are based on ET

reactions; ferric ion reducing antioxidant power (FRAP) assay, the Trolox equivalent antioxidant capacity (TEAC) assay, 2,2-Diphenyl-1-picrylhydrazyl (DPPH) radical scavenging capacity assay, and the methods based on HAT; oxygen radical absorption capacity (ORAC), and hydroxyl radical antioxidant capacity (HORAC) assay.

Keywords: Antioxidants; Bioactive compounds; Health benefits; Plants

1. Introduction

1.1. Importance of Antioxidants

Antioxidants refer to naturally occurring body chemicals, phytochemicals, or drugs that delay or inhibit oxidative damage, often triggered by free radical reactive oxygen species (Weiss and Landauer, 2003). The term "Reactive Oxygen Species (ROS)" is a broad category that encompasses various oxygen-derived ROS produced through the excitation of electrons and redox reactions (Powers *et al.,* 2024; Phaniendra *et al.*, 2014). ROS can be categorized into two types: free radicals and non-radicals (**Table 7.1**). Among them, free radicals are characterized by instability, high reactivity, and energized states which can induce oxidative stress on the cellular makeup of organisms' bodies due to their unpaired electrons (Munteanu and Apetrei, 2021).

Table 7.1: List of reactive oxygen species (ROS)

Free radical reactive oxygen species	**Formula**
Hydroxyl radical	$HO^{\bullet}$
Superoxide anion radical	$O_2^{\bullet-}$
Alkoxyl radical	$RO^{\bullet}$
Peroxyl radical	$ROO^{\bullet}$
Non-radical reactive oxygen species	
Hydrogen peroxide	H_2O_2
Organic peroxide	ROOH
Singlet oxygen	$^1O_2$

Organisms' body cells endure continual exposure to diverse oxidizing agents, some of which are vital for sustaining life. The human body has evolved natural antioxidant systems (Natural Defense – immune system) to mitigate the impact of oxidative stresses triggered by free radicals (Chaudhary *et al.*, 2023). Enzymes *i.e.,* superoxide dismutase (SOD), glutathione peroxidase, and catalase, along with molecules of vitamin E, vitamin C, β carotene, uric acid, and glutathione, collectively serve as a natural defense system within the human body (Aziz *et al.*, 2019). The crucial aspect is to maintain equilibrium between oxidants (free radicals) and antioxidants to preserve optimal physiological conditions within the human body. Excessive generation of free radicals can disrupt this equilibrium, resulting in oxidative damage to large biomolecules such as nucleic acids, proteins, and lipids, thus leveraging the risk of Non-communicable Diseases (NCDs) such as Cardiovascular diseases, Cancer, Cataracts, Rheumatoid arthritis, Alzheimer's disease, Asthma, Diabetes, and Inflammation (Lobo *et al.*, 2010). Hence, to forestall or decelerate the oxidative stress provoked by free radicals, it's essential to ingest ample quantities of antioxidants. Biologically active compounds (bioactive compounds)-rich herbs, vegetables, fruits, and grains serve as primary sources of dietary antioxidants, and the consumption of those plant-based antioxidants can ensure enhanced plasma antioxidant capacity, thereby hindering the risk of the occurrence of NCDs (Southon, 2000).

1.2. Bioactive Compounds

Bioactive compounds refer to plant-derived non-nutrient compounds (secondary metabolites). Over 5,000 plant-based bioactive compounds have been identified, but a significant percentage remains yet undiscovered (Samtiya *et al.*, 2021). Plants encompass a diverse array of bioactive compounds, including carotenoids, phenolics, alkaloids, antioxidant vitamins like vitamin C and E, and nitrogen-containing compounds such as chlorophylls, all of which serve as excellent natural antioxidants **(Figure 7.1).**

Among the bioactive compounds in plants, some of them are hydrophilic (vitamin C and most flavonoids and phenolic acids) while others are distinctly lipophilic (carotenoids, chlorophylls, and vitamin E) (Vieira da Silva *et al.*, 2016). The content of bioactive compounds and Total Antioxidant

Capacity (TAC) in plants varies depending on factors such as species, cultivars, maturity, agronomic practices, geographic origins, growing seasons, postharvest handling, storage conditions and duration, and processing methods. In addition, bioactive compounds and TAC are also varied in different tissues of plants (Azmir *et al.*, 2013).

1.3. Phenolic Compounds

Plant phenolic compounds possess an aromatic ring with at least one hydroxyl group, exhibiting structural variations. These compounds stem from plant secondary metabolism, serving vital roles in plant growth and reproduction, systematic defense against pathogens, and predators, and influencing the coloration of plants. To date, nature has revealed over 2,000 phenolic compounds, with Flavonoids and Phenolic acids comprising most of plant dietary phenolics (Vieira da Silva et al., 2016).

1.4. Phenolic Acids

Phenolic acids are organic acids characterized by a solitary aromatic ring, which demonstrates acidic qualities owing to the inclusion of a carboxyl group (COOH). Subdivision into two primary categories: hydroxybenzoic acids, and hydroxycinnamic acids, considering the generic structure (Table 2) (Vieira da Silva *et al.*, 2016). Derivatives of hydroxybenzoic acid include gallic acids, protocatechuic, p-hydroxybenzoic, vanillic, and syringic. These are often found in bound states and are components of intricate structures such as hydrolyzable tannins and lignins. These may also occur as derivatives of sugars and organic acids in plant-based foods.

Derivatives of hydroxycinnamic acid include sinapic acids, p-coumaric, ferulic, and caffeic (**Table 7.2**) (Kumar and Goel, 2019). These derivatives exist in a bound state, linked with structural elements of cell walls *i.e.,* cellulose, proteins, and lignin via ester bonds. Caffeic, vanillic acids, p-coumaric, ferulic, and protocatechuic are found in nearly all plants (Liu, 2004).

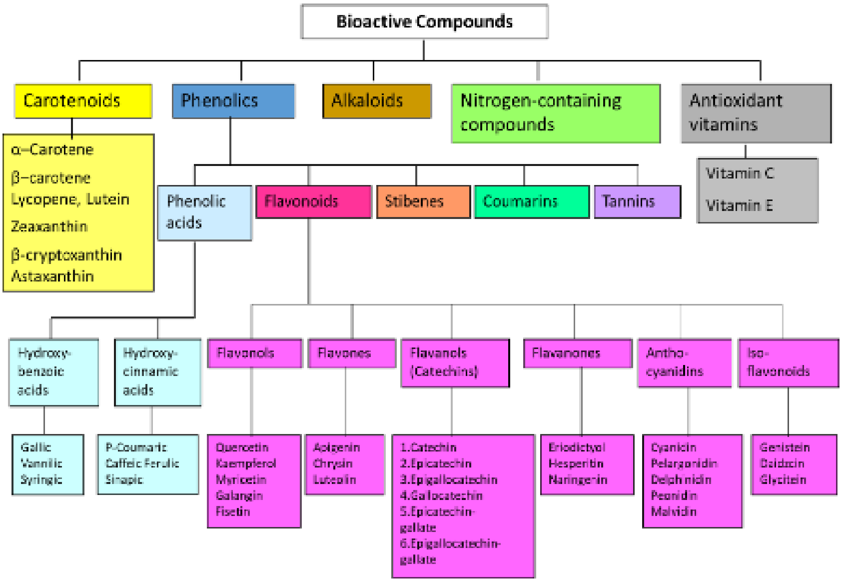
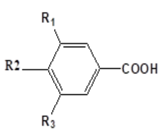
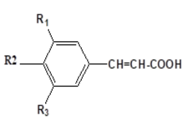


Figure 7.1: Bioactive compounds present in plants

Table 7.2: Common phenolic acid derivatives

Major group of phenolic acids	**Substitutions**			**Derivatives**
	R1	**R2**	**R3**	
(i) Benzoic acid 	H	OH	H	p-Hydroxy benzoic
	H	OH	OH	Protocatechuic
	CH_3O	OH	H	Vanillic
	CH_3O	OH	CH_3O	Syringic
	OH	OH	OH	Gallic
(ii) Cinnamic acid 	H	OH	H	p-Coumaric
	OH	OH	H	Caffeic
	CH_3O	OH	H	Ferulic
	CH_3O	OH	CH_3O	Sinapic

1.5. Flavonoids

Flavonoids, a category of phenolic compounds, typically share a basic structure comprising two aromatic A and B rings connected by three carbon atoms, commonly forming an oxygenated heterocycle C ring (**Figure 7.2**) (Dias *et al.*, 2021). Characteristic variations in the fundamental structure of the heterocycle C ring categorize them into six major groups; flavanols (Catechins), flavonols, flavanones, flavones, isoflavonoids, and anthocyanidins (**Table 7.3**) (Samec *et al.*, 2021).

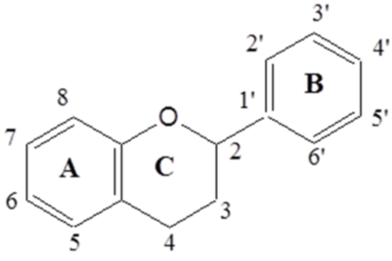
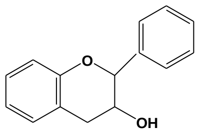
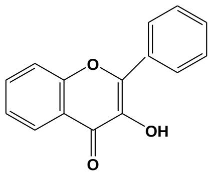
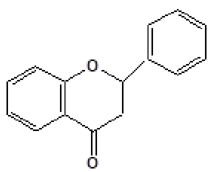
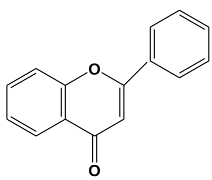
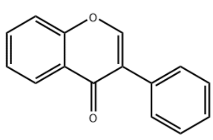
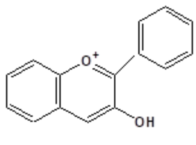


Figure 7.2: Basic flavonoid chemical structure

Most berries exhibit higher contents of phenolic acids and flavonoids compared to other fruit species, with flavanols, anthocyanidins, and flavonols being the predominant flavonoid subgroups. Berries with intense purple coloration typically contain higher phenolic content than those with a yellowish hue. Phenolic acids in most fruit species are derivatives of hydroxylated cinnamic and benzoic acid. Citrus fruits are renowned for their flavonone glycosides accumulation and are also a rich source of phenylpropanoids (Kaur and Kapoor, 2001; Macheix *et al.*, 1990).

Table 7.3: Structures of main classes of dietary flavonoids

Main flavonoids	Chemical structure	Examples
Flavanols (Catechins)		Catechin, Epicatechin, Gallocatechin, Epicatechin gallate, Epigallocatechin Epigallocatechin gallate
Flavonols		Quercetin, Kaempferol, Myricetin, Galangin, Fisetin
Flavanones		Eriodictyol, Hesperitin, Naringenin
Flavones		Apigenin, Luteolin, Chrysin
Isoflavonoids		Genistein, Glycitein, Daidzein, Formononetin
Anthocyanidins		Pelargonidin, Cyanidin, Peonidin, Malvidin, Delphinidin, Petunidin

1.6. Carotenoids

Carotenoids represent the most abundant natural pigments, with over 600 distinct types identified to date. These pigments are prevalent in plants, often found with chlorophyll in chloroplasts, and are also present in other types of chromoplasts. They display hues spanning from reddish, orange, and yellow to brown, and contribute to the characteristic yellowish hue observed in fruit flesh during ripening (Kays and Paull, 2004). Carotenoids have garnered significant interest because of their dual functions as provitamins and antioxidants.

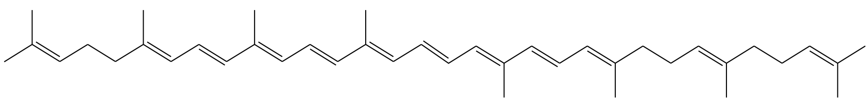
The fundamental structure of carotenoids comprises isoprene units with an acyclic skeleton of 40 carbon atoms. The defining characteristic of carotenoids is the extensive arrangement of conjugated double bonds in the central portion of the molecule, typically found in the all-trans configuration. This attribute determines the shape, light-absorbing, and antioxidant properties. Carotenoids can be cyclized at one or both ends or acyclized at both ends. Lycopene is a well-known example for acyclized carotenoids while β-carotene is characterized as cyclic carotenoids **(Figure 7.3)** (Kirti *et al.*, 2014). Dihydroxy derivatives of α-carotene and β-carotene are structurally referred to as lutein and its isomer zeaxanthin. The terminal rings of these molecules have two hydroxyl groups, and thus are characterized as xanthophylls **(Figure 7.3).** α-carotene, β-carotene and β-cryptoxanthin can serve as precursors of vitamin A.

Lutein and zeaxanthin are the main carotenoids found in the yellow spot of the human retina (macular region) hence known as macular pigments (Granado *et al.*, 2003).

Fruits with orange flesh, such as citrus fruits, papaya, apricot, mango, and cantaloupe, are abundant in β-carotene (Ruiz *et al.*, 2005), and tomatoes, watermelons, pink guavas, red-fleshed papaya, and pink grapefruit are among the lycopene-rich sources (Kris-Etherton *et al.*, 2002).

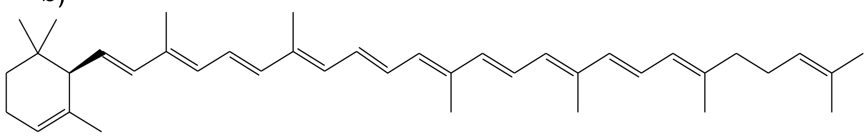
Carotenoid pigments play crucial roles in both photoprotection (shielding against excessive light) and photosynthesis in plants. Carotenoids provide photoprotection by effectively neutralizing free radical ROS *i.e.,* singlet oxygen, generated through severe light and air exposure. The same mechanism is employed when carotenoids function as dietary antioxidants when consumed, within the human body. Free radical ROS quenching ability of carotenoids' is associated with their conjugated double-bond system. The optimal protection is contingent on the chain length and the properties of the terminal groups (Foote *et al.,* 1970). Significantly, research on human health has predominantly concentrated on lycopene, as studies have shown that acyclic lycopene renders it more efficacious compared to cyclic β-carotene (Di Mascio *et al.,* 1989).

a)



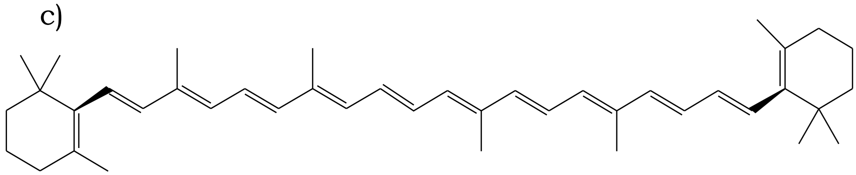
Acyclized (Lycopene)

b)



Cyclized at one end (δ-carotene)

c)



Cyclized at both ends (β-carotene)

Figure 7.3: Basic types of carotenoids

Accordingly, extensive research has been conducted to prove the carotenoids' potential in cancer prevention. Furthermore, Kris-Etherton *et al.* (2002) reviewed evidence indicating that a high intake of lycopene is associated with reduced occurrences of prostate, cervical, pharyngeal, oesophageal, gastric, bladder, colorectal, and rectal cancers.

The enhanced resistance to LDL oxidation with the increased ingestion of carotene-rich fruits and vegetables (20±30 mg daily consumption of carotenoids for 2 weeks) has been proven by a core human study in the EU. In advance, a notable correlation exists between elevated blood carotenoid levels and decreased levels of oxidative DNA damage, (Southon, 2000) thus mitigating the risk of almost all the chronic NCDs. Furthermore, it has been suggested that the oxidation of lens proteins by free radical ROS is the main cause of the formation of cataracts (Davies, 1990).

1.7. Vitamin C

Vitamin C, also known as ascorbic acid, is a hydrosoluble antioxidant vitamin and is one of the simplest structurally among plant-derived vitamins (**Figure 7.4**). However, its structure is readily oxidized in the presence of free radical reactive oxygen species, making it a highly effective antioxidant.

The plant-based biosynthesis of vitamin C takes place in two separate pathways. The conversion of GDP-D-mannose to GDP-L-galactose via a series of reactions headed to the generation of the immediate precursor of L-galactono-1,4-lactone as per pathway-one. The pathway-two involves the generation of L-galactono-1,4-lactone via spontaneous conversion of L-galactonic acid which is produced by the reduction of pectin-derived D-galacturonic acid. In the end, the dehydrogenase enzyme is involved in the conversion of generated L-galactono-1,4-lactone in both pathways to L-ascorbic acid (Valpuesta and Botella, 2004).

Compared to the other plant-derived hydrosoluble vitamins, vitamin C is present in relatively elevated concentrations within the plant matrix. Guava, kiwifruit, strawberry, citrus, cantaloupe, and pineapple are excellent sources of vitamin C among fruit species (Kays and Paull, 2004).

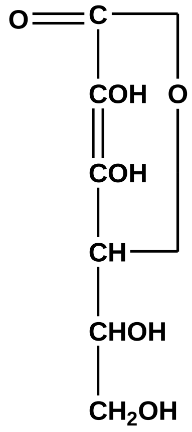


Figure 7.4: Chemical structure of vitamin C

By the early nineteenth century, there was widespread acknowledgment that consuming fruits and vegetables rich in vitamin C could prevent and treat scurvy. Vitamin C was officially identified as a supplemental treatment for scurvy in 1928. Subsequently, vitamin C became known as the antioxidant vitamin with respect to its ability to prevent or delay oxidative degeneration conditions which leads to the avoidance of chronic NCDs (Chambial *et al.*, 2013).

Vitamin C intake is crucially associated with general well-being and Individuals with sufficient dietary vitamin C intake seem to have a reduced risk of lung, oesophageal, and pancreatic cancers, as well as coronary heart disease (CHD) (Joshipura *et al.*, 2001). Furthermore, Knekt *et al.* (2004) proposed that the ingestion of vitamin C can lower the incidence of CHD in both men and women.

1.8. Chlorophylls

The dominant prevalence of green coloration in the kingdom Plantae is primarily attributed to the presence of chlorophyll pigments, which absorb wavelengths of red and blue light. Chlorophylls serve as the primary light-absorbing pigments within plants, facilitating photosynthesis by fixing carbon dioxide and releasing oxygen.

Chlorophyll, a porphyrin compound containing magnesium, is structured from four pyrrole rings. The two main forms of chlorophyll: chlorophyll a and chlorophyll b, structurally differ only with the substitution of an aldehyde (-CHO) on chlorophyll b with a methyl group (**Figure 7.5**). Typically, both types are present within the same plant following a ratio of chlorophyll a and b, approximately 2.5-3.5:1.

Two additional chlorophyll variants, chlorophylls c and d, are present in a relatively restricted range of species. For instance, chlorophyll c is identified in various marine plants. Similar to carotenoid pigments, chlorophylls are hydrophobic and therefore insoluble in water (Kays and Paull, 2004).

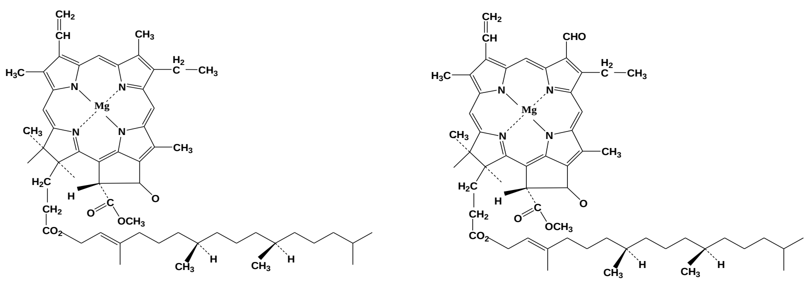


Figure 7.5: Structure of chlorophyll a (I) and chlorophyll b (II)

The process of chlorophyll biosynthesis is mediated by various external factors, with two of the most significant being light exposure and mineral nutrition. The first pyrrole ring, known as porphobilinogen, is synthesized from two δ-aminolevulinic acid molecules, which originate from succinate and glycine. It involves the polymerization of four molecules of porphobilinogen to form uroporphyrinogen, where each of the constituent pyrroles is attached with acetyl and propionyl groups.

Following a reaction series of decarboxylation, protoporphyrin is synthesized, and subsequently, the phytol tail is added following the insertion of magnesium. Chlorophyll a, characterized by a blue-green hue, distinguishes itself from yellow-green chlorophyll b solely by the substitution of a single methyl group in place of a formyl group (Kays and Paull, 2004).

Chlorophyll and chlorophyll derivatives exhibit high efficacy in binding polycyclic aromatic hydrocarbons (PAHs) – carcinogens mainly resulting from incomplete fuel combustion, as well as heterocyclic amines (formed during food grilling), aflatoxins (a mold-derived toxin that links with liver cancer), and various other aquaphobic molecules. The complex of chlorophyll-carcinogens is restrictly absorbed by the body, thus being excreted through feces (Donaldson, 2004). Dietary sources rich in chlorophylls may have a notable impact on cancer prevention, and evidently, several studies have reported the chemoprotective behaviour of chlorophyll a on human lymphoid leukemia molt 4B cells (Hibasami *et al.*, 2000).

2. Determination of Total Antioxidant Capacity (TAC)

2.1. Antioxidant Capacity Assays

Various techniques are presently employed in assessing the antioxidant capacity of crop produce. These methods can generally be categorized into two main groups based on the involved chemical reactions: hydrogen atom transfer (HAT) reaction-based assays, and assays reliant on electron transfer (ET) (Huang *et al.*, 2005).

2.2. ET-based Assays

The electron transfer (ET) based assays utilize a reaction mixture comprising two components: a probe acting as an oxidant and electrons from antioxidants. These assays rely on the below electron transfer reaction:

$$Probe\ (oxidant) + e\ (from\ antioxidant) \rightarrow Reduced\ probe + Oxidized\ antioxidant$$

The probe serves as an oxidant, extracting an electron from the antioxidant, thus creating a change in the colour of the probe. The degree of change in colour correlates directly with the concentrations of antioxidants in the reaction media. The reaction reaches its end point when the colour change ceases. By plotting the change in absorbance (ΔA) against the antioxidant concentration, it yields a linear curve. By referring to the slope of this curve, the antioxidant's reducing capacity can be quantified and typically expressed in Trolox equivalents (Huang *et al.*, 2005).

ET-based assays have become popular due to their ability to facilitate accurate quantification of the capacity of antioxidants to reduce the probe. Assays that use this principle include the ferric ion reducing antioxidant power (FRAP) assay, the Trolox equivalent antioxidant capacity (TEAC) assay, 2,2-Diphenyl-1-picrylhydrazyl (DPPH) radical scavenging capacity assay.

2.3. Ferric Ion Reducing Antioxidant Power (FRAP) Assay

The assay involves the reduction of the ferric salt, Fe (III)(2,4,6-tripyridyl-s-triazine)$_2$Cl$_3$ [Fe(III)-TPTZ] - oxidant (probe) to its ferrous [Fe(II)] form under acidic pH conditions (**Figure 7.6**).

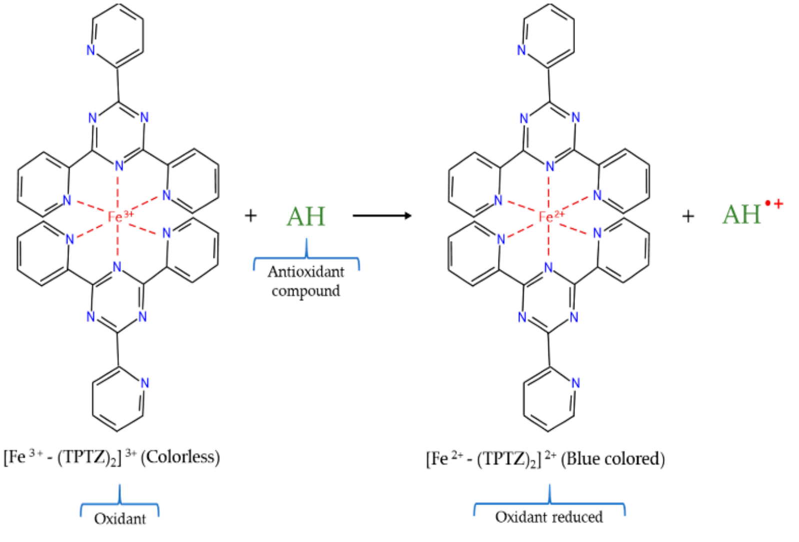


Figure 7.6: Reaction mechanism of FRAP

During the redox process, the colour of the oxidant changes to an intense blue colour with an absorption peak at 593 nm. Under the test conditions, the reduction of the ferric salt complex is encouraged, leading to significant colour development, which is evident in the presence of a reductant (antioxidant). After mixing the freshly prepared Fe (III)-TPTZ with an antioxidant, the absorbance is measured after four minutes to facilitate the redox reaction to proceed, and the read absorbance via spectroscopy is directly proportional to the concentration of the antioxidant present in the reaction medium (Munteanu and Apetrei, 2021).

The method of this assay initiates with the preparation of the FRAP reagent by mixing precise volumes of chemicals in the prescribed ratio, immediately before the assay (as outlined in **Table 7.4**). Careful attention has to be given to the chemical preparation process to ensure that the raw materials utilized are of suitable grade and high quality.

The procedure entails mixing 100 µL of methanolic extract of the samples with 900 µL of freshly prepared FRAP reagent at pH 3.6. Subsequently, the absorbance of the reaction mixture is measured at 593 nm spectroscopically after the reaction mixture has been incubated for 4 minutes (Benzie and Strain, 1996).

Table 7.4: The chemicals used in FRAP assay

Chemical	Quantity
10 mmol/L, 2,4.6-Tripyridyl-S-Triazine (TPTZ) in 40 mM, HCl	1 mL
20 mmol/L $FeCl_3$.6H2O	1 mL
300 mmol/L Acetate buffer (pH 3.6)	10 mL

2.4. Trolox equivalent antioxidant capacity (TEAC) assay

In the updated procedure, $ABTS^{\bullet -}$, the probe (oxidant), is produced through the persulfate oxidation of 2,2'-azinobis ($ABTS^{2-}$). This method relies on the ability of antioxidant molecules to deactivate the long-lasting $ABTS^{\bullet -}$, which appears as a blue-green coloured chromophore with a distinct absorption peak at 734 nm. Upon the addition of antioxidants, the blue-green $ABTS^{\bullet -}$ is converted to colourless $ABTS^{2-}$, and the absorbance is measured 6 minutes after mixing at 30°C. The entire reaction is carried out at pH 7.4 and by referring to the Trolox standard curve, the antioxidant capacity is quantified statistically (Miller *et al.,* 1993).

2.5. DPPH (2,2-Diphenyl-1-picrylhydrazyl) radical scavenging capacity assay

DPPH is a stable organic nitrogen radical that is commercially available and characterized by an intense purple hue with peak absorption occurring at 515 nm.

The standard procedure for the DPPH assay involves the following steps: a DPPH solution (3.9 mL) in methanol is combined with a sample solution (0.1 mL). The absorbance of the reaction mixture is then measured at 515 nm at different time intervals until the absorbance reaches a stable level. As the solution undergoes reduction, the initial purple colour gets fades. The inhibition percentage of DPPH is then calculated as below.

$$\%\, inhibition\ of\ the\ DPPH\ absorbance = (\mathbf{A}\, control - \mathbf{A}\, sample) \times 100/\mathbf{A}\, control$$

The degree of inhibition of DPPH absorbance correlates directly with the concentrations of antioxidants, with the concentration resulting in a 50% reduction in the initial DPPH concentration termed EC_{50}. The duration required to achieve equilibrium with EC_{50} concentration is determined from the kinetic curve and referred to as T_{EC50} (Munteanu and Apetrei, 2021).

2.6. HAT-based Assays

HAT evaluates an antioxidant's potential to quench free radicals with the donation of hydrogen atoms. HATs' antioxidant capacity assessment mechanisms involve the transfer of hydrogen atom (H) to a peroxyl radical from a phenol (ArOH):

$$ROO\bullet + AH/ArOH \rightleftarrows ROOH + A\bullet/ArO\bullet$$

The generated aryloxyl radical (ArO•) through the interaction of peroxyl radical (ROO•) with the antioxidant - phenol (ArOH), achieves stability through resonance in the presence of a protected molecule (AH). Common assays relying on hydrogen atom transfer include Oxygen Radical Absorption Capacity (ORAC), Total Oxyradical Scavenging Capacity (TOSC), and Hydroxyl Radical Antioxidant Capacity (HORAC) assay (Cekic *et al.*, 2013).

2.7. Oxygen Radical Absorption Capacity (ORAC) Assay

The Oxygen Radical Absorption Capacity (ORAC) assay evaluates the antioxidants' capacity to disrupt the radical chain reaction by monitoring the degree of inhibition of peroxyl radical oxidation within biological systems.

In this assay, peroxyl radical generators are used and are represented by hydrophilic and lipophilic azo compounds (Becker *et al.*, 2004). In the reaction media, a fluorescent sample is reacted with the peroxyl radical produced by a generator, resulting in decreased fluorescence of the fluorescent sample, which is read by a fluorimeter. This approach employs the antioxidant capacity assessments in the presence and absence of the antioxidant with the application of the area-under-curve method. Trolox is used here as a standard, and the ORAC values are expressed as Trolox equivalents (Munteanu and Apetrei, 2021).

2.8. Hydroxyl Radical Antioxidant Capacity (HORAC) Assay

This technique assesses the degree of protective capacity against hydroxyl radical formation using a Co (II) complex. Incubation of the sample extract along with fluorescein, followed by the addition of the Fenton mixture (hydroxyl radical generator) is involved in assessing the Hydroxyl Radical Antioxidant Capacity (HORAC). After recording the initial fluorescence, subsequent readings are taken every minute after agitation.

Gallic acid is utilized as the standard solution to construct the calibration curve and this assay provides direct assessments of the antioxidant's ability to impede the radical reaction (Ciz *et al.*, 2010).

3. Determination of Total Phenolic Content (TPC)

3.1. Folin–Ciocalteu Assay

Folin–Ciocalteu assay has been extensively employed in clinical and nutritional research to determine the total phenolic contents (TPC) in plant-based foods and biological specimens. The principle of the Folin–Ciocalteu assay involves the reduction of the Folin–Ciocalteu reagent by phenolic compounds under alkaline conditions. The reagent is suggested to potentially comprise a phosphotungstic acid

($H_3PW_{12}O_{40}$) /phosphomolybdic acid ($H_3PMo_{12}O_{40}$) complex. A blue chromophore is formed with the subsequent reduction of this complex, with peak absorption occurring at 760 nm (Echegaray *et al.*, 2021; Magalhães *et al.*, 2008).

The molybdenum ion at the core of the complex is recognized as the site of reduction, wherein the Mo^{6+} ion undergoes reduction to Mo^{5+} through the acceptance of an electron from the donor, a phenolic antioxidant (**Figure 7.7**) (Barrows *et al.*, 1985). Hence, the Folin–Ciocalteu assay is an ET-based method, that focuses on the phenolic antioxidants' reducing capacity. Widely used standard of Gallic acid serves as the reference, with TPC outcomes typically denoted as Gallic acid equivalents (Karadag *et al.*, 2009).

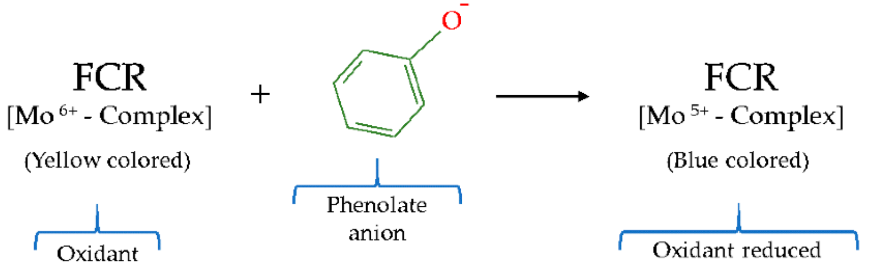


Figure 7.7: Reaction mechanism of Folin-Ciocalteu Assay

The test protocol was designed to quantify TPC by the modified Folin-Ciocaltue method (Abeysinghe *et al.*, 2007). The method in brief, 0.5 mL of 0.2 N Folin - Ciocalteu reagent is added into a test tube containing 0.5 mL of methanolic extract sample, which is diluted with 4 mL of distilled water. After an exact 3 mins of reaction time,1 mL of saturated Sodium Carbonate solution is introduced to the reaction media, and further reaction is facilitated by incubating the test samples at 30°C in a water bath for 2 hours. Thereafter, the absorbance is measured at 760 nm using spectrophotometry and the TPC results are interpreted as gallic acid equivalent (GAE).

3.2. Determination of Total Flavonoid Content (TFC)

Total flavonoid content is assessed following the method outlined by Hettiarachchi *et al.* (2020). The method involves the addition of 1.5 mL of methanolic extract to 3.5 mL of distilled water followed by the addition of 0.3 mL of 5% $NaNO_2$ along with the incubation for 5 minutes at room temperature. Next, 0.3 mL of 10 % $AlCl_3$ is added to each test set and the incubation is repeated for 6 minutes at room temperature. Then, 2 mL of 1.0 M.

NaOH is added and the solutions of each test set are made up to 10 mL with the addition of distilled water. Finally, the peak absorbance at 510 nm is read spectrophotometrically. Total Flavonoid content is expressed as rutin equivalents (RE).

4. Conclusion

In conclusion, antioxidants serve to delay or inhibit oxidative damage induced by free radical ROS. Dietary intake of antioxidants from plant-based sources, rich in bioactive compounds such as phenolic compounds and carotenoids, offers enhanced plasma antioxidant capacity and helps reduce the risk of NCDs. Plant-derived bioactive compounds have immense potential in addressing diverse health issues and fostering general wellness. Various methods, including electron transfer (ET) and hydrogen atom transfer (HAT) reactions, are employed in biochemistry research to assess the effectiveness of antioxidants in combating oxidative stress. These methods provide valuable insights into the potential health benefits of antioxidants and aid in developing preventive strategies against chronic diseases.

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Chapter Eight

Biotechnology: An Untapped Technology Resource in Sri Lanka

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Abstract

The agriculture sector in Sri Lanka can certainly be boosted by harnessing the full potential of biotechnology for increasing crop yields, creating pest- and disease-resistant cultivars, and improving the nutritional value and post-harvest quality of the produce. Biotechnology can also support the country to achieve sustainable development goals in agriculture through eco-friendly approaches such as biofertilizers, biopesticides, and biocontrol agents. However, the progress of biotechnology has been slow in Sri Lanka over decades despite the opportunities it offered for global development. The unexplored biodiversity in Sri Lanka extends abundant genetic resources from plants, animals, and microorganisms that can be used in biotechnological research to find new genes, enzymes, and bioactive compounds with commercial potential in national and international markets. Sri Lanka can leverage biotechnological tools to mitigate environmental pollution by promoting sustainable industrial processes including biofuel production, biotreatment of wastewater, bioremediation of contaminated soil and air, and aerobic and anaerobic treatment of solid waste leading towards a circular economy. Undoubtedly, the development of biotechnology-based industries in the country depends significantly on large investments in developing infrastructure such as well-equipped laboratory facilities, which is in progress. In addition, sufficient funding from public, private, and international funding bodies is needed to boost research

studies and commercialization of bioproducts. To attract investments and public trust, it is crucial to establish and update explicit rules and regulations pertaining to intellectual property rights, bioethics, biosafety, and biodiversity conservation. Working diligently to increase awareness of biotechnology as a valuable tool in sustainable development among scientists, policymakers, entrepreneurs, investors, politicians, and the public is the duty of science communicators and experts.

Keywords: Biotechnology, Opportunities and challenges, Progress, Regulatory policies, Sri Lanka

1. What is Biotechnology?

Biotechnology is a field that merges biology and technology to develop products and technologies aimed at improving human health, agriculture, industry, and the environment. It involves using biological systems, organisms, or their derivatives to develop or modify products and processes for specific applications.

Biotechnology is an integrated discipline, allied with biochemistry, cell biology, breeding, molecular biology, microbiology, immunology, synthetic biology, computational biology, and bioprocess technology that encompasses a wide range of techniques and methods, including genetic engineering, bioinformatics, and cell and tissue culture, *etc* to facilitate the application of biological agents towards technological advancements. Food processing, pharmaceutical production, disease diagnostics, and environmental protection are just a few of the areas where biotechnology has emerged as a science with immense potential for improving human well-being.

Biotechnology has extensive applications in various sectors, such as agriculture, food and nutrition, medicine, industry, and the environment. The rainbow code of biotechnology (Kafarski, 2012) categorizes biotechnology into ten different fields of application with a theme color for each (**Table 8.1**), even though some of these fields are interconnected and overlapped. This code is useful for scientific, business, and other communities including the general public as a tool for biotechnology and to recognize the unexplored potentials of the biotech industry for a country toward a biotechnology-based economy.

Table 8.1. Different Fields of Biotechnology and Their Colour Codes

Field	Colour Code	Example
Agricultural Biotechnology	Green	Pest and disease-resistant crops, Crop and livestock breeding, Sustainable farming practices
Food & Nutritional Biotechnology	Yellow	Fermented food and beverages, Lactose-free dairy, Probiotics
Medical Biotechnology	Red	Biopharmaceuticals, Gene therapy, Diagnostic tools, Stem cell therapy, Precision medicine, Medical imaging
Industrial Biotechnology	White	Biopolymer, Biofuel, Sweeteners, Solvents, Pulp & paper, Textiles, Detergents, Animal-feed
Environmental Biotechnology	Gray	Biosensors, Bioleaching, Bioremediation
Marine & Aquatic Biotechnology	Blue	Aquatic bioprocessing, Aquatic bioremediation
Dessert & Arid Region Biotechnology	Brown	Drought-resistant crops, Seawater dessert houses, Biomineralization
Computational Biotechnology	Gold	Computational genomics, Computational neuroscience, Bioinformatics
Law, Ethics & Philosophy	Violet/Purple	Patents, Geographical Indications, Laws, regulations, Ethical solutions
Bioterrorism & Biowarfare	Dark/Black	Genetically engineered pathogenic organisms, Phytotoxins

The history of biotechnological applications dates back to the agricultural age of human civilization e.g. selection, hybridization, and propagation of plants and animals. The term Biotechnology was coined by a Hungarian agricultural engineer Karoly Ereky in 1919. The old biotechnology encompasses first-generation applications e.g., microbial fermentation to produce food and beverages and second-generation applications such as antibiotic production and cell and tissue culture. The modern or third-generation biotechnology emerged in the 1990s and involves rapid alteration or manipulation of genetic material through recombinant DNA technology (Attanayaka and Balasooriya, 2022). Biotechnology is rapidly evolving globally with immense contributions to the bioeconomy toward achieving sustainable development.

2. How does Biotechnology Progress in Sri Lanka?

In Sri Lanka, biotechnology research and development has been initiated and progressed slowly, mostly in the interests of a limited number of researchers. The implementation of the Biotechnology Steering Committee at the National Science Foundation (NSF) (formerly known as the Natural Resources, Energy, and Science Authority) in 1992 was a significant step toward advancing and funding biotechnology research in universities and research institutions. In the year 1997, the Ministry of Economic Reforms, Science, and Technology recognized biotechnology as a crucial field for national advancement. It provided funds to develop human resources and capabilities in some selected universities and research institutes via a loan received from the Asian Development Bank. Biotechnology was listed as a priority area for development in the national report that the Ministry of Environment and Natural Resources submitted in 2002 for the Global Summit on Sustainable Development (Fernando, *et al.*, 2004).

Through the efforts of the NSF followed by the National Research Council (NRC) and by recognizing the priorities in agricultural biotechnology, the Council for Agricultural Research Policy (CARP) as local funding bodies contributed to developing considerable capacity in terms of human resources and infrastructure over the years in a variety of biotechnology sectors (Fernando, *et al.*, 2004).

The Ministry of Environment and Natural Resources completed a project that resulted in the establishment of Sri Lanka's national biosafety framework of Sri Lanka (NBFSL) in 2005. As a result, a database, management structure, and regulatory system for the safe handling, release, and transportation of products (food, feed, and processed) and genetically modified organisms (GMOs) derived from modern biotechnology was established. In order to fulfill the requirements of the Cartagena Protocol on Biosafety (CPB) and the Convention on Biological Diversity (CBD), which Sri Lanka has signed, it was crucial to establish a national policy for biosafety (Kankanamge, 2022). The Cabinet of Ministers gave their approval to this policy in 2005. The National Biosafety Project has completed the biosafety masterplan, which offers a roadmap for carrying out the National Biosafety Policy (Ministry of Environment, 2011). However, the Biosafety Act must be in effect to complete the regulatory component. The current draft of the Biosafety Act suggests that the Central Environmental Authority of the Ministry of Environment (MOE) as the regulating agency after implementing the the act (Kankanamge, 2022). The Attorney General's Office, the Cabinet of Ministers, and the Sri Lankan Parliament still need to approve this act.

A policy statement on biotechnology was jointly developed by the NSF and the National Science and Technology Commission (NASTEC) through extensive consultation with academia, researchers, ministry-level policymakers, industrialists, non-government organizations, and other stakeholders including the public in 2009. This was adopted as the National Biotechnology Policy for Sri Lanka by the cabinet in the year 2010 (Ministry of Science and Technology, 2009).

In 2021, the Sri Lanka Biosafety Clearing House (BCH), a trilingual website, was launched by the Ministry of Environment in collaboration with the National Biosafety Project. The Cartagena Protocol on Biosafety has been fulfilled with the launch of the BCH. Offering a portal to worldwide biosafety information, it gives details about the authorities, rules, guidelines, experts, databases of genetically modified organisms, risk assessment, awareness, contacts, approval procedure, and linkages to the global

BCH. The BCH website is updated by the Ministry of Environment's Biodiversity Secretariat (Kankanamge, 2022).

Biosafety instructional materials were prepared for various educational levels as part of the Biosafety Project. Teachers were given two complete resource books to use. The content was shared with the National Institute of Education (NIE). Further, the teachers who teach advanced level (A/L) biology received biotechnology training from the Ministry of Education and the Agricultural Biotechnology Center/University of Peradeniya. Furthermore, three certificate courses in biotechnology and biosafety have been introduced for postsecondary education. Audiovisual, electronic materials on biosafety awareness are available on the BCH website (Kankanamge, 2022).

Equipment needed to examine genetically engineered components is being upgraded as part of the National Biosafety Project to increase Sri Lanka's detecting capability. The ITI and National Plant Quarantine Services labs will carry out the regulatory testing, while the Agricultural Biotechnology Center/ University of Peradeniya functions as the national referral lab. Moreover, Sri Lanka Customs received the capacity to conduct rapid tests, and the Government Analyst Department (GAD) was given access to the Enzyme-Linked Immunosorbent Assay (ELISA) based facility. Detection methods of GE contents were taught to officers at those institutes and inspection, monitoring, and sampling of GE content were jointly trained to over 100 plant quarantine authorities, food and feed inspectors, seed inspectors, and customs officials by the Agricultural Biotechnology Center/ University of Peradeniya and the Biotech Consortium India Limited. Through the national biosafety project, Sri Lanka has been equipped with sufficient technical and human resources to implement regulatory testing (Kankanamge, 2022).

Fortunately, several undergraduate and postgraduate courses offered by state and non-state sector higher education institutes now include biotechnology in their curricula. Many undergraduate and postgraduate level research has been successfully completed with the local and international grants received. However, the finances for the continuation of research activities is one of the major drawbacks, limiting commercial-level applications.

The government of Sri Lanka made a strategic decision to establish Sri Lanka Institute of Biotechnology (SLIBTEC) Private Limited as a government-owned company on October 12, 2020. The only stakeholder of the company is the Secretary to the Treasury, and its business registration number is PV 00228896. As a Gazette under the Ministry of Technology, SLIBTEC was founded on December 11, 2020, and it was subsequently drawn under the State Ministry of Digital Technology and Entrepreneur Development. The company was earlier located in Rajagiriya at 1090, Sri Jayewardenepura Mawatha. With effect from 2021, SLIBTEC established its headquarters in Pitipana, Homagama, following the completion of the infrastructure required to support all facets of its operations. Currently, SLIBTEC is a government organization that works with the Ministry of Education. It was planned to develop an innovation park and SLIBTEC in stages to promote high-tech exports and import replacement goods. The ultimate goal of this exercise is to establish the conducive environment necessary for biotech companies to collaborate and advance their concepts into technological research and commercial products.

Ceylon cinnamon received Geographical Indication (GI) status in 2022 from the European Union (EU) Commission, signifying a momentous historical event. This is the first GI certification received by Sri Lanka. This is the outcome of a decade-long, painstaking, and laborious endeavour meticulously managed by the Sri Lanka Export Development (EDB) under the Ministry of Trade. United Nations Industrial Development Organization (UNIDO), the European Union Delegation to Sri Lanka, and the World Trade Organization (WTO) provided much-needed technical assistance and the Netherlands-based Common Fund for Commodities granted some funding. The Department of Commerce, the Foreign Ministry, the National Intellectual Property Office, the Department of Export Agriculture, the Spice Council, and the Spices and Allied Products Producers,' Traders' Association (SAPPTA) provided the EDB with excellent support throughout this ground-breaking mission (Export Development Board).

3. What are the Applications of Biotechnology in Sri Lanka?

Biotechnology can significantly contribute to address social, economic, and particularly industrial development concerns in both developed and developing nations. However, it seems that biotechnology's potential, particularly with regard to its industrial uses, is largely underutilized in many developing countries, including Sri Lanka. Sri Lankans have not been able to fully benefit from worldwide advancements in biotechnology in many fields, although products such as medicines, vaccines, diagnostics, and agricultural products are imported. The biotechnological applications in Sri Lanka with special attention to the agricultural, and environmental sectors in which considerable progress has been observed during the last decades are summarized as follows.

3.1 Agricultural Biotechnology

Since the 1970s, Sri Lanka has utilized biotechnology, starting with the commercial production of orchids through tissue culture. From that day forward, tissue culture techniques have been used to produce ornamental and aquatic plants, flower crops, fruit crops, and a few timber and medicinal species in large quantities. Molecular breeding methods have been utilized to shorten the crop improvement process. To explore genotypic diversity and for indirect selection of favourable traits (qualitative and quantitative), molecular markers like restriction fragment length polymorphism (RFLP) and simple sequence repeats (SSRs) are promising tools. Transgenic plants with beneficial genes, such as pest and disease resistance, herbicide resistance, longer shelf life, nutritional value, productivity, *etc.*, may now be produced through rDNA technology.

3.1.1. Plant Tissue Culture

Plant Tissue Culture is widely used for rapid production of virus-free genetic stock and planting materials. This technology is identified as a cost-effective clonal replication method for many ornamentals, flowery, medicinal, fruit, and forest plant species. Further, somaclonal variations make new genetic variations possible. The beginning of plant tissue culture research in Sri Lanka is traced back to the early 1970s, initiated by the researchers of crop research institutes who were trained abroad in this relatively latest field at that time. Until the early 1980s, research was mainly confined to developing micropropagation protocols. The Department of Agriculture (DOA), the Department of Export Agriculture, the Faculty of Agriculture of the University of Peradeniya, and most crop research institutes were equipped with plant tissue culture facilities, and extensive research was undertaken during the early 1980s (John, 1991; Ganashan & Balendira, 1992; Fernando, 1994).

The Department of National Botanic Gardens was the first institution to establish a plant tissue culture laboratory in Sri Lanka. Mass production of orchids (through meristem and seed culture), palms, and other flowery and ornamental plants with commercial value, and new varieties through mutation studies are undertaken at this laboratory. Monthly training programs on tissue culture with theory and practical demonstrations are conducted for individuals interested in initiating a tissue culture facility of their own (Department of National Botanic Gardens). Further, the department facilitates demonstrations on tissue culture for school children and supports conducting undergraduate and postgraduate research projects (John, 1991; Ganashan & Balendira, 1992; Fernando, 1994).

The DOA functioning under the Ministry of Agriculture is one of the largest government departments with a high-profile community of agriculturists and agricultural scientists and a network of institutions covering different agroecological zones island wide. Agricultural research, technology dissemination, seed and planting material production and distribution, and regulatory services are the major functions of this department. Therefore, most of the institutes of DOA are equipped with plant tissue culture facilities (Tissue Culture-Department of Agriculture Sri Lanka).

The Biotechnology and Tissue Culture Division of the Rice Research and Development Institute focuses on producing rice varieties with improved grain qualities and tolerance for biotic and abiotic stresses through mutation breeding by applying the indirect organogenesis method of plant tissue culture (RRDI_Div_BioTechnology – Department of Agriculture Sri Lanka).

The Plant Genetic Resource Center (PGRC), Gannoruwa, contributes significantly to the evaluation and conservation of germplasm. It is divided into two laboratories: as molecular and *in vitro* conservation. The process of conserving germplasm aseptically inside glass jars as plants is known as "*in vitro* conservation." This slow-growth conservation strategy is to preserve plants that are either not producing seeds or have recalcitrant seeds. Research on developing *in vitro* techniques to conserve many vegetatively propagated crop species, including roots and tubers and many tropical fruit crops are being carried out by this subunit and some successful protocols were already implemented. Cryopreservation techniques for long-term conservation of plant genetic resources are also being implemented (PGRC-Biotechnology–Department of Agriculture Sri Lanka).

The Plant Tissue Culture Division of Coconut Research Institute (CRI) develops *in vitro* techniques for clonal propagation, dihaploid plant production, and exchange and conservation of germplasm for crop improvements. The following are the major achievements (Tissue Culture Division, Coconut Research Institute).

- "Development of a protocol for *in vitro* plant regeneration using unfertilized ovary, a novel and promising explant for clonal propagation of coconut, for the first time in the history of coconut tissue culture" (Perera, 2006).

- "Development of a dihaploid plant production protocol via coconut anther culture for the first time in coconut tissue culture, a breakthrough towards the production of pure lines for hybrid coconut production" (Perera& Vidhanaarachchi, 2021)

- "Through the germplasm exchange program, mature embryos of 28 exotic coconut varieties were imported from India, Papua New Guinea, and Ivory Coast, raised the plants *in vitro,* and finally established in the field for future breeding programs".

- "Establishing field trials of ovary-derived clonal coconut plants and confirmation of their genetic fidelity with molecular markers."

- "Development of cryopreservation protocols using mature embryo and plumule as a measure of long-term conservation of coconut germplasm" (Welewanni, Jayasekera & Bandupriya, 2017).

- "Development of a reliable embryo culture technique for coconut and propagation of *Dikiri* coconut through embryo culture technology (Vidhanaarachchi, 1998) to supply true-to-type *Dikiri* coconut plants to growers at a nominal rate".

At present, attempts are being made by the Rubber Research Institute of Sri Lanka to evaluate the effect of different parameters that significantly influence somatic embryogenesis in high-yielding clones of rubber grown in Sri Lanka with the aim of utilizing this system in crop improvement programmes (Nayanakantha and Seneviratne, 2007).

The Plant Breeding Division of the Tea Research Institute (TRI) successfully integrated the plant tissue culture techniques including direct proliferation through existing meristems, organogenesis and somatic embryogenesis, mutation breeding, protoplast culture, and hybridization into the conventional vegetative propagation and breeding programs authenticating its practical application to reduce the time taken to develop new cultivars by six years (Gunasekare, 2012; Gunathilake *et al.*, 2020; Ranaweera *et al.*, 2020; Tea Research Institute of Sri Lanka)

The Crop Improvement Division of the Sugarcane Research Institute, Udawalawe focuses on conventional breeding for the development of high yielding (both sugarcane and sugar) and pest and disease-resistant varieties suitable for commercial cultivation under different Agro-ecological regions in Sri Lanka. Some projects applied plant tissue culture techniques to micropropagate sugarcane varieties, and crop improvements by inducing genetic somaclonal variations through gamma irradiation followed by *in vitro* screening of positive mutagens (Division of Crop Improvement-Sugarcane Research Institute, Sri Lanka).

The Horticultural Crops Research and Development Institute (HORDI) engaged in research on micropropagation of banana, grape, pineapple, papaya, and passionfruit varieties/cultivars, improving the germplasm of vegetable crop species including bell pepper, tomato, brinjal, and bitter gourd through another culture techniques, embryo rescue of bitter gourd, micro tuber production of Dioscorea, *etc* (HORDI, Department of Agriculture Sri Lanka).

Attempts were taken to micro-graft cashew, mangosteen, and citrus *spp.* through research conducted by the National Institute of Fundamental Studies (NIFS), Kandy, DOA, and Royal Botanical Garden (Ganashan & Balendira, 1992). Micropropagation of bamboo species is initiated at the Royal Botanical Garden where the tissue culture laboratory of the Mahaweli Authority of Sri Lanka started mass production under the Punarudaya National Programme (2016-2018) claiming that over one million bamboo plantlets have been produced using tissue culture technology and planted in many parts of the country (Mahaweli Authority of Sri Lanka, 2018).

There are several publications on micropropagation protocols experimented with and developed for cash crops including vanilla, nutmeg, cinnamon, cloves, cardamom, pepper, arecunut, ginger, and turmeric by the Department of Export Agriculture (E.g.: Yapabandara & Dassanayake, 1990; John, 1991; Swarnathilaka, and Nilantha, 2012; Annual performance report-2013; Swarnathilaka, Kottearachchi and Weerakkody, 2016).

Institute of Agro-Technology and Rural Sciences, University of Colombo is a leading government institute producing tissue-cultured banana plants continuously on a large scale to cater to the increasing island-wide demand (Opening of New Tissue Culture Laboratory – UCIARS, 2024).

Ornamental Fish Breeding and Training Center, Rambadagalla under the National Aquaculture Development Authority of Sri Lanka engage in ornamental aquatic plant tissue culture providing quality parent stocks and tissue-cultured plantlets to local and export markets and conducting training programmes on propagation and cultivation of ornamental aquatic plants (Mahaweli Authority of Sri Lanka, 2018).

The universities in Sri Lanka largely contribute to PTC-based research through undergraduate and postgraduate studies on developing novel protocols for the micropropagation of various economically important plants, mutation breeding, and *in vitro* screening towards crop improvements. Agrobacterium-mediated gene transformation studies (Ratnayake & Hettiarachchi, 2010) and baseline studies on direct uptake of target DNA into protoplasts (Fernando *et al.*, 1997) followed by regeneration of plantlets via *in vitro*-derived embryonic calli or protoplast were conducted for some Sri Lankan rice varieties.

Bandaranayake Memorial Ayurveda Research Institute, Maharagama is involved in the mass propagation and conservation of local medicinal plants (Sudusinghe, *et al.,* 2024). Further, at the university level and in many other research institutes and a few private sector companies have developed protocols for micropropagation and extraction of secondary metabolites from callus and cell suspension cultures of many herbaceous and woody plant species with medicinal value including, *bin kohomba* (Senarath *et al.*, 2007), red sandalwood (Warakagoda & Subasinghe, 2013), *weniwel* (Warakagoda *et al.*, 2017), *ekaweriya, komarika*, *etc.* (National State of the Art Report, Ministry of External Affairs, Sri Lanka).

Further, there are several species with timber value for which micropropagation protocols were developed including *nadun* (Abeyaratne *et al.*, 1990), agarwood (Munasinghe, *et al.*, 2021), *mee, palu* and *kaluwara* (Karunarathna & Iqbal, 2019) at the level of universities and research institutes.

In Sri Lanka, a large number of government actors are engaged in seed potato production. Tissue culture is the first step in the generation of seed potatoes in dedicated laboratories at the Department of Agriculture's Seetha Eliya and Bandarawela Research Stations of Seed and Planting Material Development Center (SPMDC), Peradeniya. The facility itself maintains the mother plants for tissue culture, which are imported from the Netherlands. Only these stations carry out the official tissue culture procedure for potatoes in Sri Lanka and no private organizations are involved in the procedure (Kuruppu *et al.*, 2020).

The first private-sector commercial tissue culture laboratory was established by the Ceylon Tobacco Company during the early 1980s starting mass propagation of orchid plants. Since the 1990s, the commercial production of tissue-cultured plants with a high commercial value has progressed. The micropropagation techniques have been optimized to receive high proliferation rates with lesser variations. To date, ornamentals like syngonium, spathiphyllum, ficus, zantedeschia, and ferns have been produced by tissue culture and exported to Europe, Japan, and Australia. Tissue culture systems have been successfully developed for *Dracaena*, *Cordyline*, *Anthurium andreanum*, *Pleomele*, *and Aglaonema* species. Tissue culturing was successfully applied with banana, strawberry, papaya, passion fruit, grapes, and pineapple. Commercial quantities of tissue-cultured strawberry plants have been exported to Holland. Tissue cultured banana gave better yields and more sucker formation compared with conventionally grown plants. The varieties tested were Ambul, Kolikuttu, and Anamalu (Ganashan & Balendira, 1992).

Private companies such as Serendib Horticulture Technologies (Pvt.) Ltd., CIC Agro-Industry, Hayleys Agro Biotech (Pvt) Ltd, Mike Flora (Pvt.) Ltd., Ramya Horticulture, Serendib Horticulture Technologies Pvt. Ltd., EuroAsia Agro (Pvt) Ltd, Golgi Tec, and Borneo Exotic Pvt Ltd are involved in the micropropagation of flowery and ornamental plants, fruit crops, and aquatic plants. Most of the private PTC laboratories mainly produce ornamental plants for the domestic and/or international markets. Large quantities of fruit plants, particularly banana and pineapple varieties, are produced by some industries like Serendib Horticulture and Hayleys Agro Biotech. Private companies like Greengrow Aquaculture Private Limited and Serendib Horticulture Technologies Pvt Ltd produce tissue-cultured aquatic plants targeting export markets. Additionally, several companies collaborate with and serve as consultants to foreign companies and governments. However, very few industries have public-private partnerships within the country.

Private sector entities have also been involved in both seed production and importation of seed potatoes from six countries since 2013 where the Netherlands played a vital role. The Tissue Culture Laboratory established by EuroAsia Agro (Pvt) Ltd. consisted of 20,000 ft^2 greenhouses to produce disease-free, high-quality seed potatoes (mini tubers) and big onion seedlings of selected varieties since a large part of the planting material requirement in Sri Lanka is met through imports. Initially, a grower network was set up in every agro-climatic zone in Sri Lanka in order to acclimatize planting materials and reach out to farmers. Under this program, *in vitro* plants, and micro tubers are produced in the tissue culture laboratory, and rooted stem cuttings and mini tubers are produced in insect-proof net houses. Under this program, early mature, high-yielding, late blight-resistant varieties adaptable to the existing cropping systems of the up-country wet zone and up-country intermediate zone were developed. Further, maintenance of an *in vitro* collection of varieties, testing micro plants and mini-tubers (in case of potato) for viruses, clonal propagation of selected varieties by shoot tip culture, elimination of viruses from virus-infected micro plants by chemo/thermo-therapy and conducting susceptibility trials on diseases for potentially new varieties are progressing both for potato and big onion (Asia Plant Biotechnology, 2023).

The majority of the growers supply their PTC products to the local market, while a few supply to the international market. Banana, foliage, aquatic plants, and strawberries are supplied to both local and international markets. The micropropagated plants are mainly exported to the USA, Canada, UK, Netherlands, Germany, Poland, Switzerland, Qatar, Pakistan, Maldives, Japan, Thailand, Australia, Israel, South Africa, South Korea, Denmark, and Russia (Padukkage *et al.*, 2023). Further, the above companies have continued their export business for more than five years.

Most of the plant tissue culture-based producers are registered members of the Association of Sri Lanka Growers of Plant Tissue Culture (ASGROPTIC). It was established in 2019 at the Sri Lanka Institute of Information Technology

(SLIIT) which was formed as a result of a research project carried out by the School of Natural Sciences at SLIIT funded by the World Bank and made available through AHEAD Operations (Padukkage *et al.*, 2023).

3.1.2. Crop Improvements

Increasing crop yields, quality, shelf life, and resistance to abiotic and biotic stresses towards high productivity have been largely attributed to genetic improvements. With the advancement of biotechnology, crops have been developed revolutionary worldwide during the past three decades. RNA-guided genome editing technology facilitates the addition and removal of important and undesirable traits respectively expanding the field of agricultural research. The crop breeding efficiency has been further improved through marker-assisted breeding. Additionally, it has opened up new avenues for the development of novel plant varieties through cisgenic or transgenic approaches (Bandaranayake, 2020).

In Sri Lanka, a wide range of crops has been subjected to a variety of improvement programs, including rice, other field crops (such as maize, millets, oilseeds, and other grain legumes), vegetables and fruits, sugarcane, tea, rubber, coconut, and export agriculture crops (such as cinnamon, cardamom, black pepper, and coffee) (Liyanage *et al.*, 1988; Sedgley & Attanayake, 1988; Attanayaka, 2001; Gunasekare, 2012; Bentota, *et al.*, 2017; Marambe, *et al.*, 2018; Perera, 2023).

Further, developments in genome sequencing provide access to the large and complex genomes of crops and their wild relatives, facilitating the identification of a broad range of genetic variation and the correlation of genetic diversity with various agronomic traits. One of the major milestones in Sri Lankan genomics history was the successful sequencing of the entire genome of *Goda wee*, which is an indigenous salt-tolerant rice variety in Sri Lanka. This was conducted by the only genome sequencing facility available in Sri Lanka back then at The Human Genetics Unit, Faculty of Medicine, University of Colombo in collaboration with John Keells Research (Singhababu *et al.*, 2017). Later, some other researchers led genome sequencing projects to understand the genetic makeup of both traditional and modern rice varieties. The Wayamba University of Sri Lanka was able to develop a cross between At354, a salt-tolerant rice variety, and Bg352, a salt susceptible rice variety which helped to map several regions of the rice genome containing salt-tolerant genes. They were also able to sequence the whole genome of the above two rice varieties using Next Generation Sequencing (NGS). This was the first reported research in the world on whole genome sequencing of a Sri Lankan rice variety mapped with the Indica rice genome, R498 and the second reported research on mapping with the *Nipponbare* rice genome in Sri Lanka (Kottearachchi, 2023). By mapping and sequencing the rice genomes, researchers have also identified key genetic markers associated with fragrance, disease resistance, drought, and salinity tolerance in order to introduce high-yielding modern breeds to enhance food security in the country (Abhayawickrama *et al.*, 2020; Withana *et al.*, 2020; Abhayagunasekara *et al.*, 2022; Amath, *et al.*, 2023; Jeewani *et al.*, 2023).

Another crucial area where genome sequencing has made an impact is the cinnamon industry, one of Sri Lanka's key export sectors. The University of Peradeniya, NIFS, Sri Lanka, and the Industrial Technology Institute (ITI), Sri Lanka have focused on sequencing the genome of Ceylon cinnamon (Bandaranayake *et al.*, 2023; Bandaranayake, & Pushpakumara, 2020; Weeratunge *et al.*, 2024). Multidisciplinary research findings strongly support securing the "Ceylon cinnamon brand" in the world market and increasing production and productivity is summarized below (Agricultural Biotechnology Centre, University of Peradeniya).

- Morphological, yield, and biochemical characterization of the Ceylon cinnamon germplasm.

- Identification of sixteen superior genotypes as parental materials for immediate breeding attempts or mass propagation through large-scale chemical fingerprinting and comprehensive analysis.

- Confirmation of chemical fingerprints of wild Cinnamon species and identification of potentially beneficial compounds

- Confirmation of the identity of *Cinnamomum* species in Sri Lanka through DNA barcoding, NG skim sequencing, and chloroplast genome sequencing.

- Assembling the first draft of *C. zeylanicum* genome and complete transcriptome.

- Assess the effect of the growing environment and harvesting maturity on the quality and quantity of bark and leaf yields using transcriptomics and metabolomics.

The tea industry, another major contributor to the Sri Lankan economy also benefited from genome mapping and sequencing. The Tea Research Institute and Institute of Biochemistry, Molecular Biology and Biotechnology, University of Colombo have worked on mapping the genome of tea plants to identify genes linked to resistance against diseases like blister blight, which is increasingly important as climate change continues to impact the crop yields (Karunarathna *et al.*, 2020).

Beyond major crops, genome sequencing and mapping led by several researchers are being applied to other key agricultural products, such as pepper, maize, and cashew, with projects associated with diversity assessments. They aim to improve yield and resistance to the biotic and abiotic stresses of those crops. These efforts are critical in ensuring that the Sri Lankan agriculture sector remains competitive and capable of adapting to global market demands and climatic challenges (Ariyarathne *et al.*, 2020; Nanayakkara *et al.*, 2020; Wimalarathna *et al.*, 2024).

The molecular biology sub-unit of the Plant Genetic Resource Center, Gannoruwa plays a central role in plant genetic resource management through molecular characterization of germplasm conserved in the gene bank, species identification of unidentified germplasms through DNA barcoding techniques, diversity assessment of crop species and gene identification for important traits in crop species (PGRC- Biotechnology-Department of Agriculture Sri Lanka). Beyond conserving germplasm, research activities are expanded in a variety of areas, such as evaluating the hybridity of crop varieties released by the Department of Agriculture (DOA), identifying crop germplasm that contains genes linked to biotic and abiotic stresses, and establishing crop improvement activities by incorporating such resistant genes into popular varieties and "pre-breeding" (Abeysekera & Jayawardena 2017; Zahara *et al.*, 2017).

3.1.3. Molecular Diagnostics

Phytopathogenic microbial species cause enormous losses to the quantity and quality of crop yields resulting in a major economic issue in the agricultural sector. To effectively manage diseases, precise and rapid detection and identification of plant-infecting microbes is essential. DNA-based methods have become popular methods for accurate plant disease diagnostics. Recent developments in standard and variant polymerase chain reaction (PCR) assays including nested, multiplex, quantitative, bio, and magnetic-capture hybridization PCR techniques, post and isothermal amplification methods, DNA and RNA-based probe development, and next-generation sequencing provide novel tools in molecular diagnostics (Hariharan and Prasannath, 2021). These molecular-based detection techniques are effective in detecting symptomatic and asymptomatic diseases of both culturable and unculturable fungal pathogens in sole and co-infections. Even though molecular diagnostic approaches have expanded substantially in the recent past, there is a long way to go in developing and applying molecular diagnostics in plant diseases. Molecular techniques used in plant disease diagnostics need to be more reliable, faster, practicable, and easier than conventional methods.

The Plant Pathology Division of the National Plant Quarantine Service, Sri Lanka is responsible for identifying pathogens in export consignments (foliage, coir, vegetables, fruits, flowers), import consignments, and samples submitted by nurserymen (NPQS Pathology Division-Department of Agriculture Sri Lanka). ELISA and molecular techniques are also used in the identification methods. The Plant Virus Indexing Center of the DOA applies molecular (E.g.: PCR) and serological (E.g.: ELISA) facilities for virus Indexing. Their services include providing technical know-how to detect viruses and other pathogenic organisms, supplying locally produced farmer-level virus identification kits, and introducing modern technology for virus disease diagnosis and prevention (Plant Virus Indexing Centre, DOA, Sri Lanka).

In addition, many research studies have focused on molecular microbiology and molecular plant pathology of various plant pathogens and diseases (E.g.: Thushari and Costa, 2023).

3.1.4. Food and Beverages

Dairy biotechnology is applied in large multinational firms, small and medium-sized businesses, and cottage industries in Sri Lanka. Popular dairy products such as curd and yorgurt are mostly made on a small scale by cottage enterprises, these are also produced for retail sales by large dairy industries like Milco, Pelwatte, Richlife, and Kothmale. Other dairy products such as butter, cheese, and probiotics are also produced at large scale.

There are numerous fermented condiments and beverages producing industries (E.g.: beer, toddy, vinegar, and liquor) that are well-established. The beer sector imports its raw materials, while other industries use raw materials like coconut and *kithul* and by-products like sugar cane molasses. In Sri Lanka, the wine industry is mostly a cottage industry that uses fruit juices and coconut water as raw materials. Pelawatta Sugar Company, Moneragala, and Sevanagala Sugar Company are the main operators of the alcohol business in Sri Lanka. Pelawatta and Sevanagala supplied around 60-70% of the total alcohol requirement of the local market through batch fermentation and distillation of molasses. Though there is potential for further improvement of the production, alcohol is imported by Distilleries Corporation to be blended into drinkable spirits (Fernando, *et al.*, 2004).

The Regulation on the Control of Import, Labeling, and Sale of Genetically Modified Foods (2006) and its Amendment (Act No. 26 of 1980) are governed by the Food Act of Sri Lanka. Without permission from the Ministry of Health, food items with 0.9% or more genetically modified content (GE) cannot be imported. Labeling is also required for food products containing GE ingredients that are meant for human consumption. "Genetically modified" must be mentioned on the label of any food product containing GE ingredients or contents, regardless of the product's size or container (Kankanamge, 2022).

There are no testing facilities for GE products at Sri Lanka's ports of entry or departure. Laboratories are not accredited and have a restricted capability for GE testing. Efforts are underway to obtain accreditation. The National Plant Quarantine Service, the Industrial Training Institute (ITI), and the Agricultural Biotechnology Center/ University of Peradeniya are the laboratories that are expanding their capacity to assess GE material (Kankanamge, 2022).

3.1.5. Recombinant Biotechnology

Modern biotechnologies like recombinant deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) techniques have minimal application in Sri Lanka. No genetically modified (GE) plants or animals are being developed and commercialized. Some experiments are being done on the greenhouse production of transgenic crops, but the use of GE technologies in animals is limited to laboratory studies. Obtaining prior authorization from responsible sectoral authorities is necessary before starting field research.

There are no reports on import consignments containing unapproved GE contents. No marketplace routinely monitors GE content either. The Ministry of Environment aims to conduct random market testing yearly. In addition, authorities do not regularly monitor field crops for unapproved GE events, as regulations prohibit the entry of GE seeds and plants (Kankanamge, 2022).

Negative attitudes and perspectives about GE research and products are widespread among the general public. Lack of funding, uncertain markets, and unclear legislative procedures deter the research community from conducting genetic modification research.

3.1.6. Farm Animal Biotechnology

Animal GE research hasn’t been conducted in Sri Lanka. Nutritional biotechnology, including the development of rumen bypass feed, digestibility, and rumen microbiota quality improvement research has been conducted at the level of field trials. Some other farm animal-based research focuses on developing vaccines, diagnosing diseases, detecting early pregnancy, and optimizing synchronization techniques for reproductive efficiency. Additionally, there are studies on molecular characterization, particularly in the area of genetic conservation (Kankanamge, 2022).

Established in 1911 as a diagnostic laboratory in Colombo, the Veterinary Research Institute (VRI) was formalized in 1967 and is currently administered under the Department of Animal Production and Health. The institute is the only national institute engaged in producing vaccines against infectious animal diseases, performing disease diagnostics, offering analytical and advisory services, and conducting research to improve the health of farm animals and poultry. The VRI further produces biological materials such as reagents, antigens, and starter cultures for yogurt and curd (Veterinary Research Institute).

Several private companies contribute to improving the productivity and well-being of domestic animals, poultry, and cattle such as Hayleys and Baurs. An industry-wide requirement for a specialist diagnostic laboratory was met with the opening of HayVet Laboratory in Kuliyapitiya. Among the services provided are rapid analyses of animal feed and feed raw materials, postmortem examinations of chickens, testing for bacteriology and antibiotic sensitivity, water quality, ELISA testing for diseases of poultry, and PCR testing for diseases of both poultry and swine.

The scientists at the University of Peradeniya began a four-year project in 2016 to provide women dairy farmers in Sri Lanka's North Central Province with genetically superior female calves. The project was supported by the Food and Agriculture Organization (FAO), the International Atomic Energy Agency (IAEA), and the Ministry of Livestock and Rural Economy of Sri Lanka. Embryo transfer and artificial insemination procedures were used to produce high milk-producing calves to improve the livelihoods of rural Sri Lankan communities. Local scientists received training, technical expertise, and equipment as part of this effort, which was entirely supported by the IAEA. After three months of production, hundreds of cattle embryos were kept in liquid nitrogen at -196 °C for future transplantation. The generation of healthy progeny is guaranteed by nuclear techniques such as radioimmunoassay for monitoring the estrous cycle, embryo implantation in the uterus, and early gestation. The genetic quality of superior animals used for breeding, particularly for males, is also assessed using nuclear-derived genomic tools (IAEA, 2020).

A pitot study involving the release of sterile male mosquitoes has been commenced, employing the Sterile Insect Technique (SIT) to manage the insect vector that transmits Dengue. No studies reported on cloning animals or commercial production of cloned animals, insects, birds, or fish in Sri Lanka (Ranathunge, *et al.*, 2022).

The laws controlling the importation of genetically engineered animals and animal products into Sri Lanka are nonexistent. Nonetheless, a few clauses in the current legislation are meant to restrict, monitor, and even outright forbid the introduction of specific GE products. The Department of Animal Production and Health, which has the authority to accept or reject such import requests, must be notified of such imports by importers. Trade restrictions that apply to plant products also apply to GE animal products. Regulations governing the traceability and labeling of GE animals and products including cloned animals are nonexistent.

The importation of animal feeds is regulated by the Animal Feed Act No. 15 of 1986. The Department of Animal Production and Health (DAPH) uses other provisions in the regulations to prohibit the importation of GE animal feed (e.g.: maize and soybean grains), even the Act itself does not ban the importation of animal feed containing GE materials. In consultation with the Department of Agriculture and the Ministry of Environment, the DAPH determines whether to approve the import of GE animal feeds if such a request is made (Kankanamge, 2022).

3.2. Environmental Biotechnology

The applications of biotechnology that focus on solving environmental perturbations to achieve a cleaner environment are collectively known as environmental biotechnology. Wastewater treatment, soil bioremediation and biotreatment of polluted air, bioindication, and biomonitoring are the key applications of environmental biotechnology. Plant, animal, or microbial species or communities are useful as bioindicators to indicate contamination of the environment by pollutants, while biomonitoring uses the bioindicator species to assess the quality of an environment.

The national biotechnology policy established in 2009 has identified environmental biotechnology as one of the key contributors that enhance the quality of life and support the national development of Sri Lanka through economic advancement. Seven strategies have been planned to achieve the objective; developing biotechnology systems for waste treatment and energy generation, promoting the manufacture of biofertilizers and biopesticides, utilizing soil microorganisms in degrading industrial waste, bioremediation of degraded lands and polluted waterways and promoting the use of bioindicators to biomonitor the quality of the environment. Over a longer period, waste management, specifically wastewater management and technology has been slowly improving in Sri Lanka. Biofertilizer research and development have also increased during the last decade as eco-friendly approaches for sustainable agriculture. Other environmental biotechnological applications such as biopesticides, biofuel, bioindicators, and biomonitoring are continued at the research level in parallel (Attanayaka & Balasooriya, 2022).

3.2.1. Wastewater Management

Wastewater released from residential, commercial, institutional, and public facilities is referred to as sewage. Greywater (from bathtubs, showers, sinks, and dish and clothes washers), and blackwater (the water used to flush toilets mixed with human waste and toilet paper), are subtypes of sewage. Food waste, municipal solid waste, industrial effluent, and soaps and detergents can also be found in sewage. Before being released, wastewater must be treated to reduce risks to public health and to the environment, which can result in financial losses. The history of managing wastewater in Colombo, the commercial capital of Sri Lanka, began in 1906 when a sewage network comprising of two treatment stations was built. There are now 19 pumping stations in the system, which was enlarged in 1972. The treated wastewater is released into the sea via pipes that are longer than a kilometer at Wellewatta and Muthuwella.

Unfortunately, the marine ecosystem has suffered because of the inefficiency of the wastewater treatment system and decay, which allowed untreated effluent to be released. The city has changed over the past 50 years into a 640,000 strong commercial metropolis. Due to the daily generation of about 379,470 m3/day, managing wastewater becomes more difficult with the current infrastructure (Sanitation Master Plan, 2021). It is also necessary to take the additional volumes of wastewater produced by the Port City Colombo economic zone into account. The Greater Colombo Wastewater Management Development Program has been in operation to develop the wastewater system in Colombo since 2014 with an estimated cost of 120 million US dollars.

The Japan International Cooperation Agency (JICA) assisted in 2017 in creating a strategic master plan for Sri Lanka's sewer sector. In 2021, the National Water Supply & Drainage Board (NWSDB) launched a Sanitation Master Plan toward meeting the UN's SDG 6 for 'clean water and sanitation for all'. The plan addresses wastewater management in other major cities, trade zones, and institutions.

The Ministry of Health, the NWSDB, and the local government authorities (Municipal Councils, Urban Councils, and Pradeshiya Sabhas) are the major government agencies involved in providing wastewater treatment in Sri Lanka. The corresponding agencies oversee the management of the sewage infrastructure facilities given to urban housing complexes. Major hospitals are connected to piped sewer networks. The Department of Health oversees the cleanliness of hospitals.

The plantation companies are primarily responsible for managing wastewater emanating from plantations, factories, and allied industries, although the government also makes contributions through World Bank development grants.

Industrial wastewater collection and treatment facilities are housed inside the Board of Investment (BOI) industrial zones, which are dispersed throughout the nation. Furthermore, a variety of public and commercial organizations run their own on-site wastewater treatment facilities.

The NWSDB oversees 13 wastewater treatment plants, six of which are located in the important cities of Ja-Ela, Rathmalana, Hikkaduwa, Kurunegala, Kandy, and Kataragama (**Figure 8.1**). Four are in free trade zones at Biyagama, Sithawaka, Kokgala, and Modarawela; three are in housing schemes at Maththegoda, Raddalugama, and Hanthana. In these treatment plants, pre-treatment for removal of grit and other debris, secondary treatment via anaerobic and aerobic reactors, clarification tanks, disinfection of treated effluent prior to discharge into surface water bodies, and sludge treatment, drying, and disposal are commonly applied.

Figure 8.1 Wastewater Treatment Plant in Kandy Municipal Site

Depending on the constituents of wastewater, and the need for re-use some industrial wastewater plants include advanced treatment methods such as reverse osmosis. In addition, government, and non-government organizations such as the International Water Management Institute (IWMI) as well as several commercial firms and consultative services provide guidance and technology for wastewater management solutions within the country, especially for manufacturing industries as well as hotels and residential buildings.

However, just 2.1% of people who live in main cities have access to centralized wastewater treatment facilities and piped sewage systems. Nearly 91.5% of the population depends on on-site amenities such as closed pit latrines and septic tanks. About 5.4% of people use shared restrooms and public restrooms, while the remaining 1% either lack access to sanitation or use makeshift latrines. In its Sanitation Master Plan, NWSDB aims to reach 100% total sanitation coverage and 4.4% centralized sewerage treatment by 2030.

The National Environment Act (NEA) no 47 of 1980 which was amended in 1988 and 2000 is the key legislation pertaining to wastewater and environmental pollution. The Central Environmental Authority (CEA) under the Ministry of Environment established in 1981 under the NEA acts as the main authority of the national environmental policy. The institutes or industries should have a license issued by the CEA for discharging wastewater and other pollutants to the environment in accordance with standards and criteria stipulated by the authority. Wastewater discharge standards are prescribed based on the type of industries and discharge methods and are given in the National Environmental (protection and quality) Regulation No. 1 of 1990. For example, specific tolerance limits are specified for effluents from rubber factories, the textile industry, and the tanning industry. Different threshold values are prescribed for effluents discharged into inland surface water compared to those discharged into coastal areas.

It is a common practice to discharge wastewater into the environment without any treatment by small-scale industries. Livestock farmers usually use the wastewater in their own agricultural farming with minimal or no treatment. Low-cost treatment methods are being introduced to piggery farming as a combination of biogas plants and a reed bed. Another low-cost intervention is stabilization ponds which are used in small-scale food and beverage industries.

Considerable research studies on wastewater management have been conducted in Sri Lanka, focusing on conventional treatment methods and novel biotechnological approaches. Studies by Perera *et al.* (2003) and Silva *et al.* (2008) explored the effectiveness of activated sludge systems, trickling filters, and stabilization ponds in the Sri Lankan context, finding them inefficient due to operational and maintenance challenges. Green technologies have been attempted and research by Gunathilaka *et al.* (2022) explored the use of phytoremediation to enhance treatment processes and promote sustainability. Microalgae, Chlorella sp. has indicated efficiency in the bioremediation of domestic wastewater as well as oil-rich palm oil mill effluent (Chandrasekara *et.al*, 2024).

3.2.2. Bioremediation of Contaminated Land and Air

Soil pollution with contaminants such as agrochemicals, petroleum, and oil is reported in numerous sites including coastal areas in Sri Lanka. The transformation of pollutants into other chemical forms or mineralization by microorganisms or plants can be identified as biodegradation. The application of the biodegradation ability of microbes and plants for converting soil pollutants to less or non-toxic compounds is commonly identified as bioremediation, while the plant-mediated bioremediation process is termed as phytoremediation. Research on both biodegradation and bioremediation are slowly progressing in Sri Lanka. Several studies have identified potential microbial and plant species for bioremediation. For example, effective bacteria species such as *Paenibacillus* sp, *Stenotrophomonas* sp., *Tistrella* sp., and *Pseudacidovoeraxl* sp. for degradation of hydrocarbons have been isolated (Premarathne *et al.*, 2012).

Contaminated air with odourous compounds is common in manufacturing industries, poultry and livestock farms, and solid waste management facilities. These emissions cause negative effects on the living conditions in the communities and may create health risks. Microbial bioremediation can be utilized in various methods such as biofilters and trickling biofilters to reduce the polluting compounds in the effluent air. Research on bioremediation of contaminated air has been conducted rarely. Bio-filtration has been studied as an effective technique for the mitigation of gaseous contaminants generated in municipal solid waste composting (Ariyawansha *et al.*, 2010).

3.2.3. Solid Waste Management

Solid waste has become a major environmental issue in Sri Lanka due to the rapid growth of population and urbanization with an estimated waste generation of 6 MTs per day leading to 4.8 billion MT of waste collected per annum in the country by 2025 (Dharmasiri, 2019). The responsibility of waste collection, transportation, and proper disposal are vested in local government authorizes such as Pradeshiya Sabha (PS), Town Councils (TC), and Municipal councils (MC) by the Municipal Council Ordinance in 1947, the Urban Council Ordinance in 1939 and the PS Act in 1987. Central Environmental Authority and the Urban Development Authority are responsible for developing and regulating the policy for SWM. National policy on waste management (2019) has been updated, with the aim of sustaining a healthy life and a cleaner environment for all and meeting the SDGs.

In Sri Lanka, solid waste is classified as municipal solid waste, packaging waste, industrial waste, construction waste, healthcare waste, electronic waste, radioactive waste, marine waste, and agricultural waste. About 62% of municipal solid waste is biodegradable organic matter originating from households, markets, and commercial establishments.

Sri Lanka has several engineered sanitary landfills, e.g., Dompe Sanitary Landfill and Arawakkalu Sanitary Landfill, and semi-engineered landfills at Sandatenna in Nuwara-Eliya and Ampara. Kerawalapitiya waste-to-energy plant established in 2021, uses incineration technology to produce around 10 MW of energy out of solid waste collected in Colombo.

Composting is a widely used biotechnological method for MSW management across the country. A number of large-scale composting complexes have been successfully established in Hikkaduwa, Kolonnawa, Medirigiriya, Anuradhapura, and Kalutara. In addition, small-scale anaerobic digesters are installed in several local authorities (Basanayake & Visvanathan, 2014). However, open dumping of MSW is commonly practiced in most of the urbanized areas, and there are around 390 dumpsites in the country e.g., Karadiyana and Kolonnawa in Colombo, Gohagoda in Kandy which need to be rehabilitated with time. The government introduced the Reduse-Reuse-Recycle (3R) principle with the cleaner production policy in 2004 and the

"Pilisaru" waste management program in 2008 to encourage citizens to waste minimization and proper management.

3.2.4. Biofertilizers and Biopesticides

The agricultural sector is under great pressure to meet the demand for food and feed for the growing populations, despite the decreasing arable lands due to increasing urbanization and conversions of agricultural lands. Following the green revolution chemical fertilizers were first used in Sri Lankan agriculture in the 1960s. With time, conventional agriculture has been converted to high-input, resource-intensive farming practices that heavily rely on synthetic pesticides and fertilizers. Although the judicious application of these synthetic inputs is clearly advantageous for crop growth and yield, the higher doses of applications have caused contamination and pollution of the soil, air, and water environment leading to soil degradation, health issues, and economic losses. On the other hand, synthetic pesticides are concerned with adverse long-term effects on human health, the environment, beneficial organisms, and natural enemies of pests. Eco-friendly inputs to meet the country's demand for crop production is one of the goals that has been set in the National Agriculture policy in Sri Lanka (2021), compiled by the Ministry of Agriculture and in accordance with the SDGs. Biofertilizers and biopesticides have been developed as eco-friendly cleaner biotechnologies to overcome the negative environmental consequences of synthetic agricultural inputs (Attanayaka and Balasooriya, 2019). In addition, they are valuable green technologies based on renewable resources in comparison with fossil fuel energy-dependent synthetic fertilizer production.

The DOA's current fertilizer recommendation for paddy emphasizes the value of adding organic matter, and it prescribes the use of 10 tons per hectare of organic fertilizer and straw in addition to the recommended chemical fertilizer. Nevertheless, there have been practical problems with applying large quantities of organic fertilizer as the recommendation. Thus, advanced types of organic fertilizers such as liquid organics and biofertilizers have been introduced.

Biofertilizers are formulations of living cells of microorganisms that promote the growth of plants by increasing the availability of essential plant nutrients. Bacteria, fungi, and or algae are used to make biofertilizers as individual species or a mixture of several species. For instance, bacterial-bacterial or fungal-bacterial partnerships are used in biofilm-biofertilizer technology. Through their stimulation of beneficial microflora, fauna, and the soil food web, biofertilizers can mobilize nutrients that would otherwise be unavailable to plants and enhance the general health of the soil.

Over the past ten years, biotechnologists, microbiologists, and other scientists in Sri Lanka have paid more attention to biofertilizers. Numerous studies have been carried out with the primary goal of developing biofertilizers for paddy the staple crop. Furthermore, research has been done on biofertilizers for a variety of plantation crops like rubber and tea as well as field crops like maize, soybeans, potatoes, tomatoes, and legumes (Aberathna *et al.,* 2022). To create efficient biofertilizer inoculants, nitrogen-fixing diazotrophic bacteria, such as symbiotic *Rhizobium* sp, non-symbiotic *Azotobacter* sp., *Azospirillum* sp., and *cyanobacteria* sp., phosphorus-solubilizing bacteria, phosphorus-mobilizing fungi, and plant growth-promoting bacteria and fungi, have been isolated from a variety of habitats targeting different crops. It was frequently discovered that applying inoculants made of combinations of species was a better alternative than applying inoculants made of a single species. Biofertilizers can also indirectly improve water retention and soil structure. Biofertilizers specifically target nutrient availability, in contrast to other microbial products like phytostimulators that increase plant hormone production, rhizoremediators that break down organic pollutants, and biopesticides that fight plant pathogens.

Commercial biofertilizers are generally formulated with active microorganisms and carrier materials to ensure effective delivery to target sites. The choice of carrier material is based on its ability to protect the microorganisms during production, storage, transportation, and field application. Additionally, the formulation and application technology must be user-friendly for farmers. Carrier materials can be organic or inorganic, such as peat, clay soils, compost, farmyard manure, plant waste, or inert substances like vermiculite, bentonite, and alginate. Solid formulations, including granules, microgranules, wettable powders, and pellets, are cost-effective and easy to produce but may have drawbacks such as short shelf life, sensitivity to temperature fluctuations, contamination risks, and lower cell counts. Liquid formulations, which are suspensions of microbial cultures in mineral oils, organic oils, or oil-in-water mixtures, are often preferred due to their longer shelf life, lower contamination rates, and ease of application.

Biofilm biofertilizers based on biofilm formation among bacterial and fungal species are the most frequently studied type of inoculant in Sri Lanka for several crops such as paddy, tea, and strawberry (Rathnathilaka *et.al.*, 2022). In another long-term study, nitrogen-fixing cyanobacteria-based biofertilizers and phosphorus solubilizing biofertilizers have been integrated with slow-releasing urea fertilizer as an Eco-friendly farming technology for paddy cultivation (Perea *et al.*, 2022). Despite their advantages, biofertilizers are not yet extensively utilized in the commercial sector because of various reasons including difficulties in mass-producing them and variable results in different soils, crops, and environments.

Biopesticides are pesticides derived using biological sources and can be classified as microbial (E.g.: fungi, bacteria, viruses), biochemical (botanicals and insect sex pheromones), and natural enemies (predators and parasitoids). During the past three decades, many studies have been conducted in Sri Lanka on the biological control of pests and diseases focusing on both microbial biopesticides and botanical extracts (Rajapakse *et al.*, 2016). Microbial species (*Trichoderma, Bacillus,* and *Pseudomonas*) have been studied long and identified as effective control agents against pathogens such as *Rhizoctonia*, *Sclerotium*, and *Fusarium* spp. in rice and other field crops such chili, bean, and tomato. For the biological control of coconut mite (*Aceria guerreronis*), a predatory mite (*Neoseiulus baraka*) has been effectively used by the Coconut Research Institute of Sri Lanka (Fernando & Artchige, 2019). The importance of botanicals utilized by Sri Lankan farmers for pest control in rice and other crops from ancient times is highly recognized even at present. Crude extracts, volatile oils, and dried powders of some of these botanicals are commercially available. However, there are limitations in commercial formulations of plant bioactive compounds or microorganisms as biopesticides due to reasons such as low persistence in the environment, high cost of production, and challenges in toxicity assays. The formulation and registration of novel biopesticides are under the authority of the Registrar of Pesticides (ROP) based on the Control of Pesticides Act No. 33 (1980) of Sri Lanka and should undergo a standard testing process for safety and efficient use in relation to human health and environmental aspects which are common for synthetic pesticides. A new biopesticide can be licensed as valid for use for a period of three years and re-registration is possible based on reassessment based on new standards.

Both biofertilizers and biopesticides are indispensable biotechnologies for the sustainable agriculture goals of Sri Lanka. Thus, further research and development on these two areas is highly important to establish commercially viable products.

4. What are the Challenges and Opportunities for the Advancement of Biotechnology in Sri Lanka?

Even though biotechnology has dominated scientific research for the past thirty years or more, Sri Lanka has not advanced adequately in this area. The biotechnology sector confronts a wide range of difficulties, including financial constraints, regulatory and ethical dilemmas, and technological upheavals. These challenges also offer opportunities for further development. Biotech businesses can set themselves up for success in this dynamic and quickly changing industry by tackling these problems head-on. Realizing the full potential of biotechnology to benefit lives and solve global problems will need collaboration, adaptation, and a commitment towards responsible innovations as this sector extends the boundaries of science and technology (Safeena, 2013).

4.1. Approved Regulatory and Biosafety Procedures

The biotech industry in Sri Lanka faces difficulties in the absence of approved regulatory procedures and biosafety protocols, even though the legislation is currently being finalized. To promote research and innovations, quarantine laws ought to be streamlined. Developing guidelines for collaborative research using local biological materials with international scientists or organizations is necessary. In the process of commercializing products or processes patenting is also crucial.

Getting through the complicated regulations and approval procedures is one of the biggest obstacles facing the biotech sector. These regulations are intended to guarantee the safety and effectiveness of biotech products, but they can also pose serious obstacles for businesses attempting to commercialize innovations. Companies must interact with regulatory agencies early in the development phase and stay up to date on regulatory changes in order to meet such commercialization issues. The extended approval procedures for biotech products can greatly increase costs and delay market entry, especially in the pharmaceutical industry.

4.2. Funding/ Financial Challenges

Significant investments in research and development are necessary in the capital-intensive biotech sector. Success in this industry mostly depends on obtaining sufficient finance and handling financial resources well. Despite some venture capital investments that the biotech sector has witnessed recently, it is challenging to secure funds particularly, for long-term, high-risk initiatives. Biotech startups that want to enhance their chances of getting funds can create a powerful value proposition and business case, assemble a team of experts in diverse fields, and look into other funding options including grants and strategic partnerships.

Contrarily, research on drug development in developed countries concentrates on preventing the diseases that are common there, with little emphasis placed on funding diseases that are visible only in underdeveloped countries that have limited purchasing power due to low income. Further, they lack sufficient incentives to invest in developing drugs for tropical diseases. The adoption of accelerated approval pathways for revolutionary discoveries is also required to promote investors. Developing drugs for tropical diseases may benefit from funding requests made to international organizations such as the World Health Organization (WHO), utilizing partnerships, and working with regional pharmaceutical manufacturing companies to share costs, prioritize projects based on possible returns on investment, and implement cost-effective technologies and processes.

4.3. Ethical Considerations/ Public Perception

Public concerns and queries about ethics frequently set back biotech advancements. To acquire public trust and acceptance it is required to address issues such as food insecurity, potential health risks, religious concerns, and equity considerations in addition to ethical concerns. Sri Lanka is a hotspot for biodiversity. The loss of biodiversity has a more detrimental effect since it considerably links with the country's economy and culture. The possible interference of biotech breakthroughs like genome editing and synthetic biology in natural systems may create complicated ethical issues.

Companies need to appropriately deal with these ethical quandaries in order to ensure that society will accept their technological innovations. Biotech companies must collaborate with policy experts and ethicists to address ethical problems, communicate openly about their research and its impacts, and establish and stick to ethical standards for their work.

The success of the biotech industry is significantly affected by how the public perceives biotechnology. By enhancing public awareness and acceptance, misconceptions and anxieties over biotech breakthroughs can be avoided. The industry should concentrate on implementing accessible and easy-to-understand communications about biotech innovations and their potential benefits, interacting with stakeholders and communities through outreach and education initiatives, and showcasing dedication and accountability toward safety are some other strategies.

4.4. Technological Advancements/ Rapid Innovation

Sri Lanka can exploit the full potentialities of biotechnology. A crucial issue is the lack of a proper mechanism for transferring mature technologies. Commercialization of biotechnology research through effective industry-academia linkage is also a critical challenge for the development of biotechnology industries. Much of the research done in the academic sector aims at solving local problems, partly because of funding considerations, and partly because of limited manpower, which make it difficult to compete in the areas of cutting-edge emerging biotechnology. Even though the university-to-industry linkage is typically weak in Sri Lanka, there is a need to enhance research infrastructure, access to advanced biotechnology tools and equipment, and opportunities for interdisciplinary collaboration to foster innovation.

Biotech companies need to stay up to date with the newest technological breakthroughs to maintain their competitiveness by absorbing novel technological improvements in the industry. This brings both opportunities and challenges. However, this can be difficult, particularly for companies with limited finances and resources. So, they could invest in flexible, adaptive research infrastructure, collaborate with academic and research institutes in developed countries, and cultivate a culture of constant learning to stay up to date with developing technology.

4.5. Talent Acquisition and Retention

To fulfill the demand for qualified professionals in biotechnology, it could be necessary to revise curricula to promote "Science, Technology, Engineering, and Mathematics (STEM)" education and offer opportunities for gaining hands-on experience. The biotech sector greatly depends on highly qualified personnel. Innovation and growth can only be accelerated by attracting and keeping outstanding individuals by offering attractive remunerations and chances for professional and career advancement.

Furthermore, in order to keep exceptional employees, an environment that supports creativity and innovation must be established. This can be done by rewarding and recognizing unique contributions, promoting risk-taking and learning from mistakes, and encouraging employee-driven projects.

4.6. Intellectual Property Protection

With regard to scientific research and capacities, developed and less developed countries differ greatly from one another. The number of patent rights obtained by countries for their technological advancements is proportionate to their R & D investments. Being a middle-income country Sri

Lanka would face difficulties in investing to develop biotechnology industries. In the biotech business, inventions might take years to be developed and brought to market, hence intellectual property protection is essential. To effectively protect their innovations, biotech businesses need to understand extensive patent laws and procedures. They may do this by establishing an effective intellectual property strategy in the early research phase, generating significant patent portfolios, and keeping up with regulatory changes.

Resolving patent disputes can be expensive and time-consuming, which are also unpreventable in the biotech sector. Before spending money on new research, companies should thoroughly conduct a patent search, seek the possibility of cross-licensing with possible competitors, and create defense plans for patent challenges in order to reduce the chance of patent disputes.

4.7. Motivation in the Private Sector

The private sector in Sri Lanka is yet to play an important role in contributing to economic development through biotechnology innovations, although heavy investments in biotech industries may not be possible, with the available physical and human resources. Biotechnology industries may require large infrastructure investments, and have a high cash-burn rate, while the returns in the initial years are quite low. This may discourage private investments, and the Government will have to promote the industry actively.

Plant tissue culture-based enterprises are more prominent in the industrial biotechnology field in Sri Lanka. The export profiles of these industries indicate the need for market expansion, especially to the Middle East, Europe, Japan, and Singapore (Padukkage *et al.*, 2023). In order to reach these markets some major constraints such as the non-availability of quality planting material in sufficient quantities to produce export-grade products and high-cost production and export are important factors to be addressed. The underexploited market and untapped potential for exports are mainly attributed to the nonavailability of adequate quantities of the desired variety of export grades and also the relatively high costs of plants. Only a limited number of commercial firms engage in large-scale exports. The majority of exporters rely on products from small-scale producers, middle collectors, and agents due to limited capacity (Padukkage *et al.*, 2023). This may vary the quality of the products. There is a great need for technology transfer, input supply, and the introduction of marketing linkages to increase exports. Most small producers lack technical know-how, credit facilities, and knowledge of marketing strategies necessary to be commercially oriented for an export market.

An environment that is based on cohesion, flexibility, communication, collaboration, and government support needs to be established to deal with business issues. Each component of the business needs to be carefully planned and updated. Otherwise, the chances of collapsing the business are high which will drastically affect the stakeholders such as employees, suppliers, and creditors, and create a public scandal. Thus, long-term sustainability needs to be planned strategically by analyzing all investments and associated risks to set short-term goals and actions toward preserving capital. The PTC businesses should be evaluated by a professional risk assessment and evaluation authority to understand future growth predictions. Further, the government needs to protect PTC businesses to maintain continuous foreign exchange earnings and employee well-being via initiating proper international channels for PTC producers and introducing incentive schemes to improve the available PTC laboratories. Continuous monitoring of such assisted facilities needs to be conducted for the long-term sustainability of the establishments.

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Chapter Nine

Hybrid Seeds: Pros and Cons in a Dynamic Economy

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Abstract

Shrinking of arable land area, rising global population and consequences of climate change have challenged global food security. Therefore, global concern has been to prioritize breeding varieties that produce high yields and favourable quality under diverse agro-climatic conditions. Consistent higher crop yield and improved adaptability to various biotic and abiotic stresses attributed by hybrid seeds can significantly enhance agricultural productivity and economic stability in a dynamic economy. However, the adoption of hybrid seeds also brings several challenges such as the high cost of hybrid seeds, making them less affordable for small-scale farmers and the dependence on seed companies for new seeds in each planting season creating economic instability. Therefore, fulfilling the demand for high-quality seeds heavily depends on the importation of seeds including hybrid seeds which negatively affects the foreign exchange reserves of the country. Hence, there is a timely importance of seeking ways to increase local hybrid seed production through significant investments in research and development by both the government and the private sector to reduce the importation of seeds ensuring sustainable agricultural productivity in Sri Lanka. Thus, this chapter focuses on addressing the potential, challenges, and strategies to strengthen the local hybrid seed industry. In this regard, we discussed the benefits and shortcomings caused by open-pollinated true-to-type seed production vs. hybrid seed production. Also, the global scenario of the hybrid seed industry which directly impacts the developing economy in a dynamic situation is discussed. The potentiality of the hybrid seed industry and the present status of the sector in Sri Lanka with few locally developed hybrid crops that are most demanding as examples, have also been indicated. Finally, future directions especially, overcoming the challenges faced by hybrid growers are illustrated emphasizing the necessity of incorporating male sterility (MS) genes in hybrid variety-improving breeding programs.

Keywords: Benefits and challenges, Dynamic economy, Hybrid seeds, Male sterile genes, Open-pollinated seeds

1. Introduction

Seed insecurity is a critical issue for sustainable agricultural production with higher productivity ensuring a consistent supply of crop produce meeting the global demand for food. Thus, the production of healthy, genetically pure crop seeds with high seed vigour and higher germination percentage plays a vital role in the commercial agriculture sector which ensures a higher yield and profit to the farmers/growers. In Sri Lanka, the agriculture sector contributes to 7% of the Gross Domestic Product (GDP) and therefore, timely availability and accessibility of good quality seeds at a reasonable price is a key factor that determines sustainable agricultural production in the country (MOA, 2020; Udari *et al.*, 2022). However, the agriculture sector in Sri Lanka is still not able to meet the demand for high-quality seeds by farmers with proper local production of seeds. Therefore, the Sri Lankan seed sector heavily depends on the importation of seeds of high-yielding varieties of various crops, which in turn negatively affects the foreign exchange reserves of the country. The recent Covid 19 pandemic situation along with subsequent economic hardships and restrictions on importations in Sri Lanka signify the importance of increasing local seed production to sustain the country's food and nutrition security. Presently global seed production is shifting towards hybrid seed production as they are attributed to higher crop yield and improved adaptability to various biotic and abiotic stresses. To enhance agricultural productivity and economic stability under the Sri Lankan dynamic economic basis, there is a timely importance of addressing the pros and cons of hybrid seed production in Sri Lanka.

1.1. What are open-pollinated seeds and hybrid seeds?

Usually, growers use two different types of seeds *i.e.,* open-pollinated seeds (OP) and hybrid seeds (F_1) (Parimala *et al.*, 2013; Chakrabarty *et al.,* 2023). In open pollination, a plant is pollinated naturally either by self-pollination or cross-pollination with another of the same variety *via* natural means such as wind, insects, birds, rain, *etc.* Pollination is a part of the reproductive process of plants where pollens from the male reproductive part are transferred to the female reproductive part (stigma) of a flower. Seeds produced from open pollination are known as true-to-type seeds and those have nearly the same characteristics as the parent plant. Thus, the advantage of using open-pollinated seeds is that farmers can save to replant those from their harvest, and it is not necessary to purchase seeds every year.

Hybrid seeds also known as F_1 seeds (first filial generation) are produced intentionally by cross-pollinating with two different parent plants that are genetically distinct. This is usually done to combine desirable traits from both parents. Two diverse parental lines or cultivars selected for hybrid production are usually inbred lines produced by continuous inbreeding through self-pollination. Therefore, inbred lines are homozygous and ensure the purity of breeding plants. Crossing between two such inbred lines that are genetically divergent but compatible parental lines produces hybrid seeds (**Figure 9.1**). Hybrid seeds are in heterozygotes state according to their genetic composition and highly uniform in morphological features. The genetic diversity between the parental lines results in better heterosis and the homozygosity of the parental lines ensures a phenotypically uniform F1 population. Thus, hybrids often exhibit hybrid vigour (heterosis), resulting in plants that are more uniform in appearance and performance and may be more vigorous, disease-resistant, and higher yielding than their open-pollinated parents. Therefore, F_1 hybrid seeds exhibit superior characteristics in terms of yield, colour, uniformity and disease resistance (Miyaji & Fujimoto, 2018).

During the 20th century, with the recognition of the advantages of heterosis between two diverse genotypes to achieve maximum hybrid vigour, hybrid seed technology was begun to use commercially for crop variety improvement both in field and vegetable crops (Miyaji & Fujimoto, 2018;

Chakrabarty *et al.,* 2023; Singh *et al.*, 2023,). In the 1950s, in the United States, hybrid corn was the main crop, and its yield had increased from 1 mt/ha in 1930 to 4 mt/ha in 1960 and approximately 12 mt/ha in 2017 (Miyaji & Fujimoto, 2018). Unlike open-pollinated seeds, saving seeds produced from F_1 hybrid plants do not reliably produce true copies. Therefore, new hybrid seeds need to be purchased for each planting season.

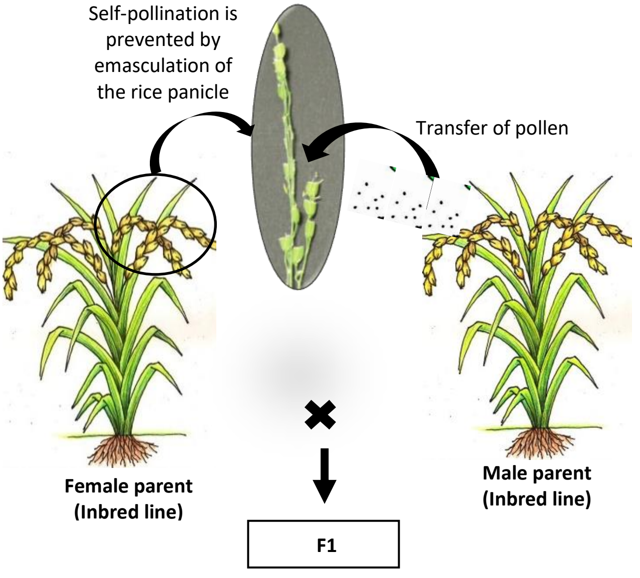

Figure 9.1. Illustration of producing F_1 hybrid in rice

The floral biology, mating type, pollination system and proper agronomic conditions need to be considered for successful commercial hybrid seed production (Virmani, 1994). Hybrid seed production usually requires a female parent with unisexual flowers or bisexual flowers with natural self-incompatibility or sterile pollen in anther. If not, those bisexual flowers need to be emasculated or remove viable pollen by artificial means before occurring of natural self-pollination. In addition, male sterile lines which are developed through cytoplasmic male sterility, or photoperiod/thermo-sensitive genic male sterility could be used as female parental lines. The selected male parent should have abundant pollen production, dispersal, and easy transfer from the male parent to the female parent for satisfactory seed setting for successful hybrid production.

Special care is also needed in commercial hybrid production in terms of isolation, pollination techniques and manipulation of growing conditions for better seed yield and maintenance of the parental lines (Miyaji & Fujimoto, 2018).

1.2. Limitations of open-pollinated seeds

Even though open-pollinated seeds can be saved for future planting reducing the cost of farming, the use of open-pollinated seeds is associated with several drawbacks that are undesirable for commercial-scale seed production. It is challenging to achieve consistently higher yields with open-pollinated varieties compared to hybrid varieties, which are specifically developed for high yield and productivity (Chakrabarty *et al.,* 2023). Therefore, the comparatively low yield of open-pollinated varieties can impact on overall profitability of commercial-scale farming while hindering to increase food production to meet the demand of the growing population. Furthermore, open-pollinated varieties have a chance of cross-pollinating with other varieties resulting in unintended hybridization which can dilute the desirable traits of original varieties during successive generations. Furthermore, open-pollinated varieties may also be susceptible to pests and diseases leading to higher crop losses compared to hybrid varieties which are specifically developed for pest and disease resistance.

Due to these limitations associated with open-pollinated seeds, farmers and commercial growers are shifting towards hybrid seeds to ensure consistent higher yield, uniformity in crop produce and pest and disease resistance (Miyaji & Fujimoto, 2018; Chakrabarty *et al.,* 2023; Singh *et al.*, 2023,).

2. Global scenario of the hybrid seed industry

Currently, hybrid seeds are widely used globally in commercial scale farming due to the numerous advantages of hybrid varieties in terms of yield, disease resistance, and crop quality. In 2023, the global hybrid seeds market was valued as USD 26.8 billion, and it is expected to grow at a Compound Annual Growth Rate (CAGR) of 11.0% from 2024 to 2030 (Grand View Research, 2024).

Global hybrid seed production primarily focuses on several major crops such as maize (corn), rice, soybean, sunflower, canola, cotton, vegetables (e.g.: tomatoes, peppers, cucumbers, brinjal) and certain grains like wheat and barley due to their economic importance and the significant yield advantages that hybrids can offer (Miyaji & Fujimoto, 2018). With the biggest revenue share of 38.4% in 2023, the cereals and grains sector dominated the global market based on crop type (Grand View Research, 2024). As cereals and grains such as rice, corn, wheat, and barley are staple foods in most countries, there is a high demand for high-yielding and disease-resistant varieties to ensure food security and meet the needs of growing populations which led to the prominent growth of hybrid seed market in cereals and grains. Hybrid fruits and vegetables are also gaining popularity due to their capability to adapt to seasonal variations, tolerance to various abiotic stresses, high yield ensuring production throughout the year, superior taste, texture, and nutritional content. According to the hybrid seeds market analysis report of Grand View Research in 2024, it is estimated that global hybrid fruits and vegetables production will grow at the fastest CAGR of 11.2% during the period of 2024 to 2030 (Grand View Research, 2024).

Hybrid seed usage is extensive in developed countries and is increasingly adopted in developing nations, driven by the need for higher productivity and food security. The leading countries in hybrid seed production include the United States, China, India, Brazil, and Chile. These countries dominate the hybrid seed market as they have advanced agricultural technologies and significant investments. The global seed industry including hybrid seed production on commercial scale is predominantly driven by various multinational seed companies such as Monsanto (now part of Bayer), Bayer Crop Science, DuPont Pioneer, Corteva Agriscience, Syngenta, Limagrain, KWS, Sakata seed, DLF, Longping High-tech, Euralis Semences, Advanta and China National Seed Group (Singh *et al.*, 2023; Grand View Research, 2024) (**Figure 9.2**).

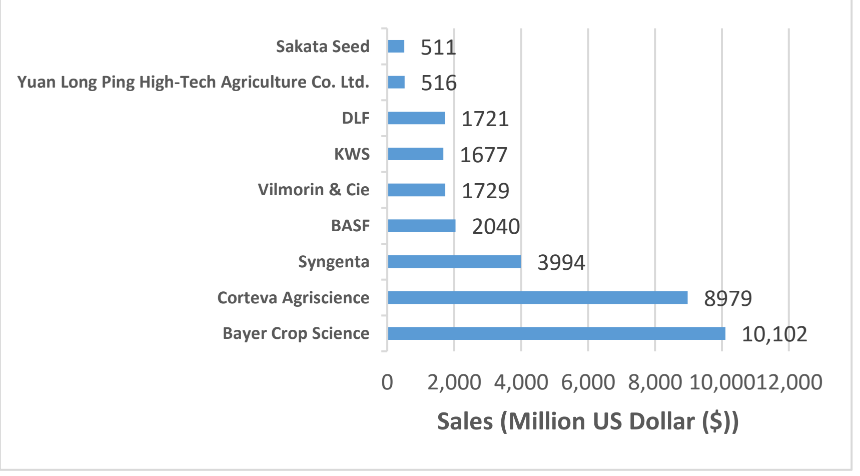

Figure 9.2. The world's largest seed companies in 2022 based on their sales (million US Dollars)
*(**Source:** https://scienceagri.com/9-worlds-largest-seed-companies/)*

The United States is a major player in the production of hybrid seeds, particularly for corn and soybeans (Singh *et al.*, 2023; Grand View Research, 2024). China has made substantial progress in hybrid rice production. They have invested heavily in agricultural research and development, and their hybrid rice varieties are widely adopted both domestically and internationally (Hybrid Rice Development Consortium, 2024). India is a significant producer of hybrid seeds, particularly for rice, vegetables, and cotton. India is increasingly focusing on hybrid rice to improve yields and food security. Indian companies are also members of international consortia that promote hybrid seed development (Hybrid Rice Development Consortium, 2024). Brazil is a leading producer of hybrid seeds for crops like maize, soybeans, and sugarcane (Grand View Research, 2024).

The global hybrid seed market is expected to grow rapidly, due to increasing demand for high-yield and disease-resistant crops. This growth is supported by increasing global population and food security concerns. Significant investment in research and development by both public institutions and private companies is leading to advancements in hybrid seed technology. When considering the global hybrid seed market, several key factors such as technological advancements, regulatory frameworks, market demand, and environmental considerations affect the global hybrid seed market (Grand View Research, 2024). Even though the high cost of developing hybrid seeds is a barrier for small-scale seed companies, large multinational seed companies continue to invest heavily in research and development to stay competitive. When considering the market competition, the hybrid seed market is highly competitive, with major players like Bayer, Corteva, and Syngenta. This competition drives innovation but also leads to consolidation within the industry (Singh *et al.*, 2023; Mordor Intelligence, 2024a; Grand View Research, 2024). According to key market dynamics, the global hybrid seed market's growth is driven by technological advancements, increasing food demand, supportive government policies, and the need for climate-resilient crops. However, challenges such as high development costs and market competition need to be managed to sustain this growth. By addressing these dynamics, stakeholders can better navigate the complexities of the hybrid seed market and capitalize on its opportunities (Singh *et al.*, 2023; Mordor Intelligence, 2024a; Grand View Research, 2024).

3. Hybrid seeds: Potential sectors to be adopted in Sri Lanka

When considering the percentage contribution of paddy, other cereals, vegetables and fruits to the national GDP, it was evident that the values remained at substantially low levels (1.0%, 0.3% 1.0% and 0.6% respectively in 2021) for years, unveiling the urgent need and the potential of increasing productivity by strategic adoption of appropriate measures (SEPC-DOA, 2021, 2022 and 2023).

Presently, many countries around the globe effectively adopt hybrid seed technology to develop and introduce novel hybrid crop varieties specifically targeting various agro-economically important traits (De & De, 2019; Wijesinghe & Wijesinghe, 2018). Hybrid seeds often result in crop populations that are more uniform in terms of growth, vigour, maturity, and other desirable traits across fields and therefore, provide predictability in crop yields and harvest times while facilitating smooth and convenient farm management practices. Hybrid seeds can also be tailored to different agro-climatic conditions including regions with specific soil types, temperatures, and rainfall patterns, allowing farmers to cultivate crops in regions where traditional varieties may struggle thereby expanding agricultural production areas. By adapting to different environmental conditions, hybrid seeds enable agricultural production in regions that may have previously been unsuitable for certain crops. This geographic expansion helps to diversify farming operations and reduce dependence on specific climatic zones. Therefore, adaptability expands the geographic range where crops can be successfully cultivated, increasing and diversifying agricultural production.

In such endeavors, the use of hybrid seeds represents one of the powerful and promising tools which offer significant potential and opportunities to transform the present status of Sri Lanka's domestic food crop sub-sector by boosting productivity, improving crop quality, enhancing resilience to stresses, and promoting sustainable farming practices in the face of evolving agricultural challenges. In adopting such strategies, it is a pre-requisite to identify and evaluate the present status, issues, challenges/limitations, and future expectations of each crop separately and address those accordingly.

Paddy

Being the staple food of Sri Lankans with a per capita consumption of about 113 kg in 2021, rice represents a sizable portion of Sri Lankans' diets. Even though Sri Lanka is presently self-sufficient in rice, with the increase in population, the demand for rice is expected to be further increased soon, urging the importance of immediate launching of strategies to increase rice production (SEPC-DOA, 2022 and 2023). Owing to various system-specific problems, during the past years, land area under rice as well as the number of farmers involved in paddy cultivation are gradually declining at an increasing rate further worsening the situation. As for any other crop, the other main problems encountered in paddy sector of Sri Lanka are the biotic (outbreak of pests such as thrips, brown plant hopper- BPH and rice gall midge- RGM and diseases such as rice blast-RB, sheath blight and bacterial blight- BB) and abiotic (drought, flood, salinity and iron toxicity) stresses that directly affect the rice production of the country (RRDI, 2024). Presently, because of climate change, unexpected extreme weather conditions such as prolonged droughts and frequent floods are common thus imposing additional negative impact on national rice production. Since hybrid seeds are specifically bred to produce crop varieties with enhanced characteristics such as higher yield potential, pests, and disease resistance, climate-resilient, and enhanced resource use efficiency compared to conventional cross-bred varieties, the development and introduction of different hybrid rice varieties could be recommended to address the present issues in Sri Lankan rice sector.

Other Field Crops

The other field crops (OFCs) sector is of immense economic importance to the continuous supply of many food commodities. The annual production of most of the OFCs i.e., condiments (chilli and onion), grain legumes (mung bean, cowpea, black gram, soybean, and pigeon pea), coarse grains (maize, finger millet, and sorghum), and oil seed crops (ground nut, sesame, and sunflower) in Sri Lanka is far below the country's present requirement. Therefore, to meet the demand, the country has to spend a huge sum of money to import those. Especially, big onion, dry chilli, soybean, mung bean and cowpea are the top OFCs imported as their domestic production remains around 10-20% of the country's requirement. Furthermore, since most of the cultivated land of OFCs is restricted to dry and intermediate zones and the cultivation mostly depends on the rain, they are often exposed to severe moisture stress conditions (SEPC-DOA, 2022, 2023; DOA, 2022). The situation is more alarming owing to the changing climatic conditions in the above areas (DOA, 2022). On top of that, the severe incident of pests (e.g. thrips in chilli; thrips and caterpillars in onion; pod borer and sap-sucking bugs in mung bean; stem borer in maize) and diseases (e.g. Leaf curl complex, die-back and anthracnose in chilli; Bulb rot and leaf twister disease in onion; Yellow mosaic virus, bacterial leaf spot, bacterial wilt and powdery mildew in mung bean; Leaf blight, stalk rot, and banded leaf and sheath spot in maize) and heavy infestation of weeds further devastate the OFC production while necessitating heavy dependence on agrochemicals leading to a significant increase in the cost of production (COP) while creating health issues (RRDI, 2024).

Out of the OFCs, based on their relative contribution to GDP, amount import, consumer demand, and agro-industrial potential, 10 crops namely maize, chilli, big onion, red onion, mung bean, ground nut, black gram, cowpea, sesame and soybean were identified as priority crops that to be considered in further improvements in their production capacities. Among the available strategies, the development and use of hybrid varieties remains as a promising approach to overcome productivity barriers addressing most of the constraints and limitations in reaching expected goals. For example, the use of a hybrid chilli variety in cultivation will result in a significantly higher yield (25-30 mt/ha) than an OP chilli variety which typically produces about 10 mt/ha. Maize is another crop with a high potential for using hybrids (DOA, 2022).

Vegetables

The vegetable sector is another area in which production could enhance using of hybrids. In the year 2020, the country produced about 1.15 million metric tons of vegetables with a mean productivity of 13.9 mt/ha. Even though the country's present demand for vegetables is fulfilled by local production, and Sri Lanka has exported about 510 mt of vegetables it has also been imported a substantial amount for the hospitality sector. However, when considering the average per capita consumption, it is much below (122 g/ day) than the daily recommended requirement (200 g/ person) reflecting the necessity of expanding the present production capacity of the sector (DOA, 2022). In addition to the common threats and challenges imposed by biotic and abiotic stresses, the vegetable sector has specific problems such as seasonality in production with gluts and lean periods, which directly influence the production. Also, vegetable production is further constrained by adverse weather conditions that result from changing and variable climatic conditions, especially during recent times causing severe crop damages, low or poor-quality produce, high post-harvest losses and even complete devastation of crops. This is one of the main reasons which leads growers away from the sector. Therefore, the development of climate-resilient high-yielding hybrid varieties would be the way forward where hybrid seed technology can play a big role.

Even though, the Department of Agriculture (DOA) has already developed technology packages towards further enhancement of the productivity of the vegetable sector, such an approach alone would be not sufficient to reach the target by effectively addressing the above-said constraints. Therefore, to overcome the above constraints and limitations more efficiently and effectively, the adoption of an integrated approach including the use of hybrid seed technology as a component would be a better and reliable option with proven results. In implementation, at the first instance, it could be targeted to enhance the productivity of crops cultivated in conventional land areas and in the later phases, emphasis could be further extended to expansion of cultivation to new geographical areas by developing new hybrids especially targeting such areas.

At the same time, since the country is focusing on further expansion of the present export volume of vegetables, it is fundamental to increase the annual mean vegetable productivity which is presently about 14.9 mt/ ha (DOA, 2022). In this context, the validity of using hybrid vegetable seeds is crucial since the development of hybrid seeds could also direct towards improving the quality attributes of crops, in terms of size, uniformity, appearance, texture, taste, nutritional content, and shelf life, not only meeting consumer preferences but also marketability.

4. Present status of the seed industry in Sri Lanka

The local seed requirement in Sri Lanka varies depending on the type of crops and the agricultural season. The DOA in Sri Lanka provides guidelines and estimates for the seed requirements of major crops. Accordingly, the total annual seed requirement for paddy is around 90,000-100,000 mt (Attanayake *et al.*, 2010; MOA, 2023). Various varieties of vegetable crops (around 40 species) are cultivated in different parts of the country throughout the year and the seed requirement for vegetables is substantial due to the diversity and continuous demand (Mordor Intelligence, 2024b).

Both the government and private sectors in Sri Lanka are involved in seed production and distribution among farmers. Accordingly, the Ministry of Agriculture (MoA), DOA and Seed and Planting Material Development Centre (SPMDC) are government institutions responsible for seed production and distribution while the Seed Certification and Plant Protection Centre (SCPPC) is responsible for seed certification. Seed and Planting Material Development Center (SPMDC) operates under the DOA, acts as the leading institute for seed-related activities and provides quality seeds and planting materials to farmers at reasonable prices on time. The private sector has contributed to seed production and imports in Sri Lanka since 1984 and at present various companies are mainly engaged in seed importation, commercial seed production, seed distribution and sale. The National Seed Policy was introduced in 1996 by the government to ensure high-quality seeds. However, as it was not successful, the government has enacted the Seed Act No.22 of 2023 to regulate the quality of seed and planting materials and safeguard farmers and seed handlers from malpractices that would harm the seed industry (Udari *et al.*, 2022).

Usually, most of the upcountry vegetable seeds such as cabbage, carrots, leeks, beetroot, beans, tomatoes, capsicum, cauliflower, knol khol and potatoes are imported. Even though seeds of low-country vegetables are produced locally, seeds of hybrid varieties and some open-pollinated varieties are imported (Wijesinghe & Wijesinghe 2018). In 2023, Sri Lanka imported 168 mt of vegetable seeds spending around 2,363 million rupees (SEPC-DOA, 2023). In addition to the formal sector of seed supply, farmers are using their seeds saved from previous harvests. According to Udari *et al.* (2022), it was reported that the formal seed sector (both government and private organizations) covers 10-12% of seed production and therefore many farmers depend on farmer-saved seeds and imported seeds.

Local production of hybrid vegetable seeds is increasing but still relies heavily on imports to meet the demand (Wijesinghe & Wijesinghe, 2018; Udari *et al.*, 2022; Sri Lanka Biz, 2024). So far, several local hybrid varieties such as Maheshi-2005 and Bathiya-2008 for tomato; Amanda-2005, Anjalee-2005, and HORDI Lenairi-2013 for brinjal and

HORDI Green and Gannoruwa white-2012 for cucumber have also been released by the DOA (Wijesinghe and Wijesinghe, 2018). The demand for high-quality fruit seeds is also rising due to increasing domestic consumption and export opportunities. Thus, to meet the local demand for high-quality seeds, especially hybrid varieties, Sri Lanka imports a significant quantity of seeds annually. The importation expenditure for hybrid vegetable seeds alone is approximately USD 25 million per year. The country also imports seeds for other crops to ensure sufficient supply and maintain agricultural productivity (Wijesinghe and Wijesinghe, 2018; Ministry of Agriculture and Plantation Industries, 2019; Udari *et al.*, 2022; Sri Lanka Biz, 2024; DOA, 2024).

However, the seed industry in Sri Lanka is currently undergoing considerable development and transformation, driven by both public and private sector initiatives aimed at increasing local seed production and reducing dependency on imports. The Sri Lankan government, through the DOA, has been actively involved in seed production, particularly in the case of seed paddy. The primary seed paddy production capacity, which was at 61%, is projected to increase to 91% by the end of 2024. This initiative aims to enhance the quality of paddy yields by providing farmers with high-quality, certified seeds, thereby boosting overall agricultural productivity (Ministry of Agriculture and Plantation Industries, 2019).

The private sector also plays a vital role in advancing the seed industry. The key companies involved in the seed industry in Sri Lanka are Tropical Seeds/OPEX Holdings, CIC Agri-Business, Hayleys Agriculture, Plantchem Pvt Ltd (Plant Seeds Private Limited), and Advanta Seeds (Mordor Intelligence, 2024b). Recently CIC Seeds (Pvt) Ltd. has launched five new varieties of hybrid vegetable seeds including two from chilli and one each from okra, capsicum, and brinjal, developed locally in collaboration with an international company. This marked a dramatic shift from the country's previous heavy dependency on imported hybrid seeds (Sri Lanka Biz, 2024).

The Sri Lankan seed market is expected to grow from USD 13.08 million in 2024 to USD 15.34 million by 2029, at a compound annual growth rate (CAGR) of 3.24% (Mordor Intelligence, 2024b). The increase in cereal and vegetable production, driven by the need for high-quality seeds, is a significant factor contributing to this growth. The country has also seen a 12.3% increase in cereal production and a nearly 50% increase in vegetable production volume in recent years (Research and Markets, 2024).

The seed industry in Sri Lanka is growing with contributions from both the public and private sectors with enhanced local seed production capabilities. Ongoing investments in research and development are expected to reduce reliance on imports and improve agricultural productivity in the coming years. Also, Sri Lanka has been making concerted efforts to enhance local hybrid seed production, driven by both public and private sector initiatives. The DOA has been focusing on increasing the production of hybrid seeds, particularly for vegetables and other high-demand crops. The contribution from research institutions would be essential in developing new hybrid varieties that are suited to local conditions.

Although there are many advantages of hybrid seeds, these advantages need to be weighed against the higher costs, potential dependency on seed companies, and possible environmental impacts. A balanced approach, incorporating both hybrid and traditional seeds, along with sustainable farming practices, could provide a way forward for the country's agricultural sector. Despite these positive developments, the seed industry in Sri Lanka faces challenges such as the need for more private sector involvement and advanced seed technology adoption. The government's efforts to encourage private investment and improve plant variety protection laws are crucial steps toward overcoming these challenges and fostering a more robust seed industry (Research and Markets, 2024; Sri Lanka Biz, 2024).

5. Local hybrid seed production

Heavy dependency of the Sri Lankan seed industry on the importation of seeds of high-yielding varieties including hybrid varieties, would negatively impact overall crop production in Sri Lanka under the dynamic economic situation in the country due to shortage of foreign reserves, restrictions on importations and depreciation of Sri Lankan rupee etc. Thus, this is high time to revisit the local seed production system and to study the ways and means of strengthening the public-private partnership for producing high-quality seeds; especially hybrid seeds in order to enhance the local agricultural productivity while ensuring a sustainable national seed supply system. Also, farmer-based communities could be encouraged to produce hybrid seeds by providing the necessary technical skills, resources and infrastructure facilities required in a systematic procedure. Accordingly, this section highlights the status and potential of local hybrid seed production of several selected crops which highly depend on seed importation.

5.1. Hybrid Chilli

The chilli, scientifically named as *Capsicum annum* is an essential condiment in food processing in day-to-day life, especially in the South Asian region. In Sri Lanka, the annual dry chilli requirement is about 55,000-60,000 mt and the country produces only about 10% locally (Hewage *et al.*, 2022). Hence, a minimum of 50,000 mt of dry chilli needs to be imported to meet the local demand. According to the Department of Census and Statistics (DCS) (2021), annual green chilli production varies from 60,000-79,000 mt. However, according to the Crop Production Programme 2023 reported by the MOA (2023) the targeted green chillies production in 2023 was 177,656 mt, but the dry chillies production was estimated at only 2,964 mt. Therefore, from these statistics, it could be noted that massive amounts of dry chillies are imported to the country. In addition, it consumes huge amounts of foreign exchange to import chilli seeds as planting materials.

The DOA has introduced 10 open-pollinated varieties namely, MI-1, MI-2, KA-2, Arunalu, MI-Hot, MI-Green, Galkiriyagama Selection, MI-Waraniya 1, MICH-3, MIPC-1 with the yield potential of 10-15 mt/ ha (Hewage *et al.*, 2022). However, due to many pests and diseases especially chilli leaf curl complex (CLCC), these open-pollinated varieties give only about 50% of their yield potential. The first local chilli hybrid, MICH HY 1, suitable for green chilli production was released by the DOA, Sri Lanka in 2015. This variety seems moderately resistant to CLCC which is the most significant issue in chilli cultivation. In 2017, another chilli variety, MICH HY 2-2017 was released for both dry and green chilli production and both have been reported to produce about 35 mt/ ha of average yield (DOA, 2024).

MICH HY 1 is a popular chilli variety in Sri Lanka and many farmers grow it by manual cross breeding. This has been produced from the cross between the Galkiriyagama inbred line as the female parent and MI Waraniya 1 inbred line as the male parent. Galkiriyagama selection-2009 variety was developed through the evaluation and selection of local landraces and recommended for North Central province in Sri Lanka, and it is resistant to CLCC and fungal diseases while green chilli yield is around 12-15 mt/ ha and dry chilli yield is around 3 mt/ ha. The male parent MI Waraniya 1-2011 is a selection from locally grown landrace in wet zone and it carries the average yield trait around 20-25 mt/ha (DOA, 2024). By exploiting the heterosis of Galkiriyagama inbred line x MI Waraniya cross, high yield and disease resistance were introduced to MICH HY 1. However, the male sterility system has not been introduced to this hybrid variety, therefore, commercial-scale seed production seems difficult and uses manual emasculation techniques.

In Sri Lanka, although hybrids have been produced and released for many crops to use as vegetables, their seed production is not widely practiced for a majority of crops. However, with the onset of Covid 19, several farmers understood the value of producing hybrid seeds and MICH HY 1 seeds were produced by a few farmers once they were given the guidance. In this regard, as the first step, seeds of Galkiriyagama and MI-Waraniya 1 should be purchased from the DOA and established in nurseries. Male parent Waraniya seeds should be planted 2-3 weeks before the planting of the female parent Galkiriyagama seeds. That is because the Waraniya plant is used to collect mature pollen and it needs to happen before the flowering of Galkiriyagama plants. It is not necessary to plant both varieties in equal amounts. Usually, Waraniya is needed only for collecting pollen. Therefore, a few plants such as either 1/3rd or 1/4th plants are enough for pollination. The number of Galkiriyagama plants should be higher as we expect the harvest from them and usually, they are maintained as 3:1 ratio of Galkiriyagama and Waraniya plants. If the plants are properly maintained, pollination can be initiated after one and a half months to two months. A fully open flower of Waraniya will be selected for the collection of pollens. In Galkiriyagama an unopened fully mature flower bud is selected, and petals should be removed. Then pollen of the Waraniyawa flower is smeared on the top of the stigma of Galkiriyagama female flowers and labelled for allowing pod development (**Figure 9.3**).

The manual pollination procedure described above is time-consuming and needs a lot of labour cost and attention. However, there is a technology called male sterile (MS) technology which could be incorporated to produce hybrid seeds on a mass scale without manual emasculation and manual cross-pollination. Therefore, research in Sri Lanka should be focused on producing hybrid chilli with MS technology.

Figure 9.3. Galkiriyagama parent showing the tagged stems of the cross-pollinated flower when producing MICH HY 1 seeds

5.2. Hybrid Maize

Maize (*Zea mays* L.) is another crop that is extensively imported as seeds for crop production and as a source for animal feed production. In 2020, total seeds imports were 29,820 mt while in 2021, the value had increased up to 75,000 mt due to the fertilizer ban (SLASS, 2022).

Presently, DOA has recommended two open-pollinated varieties, Bhadra and Ruwan which could be used to produce seeds. However, due to heterosis vigour farmers prefer to grow hybrids more and such hybrids developed and released in Sri Lanka are MI maize Hybrid 1, MI maize hybrid 2, MI maize hybrid 3, MI maize hybrid 4 and MI maize hybrid 5 (DOA, 2024). All these hybrids are reported to produce 8 mt/ha as yield potential and the general yield varies from 5.5 to 6.5 mt/ha. However, locally only a small amount of hybrid seeds is produced by manual emasculation followed by manual cross-pollination. Therefore, due to limited hybrid maize-seed production, farmers are used to purchase hybrid seeds from multinational companies by importation which consumes a lot of foreign exchange. Hence, the research should be focused on incorporating MS traits into maize hybrids that could be utilized in commercial-scale mass seed production without manual cross-pollination; a time and labour-consuming task.

5.3. Hybrid Brinjal

Brinjal (*Solanum melongena* L.) is another highly marketable and consumer-preferred low-country vegetable that shows high heterosis power. In 2022, the extent of brinjal cultivation was 10,868 ha giving 132,394 mt of total production (SEPC-DOA, 2023).

Although brinjal is considered as a self-pollinated crop it can undergo cross-pollination also up to 48% due to projecting the stigma above anthers in many varieties (Ministry of Environment and Forest India and Ministry of Science and Technology in India, 2017). As usual, in brinjals also, F1 hybrids are more preferred because of gaining higher fruit yield, superior fruit quality traits, pest and disease resistance and wide adaptation to abiotic stress factors. DOA, Sri Lanka has released several F1 hybrids such as Amanda, Anjalee, HORDI Lena Iri and several selections of brinjal such as Thinnaweli purple and Padagoda and SM 164 (DOA, 2024). Usually, the DoA is the authorized body that issues breeder seeds or the parental lines of Amanda, Anjali, and HORDI Lena Iri to registered farmers or private companies who wish to produce hybrid brinjal seeds. After producing hybrid seeds, the DOA has the authority to purchase the F1 hybrid seeds from the growers and sell them *via* Seed Certification Services to consumers. Therefore, interested growers are encouraged to register at the DOA and to purchase their interested parental lines from the breeders so that they can manually produce hybrid brinjal seeds under the guidance of the DOA. However, as the demand for brinjal hybrids could not be supplied only locally, many private companies import brinjal seeds from foreign multinational companies. Further research on developing hybrid brinjal varieties, incorporating MS technology should be enhanced to become self-sufficient with hybrid brinjal seeds in Sri Lanka.

6. Constraints and future prospects in the hybrid seed industry in Sri Lanka

Every gene has three different genotypes, AA, Aa and aa out of which hybrid has the Aa genotype. Hence, all the genes for example if 30000 genes are available in the plant and they exist in the form of heterozygous, Aa, Bb, Cc, Dd etc in all 30,000 genes in hybrid plants. This heterozygous condition is a fascinating condition of plant breeding referred to as heterosis which exhibits superior phenotypes of both parents, contributing to increased vigour, yield, size, *etc.* making the farmer and consumer well satisfied.

Therefore, seed producers produce and sell hybrid seeds as the farmer can get the best output or yield and growth from the plant. Comparatively to hybrid, other categories of seeds which are called pure lines or inbreds have the genes in the form of AA, bb alleles called homozygous. These types of pure lines are produced by selfing in consecutive times till the heterozygosity becomes almost zero. Hence, when the plant produces seeds, they contain the same genotypes as that of its mother because no heterozygosity exists, and the next generation also shows the same traits as their parents. Hence, farmers can save some seeds from the previous growing season to cultivate in the next season.

However, with hybrids, using seeds from the previous generation for cultivation in the next generation is not feasible due to their heterozygous nature. When they self-pollinate, heterozygous alleles segregate and produce different phenotypes. Therefore, farmers have no choice other than to depend on hybrid seed producers, usually multinational companies. Hence, if the hybrid seeds are not produced locally by the government or private sectors of a country, massive foreign exchange needs to be spent on the importation of hybrid seeds from multinational companies.

The local hybrid seed production process is labour-consuming because most of the crops are produced by manual emasculation followed by manual crossing with the pollen. Hence, farmers have to separately grow the male and female parents of the crop and produce hybrid seeds with technological guidance. Hence, in Sri Lanka, hybrid seeds are produced for only a few crops, and the quantity produced is minimal compared to the total seed requirement.

With the dollar crisis in 2022 in Sri Lanka, the importation of hybrid seeds was restricted, causing farmers to struggle to obtain hybrid planting materials. Therefore, many investments in local hybrid seed production processes were encouraged to save foreign exchange in the country.

The major constraint in producing hybrid seed on a mass scale is that technology needs manual emasculation followed by cross-pollination which consumes huge labour and time. But on a commercial scale mass producers in multinational companies and developed countries use the male sterility (MS) technology which is one of the most effective ways to produce hybrid seeds as pointed out by many scientists (Jindal *et al.*, 2020; Rani *et al.*, 2021) because male sterile plants cannot undergo self-pollination. Hence, this technology decreases 50% of the labour costs by withholding the hand emasculation process of the maternal inbred line (Meena *et al.*, 2018). Therefore, MS lines are highly valuable in commercial hybrid seed production systems and later the plants can be fertilized by male fertile plants. There are two types of MS technologies depending on the origin of the gene contributed to male sterility. If the gene contributed to the MS is located in the genome of the nucleus, it is called nuclear male sterility (NMS) or genic male sterility (GMS) and if the gene is located in an organelle genome of the cytoplasm, it is called cytoplasmic male sterility (CMS). One such gene governing GMS was reported in a chilli line called MS-12 by Punjab Agricultural University (PAU), Ludhiana in India (Dash *et al.*, 2001). The particular gene in the MS-12 line was identified as, *ms10* and the gene has been reported to serve for the male sterility in many chilli and pepper varieties. The gene is a recessive gene, and it is, therefore, difficult to recognise phenotypically in breeding activities (Aulakh *et al.*, 2016). Therefore, it is necessary to reorganize a closer marker to the ms10 gene to introduce into female parents by marker-assisted selection. Moreover, it is necessary to identify other potential genes that contribute to MS and closer markers for them due to the advantages of the MS technology.

In Sri Lanka, DOA has currently initiated breeding programs to introduce a male sterile gene to hybrid seed production. Transferring of the genetic male sterility trait derived by the MS 10 gene into the Galkiriyagama inbred line, the female parent of local chilli hybrid MICH HY1, through backcross breeding, has been reported by Herath *et al.* (2022). However, new commercial varieties with male sterile phenotypes have not been released in the country so far, but it has been identified as a prioritized research area.

Accordingly, it is notable that there is high potential to strengthen and streamline the local seed industry while focusing on the development of high-quality hybrid seeds adapted to the local environment to facilitate sustainable crop production in Sri Lanka. In view of this, increasing investment in research and development, active contribution from research institutes, streamlining of regulatory processes and enhancing the quality control measures would facilitate faster introduction of new high-yielding, climate-resilient varieties while ensuring a consistent supply of high-quality seeds. Government support through subsidies and financial incentives while strengthening the public-private partnerships would reduce the cost of production of hybrid seeds and improve infrastructure for storage and distribution. Meanwhile, the government can give more attention to strengthening and training selected farmer-based communities with necessary technical knowledge while providing infrastructure facilities for developing hybrid seeds facilitating to establish small-scale seed enterprises. This would facilitate the market availability of hybrid seeds at a reasonable price while lowering the chance of having a market monopoly controlled by a few key producers. Thus, it is high time to consider making such efforts in future to meet the demand for high-quality seeds and sustainable agricultural productivity in Sri Lanka and lower the heavy dependency on importation of hybrid seeds which consumes a lot of foreign exchange reserves in the country.

7. Conclusion

In examining the hybrid seeds within the global context, it is notable that the global hybrid seed market is expanding rapidly which is driven by technological advancements, increasing food demand, and the need for climate-resilient crops to mitigate unpredictable climate change impact on agriculture. In developing regions where agricultural productivity is crucial for livelihoods, the high cost of hybrid seeds and dependence on seed companies for new seeds in each planting season are significant barriers for small-scale farmers. Therefore, we discussed the challenges of hybrid seed production and possible market failure in a dynamic economy due to dependence on hybrid seed importation using the Sri Lankan context as the country faced for a financial crisis in 2022. However, it was noted that efforts are being undertaken to increase local hybrid seed production, with significant investments in research and development by both the government and the private sectors, which will lead to reduce import dependency. As an example, we illustrated the development procedure of hybrid seeds of, the MICH HY 1 chilli variety using Galkiriyagama inbred line as the female parent and the MI Waraniya 1 inbred line as the male parent for the benefit of the growers who are interested in investing in the hybrid seed production, which is highly profitable, but not adequate currently in the country. Also, we provided some insights into the understanding of the most demanding type of crops to be adopted by the hybrid technology along with indicating other potential crops. Furthermore, the importance of the ms10 gene and evidence for improving chilli and pepper varieties with ms10 genes have been indicated aiming at directing the research areas towards male sterile-line development which facilitates the hybrid seed industry immensely. Finally, we emphasized the necessity for government intervention in hybrid seed production by giving subsidies and financial incentives to hybrid growers while strengthening public-private partnerships to reduce the cost of production of hybrid seeds locally and to improve infrastructure for storage and distribution.

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