THE INSTITUTE OF BIOLOGY
SRI LANKA

THEMATIC PUBLICATION
2024

ACHIEVING A CIRCULAR AND SUSTAINABLE BIOECONOMY

Achieving a Circular and Sustainable Bioeconomy

Published by

The Institute of Biology, Sri Lanka

27th September 2024

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Citation: Name/s of chapter author/s (2024). 'Title of chapter', In: Achieving a Circular and Sustainable Bioeconomy. Colombo; Institute of Biology Sri Lanka, pp. x-y

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Technical Editing: Prof. H. D. D. Bandupriya and Dr K. G. S. U. Ariyawansa

Cover Page Design: Mr. Gihan Rajapaksha

Page Layout: Mr. Nuwan Medawaththa and Mr. Ovin Amarasinghe

ISBN: 978-624-5998-05-0 (E-Book)

27th September 2024

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Achieving a Circular and Sustainable Bioeconomy

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Preface

In an era marked by environmental challenges and resource scarcity, the concept of a circular and sustainable bioeconomy emerges as a beacon of hope. "Achieving a Circular and Sustainable Bioeconomy" explores the transformative potential of integrating biological resources into economic systems that prioritize sustainability and regeneration.

This book delves into the principles of a circular economy, where waste is minimized, resources are reused, and materials are cycled back into the economy. It emphasizes the importance of sustainability not only as a goal but as a foundational aspect of our economic framework. By harnessing the potential of bio-based materials and processes, we can develop systems that regenerate rather than deplete, creating a resilient economy that benefits both people and the planet.

As we navigate this complex transition, it is essential to understand that achieving a circular and sustainable bioeconomy is not just a technical challenge; it is a social imperative. This book serves as both a guide and a call to action, encouraging all stakeholders to embrace a new paradigm that prioritizes ecological integrity and social equity.

This book is just one small element in the expansive landscape of new innovations. We encourage you to delve deeper to discover and harness its significant potential. We trust that the insights shared here will prove beneficial to academics, researchers, educators, and students in biology and related fields.

We are grateful to the chapter authors, reviewers, and council members for their invaluable support in creating this book.

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27th September, 2024

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Acknowledgements

The Institute of Biology, Sri Lanka, sincerely acknowledges the contributions of everyone involved in publishing this book. Their dedication and generous support have been instrumental in making this publication a reality.

- We sincerely appreciate the chapter authors for their willingness and commitment to sharing their expertise by contributing to this book.

- We gratefully acknowledge the chapter reviewers for their invaluable efforts in enhancing the quality, coherence, and content of the chapters.

- We extend our heartfelt thanks to Mr. Gihan Rajapaksha for designing the cover page and Mr. Ovin Amarasinghe for creating the title pages of the chapters.

- Finally, we sincerely appreciate the dedication of Mr. Nuwan Medawaththa and Mr. Ovin Amarasinghe for their meticulous work in the final formatting of the book.

Contents

Chapter 1

Endophytes from extreme environments as a bioresource: A promising frontier in overcoming antimicrobial resistance

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Abstract

Antimicrobial resistance (AMR) refers to the ability of pathogenic microorganisms to withstand antimicrobial treatments. AMR has become one of the top ten global health threats and thus a new broad spectrum of antimicrobial agents from novel sources is urgently needed to address this global challenge. Endophytes are endosymbiotic microorganisms that may have a part or all of their life cycle within their host while maintaining a complex but stable relationship without any apparent disease symptoms. Endophytes have gained prominence for their ability to produce bioactive compounds with antimicrobial properties, offering a sustainable alternative to conventional antibiotics widely used. The current pipeline of discovery of antimicrobials is the isolation and characterization of previously unknown endophytic microorganisms isolated from the extremobiosphere. The concept of excavating the extremobiosphere is that the harsh abiotic environmental conditions like extreme temperature, high salinity, and aridity will modify the mutualistic relationship between the host plants and the endophytes that leads to the emergence of novel bioactive chemicals with great chemical diversity. This chapter will highlight recent discoveries, applications, and current trends in harnessing endophytes as a bioresource, emphasizing their role in fostering a sustainable and circular bioeconomy and aims to inspire further research, innovation, and collaboration toward achieving global sustainability goals while addressing critical challenges in healthcare and environmental management.

Keywords: Antimicrobial Resistance, Bioresources, Endophytes, Extreme habitats, Pathogens

An insight into antimicrobial resistance (AMR) crisis

Figuring The discovery of Penicillium, with the ability to inhibit bacterial growth by Alexander Fleming in 1928, and the purification of penicillin from Penicillium by Florey and Chain in 1940, paved the way for the antibiotic revolution in the field of medicine.

Antimicrobials include antibiotics, antivirals, antifungals, and anti-protozoans – medicines that are frequently used in the healthcare sector to prevent and treat many infections in humans, animals, and plants (WHO, 2023). Antimicrobial activity can be defined as the process of killing or inhibiting the growth of disease-causing microorganisms. However, the downside is that continuous exposure of pathogens to these antimicrobials rapidly develops resistance against them.

Antimicrobial Resistance (AMR) has become a worldwide problem, and in 2019, the World Health Organization (WHO) declared AMR as one of the top ten global public health threats. In 2019, the Centers for Disease Control and Prevention (CDC) documented that, on average, 2.8 million antibiotic-resistant infections occur in the USA each year, and more than 35 000 people die as a result (CDC, 2019). The increased prevalence of 'ESKAPE' pathogens: *Enterococcus faecium, Staphylococcus aureus, Klebsiella pneumonia, Acinetobacter baumannii, Pseudomonas aeruginosa*, and *Enterobacteriaceae*, along with multidrug-resistant pathogens to the existing antimicrobials in both hospital and community settings, and the extreme limitation of new types of antimicrobials has forced the healthcare sector into a situation of "Bad Bugs, No Drugs" (Talbot et al., 2006).

Therefore, discovering novel antimicrobial compounds with high efficacy and low resistance profiles is crucial and urgent. This chapter highlights how harnessing microbial diversity can pave the way towards overcoming the AMR crisis and advancing a circular, sustainable bioeconomy.

Microorganisms as a source of novel antimicrobials

From ancient times, people have depended on various types of natural products as a source of medicine, until the discovery of modern high-throughput techniques in the discovery of drugs. According to the literature, 80% of the reported drug substances were natural products or derived from natural compounds (Zuck, 1998). These natural products can be either from plants, insects, or microorganisms. However, plant-based antimicrobials have been extensively explored with diverse applications in medicine, veterinary, agriculture, and biotechnology. But in recent years, microorganisms like bacteria, fungi, actinomycetes, mollicutes, viruses, nematodes, and protists have been explored as potential sources of novel antimicrobial agents (Figure 1.1).

The drug discovery process from a microorganism depends upon the isolation of a novel or known microorganism with the potential of producing a secondary metabolite with antimicrobial activity. The exploration of diverse ecosystems and isolation of diverse genera of microorganisms is the key pathway to the discovery of novel antimicrobials.

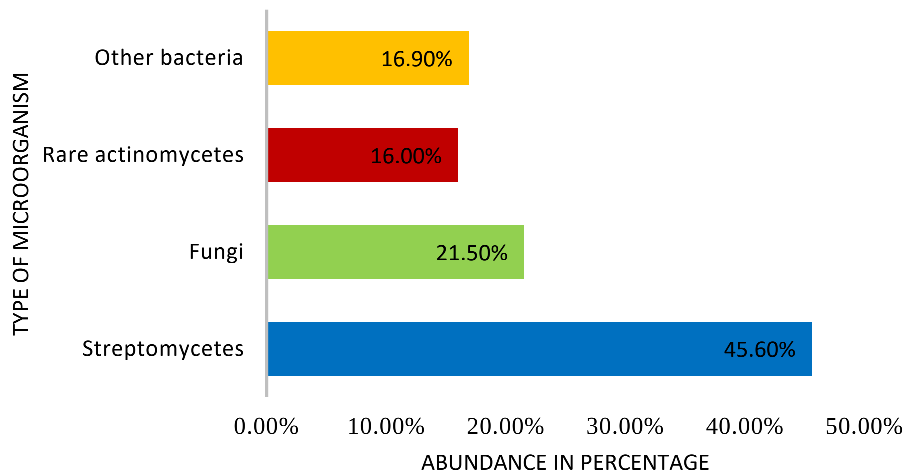

Figure 1.1: The abundance of different groups of microorganisms producing antimicrobial compounds (modified from Tiwari and Gupta, 2012).

Endophytes as a potential bioresource for novel antimicrobials

Endophytes are ubiquitous, they can either be prokaryotes; bacteria, archaea, or eukaryotes; fungi, algae, and amoeba, which reside inside the plant tissues and are significantly different from those found on the plant surface. They can reside intra- or inter-cellularly within their host tissues for their entire or a part of their life cycle and they do not cause any apparent harm to their host (Nisa et al., 2015).

Plants produce different kinds of chemicals that induce the colonization of endophytes within the host via chemotaxis (Figure 1.2). It is assumed that after entry, endophytes can remain in a quiescent (latent) state for the whole lifetime of the host plant (neutralism) or an extended period until the environmental conditions are favorable for endophytes (mutualism or antagonism). This long-term mutualistic interaction between endophytes and their host plants results in the production of a plethora of bioactive compounds with remarkable chemical diversity. These compounds represent various structural classes, including aliphatic compounds, alkaloids, peptides, phenolics, polyketides, and terpenoids. This chemical diversity underpins a broad spectrum of pharmaceutical properties, notably potent antimicrobial activities.

Endophytes from extreme environments as a source of novel antimicrobials: opening new doors

In the past, endophytes from terrestrial environments have played an important role in the pipeline for drug discovery. Still now, the limitation is that the repeated isolation of natural compounds from them has limited the development of new and effective drugs against AMR as pathogens are no longer susceptible to those antimicrobials. Therefore, a steep decline in the discovery of new drugs from the sources of the terrestrial ecosystems has been observed within the last few decades.

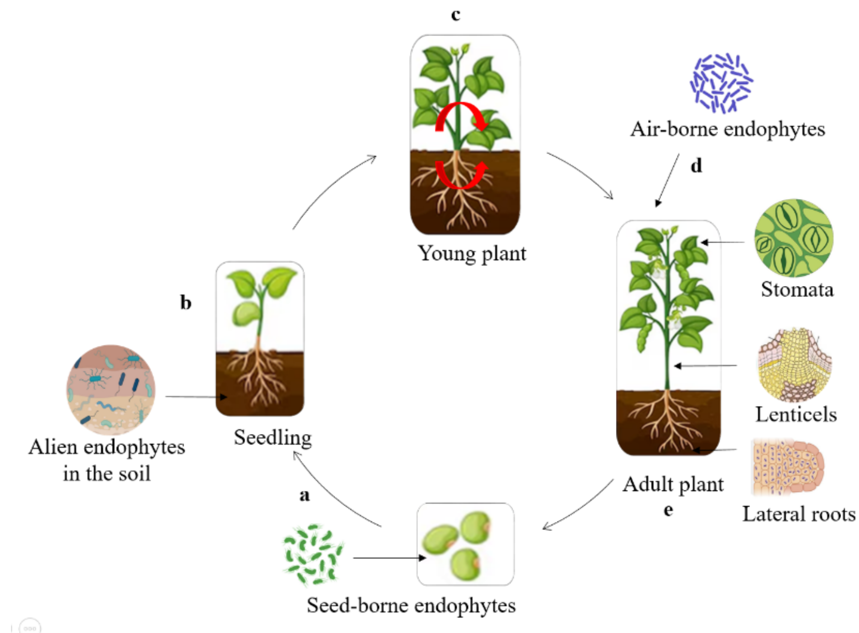

Figure 1.2: Colonization and distribution of endophytes within the plant. **a.** Vertical transmission of seed-borne endophytes **b.** Entry of alien endophytes from the rhizosphere **c.** Systematic spread of endophytes via vascular tissues **d.** Horizontal transmission

Subsequently, the unexplored and under-explored extreme environments like continental soils (Albores et al., 2018), desert soil (Harir et al., 2019), deep oceans (Giddings and Newman, 2022), and marine sediments, plants, and water (Xu et al., 2015) have gained the attention of researchers as novel sources of endophytes with the potential of antimicrobial activity. The search for novel bioactive compounds with antimicrobial properties from the extremobiosphere rests on the promise that extreme abiotic conditions will select novel and/or resistant microorganisms with novel chemistry.

Insight into different extremobiosphere with the promise of novel antimicrobials

Endophytes from marine habitats

Endophytic bacteria, actinomycetes, and fungi inhabit marine biotopes including marine plants (algae and sea grass), invertebrates (sponges, crustaceans, corals, ascidians, bivalves, and holothurians), and numerous other minor marine phyla, and their diversity and novelty of secondary metabolites are regarded as outstanding source of antimicrobial properties. Among these bioactive compounds isolated from endophytes in marine habitats are actinomadurol, cinnamycin B, pargamicins B-D, kocumarin, keyicin, nabscessins A and B, isoflavonoid E, huimycin, and xiamycins D. These compounds demonstrate potent antibacterial, antifungal, and antiviral activities, underscoring the immense potential of marine endophytes as a valuable source for novel antimicrobial agents.

Marine algae are an exceptional source of endophytes with promising antimicrobial secondary metabolites. *Nocardiopsis* sp., an endophytic actinomycete from a brown alga, and another endophytic actinomycete from a green alga, *Caulerpa taxifolia* were active against multidrug-resistant Gram-negative bacteria (Rajivgandhi et al., 2018), *Pestalotia* sp. isolated from a brown alga produces a novel chlorinated benzophenone that exhibits antibiotic activity against methicillin-resistant *Staphylococcus aureus* (MRSA) (Kamat et al., 2020), and *Pestalotia* sp.

isolated from a red alga, *Thermus islandicus* gave hydro anthraquinones with antimicrobial properties (Pavithra et al., 2020).

Endophytes from mangrove habitats

Mangroves are wetland ecosystems found in intertidal zones, where land meets the sea. These ecosystems are rich in biodiversity, encompassing a variety of plants, animals, microalgae, bacteria, fungi, and actinomycetes. The soil and sediment of mangrove habitats are excellent sources of novel actinomycetes, although comprehensive records of endophytes in mangroves remain sparse. However, novelty in the endophytic community could be expected since soil and sediment serve as a reservoir for them and mangrove-associated endophytes hold promises for uncovering unique bioactive compounds with antimicrobial properties.

The mangrove-derived endobiosphere, rich in actinomycetes, bacteria, and fungi, is a treasure of secondary metabolites with significant antimicrobial activity. Among the antibacterial compounds isolated from mangrove-derived actinomycetes are idosespene, sespenine, and xiamycin A from a *Streptomyces* sp. isolated from *Kandelia candel* (Ding et al., 2011), and antimycin from *Streptomyces lusitanus* isolated from *Avicennia marina* (Han et al., 2012). Mangrove-derived fungi have also yielded several bioactive compounds, such as pinazaphilone B, talaperoxide A, B, C, and D, peniohenone, penicillenone, halimide, plinabulin and many of them have been identified as promising antimicrobials (Table 1.1). It has been recorded that from 300 leaf segments of the mangrove plant *Rhizopora mucronata* 35- endophytic fungal strains exhibited insecticidal, antimicrobial, antiviral, anti-inflammatory, and anti-diabetic activity (Hamzah et al., 2018) which states that mangrove-derived fungal endobiosphere is a potential source of novel antimicrobials.

Furthermore, endophytic bacteria isolated from *Rhizopora mucronate* have exhibited antibacterial activity against *E. coli* and *S. aureus* (Ainy and Sembiring, 2019). These discoveries highlight the immense potential of mangrove ecosystems as a source of novel antimicrobial agents.

Endophytes from arid ecosystems

Plant-associated extremophilic and extremotolerant bacteria, fungi, and actinomycetes can thrive under harsh conditions of pH and salinity, possessing gene clusters that produce novel bioactive compounds that exhibit antimicrobial properties. Secondary metabolites like ferulic acid, cinnamic acid, quercetin, rutin, alkaloids, and flavonoids from endophytic fungi *Penicillium roqueforti* and *Trichoderma reesei*, isolated from the roots of *Solanum surattense*, exhibit antibacterial properties (Ikram et al., 2019) and fatty acid derivatives like 7-octadecenamide from *Nocardia caishijiensis*, and linoleamide from *Pseudomonas carboxydovorans* isolated from *Sonchus oleraceus* in arid environments, show antimicrobial activity (Tanvir et al., 2018).

Table 1.1: Chemical classes of main antimicrobial metabolites produced against ESKAPE pathogens by mangrove-derive endophytic fungi.

Chemical class	**Fungal Endophytes**	**Host Plant**	**Reference**
Aflatoxin-derived mycotoxin	*Aspergillus flavus*	*Hibiscus tiliaceus*	Wang et al., 2012
Sesquiterpene	*Pestalotiopsis* sp.	*Rhizopora mucronata*	Qi et al., 2019
Polyketide-derived mycotoxin	*Phyllosticta capitalensis*	*Bruguiera sexangula*	Hemberger et al., 2013
Isocoumarion	*Pestalotiopsis* sp.	*Rhizopora stylosa*	Xu et al., 2020
4H-chromen-4-one	*Penicillium aculeatum*	*Kandelia candel*	Huang et al., 2017

Endophytes from polar region

Recent studies in the polar regions (Arctic and Antarctic) have unveiled endophytes as a vast and underexplored reservoir of novel natural products. These microorganisms have evolved to thrive in extremely cold and harsh environments by synthesizing a diverse array of unique metabolites and metabolic pathways, enabling them to maintain a successful symbiotic relationship with their hosts under extreme conditions. Among the bioactive compounds reported from polar endophytes, many exhibit pharmaceutical relevance. Some examples are, *Tritirachium* sp. isolated from an Antarctic lichen (*Neuropogeon* sp.), produces diphenyl ether and macrotriolides with antimicrobial activity (Ivanova et al., 2007) and lindgomycetaceae strains isolated from a sponge from the Antarctic have yielded lindgomycin and ascosetin, novel polyketides, which showed a profound antimicrobial activity against MRSA, and *E. faecium* (Wu et al., 2015). These discoveries underscore the immense potential of polar endophytes in developing novel and effective antimicrobial agents.

Endophytes from caves

A cave is a completely dark, natural underground hollow space with constant temperature, high humidity, low pressure, low oxygen concentration, and a nutrient-limited ecosystem (Burcham, 2009). These extreme conditions are thought to foster the development of unique microbial communities, including those with novel antimicrobial properties. While current research has primarily focused on novel antimicrobials like bacteriocin, cervimycins, colistin A and fusaricidin isolated from microorganisms on cave soils, sediments, rock walls, scrapped mats and pieces (Zada et al., 2021), the untapped potential of endophytic microorganisms within cave ecosystems remains an exciting frontier. Despite the lack of literature specifically documented on endophytes from cave environments, there is a promising potential for discovering novel microorganisms with antimicrobial activity in these unique settings.

Hindrances and advances in utilizing endophytes from extreme environments as a bioresource against AMR

In the quest to combat AMR, harnessing the potential of endophytes from under-explored and unexplored extreme environments presents both obstacles and opportunities. This unique endosymbiotic relationship between endophytic microorganisms and their hosts has led to the possibility of employing these microbes and their metabolic products in biological applications. But the majority of the endophytic microorganisms from extreme habitats remain uncultured and unidentified due to the lack of knowledge about their peculiar cultivation parameters like culture media, pH, temperature, and incubation time. While the harsh conditions of these habitats may deter conventional cultivation methods, they also offer a reservoir of resilient microbial life, primed for adaptation and innovation. The difficulties in isolating endophytes from other epiphytic microorganisms and plant tissues, difficulty in mimicking the growth conditions provided by the host, difficulty in investigating the symbiotic relationship between the host and the endophytes, difficulty in re-cultivation after isolation, and difficulty in extraction of secondary metabolites with reported biological activities after re-cultivation are some of the constraints that have limited the success of utilizing endophytes in biological applications (Kandasamy and Kathirvel, 2023).

However, over the past few decades, there has been a gradual development of research bodies with advanced endophytic characterization methods involving multilocus sequence typing, microarray multiplex technology, high throughput sequencing (pyrosequencing), comparative genomics, meta transcriptomics, metagenomic sequencing, and nucleic acid-based stable isotope probing techniques. Efforts towards the improvement of endophytic compositions provide us with numerous benefits, including the discovery of unique, effective, and affordable metabolites that are difficult to synthesize chemically.

Conclusion and future perspectives

In conclusion, the exploration of endophytes from extreme environments as a bioresource offers a promising frontier in the battle against AMR. The urgent need for novel antimicrobial agents, coupled with the limitations of conventional antibiotics, has propelled scientists to explore unusual sources for solutions. Tapping into the vast microbial diversity in extreme habitats, not only uncover novel compounds with therapeutic potential but also contributes to the broader goal of achieving a circular and sustainable bioeconomy. Exploring extreme habitats for endophytes with therapeutic value underscores the importance of preserving these ecosystems and recognizing their value as sources of valuable microbial diversity.

Moving forward, advanced bioprospecting techniques, omics technologies, and synthetic biology hold promise for unlocking the full potential of endophytic microorganisms from extreme habitats. Collaboration between academia, industry, government, and non-government organizations will be crucial in translating research findings into tangible solutions for AMR coupled with global issues such as food security, environmental pollution, and climate change.

Embracing the challenges and harnessing the strength of extreme environment endophytes, will pave the way toward a more resilient and sustainable future in the fight against AMR safeguarding the public health and also preserving the biodiversity.

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Chapter 2

Revolutionizing agriculture: Harnessing the power of nanotechnology for sustainable agriventures

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Abstract

Nanomaterials offers unparalleled potential to revolutionize various arenas due to its aptitude to manipulate matter at the nanoscale. Enhanced material characteristics, precise drug delivery systems, increased energy efficiency, and inventive sensing capabilities serve as a few merits in the nanoscale range. Utilizing these features could lead to developing broad range of disciplines, spurring creativity and assisting urgent natural issues affecting the modern world. In agriculture, by enabling nano fertilizers and nano pesticides a targeted release of them at the nanoscale, enhances nutrient uptake efficiency and minimizes environmental contamination. Furthermore, the resilience of crops to both abiotic and biotic stresses, water management, and soil quality. These advancements have guaranteed sustainability in modern agribusiness. Nanotechnology enhances the productivity and efficiency of agricultural processes acting as a catalyst in commercialization ventures. It is aligning with the global imperative to secure food production in a resource-constrained and environmentally sensitive context. In addition, nanotechnology-based solutions vastly contribute to climate-smart practices. Hence, nanotechnology has emerged as a transformative force in agribusiness, offering innovative solutions to address challenges and optimize various facets of the agro-food value chains. In conclusion, the invention of nanotechnology in agriculture offers multifaceted benefits, on increased crop yield and quality to sustainable resource management. Accepting these benefits opens up the prospect for revolutionary solutions to satisfy the ever-growing demands of a rapidly evolving world while guaranteeing ecological sustainability and food security for the foreseeable future.

Keywords: Agri ventures, Nanomaterials, Nano-fertilizer, Nano-pesticides, Sustainable systems

Introduction

What is nanotechnology?

In the sense of scientific advancement, nanotechnology is an emerging approach that encompasses material management at the scale covering the 1–100 nm range. In the discipline of nanotechnology, systems with structural characteristics that stretch from single atoms or molecules to submicron dimensions are assembled and executed, and the resulting nanostructures are then assimilated into larger systems. Therefore, nanotechnology is connected with systems and materials, the components and structures of which represent novel, significantly improved chemical, physical, and biological properties, processes, and phenomena because of their nanoscale size (Ramsden, 2005). The Greek word meaning 'dwarf' corresponds to where the name "nano" originates, outlining the minor scale of the particles and structures that nanotechnology works with. A physicist, Richard Feynman is credited with igniting the field of nanotechnology with his famous 1959 speech, "There's plenty of room at the bottom"; where he envisioned the possibility of manipulating individual atoms and molecules to create smaller and more efficient machines. This visionary idea laid the groundwork for what would later become a rapidly evolving field. In reality, Norio Taniguchi first used the term "nanotechnology" in 1974 to refer to nanoscale precision machining. Practical developments, however, did not start to appear until the 1980s and 1990s with the introduction of advanced devices such as the atomic force microscope (AFM) and scanning tunnelling microscope (STM). Since then, advancements in computational modeling, materials science, and microscopy have taken nanotechnology from an academic endeavor to a swiftly expanding field that has substantive impacts on society (Hulla et al.,2015). Today, nanotechnology permeates various industries, from medicine and electronics to energy and materials science, showcasing the profound impact of manipulating matter at such a minute scale.

Nanoparticles and characteristic features of nanoelements

The reality that the chemical, physical, and biological properties of materials at the nanoscale could diverge significantly from those within a bulk material exemplifies the essence and promise of the fields of nanotechnology and nanoscience. When utilized for comparable purposes, nanoparticles (NPs) express more desirable attributes concerning bulk materials. Particles with a size range of one to one hundred nanometers are called nanoparticles. Because to their tiny size, they have a high surface area-to-volume ratio, which indicates that a sizable amount of their atoms or molecules are on the surface. Bulk materials, on the other hand, are made up of bigger particles with a lower surface area-to-volume ratio, and the majority of atoms are found inside the material as opposed to on its surface. A notable application of NPs is in the production of a novel kind of catalysts designated as nano catalysts. Large surface-to-volume ratio, surface morphology, and electronic properties boost the functions of nano catalysts derived from NPs (Khan et al., 2022). Quantum confinement effects also become noticeable, impacting optical, magnetic, and electromagnetic properties. For instance, plasmon resonance from the surface, a mechanism generated by the collective oscillation of conduction electrons, causes excitement in gold nanoparticles, which leads to intense colors. These nanoparticles are employed in biological detection, image processing, and catalytic processes due to their size and shape can be precisely controlled by manipulating their color.

In addition, the high surface area generated by NPs provides ample opportunities for functionalization and surface modifications. It is further involved in governing the stability, dispersibility, and interactions of nanoparticles with substrates or adjacent molecules. By integrating organic ligands, polymers, or biomolecules into the outermost layers of nanoparticles, one can precisely manipulate their characteristics while establishing functionalities that make them ideal for specific scenarios. For example, magnetic resonance imaging and targeted drug delivery in biomedical applications are made accessible by embedding magnetic nanoparticles with environmentally friendly polymers. To even more enable nanoparticles to realize and bind to specific targets including biomolecules, contaminants, or pathogens, surface changes can give them selectivity and responsiveness. Many systems for monitoring, diagnosis, and remediation have been constructed based on this ability. Moreover, combining various substances, which might involve metal oxides and carbon nanotubes, to create hybrid nanoparticles can result in synergistic capabilities that are desirable for energy conversion and storage applications (Nagarajan, 2008).

Nanotechnology as a catalyst for commercialization

At its core, nanotechnology involves manipulating matter on an atomic and molecular level to create materials with remarkably diverse and new properties. These nanomaterials are pivotal in the development of cutting-edge products and applications. The commercialization of nanotechnology is not merely about the creation of new materials but also encompasses the integration of these materials into existing products and processes. Thereby these concept will lead significantly improving their performance and functionality. The journey from laboratory research to market shelves is fraught with challenges, yet numerous success stories exemplify the commercial potential of nanotechnology. For instance, the use of nanostructured thermoelectric materials in micropower generators has led to more efficient energy conversion systems. Similarly, the integration of nano-catalysts in industrial processes has shown promise in enhancing energy efficiency and reducing greenhouse gas emissions (Ali et al., 2014).

In the realm of agriculture and food systems, nanotechnology emerges as a pivotal force, intertwining with various facets such as enhancing food security, refining disease treatment methods, and advancing molecular and cellular biology tools. It also plays a crucial role in detecting pathogens and safeguarding the environment. The sector of agriculture, which has traditionally focused on boosting crop production efficiency, food processing, safety, and addressing the environmental impacts of food production and distribution, now sees nanotechnology as a beacon for the future. Its potential to significantly uplift society is evident through its applications in agriculture and food systems (Dlamini et al., 2014). For the majority of developing nations, agriculture is not just an industry but also the very foundation of their economies, supporting over 60% of their populations. Nanotechnology's ability to better monitor environmental conditions, optimize nutrient and pesticide delivery, and deepen our understanding of crop biology could lead to increased crop yields and improved nutritional profiles. Moreover, it opens pathways for creating higher-value crops and tackling environmental challenges.

Recognizing the transformative power of nanotechnology, countries worldwide are investing heavily in its application within the agribusiness sector. This investment is matched by an equal focus on addressing the societal implications of nanotechnology and enhancing awareness within the agribusiness community. The advanced agribusiness sector, with nearly three decades of production, witnesses a growing demand for its products annually, attributed to their added value for end-users. The commercialization of manufacturing techniques has also spawned numerous novel applications, particularly in the food processing and animal husbandry industries (Sabourin, 2015). Therefore, understanding the nuances of nanotechnology in the agribusiness market is crucial. It provides comprehensive market insights, enabling stakeholders to make informed strategic decisions. This understanding is not just about recognizing the current market segmentation but also about anticipating the vast potential for future applications that nanotechnology holds within the agribusiness sector.

Classification and synthesis of nanoparticles

Classification of nanoparticles

Three types of nanoparticles are found in nature and categorized as organic, inorganic, and carbon-based.

Synthesis of nanoparticles

Top-down and bottom-up are the two basic methods that are applied in synthesizing nanoparticles. Bottom-up methods are considered for synthesizing nanomaterials from atoms while the top-down method is focused on breaking down the bulk material into nanoscale level.

Table 2.1: Different types of nanoparticles found in nature

Type	Characteristic features	Remarks	Examples
Organic nanoparticles	All are biodegradable and non-toxic. Some contain hollow cores and are sensitive to thermal and electromagnetic radiation.	Apply for target drug delivery	Dendrimers, Micelles, Liposomes Ferritin
Inorganic nanoparticles	Particles with the absence of carbon. Metal and metal oxide-based nanoparticles are the most common types. Metal-based: Nanoparticles that are synthesized from metals to nanometric sizes either by destructive or constructive methods. Metal oxide-based: To alter the characteristics of the corresponding metal-based nanoparticles, metal oxide-based nanoparticles are synthesized.	High surface area to volume ratio. Crystalline and amorphous structures Shapes like spherical and cylindrical. Sensitivity to environmental factors such as air, moisture, heat, and sunlight. Deliver high reactivity and efficiency	Aluminium (Al), Cadmium (Cd), Cobalt (Co), Copper (Cu) Gold (Au) Iron (Fe) Lead (Pb) Silver (Ag) Zinc (Zn) Iron oxide (Fe_2O_3) Cerium oxide (CeO_2), Magnetite (Fe_3O_4) Silicon dioxide (SiO_2) Titanium oxide (TiO_2) Zinc oxide (ZnO)

Carbon-based nanoparticles	Entire nanoparticles consist of carbon.	Fullerene: Fullerenes (C60) is a carbon molecule that is spherical in shape and made up of carbon atoms held together by sp2 hybridization. Graphene: Graphene is an allotrope of carbon and a hexagonal network of honeycomb lattices made up of carbon atoms on a two-dimensional planar surface. Carbon nanotubes: a graphene nanofoil with a honeycomb lattice of carbon atoms is wound into hollow cylinders to form nanotubes. Carbon nanofiber: wound into a cone or cup shape instead of a regular cylindrical tube. Carbon black: An amorphous material made up of carbon, generally spherical in shape with diameters from 20 to 70 nm.	Fullerenes Graphene Carbon nanotubes (CNT), Carbon nanofibers Carbon black

Table 2.2: Different methods of synthesizing nanoparticles

Method	Process	Remarks	Examples
Top-down	Mechanical milling	Mechanical milling is utilized to grind post-anneal nanoparticles, with multiple components being ground in an inert atmosphere.	Metal, oxide, and polymer-based
	Nanolithography	Creating nanometric scale structures with at least one dimension in the size range of 1 to 100 nm.	Metal-based
	Sputtering	Deposition of nanoparticles on a surface by ejecting particles from it by colliding with ions. The size and shape of the nanoparticles are determined by the thickness of the layer, temperature, and duration of annealing, substrate type, etc.	Metal-based
	Thermal decomposition	Heat drives a compound's chemical bonds to break, which leads to thermal breakdown, an endothermic chemical mechanism.	Carbon and metal oxide-based
	Laser ablation	Various solvents and irradiation are applied here. When a metal immersed in a liquid solution undergoes exposure to a laser beam, the stream of plasma condenses and forms nanoparticles. This affords a stable synthesis of nanoparticles in organic solvents and water that do not require any stabilizing agent or chemicals	Carbon-based and metal oxide-based

Bottom-up	Biosynthesis	It is a secure, environmentally beneficial, and reliable method for creating nontoxic, biodegradable nanoparticles by using plant extracts, bacteria, and fungi along with a precursor. The biosynthesized nanoparticles have distinctive and enriched properties that find their way into biomedical applications	Organic polymers and metal-based
	Chemical vapour deposition	Chemical vapor deposition is the deposition of a thin film of gaseous reactants onto a substrate. This can generate highly pure, uniform, hard, and strong nanoparticles. However, this process requires special types of equipment, and gaseous by-products are highly toxic	Carbon and metal-based
	Spinning	This is carried out by a spinning disc reactor. As a result of the atoms or molecules merging owing to the spinning, they precipitate, congregate, and dry. The distinctive characteristics of nanoparticles are dictated by a number of operational factors, including the liquid flow rate, disc rotation speed, liquid/precursor ratio, feed position, disc surface, etc.	Organic polymers
	Pyrolysis	It entails setting a precursor on fire. The precursor is supplied into the furnace at	Carbon and metal oxide-based

		extremely high pressure through a tiny hole where it burns and is either a liquid or a vapor. This method is a simple, efficient, cost-effective, and continuous process with high yield	
	Sol-gel	A solid-liquid component is suspended in a solution with colloidal particles. A solid macromolecule immersed in a solvent is called a gel. Metal oxides and chlorides are the typically used precursors in this method. Using a variety of techniques, including sedimentation, filtering, and centrifugation, phase separation is accomplished to recover the nanoparticles, and drying is implemented to remove the moisture further.	Carbon, metal, and metal oxide

Merits of nanotechnology in agri sciences

The agriculture sector has many concerns in the current times, including excessive usage of chemical fertilizers, inappropriate resource use, and climate change. In the modern time frame, nanotechnology is emerging as the sixth revolutionary technology. It is considered a developing subject of study that is heavily dominated in many other scientific domains and is predicted to have a major part in food science and agriculture in the years ahead. Distribution and administration of agrochemicals and dietary requirements, pesticides, nano-scale carriers, advanced packaging, nanosensors, veterinary treatment, fisheries and aquaculture, and recognizing deficiencies in nutrients represent a number of the direct uses of nanotechnology in agriculture.

Nano fertilizers in crop nutrients

In order to minimize costs that pertain to protecting the ecosystem and enhance the efficiency of nutrient use, slow-release fertilizers are an excellent replacement for soluble fertilizers. Nano fertilizer technology is an innovative technology developed rapidly in recent years for sustainable agriculture. One study identified that 640 mg ha^{-1} foliar application nano phosphorus resulted in 80 kg ha^{-1} P equivalent yield of cluster bean and pearl millet under an arid environment (Tarafdar et al., 2012). Furthermore, nano fertilizers will improve many properties like solubility and dispersion of mineral micronutrients, the efficiency of nutrient uptake, controlled release modes, the effective duration of nutrient release, and minimize the loss of fertilizer nutrients effectively. Mineral micronutrient formulations at the nanoscale could reduce soil absorption and fixation, enhance bioavailability, and boost the solubility and diffusion of insoluble minerals in the soil. In crop production, a nano-structured formulation could enhance fertilizer efficiency and soil nutrient acquisition ratio while restoring fertilizer. Further, nano fertilizers contribute to effective controlled released modes by covering water-soluble fertilizers in envelope-shaped, semipermeable coatings covered in resin-polymer, waxes, and sulfur, the release rate and distribution of nutrients can be precisely controlled. In addition to that, nano fertilizers can extend the effective duration of the nutrient supply of fertilizers into the soil efficiently. Also, nanostructure formulation helps to diminish the fertilizer loose into the soil either by leaching or leaking (Cui et al., 2010). Nanoencapsulation is a promising technology involved in sustainable and precision agriculture in various ways. It will significantly increase the nutrient uptake in the soil.

Its release of the nutrients can be triggered by an environmental condition or simply released at a desired specific time. Nano and sub-nanocomposites can be encased and fastened to regulate the release of nutrients from the fertilizer capsule. A patented nano-composite comprised of N, P, K, micronutrients, mannose, and amino acids that intensify the uptake and application of nutrients by grain crops has been conveyed (Jinghua, 2004). Nanoencapsulation can be done in three ways. The nutrient can be encapsulated inside nanoporous materials, coated with a thin polymer film or delivered as particles or emulsions of nanoscale dimensions (Rai et al., 2012). Furthermore, through the combination of nanodevices, nano fertilizers will synchronize the release of N and P fertilizers with crop uptake, preventing unfavorable nutrient losses to soil, water, and air through immediate crop internalization and preventing nutrient association with soil, microorganisms, water, and air (DeRosa et al., 2010).

A class of naturally occurring minerals with layered crystal structures approximating honeycomb-like structures, called zeolites, can be harnessed to gradually disperse nutrients towards the environment. Nitrogen and potassium can be supplied to its web of aggregating tunnels and cages, along with other slowly dissolving constituents consisting of calcium, phosphorus, and a whole range of minor and trace nutrients. During this technology, nanomembranes can be placed over fertilizer particles to facilitate the slow and steady diffusion of nutrients (Chinnamuthu and Boopathi, 2009). Another study relevant to “Nutrient Release Pattern of Nonfertilizer Formulations” expressed the crop's intake of nutrients, which was 72 percent in the case of nano fertilizer and 42 percent in the case of urea. Once nano fertilizers incorporate to the crop though soil it maintains for approximately 50 days in the soil profile and facilitate continuous supply among these period after zeolite was incorporated as a carrier, while the crop shut down releasing the urea after 12 days (Kannan, 2011). Hence, these studies conveyed that nanoencapsulation improves stability against degradation in the environment and increases the effectiveness of these applications. Nano-clay particles like substances used will moderate the porosity of the polymer, or else impede the diffusion of the active material being released, thereby snowballing the length of the path of the diffusion through the host polymer.

Hence, nano fertilizers offer the potential to enhance nutrient uptake, minimize environmental impact, and boost crop yields sustainably. However, further research is essential to fully understand their long-term effects on soil health, plant growth, and ecosystem dynamics. By harnessing the power of nanotechnology responsibly, we can strive towards a more efficient and sustainable agricultural future.

Nano-herbicides in effective weed control

Comprehensive pesticide executive management serves as a prerequisite to weed control tactics and is an essential aspect of global sustainable agriculture. Due to their competitiveness for resources and ability to harbor pests and illnesses, weeds constitute an enormous risk to agricultural productivity. Herbicides contribute to preserving weed-free fields and maximizing crop production by offering an intensive approach to weed control. To reduce concerns about the environment, such as soil erosion, water contamination, and the emergence of herbicide-resistant plants, however, careful herbicide use is required. Safeguarding agricultural ecosystems and assuring long-term food security requires combining various kinds of weed management strategies with conservative herbicide application. In the context of weed control, the implementation of nano pesticides is a novel approach that has considerable promise for sustainable agriculture. With their specialized formulations and more effective targeting abilities, nano herbicides minimize environmental impact while offering consistent and effective suppression of weeds. Their nanoparticles allow for stronger weed species penetration and uptake, maximizing efficacy while requiring minimal herbicide. Additionally, herbicide diffused, and runoff concerns may be mitigated with nano herbicides, safeguarding ecosystems and non-target plants. Deploying nano herbicides to maximize their efficiency represents an advancement towards more environmentally friendly and productive weed control approaches, which are necessary to meet the evolving needs of modern agriculture while maintaining environmental integrity.

One study revealed that the effectiveness of alginate/chitosan nanoparticles was evaluated in recent studies. It demonstrated the significant differences between the release profiles of free paraquat and the herbicide associated with the alginate/chitosan nanoparticles. The findings demonstrated that paraquat's association with alginate/chitosan nanoparticles modulates the herbicide's distribution spectrum and soil engagement, proposing that this system may be a useful tool for minimizing the adverse consequences of paraquat. Experiments indicated that the percentage of organic matter contained influenced the sorption of paraquat into the soil, whether it was free or attached to the nanoparticles. Another study proved the effectiveness of nanoparticles in sustainable agriculture in terms of effective usage of herbicides by using Atrazine. With a half-life of 125 days, atrazine is an s-triazine-ring herbicide that has been extensively utilized for suppressing grassy and broadleaf weeds both before and after they emerge. It is also exceptionally versatile depending on soil types. The choices of crops for rotation become limited and the effective application of herbicides is at risk due to residual issues resulting from the employing of atrazine herbicide. Hence, the application of modified silver nanoparticles with magnetite stabilized with Carboxy Methyl Cellulose applied to formation of these nano pesticides. Results evidenced that the modified nano pesticides containing atrazine residue degraded by 88% (Susha et al., 2008).

Nano pesticides in sustainable agriculture

The widespread application of nano pesticides, allowing for unprecedented degrees of precision and effectiveness in pest management, signals an exciting advancement in contemporary agriculture. Using the distinctive properties of nanomaterials, nano pesticides are more environmentally friendly, have more sustained effects, and have greater bioactivity than conventional agricultural pesticides. Nanoparticles reduce environmental pesticide residues and off-target effects while enabling targeted delivery to pest populations. Additionally, nano pesticides are promising in combating pesticide resistance, which is becoming more prevalent in agricultural pest management. Farmers can optimize crop protection regulations, guarantee food security, and advance ecologically friendly farming methods for the coming generations by utilizing the potential of nano pesticides.

Insecticides, fungicides, and nematicides that are nano encapsulated can be used to develop a formulation that successfully controls pests without allowing residues to build up in the soil. The formulation's effectiveness can be enhanced by employing a nanotechnology approach known as "slow release of the active ingredient" to shield the active ingredient from deterioration and increase perseverance. This might drastically decrease the amount of pesticide input and the associated environmental hazards. Nano pesticides diminish the rate of application by 10-15% than conventional applications. To strengthen plant contact, prolong the release of pesticides, and minimize the cost of pesticides with the smallest number of detrimental impacts on water streams, clay nanotubes, also known as halloysite, have been established as low-cost pesticide drivers. These nanotubes could reduce pesticide application by 70–80%. Different types of nanoparticles applied as nano pesticides are described in Table 2.3.

Nanoparticles in waste water management and bioremediation

Nanoparticles serve as catalysts. Applying photocatalytic decomposition assets of nanoparticles has warranted acceptance in cleaning and decontaminating polluted water (Singh et al., 2019). Chemical reactions are initiated in the presence of nanoparticles with such toxic chemical compounds in the presence of light. One of the major complications plaguing the developing world right now is the pollution or contamination of water supplies from nature. Wastewater has a negative influence not only on the environment but also on the animals, and human beings. Therefore, wastewater management is an essential need in the modern world (Kumari et al., 2019). Nanotechnology delivers a vital tool in the cleaning of wastewater. Negative electrons emerge from the nanoparticles whenever they are stimulated by a light source during water disinfection. The bacterial cells in the tainted water can be wiped out with the aid of these electrons. Furthermore, the food packaging industry could potentially employ these nanoparticles as a disinfectant (Kumari et al., 2019).

Certain synthetic substances used in agricultural systems, particularly pesticides, take longer to break down in the environment or are resistant; as a result, they can pose significant threats. Introducing nanotechnology, to degrade these under certain conditions is a promising tool in the modern world scenario (Bhandari, 2018). If pesticides are not degraded, they may enter the food chain and may cause serious health problems. Due to nanoparticles' high surface area to volume ratio, these tiny particles are more reactive and highly successful at binding to pollutants. Furthermore, it becomes feasible to synthesize nanoparticles to specifically target pollutants, enabling designed remediation strategies. With regard to their small size, they can penetrate matrices of soil, water, and air to reach regions of contamination that might be unreachable using conventional means. In addition, the stability and function of enzymes or microbes associated with biodegradation processes can be increased by using nanoparticles as carriers (Kumari and Singh, 2016). For example, nanoparticle-water slurry can be mixed in contaminated soil, and in due course of time, these particles will reduce the toxicity of slowly degradable or resistant pesticides (Dhewa, 2015).

Table 2.3: Different types of nanoparticles in nano pesticides

Type of nanoparticle	Importance	Remarks
AgNPs	Effectually been developed for the site-targeted delivery of crucial agrochemical products and as diagnostic tools for early recognition of plant pathogens. They have strong pesticidal, bactericidal, antifungal, and antiviral effects.	At successful dose levels, these nano formulations have downgraded human toxicity, demoted pest resistance problems, and lessened the cost of production when compared to conventional synthetic pesticides.
TiO_2 NPs	It is a naturally existing titanium oxide with few non-target biological consequences and low toxic effects.	Many investigations have demonstrated the widely known antimicrobial properties of TiO2NPs and shown that the administration of titanium dioxide to crops prevented the growth of bacterial and fungal diseases. When tested contrary to bacterial pathogens in tomatoes and roses, nanoscale titanium dioxide, either by itself or in combinations with silver or zinc, proved to be efficacious.
CuNPs	CuNP-based pesticides are affordable and effective as opposed to currently available conventional biocides and the entire expense of the crop is an important concern when choosing plant protection measures. Additionally, there is no tendency for pest species may develop resistance to them if	The primary implications of using CuNP are the unregulated release and improper metabolism of reactive oxygen species. CuNPs emit cupric ions, and these particles do not combine to form complexes with other compounds.

	they are used often or swapped with traditional formulations.	
ZnONPs	These are appropriate for application in agriculture due to their easy accessibility and low cost of the chemical. Nevertheless, the use of ZnONPs is correlated with phytotoxic effects, which are frequently impacted by their size range.	ZnO NPs are reported to have the ability to decrease the effect of environmental stresses on plants, such as drought, temperature, metals, metalloids, and salt. When applied at suitable concentrations, ZnO NPs increase plants' seed germination, growth, the activity of antioxidants and protein production, chlorophyll content and photosynthesis, production of oils and seeds, and uptake of essential elements. Indicate that the synthesized ZnO nanoparticles were efficient Previous study evidence delivered the removal of glyphosate in aqueous solutions at the laboratory level.

Potentials of nanotechnology in agribusiness

The agribusiness sector is on the cusp of a monumental surge, with projections estimating its global investment value to reach $2.9 trillion USD by 2030 (World Bank, 2013). This resurgence of agricultural development as a focal point in global development and investment agendas is a testament to its burgeoning significance. The spike in grain prices and the ripple effect of global food inflation have catalyzed investor interest in farming, further invigorating the sector. The value chain's expansion through agri-food processing, food retail, and service networks reflects the private sector's escalating engagement in this domain. This positive trend has not gone unnoticed in governmental and economic circles, garnering recognition and support. A consensus is forming among development institutions, agencies, and strategic investors, heralding a new era of agricultural development that is reshaping global economics. By 2050, it is anticipated that the primary growth in food demand will emanate from North America, Western Europe, and China, propelling commercial food business systems forward (Ill-Min et al., 2017). Factors such as population growth, income trends, lifestyle choices, and consumer preferences will shape this demand, which is increasingly leaning toward convenience, food safety, and quality. Currently, over 400 companies globally are engaged in nanotechnology research and development, a number poised to more than double in the next decade. Leading the charge in this innovative field are the USA, Japan, China, and the EU, setting the stage for a transformative impact on agribusiness (World Bank, 2013).

Food processing segment

The food processing industry stands on the brink of a revolution with the advent of nanotechnology, a field that holds the promise of transforming the way producers produce, process, and consume food. Nanotechnology's application in food processing is not just an incremental step but a quantum leap forward, offering unprecedented control over food at the molecular level. Nanotechnology in food processing is about manipulating substances at the nanoscale to achieve desired outcomes. This includes enhancing flavors, improving nutritional content, extending shelf life, and ensuring food safety. The use of nanomaterials, such as nano emulsions, nanocapsules, and nanocomposites, allows for the creation of food products with improved texture, taste, and consistency (Couch et al., 2016). For instance, nano emulsions can be used to create low-fat spreads that retain the creamy texture and taste of full-fat counterparts. One of the most significant benefits of nanotechnology in food processing is the ability to enhance bioavailability. Nutrients encapsulated in nanocarriers can be designed to release their contents at specific sites within the gastrointestinal tract, improving absorption and efficacy.

Nanotechnology also plays a vital role in food packaging, where nanosensors and smart packaging materials can detect and signal the presence of pathogens or spoilage, ensuring food safety and reducing waste. Nanocomposite materials can provide better barriers to gases and moisture, extending the shelf life of perishable goods (Bratovcic et al., 2015). In addition, the incorporation of nanomaterials or nanotechnological devices in packaging materials or storage containers in order to lengthen the storage time while keeping the products fresh is considered the most important type of nanotechnology application in the food industry. Nanocomposites can improve mechanical strength; reduce weight increase heat resistance and improve the barrier against oxygen, carbon dioxide, ultraviolet radiation, moisture, and volatiles of food package materials. Moreover, nanotechnology enables the fortification of foods with essential minerals and vitamins without altering their taste or appearance. For example, nanoscale iron can be added to flour or rice, combating iron deficiency without affecting the food's sensory properties (Pal, 2017). The environmental impact of food processing is another area where nanotechnology can make a significant contribution. Nanocatalysts can be used to reduce the energy required for certain processes, and nano filters can purify watermore efficiently, leading to more sustainable production methods (Ansari, 2023).

Despite these benefits, the application of nanotechnology in the food industry is not without challenges. In conclusion, nanotechnology offers a plethora of opportunities to innovate within the food processing segment. It has the potential to improve the quality, safety, and nutritional value of food while also addressing environmental concerns. As research progresses and communities around the world gain a deeper understanding of nanomaterials and their interactions with biological systems, and hence, can expect to see more nano-enabled products entering the market, heralding a new era in food technology. The future of food processing with nanotechnology is not just about making incremental changes; it's about reimagining the possibilities of what food can be and how it can be produced.

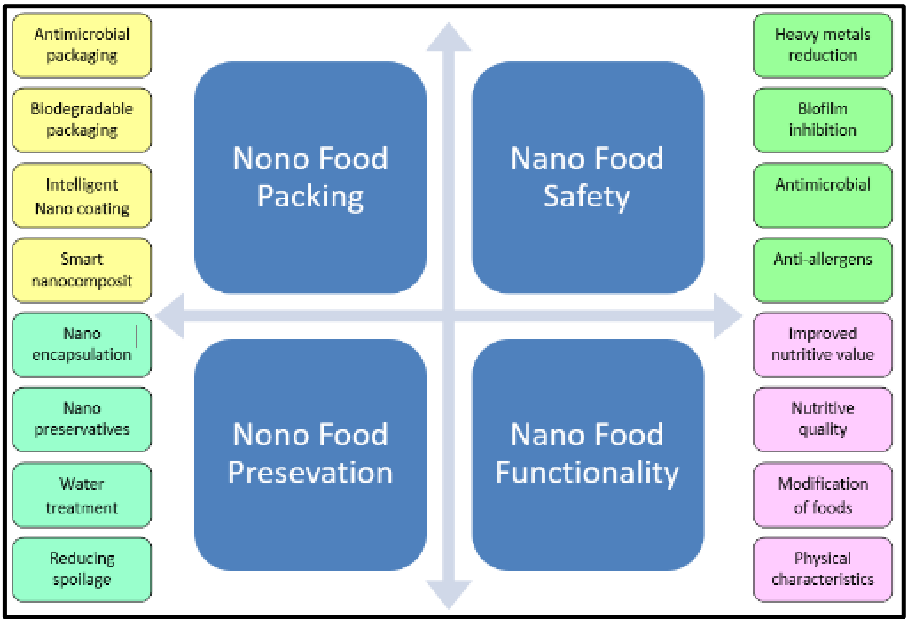

Figure 2.1: Nanotechnology for the Smart Food

Optimizing the agri-food value chain

The agri-food value chain encompasses a series of steps that food products undergo from farm to table, including production, processing, distribution, and consumption. As the global population continues to grow, optimizing these processes to ensure food security, sustainability, and efficiency is more crucial than ever. Nanotechnology, with its innovative applications, has emerged as a key player in revolutionizing the agri-food value chain. The impact of nanotechnology in the areas of input management and food processing is already mentioned in the previous sections. Another important area is the food distribution process. Nanotechnology can also optimize food distribution. For example, nano sensors can monitor the conditions of food during transport, ensuring that it remains at the right temperature and humidity levels. This is particularly important for perishable items that need to be kept within specific conditions to prevent spoilage (Adeyeye and Fayemi, 2019). Further, at the consumption end of the value chain, nanotechnology can contribute to food safety and health.

In the dynamic landscape of agricultural value chains, nanotechnology emerges as a transformative tool, enhancing transparency, authenticity, and traceability, thereby bolstering food security. It offers a sophisticated system of invisible nano barcodes that carry encrypted batch information, which can be imprinted directly onto food products and their packaging. This innovation in nano barcode technology empowers brand owners to oversee their supply chains discreetly, without divulging sensitive company data to intermediaries. More than just a security measure, nanotechnology enforces brand protection, embedding verification features within products to confirm authenticity and thwart counterfeit attempts. It enables the encryption of unique product details, including environmental data from on-farm sensors, directly onto the goods. This not only informs consumers about the quality of their food but also supports product valuation and ensures critical traceability for safety recalls (Mor et al., 2015). Furthermore, nanotechnology can encode logistical details, such as processing data, onto products or packaging, streamlining the supply chain management. A notable example is Oxonica, a company based in the United Kingdom, which has pioneered the use of nano barcodes to create a biological fingerprint for food items, offering a unique and secure method for food identification and brand authenticity (Scott et al., 2018).

Ensuring the integrity of the food supply chain is paramount, not only to comply with legal standards but also to meet the growing consumer demand for safe, high-quality food and stringent regulatory food safety measures. Nanotechnology has emerged as a beacon of innovation, particularly in the development of sensors capable of detecting spoilage and quality alterations in food products. European Union researchers, under the Good Food Project, have pioneered a portable nano sensor that can identify chemicals, pathogens, and toxins, bypassing the need for time-intensive and costly laboratory analyses (Scott et al., 2018). These nano sensors enable on-site safety and quality assessments at various points in the supply chain, such as farms, slaughterhouses, during transit, and storage and processing facilities.

Contributions to climate-resilient practices

In the face of climate change, ensuring global food security presents a formidable challenge for the 21st century, as we strive to feed a growing population without further straining our environment. The threat of climate change necessitates the enhancement of crop yields primarily through improved agronomic practices and the development of superior crop varieties. Yet, the reliance on limited resources like phosphorus or nitrogen-based fertilizers makes these methods unsustainable for long-term food security, with minimal prospects for additional enhancements (Wahab et al., 2024). Nanotechnology, which involves manipulating particles at the smallest scale, offers promising solutions to the obstacles faced in agricultural ventures. Particles at the nanoscale are at the forefront of a new wave of technologies aimed at environmental restoration, offering cost-effective remedies for some of the most daunting environmental clean-up challenges. Nanoscale iron particles, in particular, boast expansive surface areas and heightened reactivity, and their versatility allows for diverse in situ applications. These particles are notably effective in altering and neutralizing a broad spectrum of environmental pollutants, including chlorinated organic solvents and organochlorine pesticides (Hunter et al., 2017).

The realm of nanotechnology and nanobiotechnology is yielding benefits for the environment. Nanotechnology has introduced a variety of sustainable methods to address environmental issues such as water purification, reduction of greenhouse gas emissions, the energy crisis, and the remediation of pollutants that contribute to climate change (Wahab et al., 2024). Consequently, nanotechnology is paving its path in environmental applications and could emerge as a pivotal technology in the fight against climate change. Pollution, a major driver of climate change, has pushed conventional wastewater treatment methods to their limits. Nanotechnology-enhanced water treatment processes, including adsorption, membrane separation, photocatalysis, disinfection, monitoring, and sensing, utilize an array of nanomaterials to break down pollutants. Moreover, nanotechnology holds the potential to revolutionize existing technologies into eco-friendly, sustainable alternatives to address the repercussions of global warming and climate change.

Potential challenges and limitations of using nanotechnology in agriculture

While nanotechnology holds immense promise for revolutionizing agriculture through enhanced crop protection, improved soil health, and efficient resource use, several potential challenges and limitations must be addressed to fully realize its benefits. The hazards to ecology and the environment posed by using nanoparticles are a major obstacle. Nanoparticles can build up in soil and water systems because of their small size and strong reactivity, which can be harmful to aquatic life, microbes, and plants. Furthermore, it is yet unclear how these particles may affect biodiversity and soil health in the long run, which calls for thorough environmental evaluations and strong regulatory frameworks. Another limitation is the economic barrier to widespread adoption. The cost of developing, producing, and applying nanomaterials can be prohibitive for small-scale farmers, particularly in developing countries where access to advanced technologies is limited. This disparity could exacerbate existing inequalities in agricultural productivity and sustainability. Moreover, the consistent administration and accurate targeting of nanoparticles in agricultural environments provide technological difficulties. It is still difficult to make sure that nanoparticles can efficiently target particular pests or plant tissues without inadvertently harming creatures that are not their intended targets. The matter of public acceptance and perception is another.

The use of nanotechnology in agriculture may raise concerns about food safety and the potential for unintended health impacts, leading to resistance from consumers and advocacy groups. Addressing these concerns through transparent communication, rigorous safety testing, and regulatory oversight is essential for building public trust. Finally, farmers and other agricultural workers need to get extensive education and training in order to incorporate nanotechnology into current agricultural methods. The safe and effective application of nanotechnology in agriculture may be jeopardized in the absence of sufficient information and expertise. Ultimately, even though nanotechnology has the potential to revolutionize agriculture, its sustainable and fair application depends on tackling these issues through multidisciplinary research, policy creation, and stakeholder involvement.

Conclusion

In conclusion, nanotechnology emerges as a transformative force in agriculture, offering innovative solutions to enhance crop productivity and environmental sustainability. The exploration of nanotechnology, from its fundamental concepts to the commercialization catalyst, underscores its potential to revolutionize agricultural practices. The classification and synthesis of nanoparticles have paved the way for the development of nano-enhanced fertilizers, herbicides, and pesticides, which promise increased efficiency and reduced environmental impact. Nano-fertilizers have demonstrated their ability to deliver nutrients more effectively, while nano-herbicides and nano-pesticides ensure targeted weed and pest control, minimizing collateral damage to ecosystems. Furthermore, the application of nanoparticles in wastewater management and bioremediation addresses critical environmental concerns, contributing to cleaner water resources and healthier soils. The agribusiness sector stands to gain significantly from the integration of nanotechnology. Trends indicate a growing market for nano-enabled products, particularly within the food processing segment. By optimizing the agri-food value chain, nanotechnology not only enhances food security but also contributes to climate-resilient practices, ensuring the ecological balance is maintained. As we look to the future, continued research and development in nanotechnology will be vital in meeting the dual challenges of feeding a burgeoning population and preserving our planet. It holds the promise of a sustainable agricultural paradigm that aligns with the principles of green economics and eco-friendly practices, heralding a new era of efficiency and responsibility in the agri-food industry.

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Chapter 3

Sustainable bioeconomy in health: Biopsychosocial risk assessment model

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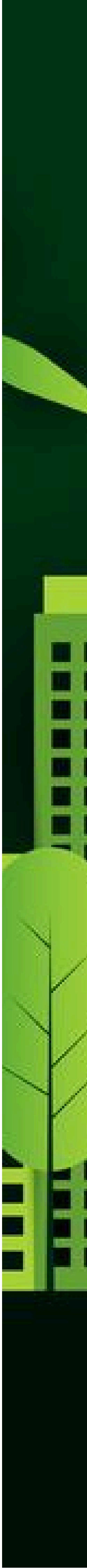

Abstract

Sustainability related to health indicates a system that satisfies the health requirements of the present without compromising the health of the future. Sustainable healthcare considers that our health and our environment around us are intrinsically linked and act in a way that supports health. Bioeconomy is the production, utilization, and conservation of biological resources related to knowledge, science, technology, and innovation to provide information, products, processes, and services aiming toward a sustainable economy. It influences health in many ways such as pharmaceuticals derived from natural products in healthcare, anti-disease agents, and disease therapeutics. It is a form of economic modelling that attempts to give the right and effective therapy as per the need. This also has a potential role in managing disease causing risk. Thus, a biopsychosocial approach-based risk assessment model emphasizes that these three domains: biological, psychological, and social factors play a widespread role in the causation of disease and would serve as a sustainable bioeconomic strategy in the health sector.

Keywords: Assessment, Bioeconomy, Biopsychosocial, Risk, Sustainability

Introduction

Health and fitness are the features required to a long, active and enjoyable life. It is correctly stated that Health is the actual wealth that a person can retain. It should be focused that a healthy mind resides only in a healthy body. Good health of both mind and body helps to maintain the required energy level to achieve success in life. Being healthy is not only related to the physical wellbeing of a person. In addition, it also involves the mental stability of a person. (Ali et al., 2017) It is also claimed that the association between disease and health has never been clear and that biological determinants of diseases are strongly influenced by cultural, social, and psychological conditions and states. (Wade and Italligan, 2017)

Sustainability in health

The term sustainability includes environmental and people wellbeing and the community. Organizing healthcare practices with elements of sustainability is important for efficient resource management, improvement of the services and cost effectiveness, in the provision of forming service excellence. The sustainable development is defined as "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Systematically undermine people's capacity (patients) to meet the needs (healthcare). (Arunadevi et al., 2022)

Sustainability practices in hospitals' operation can be subdivided into four categories: environment, customer (patients), employee (health staff), and community as an approach to achieving sustainability goals to continuously improve performance. S*ustainable health i*s a multisectoral practice that helps improve health and well-being for all by acknowledging the importance of these interconnections and how the current health gains will affect future generations. It refers to shifting from ‘research on’ to ‘research with and for’. These collaborations are the foundations of *sustainable health*. It refers to the ability to maintain and improve overall well-being in a way that is environmentally friendly, socially equitable (Alexiou, 2017), and economically viable in the long run. This concept encompasses various aspects, including personal health, public health, and healthcare systems. Healthcare systems should be designed to provide high-quality, accessible, and affordable care while minimizing their environmental impact. (Butterfield et al., 2019) This can be achieved through initiatives like reducing waste, promoting energy efficiency, and utilizing renewable energy sources in healthcare facilities. Additionally, investing in telemedicine and digital health technologies can help improve access to care and reduce the need for physical visits, ultimately lowering healthcare costs and environmental footprint. Sustainability in health is crucial for maintaining and improving the well-being of individuals and populations while preserving the environment and ensuring economic stability. By adopting sustainable practices in personal health, public health, and healthcare systems, we can create a healthier and more resilient future for all. (Marimuthu and Paulose, 2016)

Bioeconomy in health

Bioeconomy in health is the use of bio resources, processes and technologies to produce innovative products, services, and practices that result in improved health outcomes whilst promoting sustainability. The aim of this interdisciplinary approach is to create a more efficient, environmentally friendly, and cost-effective healthcare system by combining biology, economics, and health care.

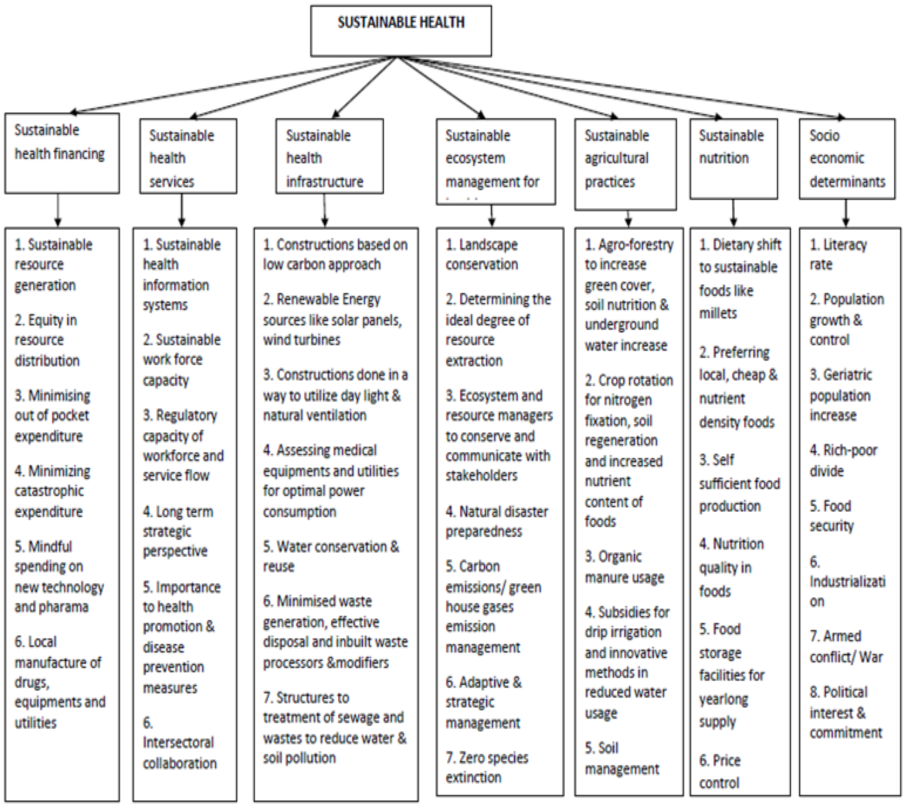

Figure 3.1: Sustainability health and its components (Arunadevi et al., 2022)

Bioeconomy is the making use of goods and services by those living within a country or region. It aims to create a more sustainable and efficient healthcare system by harnessing the power of biology, technology, and innovation. (Andy, 2021)

Types of bioeconomy vision

1 A *bio-technology vision* that enforces the significance of research under the discipline of biotechnology, application and commercialization in different disciplines and it deviates from the point of potential applicability of science.

2 A *bio-resource vision* that aims at the biological raw materials-based research and development which emphasizes the potentials in conversion and upgrading along with the establishment of new value chains.

3 A *bio-ecology vision* that highlights the importance of ecological functions that optimize the use of energy and nutrients and promote biodiversity. This plays a value on the potential for focused integrated and cyclic processes and systems. (Bugge et al., 2019 and D'Adamo et al., 2022)

Risk assessment in health

Risk is a term that refers to the process of identifying, evaluating, and prioritizing potential risks to the health of individuals and populations. It arises from a hazard and some uncertainty about its effects.

A risk assessment helps assess the potential risks that may cause real harm. Direct measures can effectively control risks. It is vital for developing effective strategies to prevent, manage, and modify these risks, that would at the end improve the overall health and well-being. All risk assessment tools have their respective strengths and limitations. However, they should be focused to effectively be implemented at clinical practice level, in order to increase awareness and understanding of health risk at all levels (Yarmohammadian, 2015).

Thus, risk assessment in health is a vital process for identifying, evaluating, and managing potential risks to individual and population health. By following a structured approach and incorporating the latest research and data, healthcare professionals and policymakers can develop targeted interventions to reduce health risks and promote well-being.

Table 3.1: Key components of bioeconomy in healthcare (adapted from Andy, 2021 and D'Adamo et al., 2022)

Components	Application	Impact
Biopharmaceuticals	Novel drugs and therapies derived from biological sources: Proteins, enzymes, and nucleic acids - lead to more effective treatments with fewer side effects.	Produced in a more sustainable manner Reducing the environmental impact of pharmaceutical manufacturing
Personalized Medicine	Advanced technologies: genomics, proteomics, and metabolomics	Tailors healthcare interventions to individual patients' unique genetic, environmental, and lifestyle factors Better health outcomes Reduced healthcare costs More sustainable use of healthcare resources.
Medical Devices and Diagnostics	Development: innovative medical devices and diagnostic tools that utilize biological materials and processes.	Efficient, Accurate, Cost-effective Improved patient care Reduced environmental impact
Regenerative Medicine	Repairing or replacing damaged tissues and organs using biological materials: stem cells, growth factors, and scaffolds	Offering new treatment options for various diseases and injuries Reducing the need for organ transplantation and associated environmental impacts
Sustainable Healthcare Infrastructure	Development of eco-friendly healthcare facilities and waste management systems and energy-efficient technologies	Minimize the environmental footprint of healthcare services

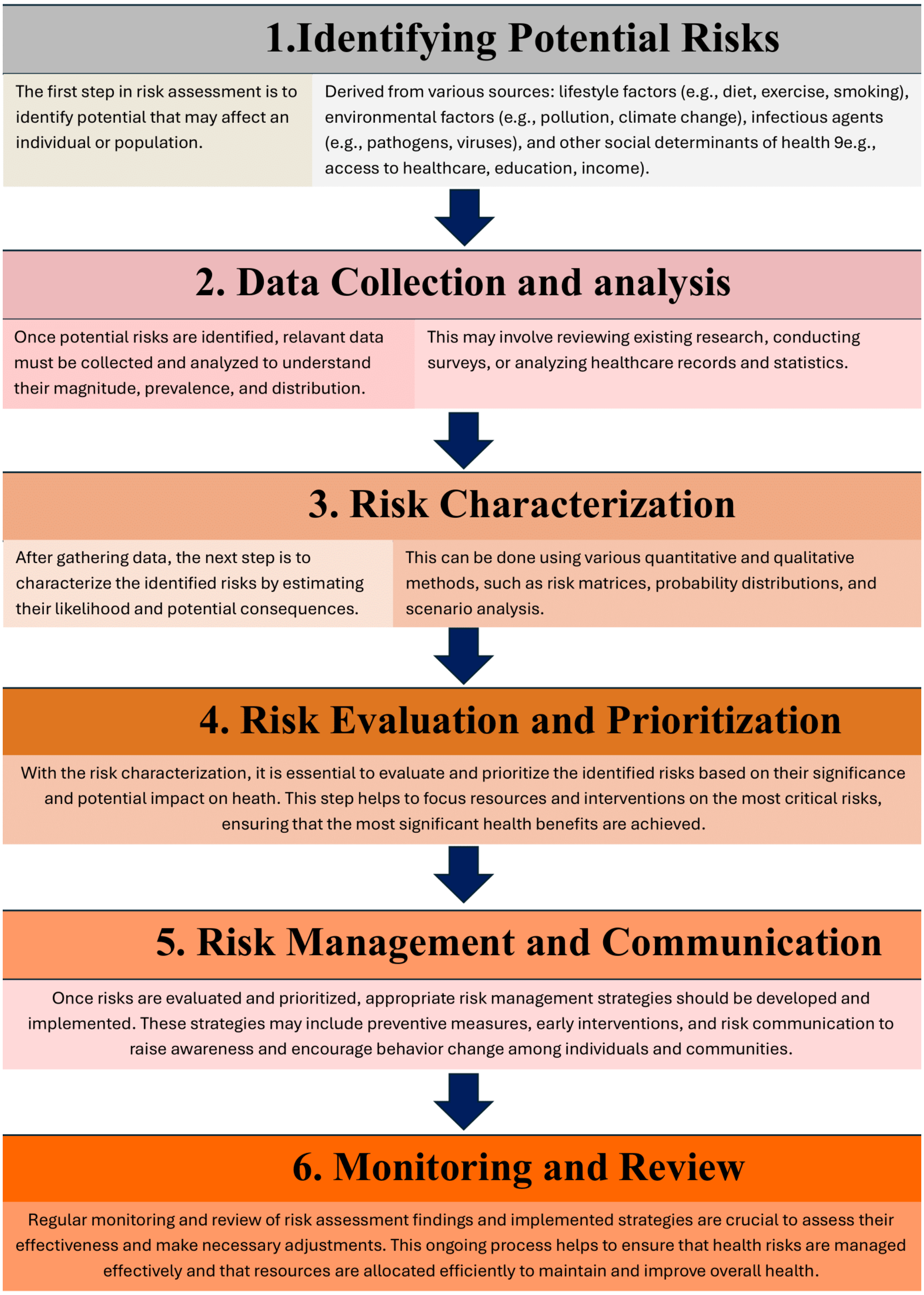

Figure 3.2: Steps of risk assessment in health (Adapted from : Yarmohammadian, 2015)

Risk assessment model

A risk assessment model is a framework or procedure used to evaluate and measure potential risks associated with factors, events, or circumstances.

These models help organizations, institutions, governments, and individuals make informed decisions, policy making by providing a structured approach to identify, analyse, and prioritize risks. By following this method, all the above sectors can make informed decisions and allocate resources effectively to minimize risks and achieve their objectives (Yarmohammadian, 2015) that help attain sustainability in a bioeconomic manner.

Biopsychosocial (BPS) model of risk assessment in health

The BPS model is a comprehensive framework used in the fields of healthcare and psychology to understand and address various health conditions, diseases, and human experiences. Developed by Dr. George Engel in the 1970s, the BPS model acts as a scope to interplay between the following factors-biological, psychological, and social factors in determining an individual's health and well-being.

The model differs from the traditional biomedical model, which rather focuses on the physical aspects of a disease or condition, whereas the BPS model is an update with three key domains:

1. Biological Factors: Physiological aspects of an individual (Genetics, anatomy, physiology). They contribute to the onset, progression, and treatment of health conditions.

2. Psychological Factors: Relate to an individual's thoughts, emotions, and lifestyle behaviours. (Tomba, 2012) They influence how a person perceives and copes with their health condition, as well as their overall mental health and well-being.

3. Social Factors: Cumulates the individual's environment, relationships, and cultural background. They impact health through various

mechanisms, such as stress (Compton and Shim, 2015), access to healthcare, and social support in terms of housing, resources and employment (Havelka *et al.*, 2009). These social determinants of health that vary among individuals and community render the vulnerability to illnesses.

It encompasses all related determinants of health and disease and supports the summing up of all these 03 factors in the risk assessment, prevention and treatment of diseases. The model as shown in Figure 3.3, helps understand how psychological and social factors influence the development, course and outcome of a disease, giving rise to the development of inter and multidisciplinary approach– health psychology and psychoneuroimmunology (Wade and Italligan, 2017).

This can be presented that when patients with the same diagnosis and laboratory test results (clinical parameters) can express completely different course of disease for different psychosocial characteristics. Thus, for efficient and early diagnosis it is necessary to extensively interview the patient during which, not only biological information, other factors are also required for correct diagnosis and effective treatment; such that psychosocial factors which determine whether the patients considers to be sick or in need of medical assistance and are interrelated with the biological factors and definitely influence the course and outcome of treatment. Meanwhile, emotional relations between patients and physicians can affect the mode and speed of recovery (Wade and Italligan, 2017).

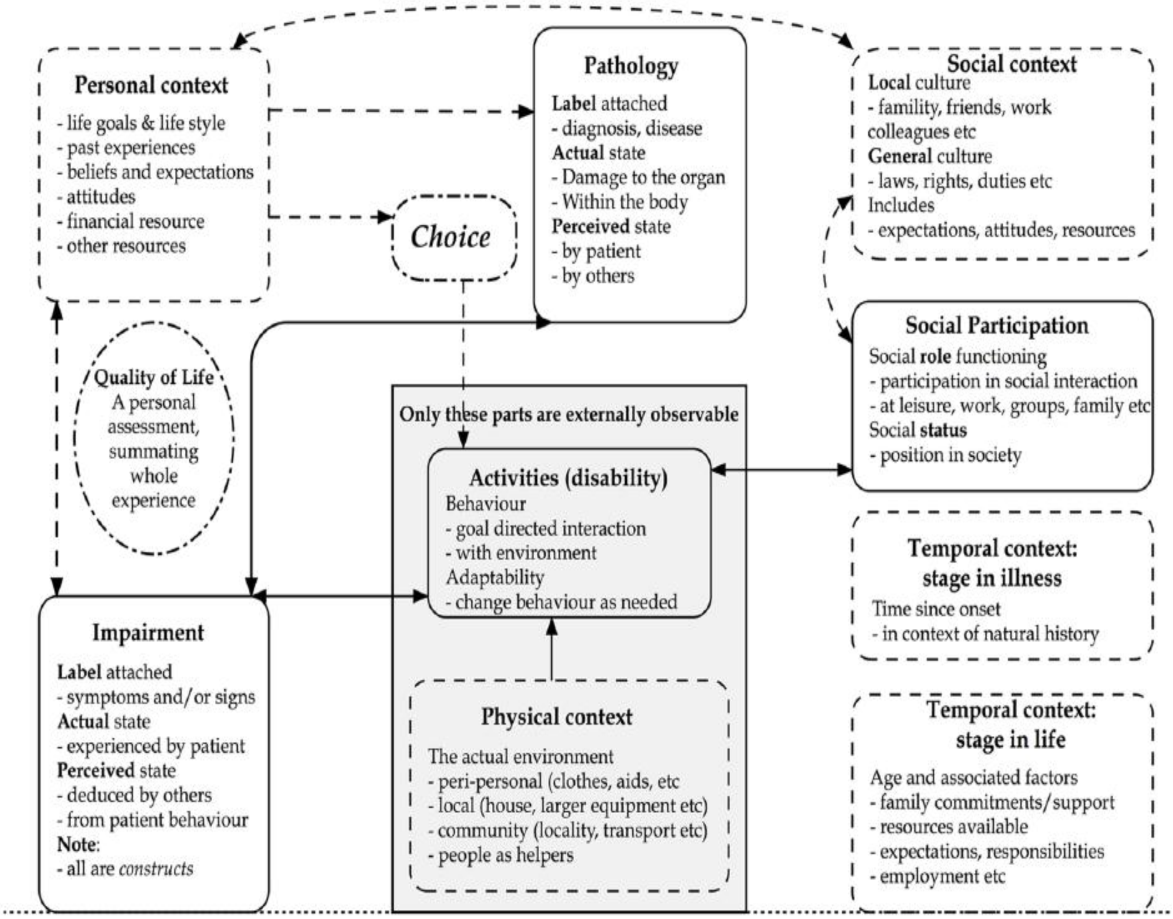

Figure 3.3: Holistic, biopsychosocial model of illness: components of importance (Wade and Italligan, 2017)

Biopsychosocial assessments are used by physicians and focus on all these three factors that affect a person's thoughts, feelings, and behaviour. It is an evaluation that takes into account all factors of an individual's life when determining the cause of the disease. It acts as a framework of risk assessment in primary care and a screening tool to determine risk level in cardiovascular and neurodegenerative diseases, on patients with chronic pain, pre and postsurgical individuals and especially in the field of psychiatry. (Kusnanto et al., 2018) The interview-based survey tools include questions related to physiology, personality relationships and finances along with non-organic signs to confirm any pain-related changes (Cohen et al., 2021) and each factor and its components is provided a score, based on the responses and a summative quantity is determined to understand the overall, impact of factors on the health and the actual and holistic profile of an individual (Bruns and Disorbio, 2009).

Sustainable bioeconomy in health via biopsychosocial risk assessment model

The sustainable bioeconomy in health, via using the BPS risk assessment model, aims to create a holistic approach to promoting health and well-being while considering the environmental, social, and economic aspects. This integrated framework can be applied in settings, related to public health, healthcare systems, and community development (Syed et al., 2020). This applies to any disease in the society and with improved health outcomes of the population, the overall health status of the society can be improved. This can lead to a bioeconomic society in terms of health and be an avenue for sustainable development of the nation. It is easier to decrease unnecessary utilization of available resources (Braveman and Gottlieb, 2014) and strengthen the efficiency of the health care framework in the society by using the BPS model (Babalola et al., 2018).

To create a sustainable bioeconomy in health using the BPS risk assessment model, the following steps can be taken:

1. *Identify Key Health Issues*: The most pressing health concerns in the community, region, or population being considered. Example: physical health conditions, mental health issues, or lifestyle-related risks.

2. *Biopsychosocial Risk Assessment*: Evaluate the biological, psychological, and social factors contributing to the health concern. Example, when considering obesity: biological factors-genetics;

psychological factors-emotional eating; social factors-limited access to healthy food options in certain communities. (Taukeni, 2020)

3. *Sustainable Bioeconomy Interventions*: Develop interventions that address the identified risks and promote health and well-being in consideration with the principles of sustainability. (Wanyenze et al., 2023)

The above can be further classified into three main domains:

a. Environmental Sustainability: Reducing the environmental impact of healthcare practices and promoting eco-friendly habits. Uses renewable energy sources in healthcare facilities, promoting recycling and waste reduction, and encouraging sustainable transportation methods.

b. Social Sustainability: Address social determinants of health by promoting equity, access, and inclusion. Creates community programs that improve access to healthcare, education, and employment opportunities and social stigma related to health conditions.

c. Economic Sustainability: Develop cost-effective and resource-efficient interventions that can be sustained over time. Implements evidence-based practices, utilizing technology to improve healthcare delivery (Wanyenze et al., 2023)

Conclusion

Illness and health are the result of an interaction between biological, psychological, and social factors. The biopsychosocial (BPS) model encourages healthcare professionals to consider the complex interplay between the three domains - biological, psychological and social factors, when diagnosing, treating, and managing health conditions. By acknowledging the influence of psychological and social factors on health, the BPS model promotes a more holistic and patient-centered approach to healthcare. This can lead to improved understanding of the pathophysiology of the disease, better treatment outcomes, and enhanced patient satisfaction, by controlling costs in a bioeconomic manner. It would also help predict various outcomes of psychological and social factors that could be incorporated into appropriate preventative and intervention strategies. Thus overall the BPS model would leads to an improved patient care, compliance, satisfaction and help develop a sustainable and bioeconomic healthcare practice.

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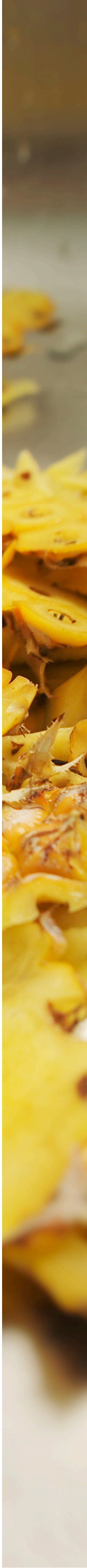
Chapter 4



Potential value-added products from pineapple waste

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Abstract

Pineapple (*Ananas comosus* L. Merr.) is a tropical fruit produced globally after bananas and mangoes and rich in vitamins, minerals, nutrients and antioxidants. In 2023, it has 29.36 million metric tons of global production accounting for the largest of Asia -pacific region. Fresh pineapple, canned pineapple, juices, jam and powder are directly produced with pineapple on a commercial scale. However, considerable waste produced as farm waste (stem, crown and leaves), peel waste (peeled skin, core) and pomace account for 60% of the general pineapple weight. Waste disposal is a growing issue contributing to worsening environmental problems. With the concept of zero-waste technologies and sustainable development goals, waste is identified as major resources for bio-based value-added products. In this chapter, potential value-added products from pineapple waste and its potential applications are discussed. Pineapple peel exhibits antimicrobial activity, anticancer and antioxidant activities giving potential medicinal value. Mainly in the biochemical sector, bromelain enzymes and wine and vinegar, and in the pharmaceutical sector cellulose nanocrystal, citric acid, ascorbic acid, ferulic acid and hydro gel are produced. Pineapple waste contributes to the bioenergy sector by producing and bioethanol, biobutanol, biodiesel, biomethane, biogas and biohydrogen. Moreover, the waste is used for bio packaging, bio-absorbent, biofertilizer and cosmetic applications. Future perspectives and challenges are discussed, highlighting the importance of applying these waste management technologies to developing countries like Sri Lanka.

Keywords: Bromelain, Circular economy, Pineapple, Waste management, Value added products

Introduction

Pineapple (*Ananas comosus* L. Merr.) is a leading edible tropical plant belonging to family Bromeliaceae. It is widely cultivated in the Philippines, Costa Rica, Thailand, Indonesia and Brazil. In 2023 it has 29.36 million metric tons of global production. Pineapple has a high nutritional profile in vitamins, minerals and nutrients. Besides agricultural properties, pineapples have a wide array of pharmacological properties such as antidiabetic, anticancer, antioxidants, antihyperlipidemic and anti-dysuria properties to promote human health. In the commercial scale pineapple are consumed as fresh pineapple, canned pineapple, juices, jam and powder. Additionally, pineapples give various culinary experiences with grilled pineapples, smoothies, cocktails and sources and promote cultural significance in tropical countries. Thus, pineapple has a broad range of uses beyond just the food industry, contributing significantly to the economic value of various countries.

As a by-product in the pineapple processing industries, a considerable amount of waste was generated as farm waste (stem, crown and leaves) and peel waste (peeled skin, core) account for 60% of the weight of general pineapple weight. Improper waste management is a growing issue contributing to worsening environmental problems. Decomposing pineapple waste releases organic compounds and nutrients. Elevated levels of these substances can disturb the natural soil balance, and when they leach into nearby water bodies, they can lead to water pollution. When pineapple waste is disposed of through landfilling or incineration, it contributes to global warming. Consequently, effective waste management practices are essential to safeguard environmental quality (AiliHamzah et al., 2021).

A supply chain that spans from production and processing to distribution and consumption includes elements of responsible consumption and production, as well as aiming to achieve zero hunger. Additionally, zero waste technology which utilizes all parts of the fruit and plant to eliminate waste production also applied to developments in the field of advanced pineapple waste processing technologies (Sarangi et al., 2023). Thus, researches have been eager to develop value-added products from pineapple waste from many decades.

Composition of pineapple waste

Several studies were carried out to know the composition and characteristics of pineapple waste (AiliHamzah et al., 2021, Sarangi et al., 2023, Azizan et al., 2020). Pineapple waste mainly consists of high content of lignin, cellulose and hemicellulose. Pineapple pulp and leaves are notable for their high protein and carbon content, respectively (AiliHamzah et al., 2021). Among pineapple waste, the peel is the richest in fiber compared to the pulp, leaf, and core. Additionally, pineapple waste contains bromelain, a proteolytic enzyme, as well as polyphenols, glucose, fructose, xylose, sucrose, and reducing sugars. The peels also have significant amounts of potassium, calcium, and magnesium. Due to this composition, pineapple can be processed into a range of value-added products. AiliHamzah et al. (2021) also highlighted the medicinal properties of pineapple waste. illustrates the health benefits associated with pineapple waste.

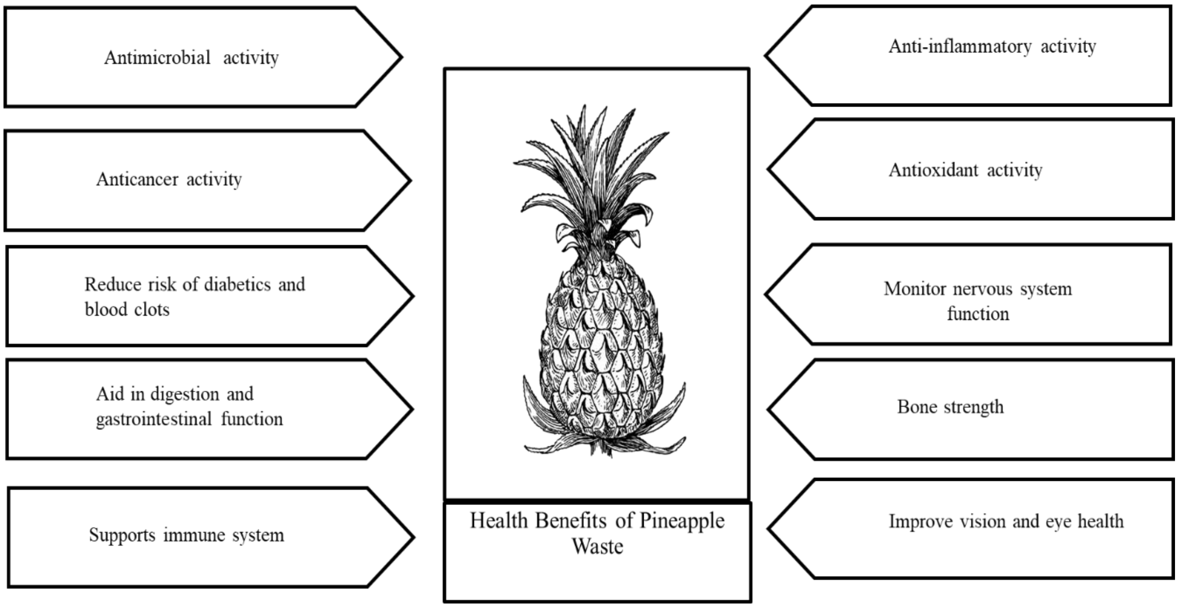

Figure 4.1: Health benefits of pineapple waste

Towards circular economy

Value added products produced from pineapple waste contributed for circular economy which creates closed-loop systems where waste from one process becomes a resource for another (Chia et al., 2024). This concept not only can environmental impacts be reduced, but also economic opportunities can be created with cost-saving and revenue-generating opportunities. Figure 4.2 demonstrates how pineapple contributed different sectors like biochemical, food, agriculture, bioenergy and pharmaceutical. These principles eliminate the traditional concept of waste and repurpose resources from products at the end of their life cycle back as raw material inputs to create new products. This article gives an overview of the innovative methods for the utilization of pineapple by-products along with their numerous potential applications in different industries and some value-added products have been discussed in this chapter.

Fibers

Natural fibers such as pineapple fibers have high cellulose content, good tensile strength and fiber length. Those properties help them to utilize in different commercial applications like textiles, plastic and rubber etc. The study from pineapple leaf fibers was extracted with a diameter as small as 3 µm and with a cut length of 6 mm, the aspect ratio (length to diameter ratio) could be up to 2000. These characteristics make these fibers very suitable for the effective reinforcement of both plastics and rubbers (Kengkhetkit et al., 2018). Recently a successful attempt was declared in India for eco-friendly feminine hygiene sanitary napkins from pineapple leaf fiber with water absorption properties (Anbalagan and Mani.,2024). In another study, it was demonstrated that pineapple leaf fiber reinforcing polylactic acid green composite manufactured by 3D printing technique (Mansingh et al., 2022).

Pineapple waste is a source of an appropriate biodegradable packaging element due to its rich of cellulose, lignin, pectin and their derivatives. Pineapple stem starch, which was extracted mechanically wet grinding, is a resistant and thermoplastic starch for food packaging (Nakthong et al., 2017). The combination of cassava starch, chitosan, pineapple leaf fibre, and zinc oxide resulted in material which is good for packaging slice bread (Armynah et al., 2022). Polyhydroxybutyrate and microcrystalline cellulose from pineapple leaf fibers is particularly suitable for the production of relatively low-cost bio composite films that are 100% compostable in soil (Sinsukudomchai et al., 2023).

Cellulose nanocrystals

Cellulose nanocrystals (CNCs) are nanoscale particles derived from cellulose, which is the most abundant natural polymer on Earth and the main structural component of plant cell walls. Generally, CNCs are produced through the controlled degradation of cellulose fibers and currently researchers are focusing to producing them from plant waste. CNCs are used in a wide array of applications (Chia et al., 2024). CNCs are biocompatible materials in various biomedical applications, nanocomposites in automotive components and structural materials and barrier film in food packaging and electronics. CNCs are used as additives in paper and cardboard manufacturing to improve strength, opacity, and printing properties. CNCs can act as rheological modifiers in various formulations, altering viscosity, stability, and flow properties. They find applications in cosmetics, paints, adhesives, and other formulations. CNCs are explored for environmental applications, such as wastewater treatment, oil spill cleanup, and soil remediation, owing to their adsorption capacity and biodegradability. Using pineapple waste to produce CNCs is an innovative approach that aligns with the principles of sustainability and circular economy. Pineapple waste, including peels, leaves, and cores, contains cellulose, which can be extracted and processed to obtain CNCs. Pineapple peel was demonstrated to be a good source of cellulose for the production of cellulose nanocrystals (Madureira et al., 2018). Cellulose based nanocomposite membrane was produced using Pineapple waste with ZnO nanoparticles and confirmed its antibacterial activity for resisting biofouling (Yanuhar et al., 2024). However, this field is needed more research to commercialize the application utilizing the waste materials.

Bromelain enzyme

Pineapple is a rich source of bromelain which is a natural complex mixture of proteolytic enzymes. The main protease that exist in the mixture is cysteine protease. Bromelain is used in different industries due to its significant therapeutic and industrial applications such as anticancer, anti-inflammatory, oxidative stress and meat tenderizing (Abbas et al., 2021). Fruits and stems are identified as rich in Bromelain (Nor et al., 2015). Other than fruit and stem, Bromelain present in crown, core, and peels, which constitute the waste of the pineapple plant. In Thailand study, Crown provided the highest protease activity followed by peel, cores, and stem, respectively (Ketnawa et al., 2012). Bromelain was extracted from waste peel from the downstream processing protocol (Bresolin et al., 2013). Kushal et al. (2024) found that the extraction of bromelain from pineapple rind using microwave assisted technique secured in considerable amount of proteolytic activity and protein content. Recently, a research group studied ways of enhancing Bromelain recovery from Pineapple by-products and found that bromelain powder produced from organic solvent free method showed high enzymatic activity from pineapple waste (Chiralli et al., 2024). Bromelain loaded silver nano particles were developed with the potential for antimicrobial products in biomedical applications (Gheisari et al., 2024). Therefore, successfully bromelain was extracted from the pineapple and utilized in different industries with the assistance of different technologies (Meena et al., 2022).

Bioactive compounds

Pineapple waste rich of many bioactive compounds such as phenolic acids, ascorbic acid, β-carotenes, and flavonoids (Madhumeena et al., 2021). Phenolic compounds such as ferulic acid, syringic acid, tannic acid, and p-coumaric acid in pineapple waste and these are important in inhibiting the formation of the free radicals in the human body. Ferulic acid has antioxidants, antimicrobial and anticancer properties, widely used in diet and cosmetics and it can be extracted from pineapple peel (Madhumeena et al., 2021). Other phenolic compounds such as p-hydroxybenzoic acid, vanillin, catechin, epicatechin, caffeic acid, malic acid, and cinnamic acid have all been found in pineapple peels (Kumar, 2021). Various analytical techniques such as gas chromatography, thin-layer chromatography, capillary electrophoresis, HPLC, and HPLC-DAD-UV are used for identification, separation and quantification. Ascorbic acid was extracted from microwave dried pineapple stem and core (Zaki et al., 2017). Further, Azizan et al. (2020) identified potential bioactive metabolites in peel, crown, and core in waste pineapples in different ethanol concentrations and peel extracted with 100% ethanol exhibited the highest α-glucosidase inhibitory activity showing the potential of using as antidiabetic drugs. A recent review article by Meena et al. (2022) explores the bioactive compounds found in pineapple waste and their potential applications. It emphasizes their activities and how they can be combined with other ingredients to create valuable products.

Wine and vinegar

Pineapple peels and core contain high sugar content which has potential to produce wine and vinegar. Vinegar plays an important role in salad dressings, ketchup, and sauces and also baking and cleaning. Wine is an alcoholic beverage generally made with fermented grape juice. But other fruits are also used to produce wine. Wine has many antioxidant and phenolic compounds, including anthocyanins and flavanols. Wine helps to prevent cellular damage caused by inflammation and oxidative stress. Vinegar is produced from two successive fermentations alcohol and acetic acid fermentation. The vinegar was prepared by varying the amount of yeast, amount of sugar, amount of yeast nutrient and time of fermentation using pineapple peel (Aye, 2016). A study carried out in Ethiopia has produced from vinegar from pineapple peel using three acetic acid bacteria strains (Chalchisa and Dereje, 2021). They have further found that the optimum yield of acetic acid production was found to be 6.15 g/L at a fermentation time of 72h by acetic acid bacterial strain. The wine was produced from pineapple peel and core using *Acetabater aceti* and *Saccharomyces cerevisiae* (Roda et al., 2017).

Organic acids

Fruit waste is an ideal source of producing organic acids considering the low cost and organic acids have a wide array of industrial applications. Some organic acid produced from pineapple waste are citric acid, lactic acid, succinic acid and formic acid (Upadhyay et al., 2010). Mainly Fermentation technology was applied for organic acid production utilizing of microorganisms. The overview of organic acid produced from pineapple residues are in Table 4.1. Citric acid uses as a cleaning agent, has varied industrial applications. Pineapple waste substrate 1.5 g was used to obtain 15. 51 g/L of citric acid with the conditions 30 ^{o}C, 40 h, pH 5, methanol concentration of 72 g/L and glucose concentration of 4 g/L (Ayeni et al., 2019). They further suggested that citric acid positive relationship between sugar concentration utilized and citric acid yield. *Rhizopus oryzae* was used to convert pineapple waste to L(+) lactic acid through solid-state fermentation the maximum lactic acid concentration obtained was 103.69 mg/g with the fermentation conditions 67.53% w/w of moisture content, 3 days of incubation, temperature of 32.2 °C, pH of 5.6, and inoculum size of 1×10^7 spores/g (Zain et al., 2021). Succinic acid is used as a flavoring agent, acidity regulator, and antimicrobial agent, and it also plays a role in the production of amino acids, vitamins, antibiotics, and cleaning agents. According to Pathanibul and Hongkulsup (2021), 6.21 g/L of succinic acid was produced from 26.16 g/L of sugars via fermentation with *Actinobacillus succinogenes* TISTR. Furthermore, Ariffin et al. (2020) noted the formation of formic acid and acetic acid after applying dilute acid hydrolysis pretreatment.

Table 4.1: Organic acid produced from pineapple residues

Organic acid	Yield	Organism/Condition	References
Citric acid	substrate 1.5 g was used to obtain 15. 51 g/L of citric acid	*Aspergillus niger*	Ayeni et al., 2019
Lactic acid	103.69 mg/g	*Rhizopus oryzae* NRRL 395	Zain et al., 2021
Succinic acid	6.21 g/L of succinic acid was produced from 26.16 g/L of sugars	*Actinobacillus succinogenes TISTR*	Pathanibul and Hongkulsup, 2021
Formic acid **Acetic acid**	1.62 ± 0.20 g/L 3.28 ± 0.26 g/L	12% sulfuric acid acid concentration (v/v), 20% solid-to-liquid ratio and 80 minutes of reaction time	Ariffin et al., 2020

Bio-adsorbent

Due to the high lignocellulose content in the pineapple waste has absorbent properties and can be utilized in waste water treatments. In the recent years, many studies have been reported on the adsorption of heavy metals such as Cd, Cu, Pb, Zn, Cr and Ni from the aqueous phase using chemically modified pineapple plant fibre (Gogoi et al., 2018). Various dyes such as methyl blue, congo red, safranin-Owere removed from activated carbon, hydrogel or silver nanoparticles produced from pine apple waste (Aili Hamzah et al., 2021).

Bioenergy

The utilization of pineapple waste for biofuel, biogas and biohydrogen has been reported (Meena et al., 2022). Pineapple waste's lignocellulosic composition has been identified as a potential source for bioethanol, biobutanol and biodiesel production (AiliHamzah et al., 2021) as the second generation of biofuel production. A recent study by Casber et al. (2019) demonstrated that a bioethanol yield of 5.98 ± 1.01 g/L could be achieved from pineapple fruit peel after 48 hours of fermentation using *Trichoderma harzianum*. Additionally, the bioconversion of pineapple waste cell wall sugars into bioethanol was successfully carried out through simultaneous saccharification and fermentation using *Saccharomyces cerevisiae* ATCC 4126 (Salafia et al. 2022). Biohydrogen can be produced through an anaerobic digestion process with fermentation involving various types of microorganisms and enzymatic processes. In the study of Cayahari et al. (2018) hydrogen percentage of the total gas produced was in the range between 5 to 32% volume ratio of hydrogen and an optimum substrate concentration of 26.4-gram VS/liter and acid pretreatment (H_2SO_4) of 0.3 N. The produced biogas is a source of bioenergy to supply electricity or as cooking gas if it contains methane.

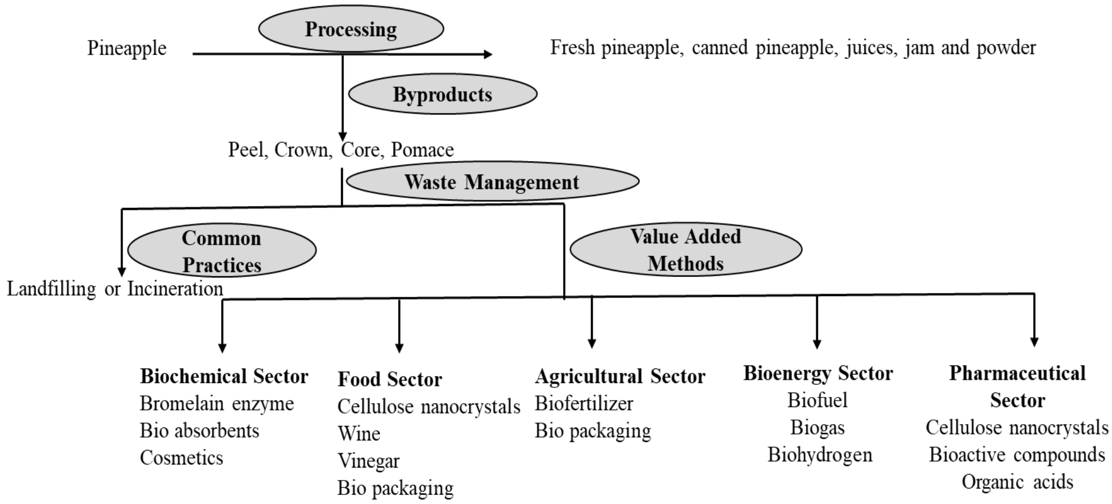

Figure 4.2: Value added products of pineapple waste

Biofertilizer

Pineapple waste materials can be converted to biofertilizer because it maintains optimum carbon/nitrogen ratio which is better for agriculture. Biofertilizers reduce the need of the chemical fertilizers and other environmental effects caused by huge number of chemical fertilizers. Pineapple waste biofertilizer produced from solid state fermentation was applied to the vegetable plantations and increased the physical properties of the plants as well as the soil quality (Lim and Matu., 2015).

Challenges and future perspectives

There are large number of useful products can be introduced from the recovery of waste materials by the waste reduction, resource optimization, value creation and innovation. However, farmers knowledge, facilities, collective method, storage, preservation, treatment of waste before processing, and relevant technology are shown as major challenges (BuhionBarrion, and Lanorio., 2024). The quality and quantity of bioactive compounds in pineapples vary depending on the variety and the extraction process used (Meena et al., 2022). Additionally, the stability and storage conditions of these natural compounds must be assessed to ensure an effective process. High cost associated with these processes slow the industrial scale production and investors are discouraged due to less support of farmers, industry people, responsible authorities and the government policies. A cost analysis conducted by a research group in Bangladesh revealed that producing yarn from pineapple leaf fiber is less expensive compared to cotton yarn (Jalil et al., 2021). Additionally, Ahmad et al. (2023) demonstrated the economic feasibility of large-scale biohydrogen production from liquid pineapple waste, highlighting its attractiveness within a circular economy. Techno-economic feasibility analysis of an integrated pineapple processing waste biorefinery was conducted by Banerjee et al. (2022) illustrating the possibility of profit making. These research groups encourage the investors for utilization of waste and give positive influence for the circular economy.

As a tropical country, Sri Lanka has higher demand of pineapple production. However, still the avenue of utilization of waste material to value added products and contributing to circular economy in infancy level. Wijesooriya. (2021) has been identified some problems arisen in value chain addition to pineapple products. However, there is a huge potential on job opportunities and income generations in the local and international market for biobased products. As a developing country, Sri Lanka has been focusing to maximize utilization of natural resources, aiming greener and more sustainable approaches and compressive waste management system in food industry. However, the researches should focus the gap existing between laboratory trial and industry scale. Future research should be focused on solving the present challenges, cost effective supply and industrial sector applications. Creating the trend in biobased products secures the stability of industries. The multidisciplinary approach with the collaboration of academics, engineers, scientists, economists, and policy makers will strength the pineapple value chain.

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Chapter 5

Major challenges confronting Sri Lankan spice exporters and potential solutions to strengthen the value chain

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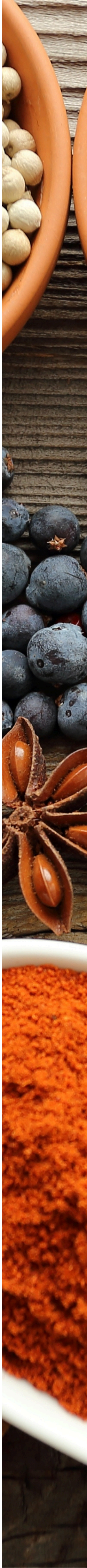

Abstract

The Sri Lankan spice industry is crucial in the global export market, with true cinnamon, black pepper, cardamom, clove, nutmeg, and mace. However, industry faces significant challenges that can compromise the safety, quality, and overall value of these spices. This chapter discusses the significant challenges confronting Sri Lankan spice exporters and explores potential solutions to strengthen the value chain. The major challenges addressed in this chapter include current policies affecting spice exporters, regulatory compliance and certification, and microbial, chemical, and physical hazards. These challenges can significantly impact the ability of Sri Lankan spice exporters to maintain high standards and meet international market demands. To mitigate these challenges, the chapter proposes several potential solutions. It emphasizes the importance of mitigating chemical hazards through Good Agricultural Practices (GAP) and addressing physical hazards and adulteration through Good Manufacturing Practices (GMP). The chapter also highlights the proactive approach of Hazard Analysis and Critical Control Points (HACCP) to ensure spice safety. Additionally, the chapter outlines strategies for ensuring quality throughout the supply chain by applying Good Storage Practices and safeguarding spice products during transportation through Good Transport Practices. It also addresses the necessity of adhering to pesticide residue limits and emphasizes the role of quality assurance and testing in maintaining high standards. By adopting these practices, the Sri Lankan spice industry can enhance its overall safety and quality standards, ensure compliance with international regulations, meet the demands of a discerning global market, and maintain the reputation of Sri Lankan spices worldwide.

Keywords: Good agricultural practices (GAP), Good manufacturing practices (GMP), Good storage practices, Hazard analysis and critical control points (HACCP), Sri Lankan spices industry

Introduction

Spices, derived from various plant parts, are important for flavor enhancement and food preservation. Traditionally, Sri Lanka's economy has relied on tea, rubber, and coconut, but Minor Export Crops (MECs) such as spices, cocoa, coffee, sesame, and essential oils are becoming prominent. Spices, especially crucial in Sri Lankan food culture, are used in many foods, including ready-to-eat products. The American Spice Trade Association defines spices as dried plant products used for seasoning, pharmaceuticals, cosmetics, and household items (The Spices Industry Cluster and Young, 2002). Sri Lanka's key spice exports include cinnamon, cardamom, cloves, pepper, nutmeg, and mace (Government of Sri Lanka et al., 2018). This chapter focuses on the economic impact of these spices, highlighting the potential of Sri Lankan spices to meet the demands of the global market. It addresses threats to spice safety, such as microbiological risks, heavy metals, pesticides, and adulteration, by emphasizing the need for strict guidelines to ensure the integrity of spices in the market.

History of spice in Sri Lanka

Sri Lanka is a tropical island in the Indian Ocean with a rich history deeply linked with the spice trade from the sixth century. Western interest in the island grew due to its strategic location and abundant resources, including spices, precious stones, and ivory. Notably, the sixth-century merchant Cosmas Indicopleustes documented the significance of Ceylon's spice trade in his book "Topographia Christiana." The island's strategic importance on the Maritime Silk Road made it a critical trading center from ancient times, facilitating the exchange of goods such as cinnamon, cassia, ivory, silk, porcelain, metals, and gemstones. Western colonization began with the Portuguese in 1505, who exploited Sri Lanka's cinnamon resources. The Dutch succeeded them in 1640, further systematizing spice cultivation and establishing plantations, particularly for cinnamon, under the control of the Dutch East India Company. This period cemented Sri Lanka's status as a major spice producer (Wikipedia contributors, 2024). The British took control in 1796, continuing the exploitation of the island's spice resources while modernizing ports and refining cultivation methods. Despite achieving independence in 1948, Sri Lanka's spice industry faced setbacks, including a prolonged civil war that hindered development. The end of the war in 2009 marked a reawakening in spice cultivation and trade. Throughout its colonial history, Sri Lanka's spice trade developed under Portuguese, Dutch, and British rule, each contributing to its long-standing legacy as a global center for spices. (UNESCO-Silk Roads Programme, 2024)

Current state of Sri Lankan spice exports

Overview of spice export trends

Sri Lanka's spice industry offers a diverse range of products. Annually, Sri Lanka exports approximately 30,000 tons of various spices, with over 90% finding their way into global food, beverage, pharmaceutical, and personal care markets. The sector is predominantly characterized by smallholders, with over 70% of cultivated land being smallholdings and home gardens. While a significant amount of Ceylon spices is exported as bulk, unprocessed spices, the country also exports essential oils and oleoresins derived from spices and herbs. From January to August 2023, Sri Lanka experienced a notable growth of 12.91% in export earnings from spices and essential oils, reaching a total of US$ 264.65 million. (Srilankabusiness.com, 2024). Specially, black Pepper, cloves, and nutmeg had significant increases of 14.87%, 317.95%, and 49.66%, respectively, during the same time (Figure 5.1). The cinnamon industry primarily targets the export market, accounting for 54% of total spice exports (Srilankabusiness.com,2023). Despite its significant contribution, the cinnamon sector faces challenges due to supply chain risks (Sugathadasa et al., 2021). However, trade statistics reveal a remarkable increase in cinnamon export earnings from 46.781 million US$ in 1971 to 2.163 billion US$ in 2020, with an average annual growth rate of 12.15% (Hewavitharana *et al.*, 2022). Sri Lankan cinnamon has approximately fifty export destinations, with Mexico ($80M), the USA ($41.1M) and Peru ($25.6M), emerging as the top three importing countries, representing more than half of the total cinnamon exports (OEC - The Observatory of Economic Complexity, 2024).

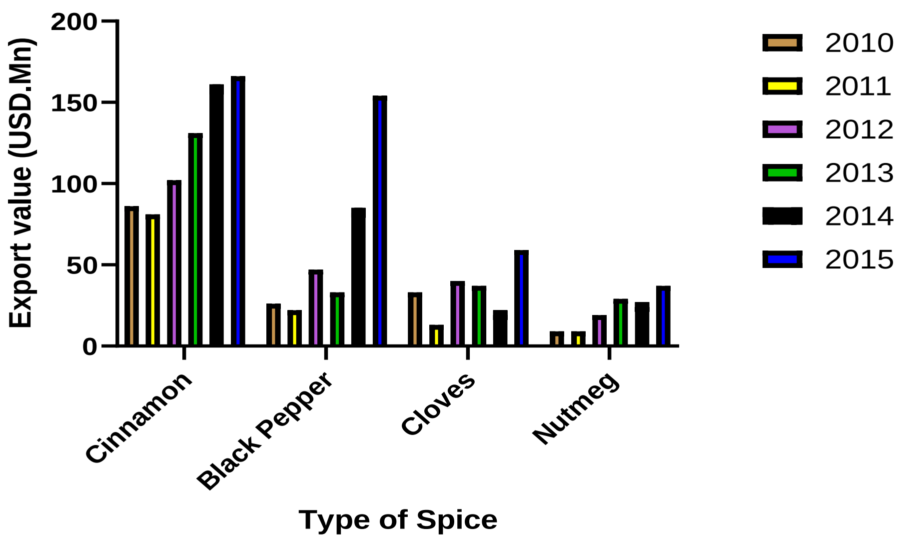

Figure 5.1: Performance of Ceylon spices in the export market (Source: Central Bank of Sri Lanka and Vision 2020 Department of Export Agriculture)

Key spice varieties exported

Cinnamon, pepper, cloves, cardamom, nutmeg, and mace are becoming increasingly popular internationally under the brand "Ceylon Spices"

(Table 5.1). Additionally, there's an increasing demand for essential oils and oleoresins from these spices.

Table 5.1: Key spice varieties exported (Source: Department of Export Agriculture)

Spice type	Growing areas	Growing season	Commercial grades	Major markets
Cinnamon	Galle, Matara, Hambantota, Rathnapura, Badulla, Colombo	March April September October	Alba C5-C4 M5-M4 H1-H2	Mexico, USA Colombia, Peru Germany
Pepper	Matale, Kandy, Kegalle, Rathnapura Gampaha, Badulla Monaragala, Hambantota	August September	GR1 GR2 White pepper	India Germany USA
Clove	Matale, Kandy Kegalle, Gampaha Matara	March April		India, USA UK Saudi Arabia
Nutmeg	Matale, Kandy Kegalle, Nuwara Eliya, Badulla	September October	No 1 No 2 BWP	Japan, UK EU, Pakistan Singapore
Mace	Matale, Kandy Kegalle, Nuwara Eliya, Badulla		No 1 No 2	
Cardamom	Matale, Kandy Kegalle, Kurunegala Nuwara Eliya	May June	LG LLG1-LLG2 LB LNS	Japan, UK EU, Pakistan Singapore

Ceylon cinnamon (true cinnamon)

True cinnamon (Ceylon cinnamon), *Cinnamomum verum J. Presl,* is native to Sri Lanka. The spice originates from the dried inner bark of the plant. Due to its sweet and delicate flavor, it is different from the bitter cassia cinnamon from other regions of the world. Historically, Sri Lanka was the primary producer of cinnamon from the 14th to 18th centuries for meat preservation and antibacterial properties (Suriyagoda et al., 2021). Ceylon cinnamon's economic significance is enhanced by its health benefits, including antioxidant and antimicrobial properties. It has been extensively studied for its anti-diabetes potential and mechanisms of action. These studies have highlighted its therapeutic potential and application in diabetes management. Among its various health benefits, cinnamon has shown promise in improving insulin sensitivity and lowering blood sugar levels (Wijenayaka et al., 2022). Distinguished by its low coumarin content, it is a safer option than cassia (Srilankabusiness.com, 2021). Sri Lanka supplies 85% true cinnamon to the global market (Institute of Policy Studies of Sri Lanka (IPS), The Department of National Planning Ministry of National Policies and Economic Affairs and Japan International Cooperation Agency (JICA), 2017).

Black pepper

Black pepper, which is rich in piperine, originates from the *Piper nigrum* L. plant. Sri Lanka produces 2% of Ceylon Pepper for the global market (Srilankabusiness.com, 2024). Sri Lankan black pepper has a floral and citrus aroma and is used in food, perfumery, and pharmaceuticals. The berries are harvested green, blanched, and sun-dried, resulting in their characteristic black color from oxidation (Coulibaly et al., 2023). Black pepper is highly valued in ayurveda and Chinese traditional medicine for treating gastrointestinal issues, arthritis, and respiratory problems. Additionally, it aids digestion by stimulating enzyme secretion. Black pepper is global significance due to its versatile culinary and medicinal applications (Spence, 2024).

Cloves

Cloves are produced from the flower buds of *Syzygium aromaticum* L. Merr. & L.M. Perry is native to Indonesia (El-Saber Batiha et al., 2020). Sri Lankan cloves hold a significant rank in the global market for their high quality and oil content. Sri Lanka supplies 8.5% of global demand (Thana Global, 2021). Clove oil is used in the food, pharmaceutical, and perfume industries. Ceylon Clove is rich in eugenol and enhances flavors in culinary dishes, pickling, sauces, and the cigarette industry. Medicinally, clove oil acts as a natural antibacterial and antioxidant agent, which benefits dental and respiratory health.

Cardamom

Cardamom is derived from the seeds of plants in the genera *Elettaria* and *Amomum,* native to India and Indonesia. It features triangular cross-section pods with tiny black seeds. They are available as whole pods, ground powder, and essential oil. Sri Lanka exports the light green Ceylon cardamom, which has a unique flavor and aroma. It enhances dishes with their citrusy, minty, and spicy aroma and taste. Medicinally, cardamom offers antiseptic, aphrodisiac, and anti-inflammatory benefits, helping reduce blood pressure, protect against chronic diseases, and improve oral health (srilankabusiness.com, 2024).

Nutmeg and mace

Nutmeg and mace are derived from the fruit of *Myristica fragrans* Houtt. It is a unique spice with nutmeg as the seed and mace as the surrounding fleshy red aril. Sri Lanka exports nutmeg in various forms, such as whole nuts, essential oil, and ground powder. Sri Lanka contributes around 5% of global nutmeg and 7% of mace demand. Nutmeg trees typically bear fruit after seven years, and they can yield up to 8,000-10,000 nuts per tree annually. Harvesting involves hand-picking and manually extracting mace from the nut. Nutmeg essential oil extends its utility to toothpaste, cough syrup, and traditional medicine practices. Nutmeg butter is used in personal care and cosmetic products. Additionally, mace powder offers health benefits such as antifungal, antidepressant, aphrodisiac, and digestive properties, contributing to overall well-being (srilankabusiness.com, 2024).

Major challenges in the spice export industry

Current policies affecting spice exporters

A standard is a formal document outlining requirements, specifications, guidelines, or characteristics that consistently benchmark the suitability of materials, products, processes, and services for their intended purposes. Standards can be categorized into product and process standards. Product standards delineate the specific attributes expected in the final product, while process standards define the characteristics of the production process itself, elucidating how a product is manufactured (Institute of Policy Studies of Sri Lanka (IPS), The Department of National Planning Ministry of National Policies and Economic Affairs and Japan International Cooperation Agency (JICA), 2017). In Sri Lanka, the spice export industry, particularly for products like cinnamon, pepper, cardamom, cloves, nutmeg, and mace, is subject to national and international quality control standards. Some quality standards for Ceylon spices are SLSI standards (for Cinnamon - SLSI 81:2010 - Fourth Revision, SLSI 81: 2021 - Fifth Revision, for pepper - SLSI 105 Part 1:2008), Codex Alimentarius Standards (for pepper - 2022 Amendment), ISO Standards (for cinnamon-ISO Standard - 6539: 1997), Indian Standards, Good Manufacturing Practices (GMP), Hazard Analysis and Critical Control Points (HACCP), and Food Act, etc.

The Sri Lanka Standards Institution (SLSI) plays a pivotal role in establishing and upholding national standards and ensuring the safety and quality of spices. Exporters must adhere to SLSI standards, emphasizing the importance of compliance for maintaining product quality and safety. GMP are actively promoted to guarantee the production of spices under controlled sanitary conditions, covering crucial aspects like hygiene, equipment maintenance, and documentation. HACCP principles are implemented by spice exporters, providing a systematic approach to identify, assess, and control potential hazards throughout the food production process, thereby ensuring product safety. Compliance with international standards, particularly those set by the Codex Alimentarius Commission, is essential for global trade, emphasizing adherence to comprehensive food safety and quality benchmarks. Establishing traceability systems is integral for tracking spices' origin and production history, aiding in quickly identifying and resolving quality issues. Strict adherence to regulations governing pesticide residue limits is imperative, requiring exporters to meet the maximum residue limits (MRLs) set by both domestic and international regulatory bodies. The industry places significant emphasis on quality assurance and testing, conducting regular assessments of parameters such as moisture content and volatile oil content. Additionally, some exporters opt for certifications like ISO 22000 or organic certifications to underscore their commitment to maintaining high quality and safety standards. To navigate this intricate landscape, spice exporters in Sri Lanka remain vigilant about changes in regulations, standards, and market requirements, seeking guidance from government authorities, industry associations, and certification bodies to ensure continuous compliance with the latest quality control standards.

Adhering to current policies and standards presents several challenges for spice exporters in Sri Lanka, encompassing financial, infrastructural, and procedural aspects. Certification costs, such as obtaining ISO 22000 or organic certifications, can be substantial, with significant expenses for initial certification, periodic audits, and recertifications. Compliance with stringent requirements like GMP and HACCP necessitates investments in modern equipment, infrastructure upgrades, and ongoing staff training. Additionally, regular assessments of parameters such as moisture content, volatile oil content, and pesticide residue limits require frequent and rigorous testing, further increasing costs. Limited access to advanced laboratory facilities capable of conducting comprehensive tests and infrastructure gaps in some regions add to the burden, leading to delays and increased expenses as samples may need to be sent to distant laboratories. Additionally, increasing consumer awareness and demand for high-quality, safe, and sustainably produced spices and global competition necessitates compliance with the highest standards, posing more challenges for smaller exporters with limited resources. Smaller exporters may also face difficulties accessing guidance from government authorities, industry associations, and certification bodies, making navigating the complex landscape of regulations and standards harder.

Regulatory compliance and certification

Exporters in Sri Lanka must be updated on regulatory changes, standards, and market demands to increase quality and safety. Seeking advice from governmental bodies, industry associations, and certification entities is essential for improving quality control standards. Certification options like ISO 22000 (Food Safety Management System), ISO 9001:2015, EU Organic certification, Fair Trade USA certification, Control Union certification, USDA organic certifications, Sri Lankan organic certification, BRC, Naturland certification, USDA organic certifications prove dedication to quality and safety in the spice export sector.

Figure 5.2: Some quality standard certification systems available for spices

Challenges faced by the spice value chains of Sri Lanka

Farm-level Challenges

Farm-level challenges significantly impact the spice industry by affecting productivity, quality, and sustainability. Cinnamon requires a tropical climate with consistent rainfall and is prone to pests and diseases like powdery mildew, which can reduce yield and quality (Pradyumna and Pandey, 2017). Black pepper cultivation is labor-intensive and susceptible to pests like mites and fungal infections, increasing production costs and potentially lowering output (Verma, 2022). Cardamom, thriving in specific mountainous climates, faces soil erosion risks, which can degrade soil health and reduce long-term productivity (Wangchuk et al., 2023). Nutmeg and mace take 7-9 years to mature, requiring significant investment and patience from farmers, while also being vulnerable to pests like nutmeg fruit flies that can damage crops (agrownet.com, 2024). Clove trees, needing specific soil and climate conditions, are also affected by pests like clove bud mites, which can lower yield and quality. In addition to these specific crop challenges, there are broader issues that affect spice farming. Climate change is exacerbating these problems by altering rainfall patterns and increasing the frequency of extreme weather events, which further threaten crop yields and quality. Poor infrastructure in rural areas can make it difficult for farmers to access necessary inputs like fertilizers and pest control measures, as well as to transport their products to the market.

These farm-level issues necessitate sustainable practices, research for disease-resistant varieties, and farmer training to mitigate their impact. Sustainable agricultural practices, such as Integrated Pest Management (IPM) and organic farming, can help reducing dependency on chemical inputs and improve soil health. Developing and promoting disease-resistant varieties through agricultural research can provide long-term solutions to pest and disease problems. Additionally, providing farmers with training and resources to adopt these practices is crucial for improving productivity and sustainability (Coulibaly et al., 2021).

Without addressing these challenges, the spice industry faces reduced productivity, increased costs, and potential declines in the quality of spices, threatening its overall sustainability and profitability.

Processing and packaging issues

Processing and packaging challenges in the spice industry are diverse. Maintaining consistent product quality throughout the processing and packaging stages is a significant challenge. In addition to quality and safety, minimizing losses and waste is a considerable challenge in processing and packaging. Inefficient techniques or inadequate storage conditions can lead to spoilage, mold growth, or insect infestation. However, selecting the appropriate packaging materials presents challenges, like cost, environmental impact, and product compatibility. Sustainability and ecological concerns add another layer of complexity, with increasing consumer demand for eco-friendly packaging solutions. Cost management is another challenge in the spice processing and packaging industry, especially for small-scale producers. Investing in modern equipment and implementing quality control measures can be financially challenging. Finding cost-effective solutions that meet quality and safety standards is crucial. Collaboration among stakeholders in the supply chain, including producers, processors, packaging suppliers, and regulatory agencies, is essential to mitigate these challenges effectively. (Marsh and Bugusu, 2007)

Transportation and distribution challenges

Transportation and distribution challenges in the spice industry include infrastructure limitations, logistics complexity, seasonality issues, market access barriers, and sustainability concerns. Inadequate transportation networks, remote locations of spice-producing regions, and the need for multiple modes of transport cause inefficiencies and increased costs. Collaborative efforts among stakeholders are essential for reducing these challenges through infrastructure, technology, and capacity-building investments (Rogoff, 2014).

Microbial, chemical, and physical hazards

In the spice industry, microbial, physical, and chemical hazards pose significant challenges, affecting consumer health and industry integrity. Spices, often cultivated in regions like Sri Lanka, are susceptible to contaminants like dust, insects, and animal waste from pre- and post-harvesting stages. Heavy metals and pesticide residues can be examples of chemical hazards threatening consumer health and industry credibility. Physical hazards, such as foreign objects like glass or metal, insects, or rodent droppings, threaten consumer safety during handling and consumption. Despite low water activity inhibiting microbial growth, spices remain susceptible to pathogenic and toxigenic microorganisms (safefood360.com, 2023). Chemical contamination can result from natural inclusions or unintended sources. Mitigating these hazards requires robust sanitation practices, stringent quality controls, and enhanced detection methods throughout the spice value chain (Zweifel and Stephan, 2012).

Potential solutions to strengthen the spice value chain

Mitigating chemical hazards through Good Agricultural Practices (GAP)

Implementing Good Agricultural Practices (GAP) is essential for ensuring the safety and quality of spice products. Adhering to GAP guidelines helps farmers manage chemical hazards effectively throughout production and post-production processes. Measures include proper handling and storage of chemicals, implementation of safety protocols and equipment, prevention of contamination, and documentation and record-keeping. By following these principles, spice producers can mitigate the risk of chemical contamination, safeguarding the integrity of their products.

Maintaining detailed records of GAP activities ensures traceability and compliance with regulatory requirements (Jona Tarlengco, 2024a).

Mitigating physical hazards and adulteration through Good Manufacturing Practices

Good Manufacturing Practices provide a crucial framework for ensuring food safety and quality in the spice industry by reducing physical contaminants and adulteration risks. Adherence to GMP guidelines helps to prevent contamination at every stage of production, including facility design, equipment cleanliness, personnel hygiene, and documentation practices. Specific focus is placed on avoiding physical contaminants like glass, metal, and plastic, which cause health risks and economic losses. Advanced technologies such as metal detectors and optical sorting machines effectively detect and remove such physical contaminants. Additionally, quality control standards for suppliers and regular audits help mitigate adulteration risks. Proper personnel hygiene and documentation practices are emphasized for continuous improvement in the quality of the spice industry. By prioritizing GMP and implementing robust quality control measures, producers can ensure the production of safe and high-quality spice products, fostering consumer confidence and satisfaction while meeting regulatory requirements (Jona Tarlengco, 2024b).

Hazard Analysis and Critical Control Points: A proactive approach to spice safety

Hazard Analysis and Critical Control Point is a proactive methodology crucial in ensuring the safety of spice products within the food and beverage industry. Tailored specifically for the spice sector, HACCP systematically identifies, assesses, and controls potential hazards throughout the production process. Focusing on critical control points enables spice exporters to identify and mitigate risks effectively. The implementation process involves assembling a competent HACCP team, evaluating the production process, implementing monitoring and control measures, documenting procedures, and emphasizing continuous improvement. HACCP principles endorsed globally encompass conducting hazard analysis, identifying critical control points, establishing limits, monitoring controls, implementing corrective actions, verifying procedures, and maintaining records. Through thorough hazard analysis and effective control measures, HACCP offers a proactive approach to spice safety, aligning with international standards and regulatory requirements (Food and Drug Administration, 2022).

Ensuring quality throughout the supply chain by applying good storage practices

Good storage practices are essential for maintaining food quality and safety throughout the supply chain. Temperature and humidity controls are crucial to prevent spoilage and contamination, tailored to specific food categories. Cross-contamination prevention involves segregating perishables, staff training, and regular audits. Proper labeling and stock rotation manage inventory and freshness, while real-time tracking systems enhance quality control, especially in the cold chain. Compliance with legislative directives ensures adherence to transportation regulations, facilitating traceability and accountability. These practices collectively preserve the integrity of spices and other food products, instilling consumer trust and confidence in their safety and quality (Barycki, 2024).

Safeguarding spice products during transportation by applying good transport practices

Integrating Good Transport Practices (GTP) is essential for safeguarding spice products during transportation. Adhering to GMP ensures spices are produced under sanitary conditions, maintaining their integrity from production to distribution. Effective distribution strategies, including meticulous route planning and vehicle maintenance, minimize transit times and the risk of spoilage. Hygiene measures in transport vehicles, such as regular cleaning and compartmentalization, prevent contamination. Real-time monitoring and compliance with legislative directives, especially regarding the cold chain, uphold quality standards throughout transportation. These practices collectively mitigate risks and maintain the quality of spice products during distribution, ensuring safe and high-quality delivery to consumers (Logistics, 2024).

Pesticide residue limits

Ensuring exported spices meet maximum residue limits (MRLs) is crucial for compliance with domestic and international regulations. MRLs, defined as the highest concentration of pesticide residues legally allowed in or on food, are based on GAP and product label specifications. These limits help monitor and control pesticide residues in the international food trade, protecting consumers from potential toxic effects. The significance of MRLs lies in their role as trading standards that ensure food safety by regulating pesticide residues. To address concerns about consumer exposure to toxic residues, adopting Integrated Pest Management (IPM) is recommended. IPM focuses on ecological balance and natural pest control methods, reducing the dependency on chemical pesticides. This approach mitigates the risks associated with pesticide residues, promoting safer and more sustainable agricultural practices. By adhering strictly to MRL regulations and implementing IPM techniques, exporters can ensure that their spice products meet safety standards, maintain consumer trust, and facilitate smooth international trade. This comprehensive approach to managing pesticide residues aligns with global food safety priorities and supports sustainable agricultural development (Aryal and Aryal, 2023).

Quality assurance and testing

In the global market, Sri Lankan spices are renowned for their rich flavors and aromatic profiles. However, the diverse climatic conditions in Sri Lanka pose risks to spice quality at every production stage. To maintain market value, spices must meet stringent quality parameters, addressing physical, chemical, and biological factors. Contamination from pesticide residues, agro-inputs, heavy metals, and other sources necessitates rigorous quality testing to ensure safety and compliance. Quality assurance is integral to the spice industry's success, encompassing the entire supply chain from procurement to packaging. Adherence to set specifications for taste, color, and aroma is crucial. Any deviations require immediate correction to maintain consumer satisfaction and brand reputation.

Quality assurance in the spice industry encompasses several critical stages to ensure the final product meets high safety and quality standards. The first stage involves the management of cultivation and harvesting practices, which is crucial for producing high-quality spices. Effective management includes using sustainable agricultural practices, selecting disease-resistant varieties, and ensuring proper harvesting techniques to maintain the integrity of the spices. The second stage is procurement, where strict spice quality inspection is necessary to select only the best raw materials. This includes evaluating the spices for any signs of contamination or subpar quality before they enter production. The third stage focuses on the monitoring of processing methods within production units. This ensures that the spices are processed optimally to preserve their flavor, aroma, and nutritional value. The fourth stage involves spice testing during packaging and storage processes. This step is vital to detect potential issues that might compromise quality, such as moisture content, microbial contamination, or pest infestation. Finally, the importance of spice quality testing and analysis cannot be overstated. Regular and rigorous testing helps to maintain consistency, adhere to safety standards, and meet consumer expectations. These stages collectively ensure that the spices retain their desired qualities from farm to table, reinforcing the reliability and reputation of the spice producers.

Spice testing evaluates parameters such as taste, texture, appearance, and safety and identifies harmful contaminants. This includes botanical evaluation, microbiological testing, organoleptic analysis, chemical residue testing, and physical analysis. These comprehensive testing and analysis services ensure that spices meet the highest quality standards, safeguarding consumer safety and satisfaction (Agnext, 2024).

Conclusion and recommendations

Sri Lankan spice exporters face significant challenges, including diverse climatic conditions, stringent quality standards, and contamination risks from physical, chemical, and biological hazards. These issues threaten the quality and safety of spices, impacting market value and consumer trust. Adequate quality assurance and rigorous testing throughout the production process are crucial to overcome these challenges and to ensure that Sri Lankan spices confirm with international standards.

Adopting IPM, improving quality assurance systems, implementing advanced testing methods, and investing in technology and training are essential to overcome the challenges Sri Lankan spice exporters face. By addressing these challenges with targeted solutions, Sri Lankan spice exporters can strengthen their value chain, ensuring high-quality, safe, and market-competitive products that meet global standards.

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Chapter 6

Mangroves of Sri Lanka is a best source for circular and sustainable bioeconomy

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Abstract

A circular bioeconomy relies on healthy, biodiverse, and resilient ecosystems and is often seen as a vital strategy for transitioning towards a sustainable and resource-efficient economy. This approach facilitates economic development and resource management through effective waste management, reduces the dependency on finite resources, lower greenhouse gas emission and drives innovation in the development of bio-based products and to align with the Sustainable Development Goals (SDGs). Circular bioeconomy of mangroves involves sustainable use and management of mangrove ecosystems to create a closed-loop system that maximizes the value of biological resources while minimizing waste due to their use and negative environmental impacts. This chapter emphasizes circular bioeconomy of mangroves under different aspects: sustainable harvesting, a source of bioenergy, ecotourism, sustainable aquaculture practices, carbon trading and restoration-conservation. By implementing a circular bioeconomic approach to mangroves ecosystems in Sri Lanka, it is possible to achieve a balance between economic development, environmental protection, and social well-being, while ensuring the long-term health and resilience of coastal ecosystems.

Keywords: Circular bioeconomy, Sustainable, Reduce, Recycle, Revenue

Introduction

A circular bioeconomy relies on healthy, biodiverse, and resilient ecosystems and is often seen as a vital strategy for transitioning towards a more sustainable and resource-efficient economy (Palahi et al., 2020). This approach involves utilizing biological materials to create products and energy, which are then recycled or reused to minimize environmental impacts. This, in turn, helps to conserve resources, reduces the need for new raw materials, and promotes sustainability of natural resources by generating a circular flow of materials within the system.

Mangroves are a very important part of our coastal ecosystems: They play a crucial role in coastal ecosystems by providing ecosystem services such as carbon sequestration, coastal protection, habitat for diverse species, part of food webs, protect communities from the impacts of climate change, and protect the oceans by catching excess silt and debris from rivers (Palahi et al., 2020). Unfortunately, they are already critically endangered (Polidoro et al., 2020) or approaching extinction in 26 out of the 120 countries that have mangroves (FAO, 2003).

The circular bioeconomy of mangroves involves sustainable use and management of mangrove ecosystems to create a closed-loop system that maximizes the value of biological resources while minimizing waste and negative environmental impacts.

Circular bioeconomy (CBE)

The CBE is an economic system that aims to minimize waste and promotes sustainability by using renewable biological resources in a closed-loop cycle (OECD, 2018). Therefore, it mainly focuses on resource efficiency, multiple output production through optimizing residues and wastes, which considers economic, environmental, and social aspects (Stegmann *et al.*, 2020). They have illustrated the CBE and its elements as in the Figure 6.1.

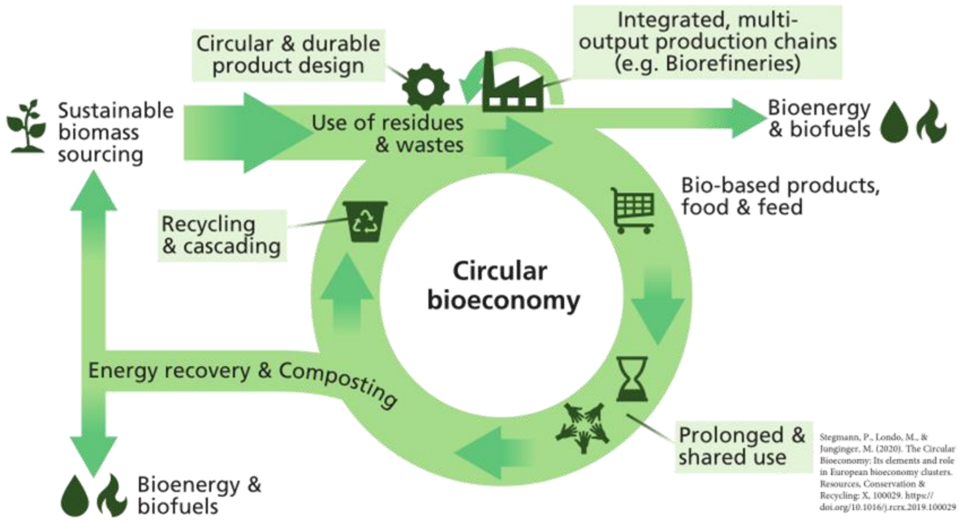

Figure 6.1, Overarching CBE Principles. Resource-efficiency, optimizing value of biomass over time and sustainability (Adopted from Stegmann et al., 2020).

The circular bioeconomy seeks to reduce reliance on finite resources and contribute to a sustainable future, i.e., CBE highlighting a sustainable way of integrating environmental benefits and economic activities (Venkata Mohan et al., 2019) and thus potentially contributes to SDGs.

CBE of mangroves

A CBE of mangroves offers a theoretical context for reorganizing and controlling mangrove resources and services, social and environmental well-being, and economic development through integrated industries to attain sustainable well-being in harmony with nature. A circular bio economy-based approaches of mangroves, its associated wetlands and the related activities could pave the pathway to a sustainable future (Holden et al., 2023). The following six aspects could be considered towards CBE of mangroves.

1. Harvesting mangrove products in a sustainable manner to support local livelihoods and economic development.
2. Utilizing mangrove biomass as a source of energy (Numbere, 2020), to reduce dependence on fossil fuels and lower greenhouse gas emissions.
3. Promoting eco-tourism activities that support conservation while providing economic benefits to local communities.
4. Implementing sustainable aquaculture practices in mangrove areas to utilize the natural productivity of mangrove forests.
5. Utilizing blue carbon as a source for carbon trading thus generates revenue (He et al., 2023).
6. Restoration and conservation efforts to protect and enhance the resilience of mangrove ecosystems, thereby ensuring their long-term sustainability and productivity.

Sustainable harvest of mangrove products: the value chain

Mangroves are one of the 'blue carbon' ecosystems and provide a wide range of goods and services, directly and indirectly, and support economic growth. For example, harvestable wood and non-wood resources, habitat for fish and other animals, protection against floods and storms, reduction of shoreline erosion and maintenance of biodiversity, ecotourism activities and capture more atmospheric carbon to mitigate the effects of climate change.

Ecologically, sustainable harvesting allows the number of mangrove populations to be maintained or even increase over time, while economic growth may feasible. Value chain is the range of activities required to bring a product or service from production to final consumption (Lowitt et al., 2015). Mangrove-based products (traditional medicines, honey, and other non-timber) can create local value chains, benefiting nearby communities, which in turn creates business opportunities and reduce transportation-related emissions. By managing mangrove products through sustainable harvesting mechanisms (e.g. selective logging, selective time for fishing and extraction of mangrove products) we can ensure a circular flow of resources thus earnings shall be ensured. However, it is imperative for a scientific planning and monitoring mechanism to ensure the sustainable harvesting however, not to destruct the mangrove ecosystems: (i) preparation of correct maps marking utilization zones, (ii) review, update and implement harvest plans, (iii) development and implementation of restoration plan, (iv) building local capacity on ecological restoration and (v) establishing permanent plot studies for data on the performance of mangroves (Mbatha et al., 2022).

Utilizing mangrove biomass as a source of energy

Global warming is due to widespread greenhouse gases emissions, resulting in significant impacts on the environment, economy, and society. In the meantime, fossil fuels are non-renewable due to their limited supply and undergo rapid depletion from excessive consumption worldwide. Inter-governmental Panel on Climate Change (IPCC, 2013) reported that "the increasing demand for energy is expected to reach 37,000 tons globally by 2035, and the reserves of oil and gas alone will not likely be able to sustain this demand". This drives us to seek alternative energy sources like thermal, tidal, hydro, solar, mechanical, and nuclear energy sources (Bhattacharya et al., 2016).

One of the alternative energy sources, other than the above, is biogas or biofuels, which reduce dependence on fossil fuels and lowers greenhouse gas emissions. Mangrove ecosystems are efficient natural carbon sinks and are generally considered sources of CO2 (and CH4) to the atmosphere and thus become a growing potential source of biofuel. Microorganisms coexisting in the mangrove ecosystems are functioning as promising potential for biofuel production (Merheb et al., 2018). Biomethane, a renewable natural gas generated from anaerobic digestion of organic materials, could be explored from the mangroves swamp, is considered an eco-friendly alternative to traditional fossil fuels. Biomethane, serves as a renewable energy source, with its high calorific value, enhances overall biorefinery efficiency, serving purposes like cooking, heating, and lighting (Ezhumalai et al., 2023). This will reduce the investment for energy production.

Furthermore, mangrove wood biomass (genera such as Bruguiera, Rhizophora, Avicennia, Sonneratia) is a solid fuel and an excellent source of renewable energy (Numbere, 2020). It is an alternative energy source (firewood and charcoal) for petroleum products that pollutes the environment and has adverse environmental consequences (Numbere, 2020). The use of firewood would produce less carbon footprints as compared to petroleum. It shall be strictly practice encouraging “sustainable control harvesting” and “aggressive afforestation programs” to counter the negative consequences of tree/parts removal.

Promoting eco-tourism via mangrove conservation

The mangrove environment provides a comprehensive nature resource base and attracts tourists while it functions as an economic and non-economic contributor to mankind. Global tourism shows continuous growth; nature-interesting travelers and ecotourists are important contributors. Countries with high nature value, landscapes and biodiversity can cater to such tourists. Many tourists are fascinated by the beauty and biodiversity of mangroves, where the global reach of mangrove tourism is extensive, with almost 4,000 attractions in 93 countries (Spalding and Parrett, 2019); and it was indicated, as an example, that mangrove tourism contributes one billion US$ per year toward Florida's economy (Mapping Ocean wealth, htpps://oceanwealth.org). Eco-tourism, focusing on mangrove forests, can generate significant revenue for local economies while fostering environmental awareness through activities such as guided tours, birdwatching, and eco-tourism. Sri Lanka being a tropical country as well as an island, has comprehensive advantage for this market segment.

A case study by Tresnati et al. (2020) is a good example of a mangrove ecotourism approach, which was carried out in the Tongke-Tonge Village, Sinjai District, South Sulawesi, Indonesia: It provided income to the government of Sinjai District amounting to Rp. 300,000,000 that came from a levy of Rp. 5,000 per person. This levy is equivalent to 60,000 visitors per year, an unexpected number. They further reported that because of this project, the mangrove forest has restored aquatic biodiversity of 48 species of macro-zoobenthos and fauna. Similar activities shall open a variety of avenues and opportunities for income generation, thus supporting a circular economy for the locals and the nation. This model can be replicated in Sri Lanka too after careful assessment of the target area. As a result, sustainable mangrove conservation initiatives can be ensured in the longer run along with economic and livelihood improvements.

Circular aquaculture for sustainable aquaculture practices

Aquaculture provides year-round employment and has the potential to bring long-term economic growth. Sri Lanka is embarking on various aquaculture development plans, targeting doubling of the current aquaculture production to approximately 90,000 metric tons (Drengstig, 2020).

However, aquaculture and fishing operations (aquaculture pond establishment is the primary source) widely criticized for mangrove ecosystems degradation and loss resulting modification of its habitats, functions, and services. Madumadhawa et al. (2023) reported that about 25% of mangrove habitats are estimated to have been destroyed between 1980 and 2005 due to shrimp farming and development activities. This will significantly be contributing CO_2 emission, losses in land use carbon footprint and soil ecology (Anikwe and Ife, 2023). Therefore, it is high time to introduce resource efficient techniques through implementing circular practices in aquaculture and fishery systems that call for more sustainable aquaculture practices and to protect mangroves. These kinds of operations significantly increase the productivity on food production, economic growth, and environmental management could help to reduce blue carbon emissions through mangrove restoration, which in turn sequesters blue carbon.

Integrated Mangrove Aquaculture (IMA) is characterized by low-density shrimp and fish aquaculture where mangrove trees are incorporated into the farm system. In this approach, mangroves are left when constructing ponds or incorporate the addition of mangroves into areas that had previously been deforested (McSherry et al., 2023). The IMA has its own advantage where it has potential to balance biodiversity benefits with aquaculture production, it shall more financially feasible production option for smallholders, which in part drives their adoption that depends on the design of IMA system (Joffre et al., 2015; Bosma et al., 2016), help to prevent shrimp disease due to organic management practices that achieve a higher level of disease resistance in shrimp because of low off-farm inputs to maintain and enhance farming ecosystems (Naturland, 2016), easier pond management, increased diversity of farm products (shrimp, fish, and crab) and that leads to increase income stability, mangrove conservation (Anikwe and Ife, 2023).

Furthermore, Naturland (2016) has reported that “if 1.5 million ha of global deforested mangroves to shrimp farms were converted to organic aquaculture (IMA), it would rehabilitate 50% (0.75 million ha) of mangrove forests”. Hence, despite of many benefits in the IMA practices, this farming system will also face ecological and technological problems due to its operation in integrated conditions because of the effects of intensive human intervention with their poor socioeconomic conditions (Ahmed et al., 2018). Therefore, Institutional supports with technical and financial assistance is needed to overcome these challenges.

Carbon trading

Mangroves sequester large amounts of carbon dioxide, making them valuable for carbon trading initiatives. Globally, the blue carbon sequestration rate is about 53 million tons annually, of which 16 million tons (30%) are by mangroves (Siikama¨ki et al., 2012). This is considered a cost-effective option to mitigate negative impacts due to climate change (Thomas, 2014).

More than half of the extent of investible global mangrove blue carbon (59.4%) would not be financially viable for carbon finance at current market rates. However, the 1.1 Mha of financially viable mangrove blue carbon would contribute to climate mitigation at a rate of 26.2 ± 4.6 $MtCO_2e$ year whereas 200±100 ha of mangroves in Sri Lanka is viable for climate mitigation at a rate of 10±4.0 tCO_2e per year (Zeng, et al., 2021). E.g. the protection of 0.33 Mha of financially viable mangrove forests for blue carbon projects in Indonesia could potentially generate an annual return on investment of US$513 million in NPVs per year (Net Present Value), which is about 1.8% of the country's NDCs (Nationally Determined Contributions).

Therefore, protecting and restoring mangroves can contribute to climate change mitigation efforts, which is a sustainable investment for circular bio economy and will reduce the cost for efforts that control the carbon emission to the atmosphere.

Engaging in mangrove restoration and conservation efforts

The current United Nations Decade on Ecosystem Restoration (2021-2030) prioritizes conservation and restoration of wetland ecosystems, such as mangroves. There are ecological benefits and economic value in restoring mangroves. Restoring degraded mangrove areas contributes to circularity by reviving ecosystems and their associated services. For example, restoring wetlands including mangroves can offer 14% of the mitigation potential needed to limit global warming to 2°C (UNEP/FAO, 2020).

Restoration and conservation efforts of mangroves will be the baseline activities to meet the above discussed aspects. The Sri Lankan government leads many sustainable proactive initiatives to conserve and protect the mangrove ecosystems in Sri Lanka: the National Policy on Conservation and Sustainable Utilization of Mangrove Ecosystems in Sri Lanka, the National Guidelines for the Restoration of Mangrove Ecosystems in Sri Lanka, the National Strategic Action Plan for Conservation and Sustainable Utilization of Mangrove Ecosystems in Sri Lanka (2022-2026), declaring mangrove protected areas, restoration of mangroves and many more activities.

Concluding remarks

Mangroves are vital components of coastal ecosystems, offering a multitude of economic and ecological benefits. In brief, the circular bioeconomy of mangroves shall be investigated under "3R concepts" – Reduce, Recycle and Revenue (Figure 6.2): where it reduces the generation of wastes due to efficient resource management; the wastes that are generated do not leave the environment by means of their cycling process. Due to this, the financial expenditure to control and manage waste shall be reduced and at the same time, it also facilitates the pathway for financial earnings or revenue like carbon trading of mangroves. By understanding and harnessing the potential of mangroves, we can ensure and facilitate both the circular economy and the ecological well-being of mangroves for current and future generations.

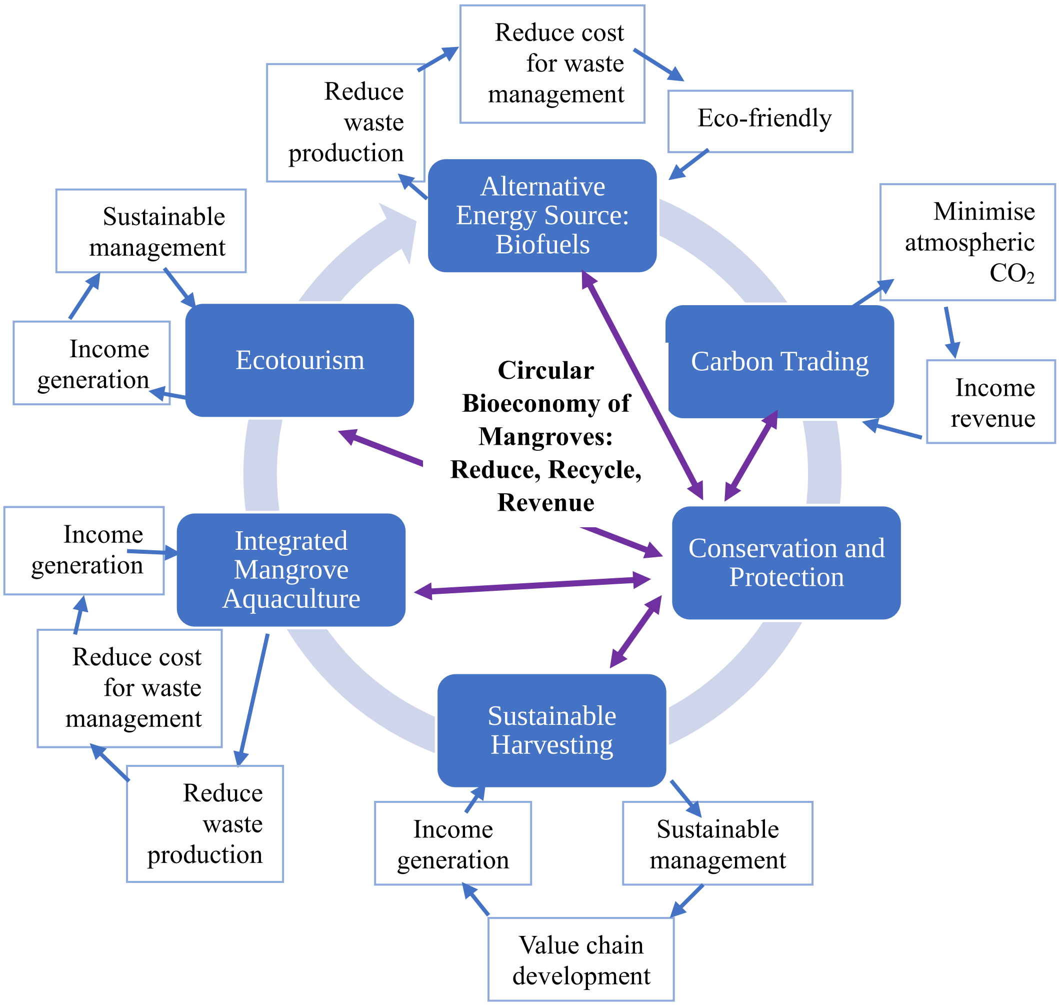

Figure 6.2: Overarching CBE approaches in mangrove ecosystems. 3R Concepts- Reduce, Recycle and Revenue - approaches as a circular economy principles for sustainable management and utilization of mangroves.

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Chapter 7

Potential use of microorganisms for economic sustainability in the food industry

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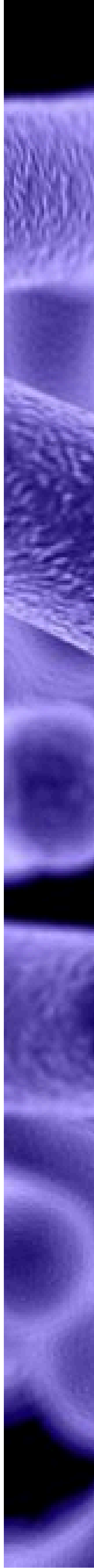

Abstract

Economic sustainability is of critical importance within the broader sustainability framework, making a crucial and determining impact on the long-term survival of an organization amidst market competition. Among diverse strategies to attain economic sustainability in the food industry, microorganisms play a vital role, as their applications have been spread throughout food value chains. At the same time, they exert minimum negative influence or positive impacts on the social and environmental pillars of sustainability. Fundamental methodologies in achieving economic sustainability in the food industry encompass the reduction of operational or raw material costs, increasing production rates, and profit generation by utilizing food waste as substrates. In this chapter, the integration of microbial technologies for the achievement of economic sustainability has been widely discussed in areas such as nitrogen fixation and bioremediation in crop production, fermentation, bioethanol production, compost production, and anaerobic digestion in food waste management. At present microorganisms are genetically engineered to customize their metabolic activities to enhance their suitability for operations in the food industry. Despite the high cost of such biotechnological advancements, considering the long-term economic sustainability, scientists tend to use these contemporary techniques. This review critically evaluates the beneficial effects of using microorganisms for economic sustainability while providing strong shreds of evidence backed by recent advances in the food industry.

Keywords: Economic Sustainability, Food Industry, Microorganisms

Potential use of microorganisms for economic sustainability in the food industry

The measures to achieve sustainability in the food industry operations have prevailed in a broad range from a perspective of a scientific rationale that extends throughout the farm-to-fork value chain, where the composition of the term sustainability refers to a combined concept of three pillars called economic, environmental and social (Kotob, 2011). The decision-making framework of food industries has to be in a way to achieve sustainability not only with a scope to protect the planet in the long run but also to optimize industry profits or in other terms, to succeed in the "economic" pillar of sustainability. In most cases, this could be occurred interchangeably (Malochleb, 2018). However, economic sustainability does not mean itself to maximize the profit margins of the food industry where the desirable impact of it refers to cost-saving and sustainable revenue generation. The opportunities to achieve economic sustainability in a particular food industry could be identified in almost all the nodes in the farm-to-fork value chain. The World Business Council for Sustainable Development has stated that the businesses that experimented with sustainable practices have experienced greater financial success. Lower production costs, enhanced product function, and quality increased market share due to the tendency of the consumers to purchase sustainably produced food, improved environmental performance, improved relationships with stakeholders, and lower risks are some of the dividends which they have had where the economic sustainability has been achieved successfully (Baldwin, 2011).

The potential uses of microorganisms (MOs) for the sake of achieving the economic sustainability of the food industry will be elaborated on throughout this chapter. It will cover the aspects of the entire food value chain starting from crop production to food processing operations, and waste management.

The history of using MOs in the food industry aspects runs down even to the prescientific era when wine production originated. Starting from there onwards, MOs have now been used for years in raw material preparation, crop cultivation, fermentation, ripening, taste and aroma development, improving the functional properties, waste management, etc., which could assist in the process of achieving economic sustainability (Jay et al., 2005), and the contribution of the MOs towards cost-saving or sustainable revenue generation must be obvious while achieving the economic sustainability. For example, microbial enzyme-based processes are preferred over chemical processes, due to efficient process control, high yield, low refining costs, and process safety (Raveendran et al., 2018). However, there are different types of cost-effective mechanisms based on chemical usage instead of MOs for the same purposes, but the adverse effects of such mechanisms on humans and the environment do not permit industries to use them continuously (Wang et al., 2020).

Economic sustainability of the food industry

Economic, environmental, and social are the three basic components of sustainability, however, there is no universally recommended definition for the components of sustainability, although the environmental and the social components too could be addressed, negatively or positively during the efforts towards achieving the economic component (Purvis et al., 2019). The depletion of arable lands and the rapid global population growth were the two significant factors that influenced the food industries to consider the environment and the social components of sustainability (Hamprecht et al., 2005).

When studying the major causes that affected the food industries to deviate from economically less sustainable solutions, four major facts could be identified from the economic perspective. They are the globalization of the agriculture and food-based industries, changes in consumption patterns, changes in food delivery patterns, and the rapid increase of the retailer level of the food value chain. Controlling the performance of the farm-to-fork value chain operations to save costs and generate sustainable income could theoretically lead to achieving economic sustainability in the food industry (Hamprecht et al., 2005).

Although the contribution of microbiological solutions for economic sustainability (ES) of the food industry is enormous and runs down to the pre-historic era, not all industries have adapted to them yet. A proper food waste management plan is one of the aspects of reducing the cost through efficient usage of energy. Methane generated at the wastewater treatment plant in Sierra Nevada Brewing Company (USA) is used to fuel cell units, which supply the electric power and heat to the brewery where the cost of fuel usage is reduced by large margins. In addition, wastewater treatment plants and anaerobic sludge digesters are established in the factory premises of that company enabling waste recycling and reuse of treated water without the support of the relevant municipality to achieve economic sustainability (Baldwin, 2011).

Sustainable use of microorganisms in the food industry

Crop cultivation

MOs have been used in crop cultivation for years. From them, the biological fixation of nitrogen to produce alternative nitrogen sources to be used for crop cultivation held an important place. The uses of MOs in crop cultivation indirectly affect the food industry operations, and the way they strengthen the economic sustainability of the food industry is basically due to the higher production yields and the low cost of production (Capozzi et al., 2021).

Biological fixation of nitrogen

Nitrogen is an essential soil nutrient for the growth and development of plants. Biological nitrogen fixation converts atmospheric nitrogen into nitrate or ammonium, which plants can readily absorb. Biological nitrogen fixation is less expensive compared to the Haber–Bosch process, developed in 1913 to fix nitrogen because it requires a temperature of 400–500 °C and approximately a pressure between 2×107–2.5×107 Pa to produce the nitrogen. Therefore, the maintenance cost is massive. The energy requirement is less when the nitrogen is fixed using microorganisms, as it is an enzymatic process. Nitrogen fixation is catalyzed by nitrogenase enzyme and it is similar in most nitrogen-fixing bacteria. The economic advantages of using them include a reduction of cost and an increase in the yield within higher margins (Soumare et al., 2020).

Management of soil-borne diseases

The use of MOs as bio-control agents in soil is one of the methods in crop production to suppress the functionality of soilborne plant pathogens through parasitism, production of toxic chemicals, causing competition for the host and nutrients, and building resistance in plants against disease-causing pathogens. Soilborne pathogens are one the most devastating organisms in crop production, which cause significant economic losses if not, identified in the early stages of the disease. Since the use of bio-control agents alone may be ineffective and costly, implementing an integrated bio-control mechanism is the best way to gain an economic advantage (Panth et al., 2020).

Pest-resistant microbial genes for crop protection

Microbial genes have been used for different purposes in the food value chain. The use of microbial genes as transgenes for plants as a pest-resistant strategy has become common in crop production nowadays. Transgenic Bt corn is one of the best examples in this regard. Insecticidal proteins are produced by the bacterium *Bacillus thuringiensis* (Bt) and the fall armyworm (*Spodoptera frugiperda*) is a destructive pest of corn that could be destroyed using Bt toxic proteins. In the early stages, these proteins were extracted from microorganisms and manually applied to the plants. However, the efficiency of this mechanism has been improved with biotechnological advancements where the genes responsible for the toxic protein production were used as the transgenes for corn plants. Although the research and development cost for biotechnological advancements is considerably high, when considering the effectiveness of the solution, the use of microbial genes is one the most successful methods in modern agriculture to achieve economic sustainability (Banerjee et al., 2017; Padkina and Sambuk, 2016).

Use of effective microorganisms (EM)

Effective microorganisms contain mixed cultures of beneficial and naturally occurring MOs such as lactic acid bacteria and yeasts, photosynthetic bacteria, actinomycetes, and other several types of MOs. Among them lactic acid bacteria are predominant. This mixture can be applied after diluting to the soil, which could contribute to increasing the microbial diversity of soils and plants. In this way, EM is an added dimension for optimizing the best soil and crop management practices such as crop rotations, conservation of tillage, crop residue recycling, and bio-control of pests, which ultimately contributes to enhancing the crop production to achieve an economic sustainably (Higa and Parr, 1994).

Microbe-optimized plants

Genotypic and phenotypic variations in plants select different microbiomes. This indicates that the ability of a plant to support a particular beneficial microbiome is a plant trait under selection. At the same time, the optimization of microbial biofertilizers and biopesticides is advancing drastically enabling them to be used in various soils, crop varieties, and environments. Increasing efforts to explore microbiome engineering could lead to microbial consortia that are better suited to support plants. The combination of all these approaches could be integrated to achieve increased productivity, disease resistance, stress tolerance, improved plant-water-soil relationship, and phytoremediation to address food security while securing constant economic benefits to the food industries indirectly. At the same time, it becomes a sustainable solution beyond increasing the use of costly inorganic fertilizers (Trivedi et al., 2017).

Bioremediation of soil

Bioremediation is a concept that is not related only to crop production. It includes degrading, removing, altering, immobilizing, or detoxifying various chemicals and physical materials from the environment using bacteria, fungi, and plants. Thus, it could also be used to recover contaminated soil. Bioremediation has the advantage of being an environmentally friendly and cost-effective solution that exploits plants to immobilize or extract contaminants from soil and water, and fungi and bacteria to degrade them into compounds that are less dangerous or non-dangerous. Arable lands that are polluted cause huge economic losses compromising cultivation. Thus, using a method like bioremediation using MOs allows for the restoration of the lands and makes them suitable for cultivation. For example, some bacterial strains (strains belonging to the genera *Bacillus*, *Acinetobacter*, *Sphingobium*, *Rhodococcus*, and *Pseudomonas*) have been utilized to restore petroleum hydrocarbon-contaminated soil. Two fungal species, *Paecilomyces javanicus* and *Metarhizium anisopliae* isolated from a former lead mining area in Scotland have been used successfully to transform metallic lead into chloropyromorphite which is less dangerous for crops (Abatenh et al., 2017; Rigoletto et al., 2020; Wang et al., 2020).

Food processing operation

The use of MOs in food processing operations directly affects the economic sustainability of the industry. MOs are used in food fermentation, as a source of food supplements, etc. Further, microbial metabolites are also used as raw material for food.

Fermentation

Natural fermentation processes have been used as food preservation techniques for years. The origin of cheese production in Iraq following the domestication of animals dates back to 6000 BC. Natural fermentation occurs due to MOs in the environment where the activity of undesirable microflora is suppressed by the metabolites of fermentative MOs. A set of unique sensory characteristics achieved through fermentation is an extra dividend. Natural fermentation is inadequate with the increasing population. Thus, the food industries have converted to the deliberate addition of MOs (Rani and Soni, 2007; Ross et al., 2002).

During fermentation, MOs convert the raw material of the food or beverage into microbial metabolites, which directly contribute to shelf-life extension or increase product quality. In the process of producing metabolites by MOs, enzyme pathways are used. The required conditions for the enzyme pathways to succeed in the expected products are mild compared to the required conditions suppose the products are to succeed in other physical conditions, where high temperature and high pressure are required and which are costly to maintain. The recommended fermentation temperature is 15 to 20°C for white table wines and 20 to 25°C for red wines which are not hard and costly to maintain (Moreno and Peinado, 2012).

During fermentation, the metabolites produced by the MOs themselves work to maintain conditions like low pH values, which suppress the undesirable MOs. Bacteria like *Bacillus subtilis*, *Enterococcus fecalis*, *Pseudomonas aeruginosa*, and *Proteus*, and fungi like *Alternaria*, *Aspergillus*, and *Cladosporium*, can be causal agents of yogurt spoilage. However, the lactic acid produced by lactic acid bacteria does not allow them to survive under low pH. Also, the MOs involved in fermentation will reduce the activity of undesirable MOs through the production of bacteriocins (Pal et al., 2015; Raveendran et al., 2018).

Microorganism as a biocontrol agent

Brettanomyces bruxellensis is a significant wine spoilage MO that produces detrimental compounds that harm the organoleptic properties of wine and cause economic losses in the wine industry. Thus, selected yeast and lactic acid bacteria are used as bio-control agents for *Brettanomyces* *bruxellensis*to reduce economic losses (Berbegal et al., 2018). Further, *Fusarium culmorum* fungal contamination of bread is a critical concern for producers since it causes economic losses due to negative sensory properties and safety hazards (mycotoxins). *Lactobacillus plantarum* has been successfully experimented to be used to reduce *Fusarium culmorum* by adding them to bread dough (Russo et al., 2017).

Research conducted in China has indicated the potential use of *Aspergillus niger* and its intracellular enzymes to detoxify Aflatoxin B1 in food and feed. Among the high-cost methods like extrusion cooking under high temperatures and high pressure and the use of magnetic carbon or ammonization for aflatoxin degradation, the use of MOs as a biological detoxifier is cost-effective for food industries which leads to a sustainable economy (Fang et al., 2020; Peng et al., 2018).

Microorganisms as a source of food

Microbial cells are used directly as single-cell proteins or as a source of proteins. The term "Single-cell proteins" refers to dead and dried cells of bacteria, algae, molds, and yeasts. The economic advantage of these food sources is the ability of them to be grown on cheaper feedstocks like molasses, methanol, cheese whey, or any kind of agricultural or forestry waste. Although they are beneficial and potential as sustainable food sources, the level of economic advantage fluctuates based on aspects such as the large land requirement for algal growth and bacterial toxin production (Rani and Soni, 2007). Some bacteria seem to be a good food source for rotifers in freshwater, which indirectly contributes to the food industries to maintain a sustainable economy. Rotifers are regarded as living food capsules for transferring nutrients to fish (Ooms-Wilms, 1997).

Microorganisms as a source of food supplement

A food that intends to supply additional nutrients is called a food supplement. With the ability to be grown even on industrial waste, microbial food supplements have become a cost-effective method for food manufacturing industries (Béligon et al., 2016). The use of MOs in lipid manufacturing is a spectacular example as it possesses several dividends compared to other oleaginous species cultures such as plants and fish. A wide range of substrate availability is also an advantage in this regard. For example, the potential demand for Omega 3 Poly Unsaturated Fatty Acids (based on 500 mg/day) is 1.274 million tons and the supply by fish is 0.84 million tons so the gap is 0.434 million tons. Therefore, searching for alternate sources is vital to cater to the increasing population (Béligon et al., 2016).

In addition, mycoproteins produced by MOs are also used as food supplements. Since the typical protein content of mycoproteins ranges from 42% to 50% on a dry weight basis (db), it is one of the best protein sources that can easily be succeeded by growing on industrial waste. Apart from that, a range of metabolites produced by MOs such as amino acids, organic acids, and vitamins can be used as food supplements (Rani and Soni, 2007). However, genetically modified MOs are a far more promising source for the food industries in securing a sustainable economy in the manufacture of protein supplements for animal feed. It leads the food industry not only to supply good-quality proteins but also to fill the deficit created by the expansion of the population (Kuhad et al., 1997).

Bio-peptides or protein hydrolysates are convenient sources of protein for human nutrition due to their high absorbance in the gastrointestinal tract compared to natural protein sources like fish or meat. When studying the composition of spirulina microalgae, the protein content ranges around 50 to 70% on a dry weight basis, and it contains five essential amino acids including leucine, valine, and isoleucine. Moreover, it has a significant digestibility (83 to 90%). Since animal protein production requires a large number of resources and as the percentage content of protein is high in microalgae, they can be considered an economically sustainable protein source for the industry (da Silva Vaz et al., 2016).

Except for being used as food supplements, there are instances where the MOs are used to add a functional benefit to food. Riboflavin-fortified kefir using selected *lactobacillus* bacteria like *Lactobacillus plantarum* has been indicated as an economically sustainable solution for food industries due to the emerging demand for functional beverages (Yépez et al., 2019).

Microbial metabolites

Pigments

Since color is a decision-making parameter in the sensory profile of a particular food, developing pigments for food is quite challenging. Consumers prefer pigments to be natural rather than synthetic compounds and most importantly the impact of pigments on the price of the food items is to be at the lowest. Producing pigments using natural compounds while maintaining a consistent supply to the food industries is also quite challenging. Thus, the use of MOs for natural pigment production is an economically sustainable way for the food industries as they could be produced in large quantities for relatively a lower cost. The tendency of the food industries not to use synthetic pigments has emerged years back due to the possibilities of contamination with carcinogenic compounds embedded in synthetic pigments like metanil yellow and red dye No.3.

Thus, the solutions for food pigments from natural sources were from plants, insects and microbial origin. Some of the major drawbacks of using natural compounds are less consistency, lower stability, and high cost of production. From the economical perspective, pigments of microbial origin have several dividends such as cheaper production, higher yields, easiness of extraction, lower-cost raw materials, less seasonal variations of production, and strain improvement techniques to increase natural pigment. In addition, the anticancer, antioxidant properties, and other functional properties of the pigments of microbial origin multiply the demand (Sen et al., 2019).

Flavor compounds

Currently, food flavor compounds are often produced for very low costs using byproducts of the paper and petrochemical industries. However, there are microbial solutions for the development of flavor compounds. Although they are potential sustainable solutions for food industries, it will take some time to reach the commercial level with significant economic benefits. Nevertheless, there is no doubt that microbial processes will slowly make their way into the food industry as the demand for flavor compounds using natural sources increases (Smith and Palumbo, 1981).

Functional properties

Since MOs are used to reduce food spoilage, increase shelf life, and as effective bio-control agents, they have shown significant results in improving food safety and other functional-related aspects. Food safety-related aspects are not limited to generating conditions like low pH values which are undesirable for spoilage-causing organisms, but the mechanisms range in a broad area. For example, metabolites produced by

MOs that possess antioxidant activities are used to reduce food spoilage. A study conducted on stress-exposed mangrove-related microbes has shown the development of specific antioxidant metabolites which could have high practical importance in food processing under circumstances such as prevention of food lipid oxidation (Tan et al., 2018). The economic sustainability of a food industry by applying the functional properties of the microbial metabolites can be achieved because of the low-cost and mild conditions required to grow these MOs.

Waste treatment

Waste generated in food industries can be food waste (FW) or non-food waste. Among them, food waste generated can be categorized into two more categories plant-derived food wastage and animal-derived food wastage. Incineration and landfill of food waste were the methods used in the recent past where economic and environmental sustainability remains less viable. Thus, biological processes such as anaerobic digestion, aerobic composting, bioethanol fermentation, and feed fermentation have been discussed and researched widely about food waste management for the sake of energy production and beneficial resource generation such as high-value products and fertilizer for crop production. These methods are used in both animal and plant-derived food industry waste disposal (Ravindran and Jaiswal, 2016).

Incineration is a process of releasing heat energy by burning the mixed food waste using fuels at 800–1000°C, and the destruction of pathogenic microbes and a volume reduction of 90% are achievable through it. However, it should be noted that the incineration of FW also has the obvious disadvantage of high capital and operation costs where 70kWh is required per ton of wet food waste for incineration. Thus, it could not be considered an economically sustainable solution for industries. At the same time, even though the landfill is not costly compared to incineration, from an economic perspective burying food waste which possesses the potential to generate income using MOs is not sustainable (Khoo et al., 2010; Pham et al., 2015).

In addition, using food industry waste from the industry itself might be more productive than using municipal solid food waste or municipal wastewater as a source of energy or other productive resources, as the composition of the food industry waste is not diversified largely being raw material specific.

Aerobic composting

Aerobic composting is a process engaging aerobic MOs such as bacteria, actinomycetes, and fungus to decompose organic matter in food waste to compost under aerobic conditions. Aerobic waste treatment methods could be used for solid sludge as well as for wastewater. Food industry waste with abundant organic matter and nutrients such as nitrogen, phosphorus, and potassium can work as an excellent feedstock for aerobic composting which ultimately end up as fertilizers. In fact, among the range of advantages of aerobic composting, ease of operation, low cost of production, and high demand due to effective nutrient recovery are at the top. In addition, fertilizer production becomes a source of extra income. For example, canning industry breweries, malt houses, dairy industries, fish wastes, slaughterhouse effluents and residues, sugar industry wastes and effluents, wine industry wastes, and oil industry waste are potential organic waste resources from food industries for aerobic composting. The extra income generated through compost production can contribute to the economic sustainability of the food industry (Ma and Liu, 2019; Ranalli et al., 2001).

Anaerobic digestion

Anaerobic digestion of agricultural and food industrial wastes is one of the most attractive methods for solids treatment as the process enables excellent waste stabilization along with its ability to recover both energy and compost. Energy generation by itself refers to biogas production. In this process of digestion of wastes, complex organic compounds are hydrolyzed and fermented by rapidly growing acidogenic bacteria such as P*ropionibacterium* into volatile fatty acids. These volatile fatty acids are then oxidized by slowly growing acetogenic bacteria such as *Acetobacterium* into acetate, molecular hydrogen, and carbon dioxide. These end products are suitable to be used as substrates for the methanogenic slowly growing bacteria such as *Anaerolineaceae*. Anaerobic digestion of food waste has been identified as one of the most reliable and economically feasible technologies when it comes to full-scale operations. However, the high initial cost for the establishment, the requirement of highly skilled laborers at the beginning, and the need to use aerobic post-treatment techniques are some concerns (Denac et al., 1988; Novak and Loubiere, 2000).

Feed fermentation

The pretreatment process followed by fermentation processes of food waste is the two basic steps of biochemical feed production in which food waste is conveyed to crushing, screening, dehydration, and drying, followed by the addition of probiotic MOs to convert macromolecular organics into absorbable small molecular organics through solid-state fermentation. Thereafter, the produced amino acids and proteins start to gradually accumulate in the feed via the proliferation of single cells. Low cost, high mechanization degree, and high resource utilization rate are the top advantages of biochemical feed fermentation. Low cost and the ability to be used as a resource for the animal feed itself provide an advantage for the food industries. Due to the presence of higher amounts of protein and fat in the final composition after fermentation of food industry wastes such as whey, molasses, and brewer's solid wastes, they have been experimented with for possibilities of use as livestock feed enrichment (Aggelopoulos et al., 2014; San Martin et al., 2016).

Bioethanol fermentation

The increasing commercial price of gasoline has spontaneously increased the demand and the price range for bioethanol. When it comes to practical use, bioethanol is usually blended with a considerable proportion of gasoline to partially replace fossil fuel because of its combustibility and density. Around 40 countries have allowed the use of biofuel-ethanol and automotive ethanol-gasoline where the annual consumption of bioethanol is around 600 million tons. It accounts for about 60% of global gasoline consumption. In many countries, corn and sugar crops have been commonly experimented to be used as feedstocks for bioethanol production. Due to many obvious reasons, this approach is not economically viable and environmentally sustainable. Thus, it is necessary to develop alternative, green, and sustainable feedstocks except for corn and sugar in bioethanol production for environmental and economic sustainability. In such a situation, food waste rich in carbohydrates has been demonstrated to be an excellent feedstock for bioethanol production through aerobic or anaerobic fermentation when considering economic and environmental sustainability (Jiao et al., 2019; Manzetti and Andersen, 2015).

For example, the production of bioethanol from lignocellulosic feedstocks such as agricultural and forestry residues is receiving increasing attention due to the less sustainable supply of fossil fuels. One of the key challenges in this regard is high cellulase production cost. Therefore, scientists have explored ways to develop MO strains that can produce high-quality cellulase under cost-effective methods for biorefinery of agricultural, food industry, and forestry wastes. Fungal species such as *Trichoderma reesei*, *Chrysoporthe cubensis*, *Phoma exigua*, and *Penicillium piceum* are used as cellulase producers. The use of genetic engineering has been shown to improve the cellulase-producing potential of the above species even though the research and development cost is high (Zhao et al., 2016).

The influence of microorganisms on environment and society

Succeeding one pillar of the sustainability concept does not complete the criteria for the food industry to achieve success. The sustainability of the other two pillars, environment and society also have not to be harmed when achieving economic sustainability of the food industry by using potential MOs.

Biological nitrogen fixation using MOs has the potential to reduce nitrogen fertilizer usage to ~0.160 billion tons per year. It corresponds to a reduction of 0.270 billion tons of coal consumed in the production process. Besides the economic advantage of this, the reduction of coal consumption directly reduces the principal emissions such as Sulphur dioxide, which contributes to acid rain and respiratory illnesses (Soumare et al., 2020). In addition, the physical or chemical methods to be used instead of microbial mechanisms become less applicable. For example, bioremediation using microbial incorporation for a large land area with relatively low concentrations of the contaminated compound is more effective than using chemicals. Phytoremediation or microbial remediation shows good potential in such conditions for which it is not cost-effective to use traditional physical or chemical methods. At the same time, it ensures less harm to the environmental ecosystem (Macek et al., 2008). Integrated applications for pest management are always recommended in crop cultivation. However, single-use can be seen in lower costs and possible reduction of labor for the farmer. At the same time, single-use does not require the determination of compatibility between the different components (Schmitt and Seddon, 2005).

When considering the global context, the increasing demand of consumers towards natural raw materials over synthetic raw materials has created a food industry trend to go ahead with more ingredients that are natural. Such raw materials cause less harm to the ecosystems. For example, natural colors are assumed safe as they are non-allergic, non-toxic, non-carcinogenic, and biodegradable thereby rendering no risk to the environment or humans. The lower risk advantage of natural colors and the changing perception of consumers to preferably consume natural products are advantages beyond the economic benefit (Sen et al., 2019).

Incineration and landfilling were the oldest methods of solid food waste management. However, step-by-step efforts to convert food waste away from the traditional methods towards recycling or composting facilities are known to gain environmentally improved results as the energy required for the digestion is much less and the end product of waste is also beneficial. For example, Sonesson et al., (2000) have shown that anaerobic digestion performs the lowest environmental impact of all solid waste management systems. The generation of food waste is inevitable, especially during the pre-consumption stage. The environmental damage caused by the formation of greenhouse gases and groundwater contamination via food waste decomposition due to landfills can be largely avoided (Ravindran and Jaiswal, 2016).

Conclusion

The MOs are used in a wide range within food industries, starting from crop production and livestock to waste management. MOs play a vital role in many instances. Among many advantages and positive impacts of them, the contribution towards achieving economic sustainability of the food industry has grabbed the attention of scientists. Achieving economic sustainability using MOs is directed basically to reduce production costs, maximize profits, and increase the demand for the products. Starting from a stage where the major objective was to reduce energy usage for cost reduction, it has now been revolutionized by biotechnological advancements, which can purposely use microbial genes to enhance the traits of other organisms or to transfer genes from other organisms to microorganisms. Thus, even though the research and development cost for genetic engineering is high, the future perspectives of achieving economic sustainability in the food industry will be tightly bound to using MOs.

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Chapter 8

Bioenergy for a circular bioeconomy: Status and prospects for Sri Lanka

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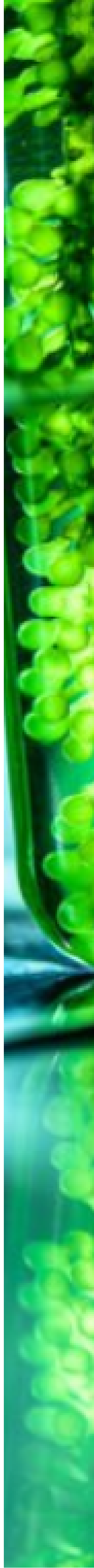

Abstract

Sri Lanka, having suffered the brunt of the COVID-19 pandemic and braving the worst economic crisis in its history, is experiencing a high poverty rate; 31% of the population living below the poverty line as of 2023. Over 55% dependence on petroleum imports for electricity/heat, and nearly 100% dependence on petroleum products for transportation, led to a drastic hike in the prices of essential goods/services, worsening this dire situation. However, as a tropical agricultural island in the middle of the Indian Ocean, Sri Lanka is blessed with an immeasurable wealth of bioresources, making bioenergy a highly suitable source of energy. Bioenergy has been the earliest source of energy for Sri Lanka and has a significant potential to help meet the country's current energy demand self-sustainably, leading to decentralized, carbon-neutral, renewable energy production, establishing long-term regional and national energy security, and ultimately contributing towards a strong circular bioeconomy in Sri Lanka. This chapter will investigate (1) the current status of bioenergy production in Sri Lanka, its role and impact on the local economy, society, and environment (2) the prospects of developing the bioenergy sector in Sri Lanka to reach its fully sustainable potential by identifying the gaps in local research, development, and innovation (3) the strengths, weaknesses, opportunities, and threats associated with bioenergy production in Sri Lanka and (4) recommend actions for stakeholders to alleviate the identified weaknesses/threats while building on the identified strengths/opportunities.

Keywords*:* Bioenergy, Biomass feedstock, Conversion technologies, Research and Innovation, SDGs

Introduction

Bioenergy is derived from the organic matter of recently live organisms, which can be used to produce heat, electricity, transportation fuels, and other energy-rich, combustible products. The bioresources that produce biomass can be sustainably exploited if their usage rate is matched with their regrowth rate over the long term. Bioenergy is classified based on the source of biomass feedstock, ranging from food crops to genetically modified microalgae (Figure 8.1). These bioresource feedstock can be chemically and/or physically and/or biologically processed and converted into biofuel products that can be used for one or more energy purposes.

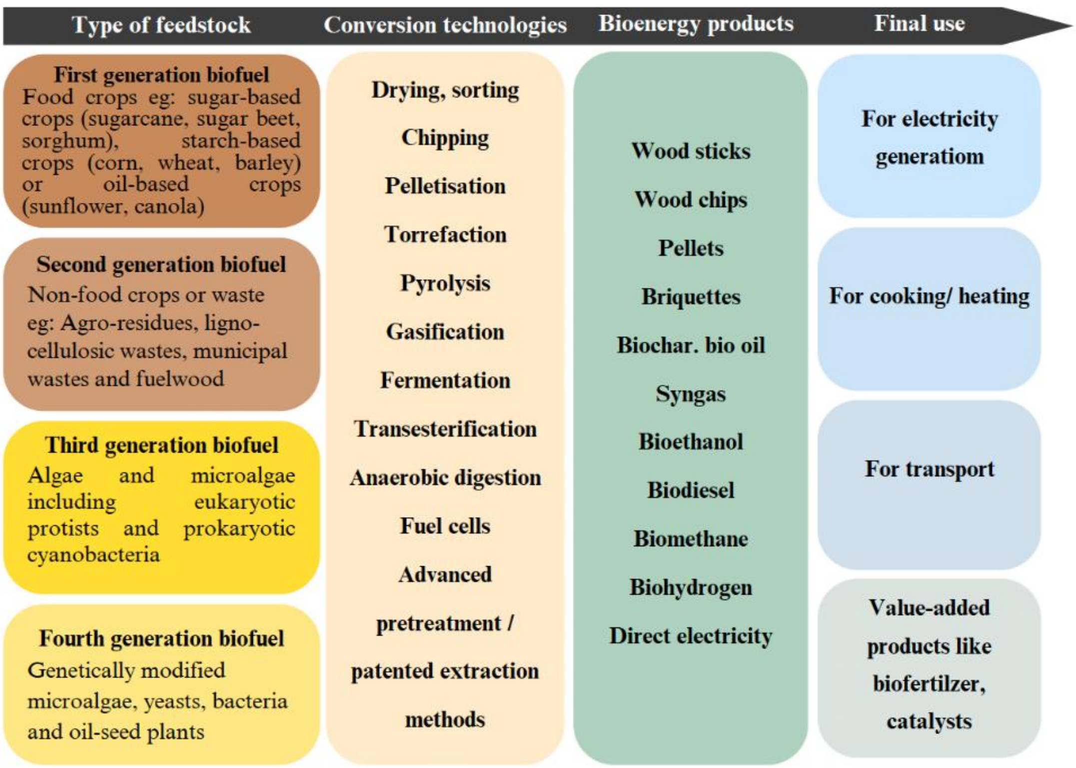

Figure 8.1: Feedstock, conversion technologies and products in the global bioenergy sector.

Sri Lanka, with its tropical climate, is blessed with extensive vegetation, unmatched biodiversity, and a well-developed agricultural sector. These have contributed to an exceptionally high biomass energy potential of 3.5 tC/ha/yr, which is higher than the global average (Energy Profile of Sri Lanka – IRENA, 2023). Hence, bioenergy is one foremost viable option for sustainable energy at the level of locally available technology and self-dependent input resources that can significantly reduce the dependency on oil imports and lead our nation towards long-term energy security, self-sustainability, rural development, and contribute to a zero-carbon future, zero waste future under a circular bioeconomy. However, at present, bioenergy contributes to less than 1% of the total energy generation in the country and to just 2% of the total installed capacity of renewable energy (Energy Profile of Sri Lanka – IRENA, 2023). The scarcity of innovation, commercialization, and communication in the bioenergy sector and the lack of implementation of a systematic approach in its development have made bioenergy unsuccessful in significantly replacing or supplementing non-renewables in the local energy sector. The following chapter expands on the current use of bioenergy in Sri Lanka, the future prospects, and associated barriers to the production and utilization of bioenergy for enhancing energy access, promoting sustainable livelihoods, and supporting energy security for the country.

Status of bioenergy production and consumption in Sri Lanka

At present, local bioenergy production is rudimentary and small-scale, with direct use of biomass or minimally processed biomass for cooking/ heating and electricity generation purposes. Firewood is sourced directly from non-crop vegetation/crop wastes and used for cooking/heating purposes in most rural and sub-urban households and some food/

beverage industries. Some fuelwood species like *Gliricidia*, *Eucalyptus, Acacia, and Calliandra* are grown in tea, rubber, and coconut plantations to supply the energy needs within the facility. Firewood, rice husk, paddy residue, sawdust, and coconut shells are dried and chipped for direct use or converted into higher energy dense pellets/briquettes or charcoal through techniques like pelletization (drying, pressurizing biomass to conform into homogenous forms, with ease of storage and increased shelf-life) and pyrolysis (thermal decomposition (>400°C) of woody waste in absence of/ limited oxygen into biochar) for use in electricity generation, cooking, and heating purposes in urban households and certain manufacturing facilities (see case study 1 and 3 below). Municipal waste and organic effluents generated from housing communities, farms, hotels, and other institutions are used for biogas production through anaerobic digestion (bioconversion of organic compounds into methane using methanogenic bacteria) for use in power generation/cooking (see case study 2 below). Further, initiatives and pilot-scale projects with international collaboration are being carried out to promote commercialization and increased public exposure of biomass-based energy alternatives (see case study 4 below).

Case study 01: Dendro and paddy husk powered Tokyo Cement production

Figure 8.2: The supply chain and setup of Tokyo Cement Biomass Power Plant - Mahiyanganaya (Tokyo Cement, 2024).

Tokyo Cement has pioneered renewable energy generation in the local corporate sector with the setting up of Sri Lanka's first-of-its-kind 10 MW biomass power plant running on paddy husk, in 2008 in Trincomalee and a large scale dendro power plant with a capacity of 6 MW in 2014 in Mahiyangana (Figure 8.2). This has enabled them to earn 43,000 Carbon Credits per annum from the UNFCCC and supply directly to the national electricity grid, illuminating the lives of over 30,000 rural households. With the addition of another 8 MW capacity biomass power plant at Tokyo Eastern Cement Factory in Trincomalee, Tokyo Cement Group is the single largest contributor of renewable biomass energy in Sri Lanka with a total installed capacity of 24 MWh of electricity. Under its Community Trade sustainable fuel-wood tree planting program, the project has so far planted over 6 million *Gliricidia* trees in the surrounding areas, to ensure a continuous fuel supply. The project uplifts the livelihoods of nearly 2,500 farming families, creating nearly 500 direct employment and over 1000 indirect employment opportunities, for the rural farming communities. Currently, they contribute 60,000 MW/h of green energy annually to the national grid. In addition to making their entire local production process 100% energy independent, these efforts have enabled them to reduce their carbon footprint to a mere 100,000 MT CO_2 per year.

Case study 02: Food waste to biogas at Sri Lankan Airlines

Kitchen waste is diverted into the sealed tank for the production of methane. This project produces 4500 kg of biogas per annum and has replaced a 5 kWhr boiler at Sri Lankan Airlines headquarters premises, providing a solution for managing waste generated at the canteen and garden while also producing fertilizer from the remaining slurry (Figure 8.3).

Figure 8.3: Biogas tank and waste inlet at SL Airlines HQ premises (SriLankan, 2024).

Figure 8.4: Improved stoves marketed by 'Janalipa', the biochar and rice husk pellets used as feedstock (Janalipa, 2024).

Case study 03 – Rice husk pellets/ wood biochar fueled "Janalipa"

Improved cookstoves could play a big role in reducing overall expenditure on firewood, saving around 41% of the fuel wood currently used in traditional cookstoves (Musafer, 2020). One example is the improved stoves brand 'Janalipa', which provides relief for the 02 drawbacks of traditional stoves, i.e., 1. Indoor pollution and health hazards due to the release of soot, and smoke 2. Unavailability of firewood in urban areas. These improved stoves that come in two models (the economical clay and the premium terracotta) use rice husk pellets or wood biochar as feedstock and produce zero smoke/ soot during combustion (Figure 8.4).

Case study 04 – Bioenergy projects with international collaboration in Sri Lanka

The United Nations Development Programme (UNDP)/Global Environment Facility (GEF) - funded 'Promoting Sustainable Biomass Energy Production and Modern Bio-energy Technologies' project was carried out by the Sri Lanka Sustainable Energy Authority (SLSEA) from 2013 – 2018 (Renewable Energy Resource Development Plan 2021-2026 SLSEA, 2024). Outcomes of this project include the development of a standard for sustainable production of fuelwood, namely, SLS 1551:2016 which addresses issues of traceability, legal requirements, etc. to promote and support the use of sustainably produced fuelwood in industrial thermal applications. Biomass transport study, biomass pricing study, and solid biofuel standard were also other mechanisms that were set up. A survey on biomass resources, land use, and land availability for different growing models plus a survey on current management practices, socio-economic benefits, and challenges in 11 districts have been completed and validated. Best fuel wood growing models and handbook on fuel wood growing models have been published. A technical study report on the utilization of technology in biomass energy conversion systems has been completed and validated through key stakeholder validation workshops. Further, SLSEA and UNDP jointly commenced the 'The Biomass Energy 2022' project, which aims to make Sri Lanka more resilient to shocks in the energy sector by 2030. The objective is to increase the power generation capacity of the country from the current 4,043 MW to 6,900 MW by 2025 - with a significant increase in renewable energy. This project expects to further expand biomass production to agricultural waste and develop collection systems to process 100,000 tons of agricultural waste annually (Biomass Energy 2022, 2024), (Biomass phase 2 UNDP in Sri Lanka, 2024).

Prospects for bioenergy in Sri Lanka

Prospects: Local research and development

Basic and applied research initiatives on bioenergy in Sri Lanka are carried out by universities and research institutes affiliated with stakeholder government institutions (examples given below). These mainly focus on exploring the energy potential of various unique and relatively unused feedstock for specific energy products with value-added byproducts and the development of conversion technologies suited for our country.

- Pyrolysis reactor for biochar from rice husks (Illankoon et al., 2023)
  This study has investigated the design and development of a pyrolysis reactor for batch-type biochar production from rice husks. The designed novel dual-chamber reactor comprises two concentrical metal cylinders (the outer cylinder for energy

generation and the inner one for pyrolysis) and a syngas circulation system. The reactor consumes 11 ± 0.1 kg of rice husk as feedstock and 6 ± 1 kg h^{-1} of wood as fuel to give a biochar yield of 49% with an average production rate of 1.8 ± 0.2 kg h^{-1} and gaseous by-products CH_4, CO_2, H_2, CO which contribute 23.3 ± 2.3 MJ m^{-3} of energy that is used as fuel for the pyrolysis process.

- Techno-economic analysis of paddy waste for bioenergy (llankoon et al*.,* 2022)

  The study has explored the energy potential of the solid waste generated by the rice industry: rice straw (RS) and rice husk (RH) using statistical data on rice production and paddy cultivation in each district of the island to provide geo-referenced results with grate-fired combustion boiler accompanied by steam turbine cycle (GFC/ST) as the energy generation technology. The findings show that the total energy capacity using by-products of the rice industry is estimated to be 2129.24 ktoe/year of primary energy, with a capacity of 977Mwe, producing 5.65 TWh of electricity annually. The districts with the highest Profit Index values are Anuradhapura, Ampara, Polonnaruwa, and Kurunegala, with annual energy potentials of 286 ktoe, 279 ktoe, 231 ktoe, and 160 ktoe, respectively.

- Potential of *Gliricidia* as bioenergy feedstock (Hitinayake and Gunathunga, 2015)

  This study has estimated the *Gliricidia* wood resources available in the Kandy district for dendro thermal power generation, focusing on estimating *Gliricidia* woody biomass produced under different cropping systems, logging frequencies, and agro ecological zones. *Gliricidia* wood produced under pepper, coconut, tea, and live fence systems annually are 114,085 t, 7,297 t, 111,644 t, and 18,720 t, respectively, equivalent to 126 GW of electricity.

- Bioethanol from bagasse/vinasse (Jayasekara et al., 2021)
  This study has uncovered a 50% vinasse + bagasse medium that facilitates maximum growth of lignocellulolytic fungi and fermentative yeast. *Aspergillus niger- Candida tropicalis* co-culture in heat-treated bagasse gives a 0.005% ethanol yield whilst *Trichoderma* sp. - *C. tropicalis* co-culture in non-heat-treated bagasse + vinasse medium gives a 0.0031% yield.

- Bioethanol from corn wastes (Banu and Mahendran, 2019)
  This research has investigated bioethanol production from corn feedstock. It has been found that 30% corn mash with yeast produced the highest yield of 13.6% bioethanol.

- Bioprospecting cellulase - secreting microbes for simultaneous saccharification and fermentation of lignocellulose.
  This research has focused on isolating cellulase producing (from cow dung and termite gut) and fermenting bacteria (from palm wine) for bioethanol production from the abundantly available lignocellulosic wastes/agro-residues. A significantly effective simultaneous saccharification and fermentation function of *Bacillus* and *Achromobacter* co-culture has been identified (Weerasinghe, et al., 2021). Jayasinghe et al., (2019) have investigated the extracellular enzyme production by 10 bacterial isolates (*Bacillus*

thuringiensis, B. amyloliquefaciens, B. pumilus, B. aryabhattai, Pseudomonas stutzeri, P. aeruginosa, Sphingomonas sp., Burkholderia lata). *B. thuringiensis, Sphingomonas sp., B. amyloliquefaciens* and *P. stutzeri* produce cellulases, out of which, *P. stutzeri* is the most efficient degrader of cellulose.

- Freshwater flora into bioethanol (Christy et al., 2023)
  This study has aimed to convert the low-value freshwater flora into high-value bioethanol using *Saccharomyces cerevisiae* and to optimize the conditions for yield enhancement with the *Azolla filiculoides* substrate. Accordingly, *Azolla filiculoides* substrate has produced significantly higher alcohol yield with *Saccharomyces cerevisiae* when a combination of chemical and enzymatic pre-treatment techniques was used. Significantly higher alcohol yield (19 times than the non-optimized) was obtained after 36 h, at 40°C and 0.75 M H_2SO_4 concentration with an inoculum concentration of 75 g/L at 200 rpm

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- Bioprospecting native microalgae for lipids in biodiesel production
  Chlorella sp., *Chlorococcum* sp., and *Chlamydomonas* sp. isolated from Beira Lake, cultivated under standard conditions have average lipid yields of 11.34 ± 1.01%, 15.00 ± 1.40% and 2.10 ± 0.50% respectively. *Scenedesmus* sp. cultivated under ambient conditions in scaled-up closed bioreactors and in open bioreactors gave av Hossain etalerage lipid yields of 11.7 ± 1.05 % and 14.93 ± 1.55 % respectively. GCMS analysis of the biodiesel product from *Chlorella* sp. indicates significant levels of saturated fatty acids including palmitic and stearic acids, monounsaturated fatty acids

like cis-11- eicosenoic acid, and polyunsaturated fatty acids including linoleic and linolenic acids. The fatty acid ratios have been used to calculate the saturation value, cetane number, density, iodine value, and pour point of the produced biodiesel, which are in accordance with the ASTM D6751- 20a standards (Jayasekara et al., 2024), (Jayasekara et al., 2023). Hossain et al., (2020) has explored the lipid contents of cyanobacteria isolated from several local reservoirs for biodiesel production. The total lipid content has been recorded highest in *Oscillatoria* sp. (31.9 ± 2.01% of dry biomass) followed by *Synechococcus* sp. (30.6 ± 2.87%), *Croococcidiopsis* sp. (22.7 ± 1.36%), *Leptolyngbya* sp. (21.15 ± 1.99%), *Limnothrix sp*. (20.73 ± 3.26%), *Calothrix* sp. (18.15 ± 4.11%) and *Nostoc* sp. (15.43 ± 3.89%), *Cephalothrix* sp. (13.95 ± 4.27%). Madusanka and Manage, (2018) have focused on Biodiesel B6 blend preparation from *Microcystis* bloom collected from Beira Lake. Soxhlet extraction of lipids with Isopropanol: n-hexane (3:2) solvent system followed by transesterification has yielded biodiesel with properties within the ASTM D and Ceylon Petroleum Corporation specifications for no: 02-grade auto diesel.

- Innovative microalgae pretreatment and lipid extraction methods (Sandani et al., 2022)

  A novel strategy for microalgae cell disruption and wet lipid extraction using the Electro-Fenton process with sacrificial steel anode has been identified. *Chlorella homosphaera* cells (wet biomass) disrupted using EFP have given a significantly higher lipid yield of 19.99%.

- Biogas potential of waste produce (Thenabadu et al., 2014)
- Bio Methane Potentials (BMP) of fruit/ vegetable waste and food waste with biodegradability of 59.3% and 83.6%, have been found to be 0.3$m^3$and 0.56 m^3CH_4/kg, respectively, at 100 kPa and 25°C, with estimated corresponding energy quantities of 10.5 and 20 MJ/kg.

These reveal the vast potential for the expansion of the bioenergy sector in Sri Lanka, particularly for second and third generation biofuel production and consumption. However, it is apparent that there is a substantial gap between research and actual implementation in Sri Lanka. Hence, bridging this gap through innovation, scaling up, and demonstration through pilot scale projects to reach at least the early commercial stages is vital to reach the substantial prospects identified through these research findings.

Prospects: Lessons from the global scenario

In the global bioenergy sector, mainly first/ second generation categories of feedstock and advanced biomass co–conversion with enhanced biological/ physical/ chemical processing technologies are being employed in profitable, sustainable, green ventures in both developing and developed countries (Figure 8.5), with the aim of establishing a zero-waste, circular economy model of bioenergy production and use. In contrast, third generation biofuels are still in the stages of applied research, pilot projects, and early commercialization attempts. While the identified prospects of using oleaginous microalgae are significantly higher than the preceding generations, particularly due to their multi-product potential (Figure 8.5), issues with large-scale harvesting and lipid extraction add up to higher costs, making it less competitive for commercialization in the current energy markets. Similarly, fourth generation biofuels, with even higher identified prospects, are at the experimental stages, being explored for potential implementation without adverse impacts on the community/ environment.

Bioethanol from Cassava – Thailand **1st generation**

Research teams from King Mongkut's University of Technology Thonburi (KMUTT) and the BIOTEC Cassava Starch Technology Research Laboratory developed improved feedstock and fermentation processes for producing bioethanol from cassava. This technology, referred to as Very High Gravity Simultaneous Saccharification and Fermentation (VHG-SSF), achieves higher yields, reduced energy and time during fermentation, and significant GHG savings. Thailand is now considered a world leader in this technology and KMUTT's cassava distillery produces 200 liters of bioethanol per day for use in cooking/ transportation.

Black and White Pellet production – Futerra Fuels, Portugal **2nd generation**

Employs novel torrefaction technology to produce black and white pellets from the 600,000 t of biomass feedstock from the local municipality. The torrefaction lines are modular, compact and semi-transportable, suitable for both small-scale and large-scale projects and is based on the unique swirling fluidized bed principle. The technology generates a fast heat transfer from hot flue gases to the solid input material. This results in a continuous torrefaction process, homogeneous quality and a clean final product with the following characteristics: hydrophobicity, low emission levels of fine dust, sulphur oxides and nitrogen oxides, high calorific value of 19 to 22 GJ per t, clean combustion with less pollution. The annual production of white (wood) pellets is 85,000 t, and of black (torrefied) pellets is 120,000 t.

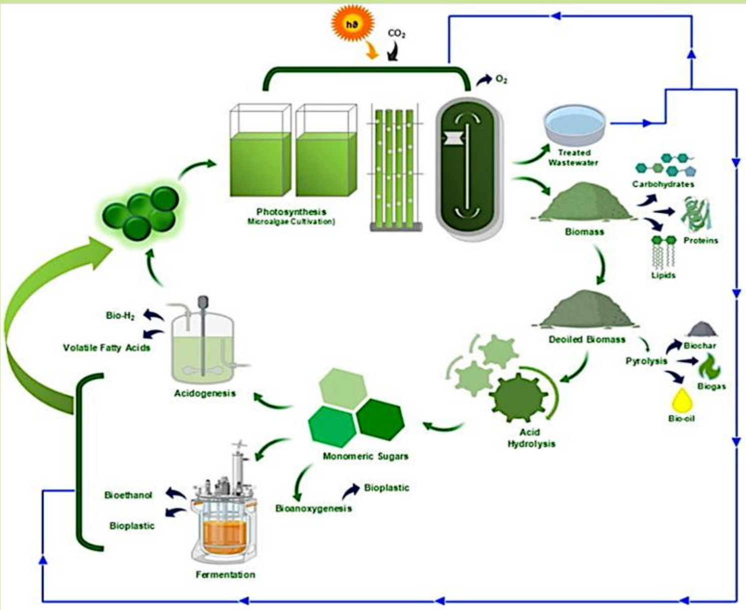
Biogas from avocado waste – Olivado, Kenya **2nd generation**

Olivado is the number one organic avocado oil producer, with 90% of the global organic extra-virgin avocado oil production. The conversion of process residues, such as skins, stones and wastewater, covers all energy needs of the factory (electricity and heat). The biogas plant consists of two digesters with a capacity of 1,400m^3 of substrate each. The plant is designed to produce 3,500 Nm^3 of biogas per day. The avocado seeds are crushed; the pulp and green process water are then pumped into a 24 m^3 mixing tank. The feedstock is then fed into the digesters. The biogas is used in a plant with a total thermal capacity of 931 kWhr and electricity generation capacity of 400 kW. Additionally, there is a biogas bottling plant where the methane concentration of the biogas is increased to 97% before being bottled. These are used to fuel the company's vehicles. With a 97% methane content, the biomethane can be used to fuel the company's vehicles. The digestate is separated into two phases: a solid digestate used as organic fertilizer and a liquid digestate recycled back, into the mixing tank to inoculate the fresh feedstock. The feedstock input is about 3,600 tonnes per year. From the biogas output, about 410,000 kWh of electricity and 200,000 kWh of thermal power can be produced annually.

Biodiesel from waste oil – Cargill, Belgium **2nd generation**

Cargill biodiesel facility is one of the largest waste-to-biofuel facilities in Europe. It is manufacturing 35 million gallons per year (mgy) of advanced biodiesel from residual and waste materials. The patented RepCat process offers feedstock flexibility and employs a repeatable, or recyclable, catalyst. The industry-leading technology employed at Cargill's Ghent plant is used to convert all types of liquid waste oils and fats—including used cooking oils, tallow and residues from edible oil production—into advanced biodiesel for the maritime and trucking sectors.

Microalgae-based cascading, closed loop biomass refinery model **3rd generation**



Microalgae have broad and unique application potential in the domain of renewable fuel, nutraceuticals, cosmetics pharmaceuticals, and fertilizer. Biorefining of microalgal biomass in a circular, self-sustainable closed loop with the aim to maximize resource recovery is being considered as one of the sustainable options that will have both economic and environmental viability.

Figure 8.5: Lessons from the global bioenergy sector (The role of bioenergy in the clean energy transition and sustainable development – UNIDO, 2024), (Cargill, 2024), (Mohan et al., 2020).

The strengths, weaknesses, opportunities, and threats for bioenergy production in Sri Lanka

The internal factors (strengths, weaknesses) and external factors (opportunities, threats) of bioenergy production in Sri Lanka, based exclusively on the current realities, identified and critically analyzed, to devise potential recommendations for the stakeholders in this sector are given below.

Strengths
Technical High biomass potential with an ideal tropical climate, ample water, and sunlight
Socioeconomical Development of rural areas, Creation of direct and indirect jobs, Diverse and decentralized energy supply; uninterrupted, self-sufficient, stable supply of power throughout the country, Independence from fossil fuels, Promotion of production of local fertilizer and other value-added bio-based products
Environmental Restoration of abandoned lands, reduction of greenhouse gas emissions (GHGs) like methane, SOx, and Nox, Improvement in solid waste management
Weaknesses
Technical Low productivity of marginal lands, high installation, operations, and maintenance costs, High labor costs, labor intensive processes with long handling and processing, Unskilled labor and lack of proper training, Health risks to employees during handling raw/processed material, Interruptions in the supply of raw materials, Non-uniformity of quality/quantity of bioenergy produces, Production is dependent on climate/weather, Data on feedstock availability are unavailable/not updated, Lack of knowledge on how imported technologies perform under local conditions, Lack of updated/advanced, efficient technologies in the production process, Lack of dedicated, continuous research and developmental efforts
Socioeconomical Loss of marginal lands which are a source of free bioresources, for poor rural communities, Conflicts between local communities and developers, Lack of funds for investment due to the economic crisis, Limited market due to lack of public awareness
Environmental High dependence on land availability, Possibility of endangering sensitive ecosystems, Possibility of affecting quality of soil, water, and biodiversity due to monoculture of energy crops, Can cause indoor pollution due to soot, smoke (firewood)

Opportunities
Technical New incentives for research and development in green technologies, Support of international NGOs for bioenergy projects with technology and knowledge transfers
Socioeconomical Support of government with new policies that promote renewables, taxes/duties exempted for import of renewable energy production equipment, High market growth potential, Source of rural income, contribution to the national economy, Improved standards of living for urban and rural communities alike, International attention on prioritizing renewable energy and GHG mitigation, Attracts foreign investments, Economically competitive with increasing fossil fuel prices, Increasing population and increasing energy demand
Environmental Implementation of 'debt for nature' projects which promote sustainable land use change, forest management and agricultural area zoning
Threats
Technical Limited national grid capacity that cannot handle large power loads at once, Power purchasing by CEB is based on a competitive basis, making bioenergy production limited, due to high costs and low returns, No perfect electricity purchasing policy; there is conflict between the Electricity Act and the SLSEA acts, Low research and studies on economic feasibility, Delay and difficulty obtaining approvals, loans, funding for bioenergy projects due to tedious legal processes, inefficient government proceedings
Socioeconomical Competition of land for food, competition with other renewable energy sources like solar, wind, and hydro Political interests, and monopolization of the energy industry by corrupt institutions/policymakers Uncertain future national policies, low social acceptance
Environmental Unregulated harvesting can lead to deforestation, soil erosion, and impacts on natural cycles Excessive use of fertilizer and pesticides leads to water pollution

Recommendations for stakeholders of the bioenergy sector

SLSEA established in 2007 under the Ministry of Power and Energy focuses on promoting indigenous energy resources in Sri Lanka, including bioenergy, and increasing fuel diversity through renewable energy development. Fuel diversification in the transport sector is particularly encouraged, with special emphasis on the promotion of biofuels. The Climate Change Secretariat, Central Environmental Authority and Sri Lanka Carbon Fund functioning under the central authority of the Ministry of Environment also have major stakes in the bioenergy sector. In addition to these regulatory bodies, the general public, research institutes, and industries hold major stakes in this sector. For example, The Bioenergy Association of Sri Lanka is a civil society formed by a group of concerned citizens to promote the use of indigenous resources such as biomass for power generation, to reduce the dependency on imported fuel. The National Engineering Research and Development Centre (NERDC) is an institution that carries out scientific research and development and provides education and awareness to improve Sri Lankan industries using indigenous knowledge, technology, and resources. With heightened international regulation on coal and the commitment made by the previous government's "70% power by Renewable Energy" mandate, Sri Lanka became a co-sponsor of the "No New Coal" compact during COP26. The current government too has set out to achieve the ambitious target of generating 70% of the electricity by renewable means and carbon neutrality by 2050. Therefore, renewable energy projects such as major/mini hydro, solar, wind, and biomass projects and clean fossil fuel-based projects like liquid natural gas (LNG) are given priority to achieve the energy and power needs. Based on the SWOTs however, it is apparent that there are more hurdles than aids for the operation and development of the local bioenergy sector. This does not reflect that the task at hand is impossible, it just shows that we should not make a hurried, unprepared shift towards massive energy production from biomass. Instead, we should progress at a slower yet steady pace. Solidifying the legal frameworks and policies, controlling energy and food production to avoid food/energy crisis, and establishing dedicated energy production for self-consumption in industrial/household units are some steps that should be essentially followed in the initial stages. The recommendations given below focus on means to evade/reduce the influence of weaknesses/threats while expanding the influence of strengths and opportunities given below, with the aim to make bioenergy production in Sri Lanka economically, socially, and environmentally sustainable.

Technical
Government and regulatory bodies Assessing the adequacy of national electricity transmission and distribution networks to allow for decentralized high energy supply, enabling IPPs to readily access the grid by revising regulation and improving grid capacity, encouraging technology and knowledge transfer with mature bioenergy markets, participating in international collaboration on standards, adopting efficient and transparent administrative, legal, and regulatory procedures for developers and/or investors, providing biomass potential information by creating atlases of biomass resources and GIS-based tools with periodic updates. ***IPPs, industries, businesses, and entrepreneurs*** Deciding scalable capacity and physical distribution of bioenergy plants based on current and planned feedstock availability, supporting feedstock flexibility for bioenergy plants, undertaking comprehensive assessment of natural resources and spatial development plans, encouraging biomass pretreatment before use to improve quality, to remove pollutants, etc., testing and sampling technologies under local conditions before full installation, adopting technologies that have a good track record elsewhere, and that provide all details necessary for operation/repair/maintenance ***Research institutes/universities*** Identifying and developing cost effective cogeneration techniques for power, heat, and fuel simultaneously to maximize output

Socio-economical

Government, regulatory bodies

Prioritizing land for food production until local demands are met and focusing use of the abundant wastes for bioenergy generation, establishing small-holder cooperatives for local communities' benefit-sharing, establishing a specific body for dispute settlement between locals and developers, raising awareness among the local populace of the benefits of bioenergy through communication campaigns, developing higher education curricula and training to meet skill requirements for the bioenergy sector, strengthening and continual implementing of the current renewable energy policies with short, medium, and long-term targets and updated improvements, regardless of the governing power/political agendas, facilitating capital grants, loans, tax incentives for parties interested in bioenergy production, reducing risk associated with bioenergy projects by guaranteeing levels of remuneration like feed-in-tariffs through long-term power purchasing agreements, setting up policies that enable fair and equitable sharing of benefits and risks to all partakers, encouraging public-private sector partnerships for raising funds at low interest rates, monitoring market trends at global, regional, and local scale to develop policies that are responsive for external changes in a foreseeable manner

Investors

Supporting investment in energy infrastructure, providing financial support for interested entrepreneurs to turn their inventions into innovation

IPPs, industries, businesses, and entrepreneurs

Developing integrated biomass supply chain for food, energy, and other value-added products, adopting the cascading use of biomass by synergies with sectors like construction

Research institutes/ universities/NGOs

Communicating, publishing, and promoting the studies on bioenergy benefits, techno-economic studies, and novel local initiatives/inventions in simple non-scientific form for the general public's awareness/use.

Environmental
Government and regulatory bodies Adopting sustainability certification schemes for biomass, regulating the use of fertilizers and irrigation practices to fit sustainable cultivation methods, establishing standards for negative externalities like noise, and waste disposal and ensuring enforcement, adopting fine/tax systems like the carbon tax to regulate exploitation and promoting zero emission energies, regularly monitoring compliance to set regulations of projects to deter illegal/harmful overexploitation activities, using a systematic LCA approach to assess the net GHG emissions of bioenergy projects ***IPPS, industries, businesses, entrepreneurs*** Adopting zero waste (reduce, reuse, recycle) procedures and ensuring constant compliance with the limits of permitted activities ***Research institutes/universities*** Identifying and developing effective bioremediation and restoration methods to improve the productivity of marginal lands, further investigating the possibility of co-cultivation of energy crops in agricultural lands, investigating the feasibility of using unexplored bioresources such as new energy crops more suited for our country

Sri Lanka's future with bioenergy: achieving the SDGs

Bioenergy production and utilization in Sri Lanka can play an important and constructive role in achieving the agreed United Nations Sustainable Development Goals (SDGs) and implementing the Paris Agreement on Climate Change, which reiterates the "need to promote universal access to sustainable energy" while calling for "action to conserve and enhance sinks and reservoirs of greenhouse gases" and for "reducing emissions from deforestation and forest degradation." thereby advancing climate goals, food security, better land use, and sustainable energy for Sri Lanka (Table 8.1) (IEA Bioenergy report, 2022).

Table 8.1: The UN's SDGs that can be achieved with bioenergy sector development in SL.

1 NO POVERTY	Bioenergy offers farmers, SME owners, and related industries the possibility to increase and diversify their production and generate additional revenues, boosting the local economy. The use of homegrown energy products instead of imports will strengthen the local economy.
2 ZERO HUNGER	Bioenergy production and use can be optimally done to achieve food security and improved nutrition, promoting sustainable agriculture using organic/biofertilizers and improvement of barren lands through energy crop plantation.
3 GOOD HEALTH AND WELL-BEING	Use of bioenergy and other renewables will lead to the retirement of fossil-based power plants, especially coal. This will lead to a reduction in particulate matter, NOx, and SOx concentration in the air, improving the air quality, and leading to better health conditions.
4 QUALITY EDUCATION	Propagation of mass adoption and acceptance of bioenergy and other renewables through increased education, capacity building, and vocational training for indigenous renewables manufacturing technologies.
6 CLEAN WATER AND SANITATION 14 LIFE BELOW WATER	Some bioenergy technologies (biogas production) specifically address the treatment of wastewater and help reduce water pollution. Bioenergy conversion of waste that would otherwise be discharged into waterways can strongly contribute to the preservation of aquatic life.
7 AFFORDABLE AND CLEAN ENERGY	Utilization of Sri Lanka's available natural resources while reducing the dependence on imported fossil fuels, giving rise to the adoption and use of clean energy technology in the country.
8 DECENT WORK AND ECONOMIC GROWTH	The increased use of bioenergy reduces the dependency on imported fossil fuels, reducing the financial burden. This will lead to the development of a robust ancillary industry supporting the primary industry of energy generation resulting in greater economic productivity and job creation in the country.
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 12 RESPONSIBLE CONSUMPTION AND PRODUCTION	The development of a secondary, robust, ancillary industry directly supporting the primary industry of power generation will foster increased innovation and research in the clean technology sector in Sri Lanka.
13 CLIMATE ACTION	The increased adoption of renewable energy will not only lead to a drastic reduction in GHG emissions from the power sector but will also result in the development of climate resilient infrastructure and subsequent industrialization using sustainable technologies.
15 LIFE ON LAND	Chances to promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.
17 PARTNERSHIPS FOR THE GOALS	Opportunities to collaborate with global and local RE players as well as international markets to develop a network of partnerships that can be leveraged for technical and financial enhancement in the RE sector in the country.

Conclusion

Sri Lanka is blessed with a high bioenergy potential due to its naturally occurring biodiversity and tropical climate. Despite this, these abundant bioenergy resources are yet underutilized in Sri Lanka. With the wide range of available feedstocks and many different conversion technologies, there are many opportunities across many sectors to implement bioenergy projects. Bioenergy can provide flexibility in the power sector to balance expansion of intermittent and seasonal hydro, wind, and solar resources. Moreover, bioenergy is the main viable renewable energy option for Sri Lanka at the level of locally available technology and self-dependent input resources. This chapter investigated the status of bioenergy production in Sri Lanka, current research and development gaps, prospects for expansion, and finally presented the strengths, weaknesses, opportunities, and threats in the bioenergy sector along with recommended actions for the various stakeholders in the industry.

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Chapter 9

Harnessing microbes for circular and sustainable waste conversion for maximizing bioeconomy potential: Advancements in bioplastics, biofuels, and nutrient-rich soil amendments.

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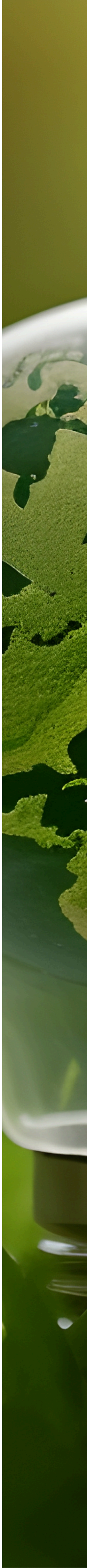

Abstract

The escalating challenges stemming from urbanization, technological advancements, industrial expansion, and population growth have resulted in a significant increase in various waste products, which pose severe threats to ecosystems and human well-being. Among these, organic waste is a major concern, but other types of waste, such as chemical and electronic waste, are equally or even more harmful. This chapter delves into the intricate nexus of environmental degradation and health hazards exacerbated by insufficient waste disposal infrastructure and limited recycling capabilities. Despite substantial financial investments, the persistent accumulation of organic waste persists as a formidable obstacle. However, nations, including Sri Lanka, are forging ahead with comprehensive waste management strategies, yielding significant environmental and economic benefits. This chapter highlights microbial solutions as a pivotal approach, particularly pertinent for developing nations. Various microbial consortia and diverse microorganisms, both natural and engineered, offer a plethora of applications ranging from bioplastic synthesis – biofuel production – to soil amendment development. Harnessing microbial processes not only reduces dependence on imported fossil fuels and plastic materials but also enhances soil health, fosters sustainable agricultural practices, and spurs economic growth within the bioeconomy sector. The transition towards circular and sustainable waste conversion practices presents a pathway for innovation, job creation, and economic expansion, aligning with Sri Lanka's vision for a resilient and environmentally harmonious future. Embracing these strategies signifies a shift towards circular and sustainable bioeconomy principles, marking a significant step towards holistic environmental management and economic prosperity.

Keywords: Biofuels, Bioplastics, Circular bioeconomy principles, Microbial solutions, Organic waste management

Introduction

"Microbes are nature's alchemists, transforming waste into wealth and paving the way for a circular and sustainable bioeconomy."

Microbes, often overlooked due to their microscopic size, play a pivotal role in waste management as nature's efficient recyclers. This chapter delves into the intricate mechanisms of microbial processes in waste conversion, showcasing their indispensable role in circular and sustainable waste management strategies, particularly in maximizing the bioeconomy potential. Microorganisms exhibit a diverse array of metabolic pathways, including fermentation, anaerobic digestion, and bioconversion, which are harnessed to convert organic matter into valuable resources. Fermentation, for instance, converts sugars into valuable products like biofuels, reducing reliance on fossil fuels and cutting greenhouse gas emissions. Anaerobic digestion produces biogas for renewable energy (Haririchi et al., 2022; Kabaivanova et al., 2022). Additionally, microorganisms can be employed to address environmental disasters, such as oil spills, where specific bacteria degrade hydrocarbons, mitigating ecological damage. The Deepwater Horizon spill in 2010 exemplifies this, as microbial communities played a crucial role in breaking down the released oil (Pallardy, 2024). Bioconversion also transforms waste into biodegradable plastics, enzymes, and nutrients for the soil, enhancing agricultural productivity and sustainability. These processes underscore the critical role of microbes in circular and sustainable waste management, and their natural capabilities can be optimized in controlled environments for industrial-scale applications.

Engaging the circular economy principles, such as Resource Recovery, Waste Valorization, Environmental Sustainability, and Economic

Opportunities (Mandpe et al., 2023), signifies a paradigm shift towards viewing waste as a valuable resource rather than a liability. The concept starts by leveraging microbial capabilities to recover valuable resources like organic matter, nutrients, and energy-rich compounds from waste streams, reducing reliance on new resources and minimizing waste generation. Microbial processes also facilitate waste valorization by transforming waste materials into high-value bio-based products such as bioplastics, biofuels, and nutrient-rich soil amendments. This not only reduces the environmental impact of waste disposal but also creates a closed-loop system where waste serves as a valuable input for new products, promoting sustainability and reducing the depletion of finite resources. Moreover, microbial waste conversion significantly contributes to environmental sustainability by mitigating greenhouse gas emissions, reducing pollution, and optimizing natural resource use. From an economic perspective, it unlocks numerous opportunities within the bioeconomy sector, fostering innovation, job creation, and economic growth across various industries such as biotechnology, agriculture, renewable energy, and waste management. By embracing these principles, waste materials are repurposed, recycled, or transformed into novel products, reducing waste generation and mitigating environmental impact. This holistic approach not only addresses pressing environmental challenges but also unlocks economic opportunities within the bioeconomy sector. Furthermore, understanding and harnessing microbial capabilities are key to developing innovative solutions such as bioplastics, biofuels, and nutrient-rich soil amendments. Integrating microbial processes into waste management strategies promotes not only environmental sustainability but also fosters a culture of innovation and economic growth in the bioeconomy realm. This chapter aims to elucidate the critical role of microbes in circular and sustainable waste conversion, highlighting their immense potential in driving towards a more sustainable and resource-efficient future.

Bioplastics production

Bioplastics are plastic materials produced as an alternative to traditional plastics. Bioplastics are sourced from renewable biomass like agro-industrial waste, woodchips, vegetable oils, cornstarch, and recycled food waste, etc. The process of bioplastic formation begins with sourcing raw materials such as starch, cellulose, or vegetable oils. Microbial fermentation transforms these raw materials into intermediate compounds, followed by enzymatic polymerization that creates larger polymer chains ensuring structural integrity. Some bioplastics may undergo chemical synthesis to modify polymer chains or add functional groups. The final step involves molding the processed polymer material into various bioplastic products, ranging from packaging materials to biodegradable plastics. This sequential process is essential for understanding bioplastic formation and its potential applications across industries (Figure 9.1).

Microbial synthesis of bioplastics

Microbial synthesis is a significant possibility for the area of creating sustainable materials. Modern technology makes it easy to synthesize bioplastics with the usage of substances derived from microbes.

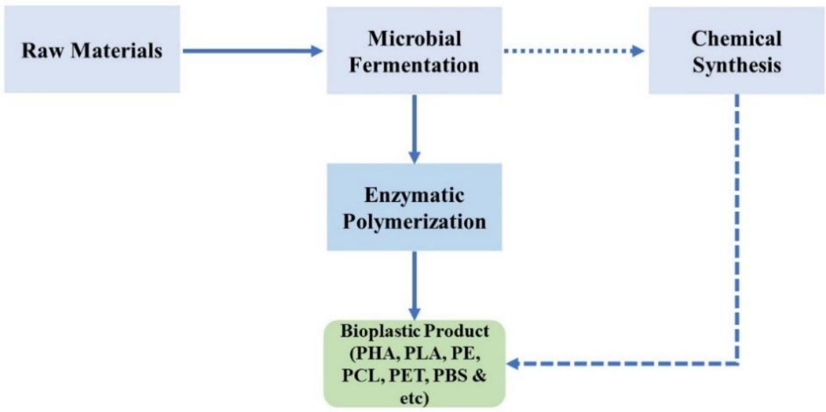

Figure 9.1. Bioplastic Formation Procedure (Costa et al., 2023; Jõgi & Bhat, 2020).

A considerable number of studies have demonstrated the ability of microorganisms, including bacteria and archaea, and lower eukaryotes to biosynthesize biopolymers, such as polyhydroxyalkanoates (PHAs), polylactic acid (PLA), poly-3-hydroxybutyrate (PHB), starch-based and cellulose based bioplastics through metabolic and enzymatic pathways. Various bacteria such as *Bacillus*, *Escherichia coli*, *Pseudomonas*, *Cupriavidus*, and *Corynebacterium*; algae like *Chlorella*, *Spirulina*, *Phaeodactylum tricornutum*, *Nostoc muscorum*, and *Synechocystis* possess the ability to produce bioplastics (Sangtani et al., 2023; Ali et al., 2023). Additionally, researchers have been promoting the production of bioplastics through modifications to different endogenous microbial strains and fermentation process conditions. In the production process, substrate selection, microorganism selection, culture preparation, biopolymer production, harvesting, purification, formulation and processing are fundamental aspects.

Advancements in bioplastic materials and applications

Bioplastics from microbes have proven advantageous in various aspects, such as biodegradability, renewability, biocompatibility, and the ability to obtain materials with unique properties (De Souza & Gupta, 2024). In addition, various strategies are used to enhance the functional properties of bioplastics. These biopolymers find diverse applications in industries including packaging, cosmetics, pharmaceuticals, medical, biomedical, and agriculture, offering sustainable alternatives to conventional materials.

Environmental benefits of bioplastics over traditional plastics

Bioplastics can be used as a sustainable substitute for conventional fossil-based plastics. The environmental damage caused by the plastics used today is very high, and bioplastics offer a favorable solution to reduce this damage. By using renewable resources in the production of bioplastics, this approach can be aligned with the principles of circular economies and sustainable development goals. This aims to reduce dependence on fossil resources, create innovative recycling routes, and reduce environmental impacts associated with plastic manufacturing processes. This substitute for plastic production is an ideal solution to reduce environmental pollution caused by plastics while obtaining economic benefits for a country such as Sri Lanka. Considering the environmental benefits of bioplastics, they are made from renewable biomass sources, thereby reducing dependence on non-renewable fossil fuels. In addition, the production of bioplastics generates significantly lower greenhouse gas emissions compared to conventional plastics. Moreover, some bioplastic materials are biodegradable, breaking down naturally and preventing the accumulation of non-biodegradable plastic waste. However, proper disposal in industrial composting facilities is critical for biodegradation, which depends on their chemical structure. Furthermore, bioplastics are generally less toxic and free from harmful chemicals such as bisphenol A (BPA) commonly found in conventional plastics, exemplifying their environmental benefits (Pei et al*.,* 2011).

Biofuel generation

Biofuel is a renewable energy source derived from biomass, including plant, algal, or animal materials. Examples include bioalcohols (ethanol, methanol, butanol), biodiesel, green diesel, vegetable oil, algae fuel, bioethers, biogas, syngas, and solid biofuels (wood pellets, dried manure). The two most common types in use today are bioethanol and biodiesel, representing the first generation of biofuel technology. It is considered a cleaner and more sustainable alternative to fossil fuels, contributing to energy needs while creating new markets, job opportunities, and economic growth, particularly in rural and agricultural communities (Hasan et al., 2023).

Microbial pathways for biofuel production

Microbial pathways play a crucial role in biofuel production, especially in biodiesel and bioethanol synthesis. Engineered microbial strains metabolize substrates efficiently, tolerate inhibitory compounds, and optimize metabolic fluxes for enhanced fermentation product yields. These strains, whether natural or engineered, must exhibit attributes like high substrate utilization, temperature and pH tolerance, and efficient sugar transport pathways to enable large-scale biofuel production economically (Love, 2022). Genetic engineering tailors microbial metabolism to enhance productivity and reduce operational costs in biofuel production from lignocellulosic biomass. Various microorganisms catalyze fermentation, bioconversion, and metabolic transformations essential for biofuel production. Understanding these relationships is vital for optimizing production processes and sustainability.

The following table outlines the key microbes associated with different types of biofuels, highlighting their pivotal roles in bioenergy generation:

Table 9.1: Common types of biofuel and Associated Microbes. (Love, 2022; Koppolu & Vasigala, 2016; Elshahed, 2010).

Type of biofuel	Microbes associated
Bioalcohols	Ethanol: *Saccharomyces cerevisiae*
	Methanol: *Methylophilus methylotrophus*
	Butanol: *Clostridium acetobutylicum*
Biodiesel	*Propionibacterium shermanii*
Green Diesel	*Geobacter sulfurreducens*
	Shewanella oneidensis
Algae Fuel	Various microalgae species like *Chlorella* and *Nannochloropsis*
Biogas (Methane)	Methanogenic *archaea* spp.

This compilation serves as a concise reference illustrating the diverse microbial consortia harnessed in biofuel production, underscoring the pivotal role of microbiology in advancing sustainable energy solutions.

Technological advancements in biofuel extraction and refinement

Technological advancements in biofuel extraction and refinement encompass various processes, including wet washing, dry washing, membrane extraction, and adsorption-based refining. These methods are designed to improve efficiency and sustainability by refining purification techniques for biodiesel and glycerol, thus reducing environmental impact and increasing biofuel production from diverse sources such as algae and waste materials (Jariah et al., 2021). Other innovative approaches involve biological processes employing genetically modified microorganisms, catalytic conversion using advanced catalysts, utilization of ionic liquids for biomass processing, hydrothermal techniques, pyrolysis, and gasification for syngas production, membrane technologies for purification, and enzymatic hydrolysis for efficient biomass breakdown into sugars. These advancements significantly enhance biofuel yield, quality, and environmental sustainability within production processes.

Advantages and challenges of biofuel formation and the bioeconomy in Sri Lanka

The development of biofuel formation and a bioeconomy in Sri Lanka presents both opportunities and challenges. Advantages include enhanced energy security through reduced reliance on imported fossil fuels, environmental benefits such as lower greenhouse gas emissions, job creation in sectors like agriculture and renewable energy, resource efficiency supporting sustainable practices, and rural development opportunities. However, challenges such as land use competition with food crops, limited feedstock resources, technological complexities, environmental impacts, and the need for supportive policy framework must be addressed to fully realize the potential benefits while mitigating risks. Balancing these aspects is crucial for Sri Lanka to harness the advantages of biofuel production and sustainable bioeconomy development effectively.

Nutrient-rich soil amendments

Nutrient-rich soil amendments are materials added to soil to enhance its properties and provide essential nutrients for plant growth. They are mainly divided into two categories: Organic soil amendments and inorganic soil amendments. Examples of organic soil amendments include compost, biochar, manure, and biosolids, while lime, sulfur, and gypsum are categorized as inorganic soil amendments. These amendments can improve soil fertility, structure, and pH levels, supporting optimal plant development.

Microbial biofertilizers and their impact on soil fertility

Microbial biofertilizers play a significant role in enhancing soil fertility by facilitating nutrient availability to plants. These biofertilizers encompass various microbial groups, such as nitrogen-fixing bacteria (e.g., *Rhizobium, Azotobacter*), phosphate-solubilizing bacteria (e.g., *Bacillus, Pseudomonas*), and also plant growth-promoting rhizobacteria (PGPR)(Bargaz et al., 2018; Bhardwaj et al., 2014). Nitrogen-fixing bacteria convert atmospheric nitrogen into ammonium ions, which plants can readily uptake. This process reduces the dependency on synthetic nitrogen fertilizers, thus mitigating environmental pollution and reducing production costs for farmers (Seneviratne et al., 2021). Similarly, phosphate-solubilizing bacteria solubilize insoluble phosphates in the soil, making them available for plant uptake, leading to improved phosphorus nutrition in crops. PGPRs enhance plant growth by various mechanisms, including the production of phytohormones (e.g., auxins, cytokinins), siderophores (iron-chelating compounds), and enzymes that promote nutrient uptake and root development. Additionally, PGPRs can induce systemic resistance in plants against pathogens, contributing to sustainable agricultural practices. The impact of microbial biofertilizers on soil fertility is significant, promoting nutrient cycling, improving soil structure, and supporting plant health and productivity. Successful applications of microbial biofertilizers have been observed in various crops, including legumes, cereals, and some vegetables, showcasing their potential for sustainable agriculture, Bioeconomy and also environmental conservation.

Bioremediation of contaminated soils using microbial agents

Bioremediation using microbial agents offers a sustainable approach to mitigate soil contamination caused by pollutants such as heavy metals, hydrocarbons, pesticides, and industrial chemicals. Microorganisms, including bacteria, fungi, and algae, possess unique metabolic pathways capable of degrading or immobilizing contaminants, thus restoring soil quality and ecosystem health (Atuchin et al*.,* 2023; Raklami et al., 2022). For instance, certain bacterial species such as *Pseudomonas, Bacillu*s, and *Arthrobacter* are known for their ability to degrade hydrocarbons through enzymatic processes such as hydroxylation, oxidation, and esterification (Sierra-García et al., 2014). These microbes utilize pollutants as carbon sources, breaking them down into harmless compounds or incorporating them into biomass, reducing their environmental impact. Similarly, fungi such as white-rot fungi (e.g., *Phanerochaete chrysosporium*) are effective in degrading recalcitrant pollutants like polycyclic aromatic hydrocarbons (PAHs) and lignin-based compounds. Their enzymatic systems, including lignin peroxidases and laccases, facilitate the breakdown of complex organic pollutants into simpler forms, aiding in soil remediation.

Bioremediation projects utilizing microbial agents have demonstrated success in cleaning up contaminated sites, restoring soil functionality, and promoting ecological balance. These projects often integrate microbial consortia tailored to the specific contaminants present, highlighting the versatility and effectiveness of microbial bioremediation strategies. Utilizing a blend of microbes tailored to specific pollutants demonstrates the efficacy and adaptability of bioremediation. When coupled with soil nutrient supplementation, bioremediation promotes plant growth and aids ecosystem recovery, fostering sustainable agriculture practices and environmental well-being (Raffa & Chiampo, 2021).

Bioeconomic benefits of nutrient soil amendments

Nutrient-rich soil amendments play a crucial role in the bioeconomy by offering significant economic benefits. They contribute to increased crop yields, reducing input costs, and improving soil health, leading to economic gains for farmers and agricultural businesses. By enhancing soil fertility and structure, these amendments lower the need for synthetic fertilizers and pesticides, translating into cost savings and environmental benefits (Urra et al., 2019). Moreover, nutrient-rich soil amendments can be processed into value-added products like microbial biofertilizers, creating additional revenue streams. The market demand for sustainably produced food also drives premium prices for products grown with these amendments, further incentivizing their use. Overall, nutrient-rich soil amendments not only promote agricultural productivity but also contribute to economic sustainability, market competitiveness, and environmental stewardship within the bioeconomy paradigm. Figure 9.2 highlights the interconnected processes starting from the application of nutrient-rich soil amendments to the impact on soil health, nutrient availability, crop productivity, sustainable agricultural practices, and ultimately, the contributions to circular economy and bioeconomy principles. It also emphasizes the economic benefits and environmental sustainability achieved through these practices in agroecosystems (Urra et al. 2019; Luo et al., 2018; Rashmi et al., 2023).

Figure 9.2. Enhancing Soil Health: From organic to inorganic amendments, fueling sustainable agriculture and circular economy. (Urra et al. 2019; Luo et al., 2018; Rashmi et al., 2023)

Economic and environmental impacts

Economic potential of microbial waste conversion in the bioeconomy

The economic potential of converting waste using microbes is considerable and offers multiple benefits. Processes such as anaerobic digestion and biotransformation convert organic waste into valuable products such as biofuels, biogas, bioplastics, and biofertilizers. This not only helps manage waste but also creates new sources of income. For instance, producing biogas from organic waste through anaerobic digestion reduces landfill waste and generates renewable energy that can be used for heating, electricity, and as vehicle fuel.

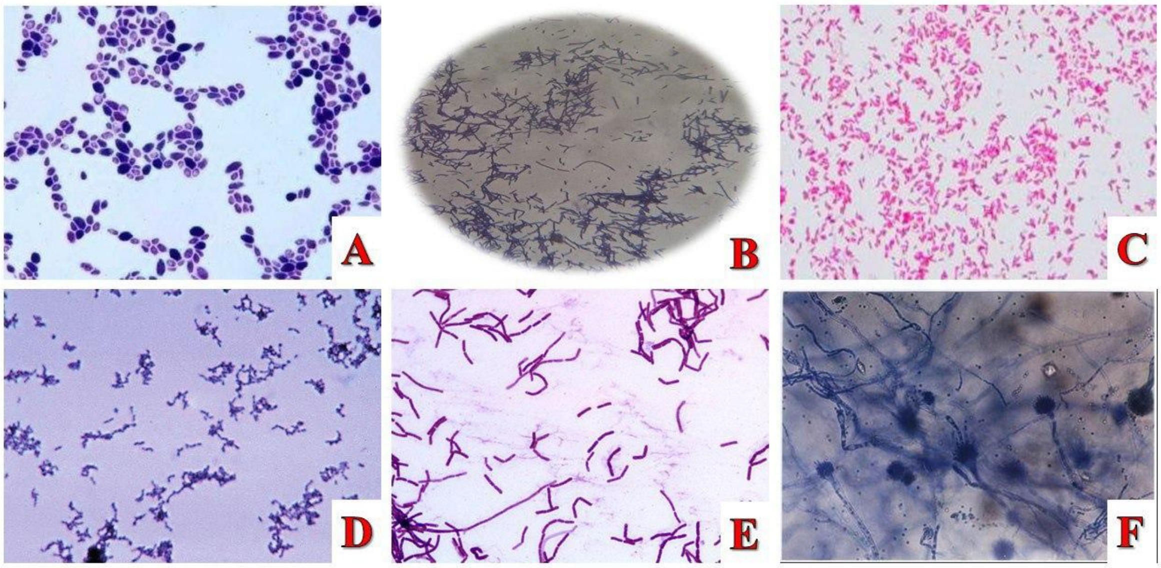

Figure 9.3. Common Microbial Species in Sustainable Processes A) *Saccharomyces cerevisiae* for bioethanol (Fakruddin et al., 2013), B) Genetically engineered *Escherichia coli* in biodiesel (Prabhurajeshwar & Chandrakanth, 2019), C) *Lactobacillus spp*. for PLA bioplastics (Islam et al., 2016), D) *Propionibacterium shermanii* in biodegradable plastics (Sulieman, 2017), E) *Bacillus spp*. for composting in soil amendments (Jumaah et al., 2014), and F) *Aspergillus spp*. enrich soil nutrients by organic breakdown (Mamishi et al., 2016).

This can significantly lower energy costs for municipalities and businesses, providing a sustainable energy alternative. Moreover, transforming agricultural and food waste into valuable chemicals and materials supports various industries, including agriculture and pharmaceuticals. Microbial processes can produce enzymes, antibiotics, and other bio-based chemicals more efficiently and with less environmental impact than traditional chemical methods. This ability to create high-value products from low-value waste supports a circular economy, where resources are reused and recycled, enhancing economic efficiency and sustainability. Additionally, microbial waste conversion technologies can boost rural economies by creating jobs in biotechnology research, waste management, and the production of bio-based products. Establishing biorefineries and waste conversion facilities in rural areas can provide employment and contribute to local economic growth. The bioeconomy can thus revitalize regions rich in agricultural and organic waste resources but facing economic difficulties.

Principles of the microbial bioeconomy

Adhering to key principles is vital for establishing a sustainable and efficient microbial bioeconomy, aiming to create an environmentally friendly, economically viable, and socially responsible ecosystem. These principles include utilizing renewable resources like plant biomass and agricultural waste, promoting sustainable production practices to minimize waste and emissions, and ensuring efficient resource utilization through closed-loop systems. Additionally, adaptability, efficiency, innovation, collaboration, transparency, renewability, and sustainability are fundamental in driving continuous improvement. These guiding principles collectively contribute to shaping a resilient and sustainable microbial economy (Figure 9.4).

Environmental benefits, such as reduced carbon footprint and waste diversion

The environmental benefits of microbial waste conversion are significant, particularly in terms of reducing carbon footprints and diverting waste from landfills. Microbial waste conversion processes, such as anaerobic digestion and composting, play a pivotal role in mitigating greenhouse gas emissions by transforming organic waste into valuable products like biogas and compost. These processes help sequester carbon and reduce methane emissions, a potent greenhouse gas typically emitted from decomposing organic waste in landfills (Naveen et al., 2023, Tabaroei, & Garg, 2023).

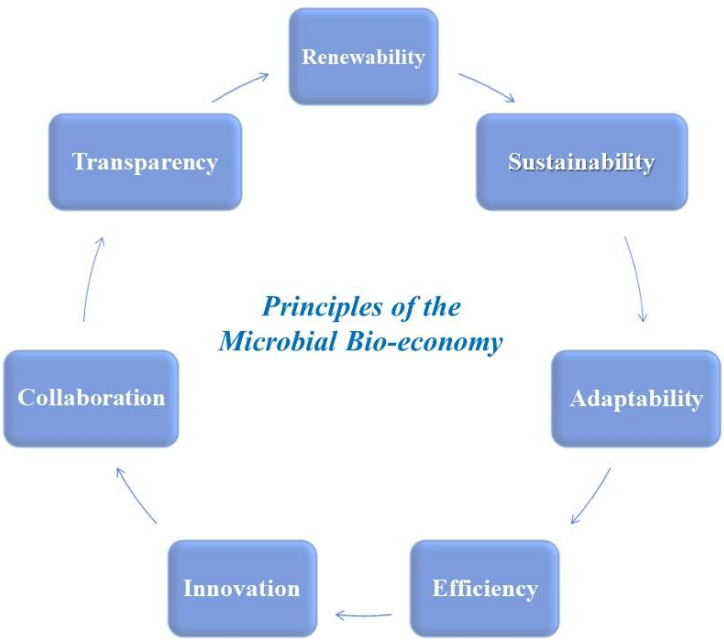

Figure 9.4 : Principles of the Microbial Bioeconomy (Chandel et al., 2020; Issa et al., 2019; Akinsemolu et al., 2023)

Reduced Carbon Footprint: By converting organic waste into biogas, which can be used as a renewable energy source, microbial waste conversion helps to offset the use of fossil fuels. This not only reduces carbon dioxide emissions but also lessens the overall carbon footprint of energy production. For instance, using biogas for electricity and heat generation is more environmentally friendly than relying on coal or natural gas. Moreover, the production of bioplastics from microbial processes can replace petroleum-based plastics, further decreasing fossil fuel dependence and associated emissions (Bhatia et al., 2023).

Waste Diversion: Microbial waste conversion technologies also contribute to waste diversion by transforming organic waste into valuable byproducts, thereby reducing the volume of waste sent to landfills and incineration facilities. This not only minimizes the environmental impact of waste disposal but also recycles nutrients back into the ecosystem. Compost produced through microbial processes enriches soil health, enhances agricultural productivity, and reduces the need for chemical fertilizers, which can have detrimental environmental effects (Kataya et al., 2023).

Policy implications and incentives for promoting microbial waste conversion technologies

Supporting microbial waste conversion technologies requires strong policies and incentives. Governments and policymakers can create an environment that encourages the use of these innovative and sustainable technologies. Firstly, offering subsidies and tax breaks to businesses that use microbial waste conversion can make it more affordable and appealing. These incentives can help cover the costs of setting up and running these technologies, making it easier for companies to adopt environmentally friendly practices. Secondly, governments can establish clear rules and standards that support microbial waste conversion. By creating regulations that require proper waste management and favor microbial technologies, industries will be encouraged to use these methods. This can help ensure that waste is managed sustainably. Thirdly, promoting partnerships between the public and private sectors can boost innovation in microbial waste conversion. Governments can support collaborations between universities, research institutions, and private companies by providing funding and resources. These partnerships can speed up the development and commercialization of new technologies. Additionally, raising awareness about the benefits of microbial waste conversion is crucial. Governments can sponsor educational programs, workshops, and seminars to inform industries and communities about the environmental and economic advantages of these technologies. Increased awareness can lead to greater acceptance and adoption. Moreover, incorporating microbial waste conversion into national and regional waste management plans can ensure a coordinated approach. Governments can create comprehensive strategies that include microbial technologies, promoting a circular economy and reducing the need for landfills and incineration. Finally, international cooperation and sharing knowledge can enhance the development of microbial waste conversion technologies. Countries can work together on research projects, share best practices, and align regulations to support a global microbial bioeconomy. This collective effort can accelerate progress and create a more sustainable global waste management system.

Future directions and research challenges

Emerging trends in microbial waste conversion research

Emerging trends in microbial waste conversion research are revolutionizing bioplastic, biofuel, and nutrient-rich soil amendment production, driving sustainable solutions in the bioeconomy sector.

In biofuel production, there's a growing focus on microbial consortia engineering and synthetic biology approaches to enhance the efficiency and yield of biofuel conversion pathways. This includes genetic manipulation of microbes to optimize biofuel synthesis, utilizing advanced fermentation techniques, and exploring novel feedstocks such as lignocellulosic biomass and algae for biofuel production. Additionally, research efforts are directed towards microbial electrochemical systems for bioelectricity generation from organic waste, offering a dual benefit of waste treatment and renewable energy production.

For bioplastic production, researchers are exploring microbial fermentation pathways for the synthesis of biodegradable polymers from renewable sources. This includes the development of engineered microbes capable of producing specific bioplastic precursors, such as PHAs and PLA, from organic waste streams. Innovative bioreactor designs and process optimization strategies are also being investigated to scale up bioplastic production while minimizing environmental impact.

In the realm of nutrient-rich soil amendments, microbial biofertilizers are gaining prominence as sustainable alternatives to chemical fertilizers. Research is focused on harnessing beneficial microbial strains that promote plant growth, enhance nutrient uptake, and improve soil health. This includes exploring the role of plant-microbe interactions, microbial consortia dynamics, and microbial-mediated nutrient cycling in agricultural systems. Furthermore, bioremediation techniques using microbial agents are being developed to remediate contaminated soils and restore ecosystem balance.

Overall, these emerging trends highlight the transformative potential of microbial waste conversion technologies in advancing sustainable bioeconomy practices, promoting resource efficiency, and mitigating environmental impacts associated with traditional industrial processes.

Potential barriers and research gaps in scaling up microbial processes

Scaling up microbial processes for waste conversion faces several potential barriers and research gaps that need to be addressed for successful implementation in large-scale applications. One major barrier is the complexity of microbial consortia and metabolic pathways involved in waste conversion. Understanding and engineering these microbial communities for optimal performance under varying conditions, such as substrate availability, pH, temperature, and nutrient levels, remains a significant challenge. Research is needed to elucidate the interactions within microbial consortia, identify key metabolic pathways, and develop strategies for stable and efficient microbial activity at scale. Another challenge is the scalability of bioreactor systems for microbial cultivation and waste conversion. While lab-scale studies demonstrate promising results, translating these findings to industrial-scale bioreactors requires addressing issues such as mass transfer limitations, reactor design optimization, and process control strategies. Research efforts should focus on developing scalable bioreactor technologies that ensure uniform substrate distribution, efficient nutrient delivery, and effective waste product removal. Additionally, the economic feasibility of microbial processes at scale is a critical consideration. Cost-effective production of enzymes, microbial inoculants, and growth media, as well as downstream processing for product purification and recovery, are key challenges. Research gaps exist in developing sustainable and low-cost inputs for microbial processes, optimizing bioprocess economics, and assessing the overall techno-economic feasibility of large-scale microbial waste conversion systems. Furthermore, regulatory and environmental factors pose barriers to scaling up microbial processes. Compliance with regulatory standards, safety protocols for handling genetically modified organisms (GMOs), and environmental impact assessments are essential considerations. Research is needed to address regulatory frameworks, risk assessment methodologies, and public acceptance of microbial-based technologies in waste management and bioeconomy sectors. Addressing these potential barriers and research gaps through interdisciplinary collaborations, innovative technology development, and holistic systems thinking will be crucial for successful scaling up of microbial processes in waste conversion and advancing sustainable bioeconomy practices.

Strategies for overcoming challenges and realizing the full bioeconomy potential

Strategies for overcoming challenges and realizing the full bioeconomy potential encompass a multifaceted approach integrating scientific innovation, policy frameworks, and stakeholder engagement (Figure 9.5). Firstly, fostering interdisciplinary research collaborations and knowledge exchange platforms can facilitate the development of robust microbial technologies for waste conversion, addressing technical challenges and accelerating innovation. Investing in research and development initiatives focused on synthetic biology, metabolic engineering, and bioprocess optimization is crucial for enhancing the efficiency and scalability of microbial processes. Secondly, implementing supportive policy measures and regulatory frameworks that incentivize sustainable practices and bio-based industries can create an enabling environment for bioeconomy growth. This includes providing financial incentives, tax breaks, and regulatory exemptions for bioeconomy projects, as well as promoting circular economy principles and sustainable resource management practices. Collaborative efforts between government agencies, industry stakeholders, and research institutions are essential for shaping conducive policy environments that foster bioeconomy development. Thirdly, enhancing public awareness, education, and outreach programs can promote acceptance and adoption of bio-based solutions, overcoming societal barriers and driving market demand for bioeconomy products. Engaging with communities, raising awareness about the environmental benefits of bio-based technologies, and showcasing success stories of sustainable bioeconomy initiatives can build public trust and support for transitioning towards a bio-based economy. Moreover, fostering international collaborations, knowledge-sharing networks, and capacity-building initiatives can leverage global expertise and resources to address common challenges, harmonize standards, and accelerate innovation in the bioeconomy sector. By embracing a collaborative, inclusive, and forward-thinking approach, stakeholders can collectively overcome challenges and unlock the full potential of the bioeconomy, contributing to sustainable development, environmental stewardship, and economic prosperity.

Figure 9.5: The challenges faced in scaling up microbial processes in Waste Conversion and the strategies to overcome challenges (Estévez-Alonso et al., 2021; Crater & Lievense, 2018; Palaniveloo et al., 2020)

Conclusion

In conclusion, microbial waste conversion presents a promising avenue for addressing both environmental challenges and economic opportunities. Through processes such as bioplastics production, biofuel generation, and nutrient-rich soil amendments, microbial technologies offer innovative solutions for sustainable waste management and resource utilization. The transition towards circular and sustainable waste management practices is imperative, given the environmental benefits and economic potential associated with microbial waste conversion. However, to fully capitalize on these opportunities, policymakers must implement supportive policies and incentives to promote the adoption of microbial waste conversion technologies. Additionally, ongoing research efforts are needed to address existing challenges and explore emerging trends in microbial waste conversion. By overcoming barriers and advancing research in this field, we can unlock the full potential of the microbial bioeconomy and pave the way towards a more sustainable future.

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Chapter 10

Marine bioresources as sustainable food and nutrient sources in shaping the bioeconomy

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Abstract

Marine bioresources encompass a broad spectrum of organisms ranging from microorganisms (including bacteria, fungi, cyanobacteria, marine plants, algae and some marine protozoa and marine protists) to marine invertebrates and marine vertebrates such as fish and mammals. Many of these organisms possess the potential for developing marketable products and processes. Sustainable use of oceans, sea and marine resources is one of the key sustainable development goals declared by the United Nations in 2015. Such entities would target achieving a blue economy, while significantly reducing marine pollution, minimizing the impacts of ocean acidification, overfishing and conservation, and sustainable use of oceans and marine resources by implementing international law. Numerous compounds used in the food industry such as natural preservatives, pigments, stabilizers, gelling agents, functional food ingredients, nutraceuticals, dietary supplements, and probiotics are extracted from marine bioresources. The nutritional properties of bioresources and their sustainable use for successful achievement of bioeconomy as food and other nutrient sources have been discussed in this chapter. Said bioresources can be extended from edible marine invertebrates like molluscs, arthropods etc. to vertebrates like fish and marine flora including sea grasses, and seaweeds (marine algae) enriched with proteins, vitamins and high content of minerals. Furthermore, seafood preferences and consumption over different geographical regions and their nutritional and health attributes have been highlighted. The use of new technologies such as marine biotechnology, consisting of eDNA, qPCR assays, and functional metagenomic applications can be identified as the successful biotechnological methods used in marine sciences. Hence, the new technology can help produce marine bioresource derivatives in terms of applying the bioeconomy concepts for food and nutrient sources.

Keywords: Marine bioresources, Bioeconomy, Sustainable development, Marine biotechnology

Introduction to Marine bioresources and bioeconomy

Oceans and coastal ecosystems cover more than 70% of the Earth's surface and provide economic and environmental services (European Commission, 2019). Marine bioresources comprise a variety of organisms such as microorganisms including bacteria, fungi, cyanobacteria, micro- and macro-algae, sponges, molluscs and other invertebrates, fish and marine plants. In addition, the compounds derived from the mentioned organisms come under the category of marine bioresources (Vasconcelos et al., 2019). Some of the marine bioresources, including fish, marine algae etc. have the potential for the development of marketable products and processes. Approximately 30,000 such products are found in the market with recent discovery rates exceeding 1,000 compounds each year (Arrieta et al., 2010; Lindequist, 2016).

Therefore, the potential for the development of commercial products from marine bioresources can be considered as an important part, which contributes towards the growth of the blue bioeconomy. The German Bioeconomy Council has defined bioeconomy as 'the production and utilization of biological resources to provide products, processes and services in all sectors of trade and industry within the framework of a sustainable economic system'. Therefore, Blue bioeconomy refers to the same concept, however, with a special emphasis on biological resources originating from aquatic environments. "blue bioeconomy" is considered as an emerging innovative sector, involving biotechnology, with applications in a variety of market sectors (European Commission, 2019). The term 'blue economy' was described by the World Bank as 'the development of oceanic economic activities in an integrated and sustainable way' (World Bank, 2017). Concurrently, the European Union defined the 'blue economy' as indispensable to our future welfare and prosperity and as a 'source of food, energy, transport or leisure, and as a driver for new jobs and innovation' (European Commission, 2019).

Edible marine bioresources include mainly the finfish and shellfish species. Such fish species can be categorized broadly as pelagic and demersal species, based on their habitat type. Pelagic fish are mainly planktivorous fish inhabiting the surface layers of the water column, usually above the continental shelf and in waters not exceeding 200 m in depth (e.g. anchovies, sardines, swordfish, tuna, mackerel). Demersal species live and feed on or near the bottom of the seas (e.g. cods).

In general, abiotic factors such as light intensity, temperature, nutrients and salinity have much influence on the biological components in the oceanic ecosystems. Furthermore, extreme fluctuations in climate conditions provide major outbreaks through the variations and create competitive environmental conditions for the bioresources (Plaza et al., 2008).

Fishing, aquaculture and seafood demand in different regions of the world

Sustainable fishing practices and aquaculture is a major component of the blue bioeconomy, which provides the primary source of protein for humans marine fish, as the major seafood entity. As an important source of essential amino acids, omega fatty acids and micronutrients, fish can fight against hunger and malnutrition, especially in low-income and food-efficient countries. Today, industrial fisheries in many geographic regions extract large quantities of different marine species, including tuna, mackerel and marine invertebrates such as sea cucumbers, both for domestic consumption and export market (Kimani et al., 2009; Conand, 2008). Due to rising populations and income, there is a remarkably increased demand for Indian Ocean fish, encouraging industrial fishing vessels to pursue increased production (Food and Agriculture Organisation, 2018).

The Middle East has a long tradition of fishing and seafood consumption due to the easy access of this region to the Red Sea and the Arabian Gulf, which provides diverse food fish species. According to the Food and Agriculture Organization (FAO), the Middle East and North African region's aquaculture production increased from 170,000 tons in 1990 to 1.4 million tons in 2018, which presents an enormous opportunity for economic growth in this sector (Victorero et al., 2018).

Because of the well-known nutritional and health benefits of seafood, such as sensory attributes, and easy digestibility, it is much preferred by the world’s population, especially in developing countries. For example, fisheries and aquaculture supply over 1.5 billion people almost 20% of their average animal protein intake. (Food and Agriculture Organization, 2018).

The global per capita fish consumption had grown from 9.0 kg (live weight) in 1961 to 20.5 kg in 2018 (Food and Agriculture Organisation, 2018). Moreover, this growth is higher than the consumption of other animal proteins (meat, dairy, milk etc.), which has increased by 2.1% per year. Asian countries contributed to 70% of the increase in food fish consumption. Further, the future per capita fish consumption is expected to be increased mainly in high-income countries in East Asia. Africa has the lowest per capita fish consumption. Thapa et al., (2015) showed that culture and ethnicity are closely linked with seafood preferences. The FAO statistics have clearly shown that different cultures are associated with strikingly different consumption quantities per capita, and some cultures are strongly linked with high fish consumption patterns, especially in the Mediterranean parts of Asia and Northern Europe.

Fish is an important part of the traditional European diet (Issifu et al., 2022). According to Cardoso et al., 2015, Portugal is one of the best seafood markets in Europe. The same authors surveyed the seafood consumers in the Portugal market identified their preferences and confirmed that geography and cultural dietary preferences appear to have a strong influence on consumption patterns. Portuguese prefer wild to cultured fish as well as fat to lean fish (low-fat fish). Salted/dried and canned fish are least preferred. Soaked cod, hake, and canned tuna are the most eaten seafood products. Men consume more cephalopods and sardines and women eat more redfish. Consumers in Southern Portugal exhibit a stronger tendency to wild and whole fish and consume more sardines (Cardoso et al.,2015).

Bangladesh is equipped with a variety of marine fish resources, and it is traditionally complemented to rich in their diet. Thus, their daily fish consumption is normal. A few research has been carried out on consumer preference for sea fish consumption in Bangladesh and investigated the annual fish price fluctuations, household income, age, gender, level of education and religious views found to have significant positive associations with fish consumption (Dastgupta et al., 2021).

According to the National Aquatic resources, Research and development Agency (NARA) statistics, 2022, the average monthly household fish consumption in Sri Lanka was 9.0 grams/day/person in year 2019, with a 72% decrease compared to the year 2016. Marine capture fisheries have contributed 80% to the total household fish consumption of the country in 2020 and of which the large pelagic species have constituted 42% followed by the small pelagic species (38%) and inland fish (16%). The contribution of crustacean species was minimal, which was about 4%.

Seaweeds have traditionally been used in Asian cuisine (Jaspars and Folmer, 2013). Currently, human consumption of green algae (5%), brown algae (66.5%), and red algae (33%) is high in Asia, mainly in Japan, China, and Korea (Rogel-Castillo et al., 2023). Despite edible seaweeds being a good nutrient source, they are not widely consumed in Western diets (Brownlee et al., 2011) due to toxicity from high iodine levels and accumulation of arsenic (Bouga and Combet, 2015; Cherry et al., 2019; Wells et al., 2017). However, several studies have reported a growing interest in seaweeds among consumers in some European countries (Palmieria and Forleo, 2020), although they are still considered unusual foodstuff (Barbier et al., 2020).

The main edible seaweeds are Japanese kelp (*Laminaria japonica*), Kombu (*Sacharinna* spp.), *Gracilaria* spp., Nori Nei (*Porphyra* spp.), Eucheuma seaweeds nei (*Eucheuma* spp.), Laver or Nori (*Porphyra tenera*), Wakame (*Undaria pinnatifida*), Elkhorn Sea moss (*Kappaphycus alvarezii*), Hijiko or Hiziki (*Sargassum fusiforme*), Umudggasari (*Gelidium amansii*), and Gamtae (*Eckonia cava*), among others (Sarker et al., 2021; Zhang et al., 2022). Edible seaweeds are consumed directly, for example, as an ingredient for sushi wraps or in salads and soups (Rogel-Castillo, et al., 2023).

Consuming seafood in terms of nutritional values and health benefits

Seafood consists not only fish, but also shellfish, which include crustaceans and molluscs. Crustaceans mainly comprised of crayfish, crab, shrimp and lobster. Molluscs include univalves (abalone, snail, and conch), bivalves (mussel, oyster, and scallop) and cephalopods (squid, cuttlefish and octopus). Therefore, seafood includes basically finfish and shellfish species (European Food Safety Authority, 2014) and sea vegetables such as algae or seaweeds, in the broader definition.

The tradition of consuming seafood has existed among people as a delicacy of the human diet for many centuries (Kim and Wijesekara, 2010). An ancient belief had been raised that the consumption of seafood links with longevity and would give more health benefits in different parts of the world (Jayasekara et al., 2020). Recent scientific discoveries have proven that a sufficient intake of seafood nutrients has been linked to preventing chronic heart diseases and many other health-related problems (Hellberg et al., 2012; Rao et al., 2016, Figure 10.1.). Furthermore, considerable scientific evidences have shown that sufficient intake of seafood or food supplements contributes to promoting health (Cencic and Chingwaru, 2010).

The demand for seafood including fish, shellfish and seaweeds in the global food market has increased due to the presence of polyunsaturated fatty acids (PUFA) such as eicosapentaenoic acids (EPA) and docosahexaenoic acids (DHA) (Elvevoll et al., 2008) as well as easily digestible proteins (Kitts and Weiler, 2003), bioactive peptides (Kim and Wijesekara, 2010), free amino acids (Elvevoll et al., 2008), enzymes (Fernandes, 2010), vitamins (Holick, 2009), minerals (Andersson *et al*., 2010) and other functional ingredients (Wu *et al*., 2009), which play significant beneficial roles in humans (Cohen et al., 2005; Elvevoll et al., 2008).

The average protein contents of marine fish may fluctuate between 15 - 24% (Stancheva et al.,2013). Usually, marine fish contain slightly lower moisture and higher protein contents than freshwater fish (Jayasekara and Mendis, 2020). Among commonly consumed fish categories, 100 grams of edible parts of tuna, mackerel, anchovy, cod, and herring contain 23.5g, 17.4 g, 21.1 g,17.6 g, and 17.3 g of proteins respectively (European Food Safety Authority, 2014). The myofibrillar protein contents offish reported ranging between 65 - 75%, whereas sarcoplasmic proteins including enzymes are in the range of 20 - 35%. Myosin protein constitutes approximately 50–58% of the myofibrillar proteins of finfish. Crustacean flesh such as crabs, lobster, prawns and shrimps contain slightly high protein contents, 20.4%, 17.3%,17.6% and 16.7% respectively. Cuttlefish contain 16% w/w protein in its composition (European Food Safety Authority, 2014).

Fish proteins are considered easily digestible and rich in essential amino acids that cannot be synthesized within the body (lysine, methionine, cystine, threonine and tryptophan) (Costa, 2007). The importance of seafood is appreciated over other protein sources, especially compared to most plant proteins, which lack one or more essential amino acids. Seafood

is a good source of lysine, which is severely restricted in cereals, the most important staple food in the world. Certain marine fish including mackerel, tuna, etc. are exceptionally rich in the amino acid, histidine (Usydus et al., 2009). The enhanced digestibility of fish proteins has mainly resulted due to the absence of strong collagenous fibers and tendons in fish muscles compared to land animals. The excessive consumption of other animal proteins causes various cardiovascular diseases due to their high lipid content (Barrón-Hoyos et al., 2013). Seafood provides a better solution for high-quality protein having a lesser risk of high lipid contents in the diet.
The lipid content of marine organisms is composed of triacylglycerols, phospholipids, sterols, wax esters, and unique lipid groups such as glyceryl esters, glycolipids and hydrocarbons. The fat content of seafood species varies between 0.24 to 14.72% (Stancheva et al., 2013). Based on the fat content, they can be classified as: high fat (> 8.0 g 100 g^{-1} w/w.); medium fat (4-8 g 100 g^{-1} w/w.); low fat (2-4 g 100 g^{-1} w/w.); and lean fish (< 2 g 100 g^{-1} w/w.). For example, herring contains 13 g of fat per 100 g edible part and hence categorized as high fatty fish while cod is classified as a lean fish containing 0.6 g of fat per 100 g edible parts. Crabs and lobsters have 1.5% fat whereas mussels have 2.1% and clams have 1.1% fat content (European Food Safety Authority, 2014). Even though majority of the fish contain low calories, some fatty fish species contain a high amount of energy, mainly due to their fat contents (Kumar et al., 2014).

Devadason et al., 2016 comparatively analysed the lipid content and fatty composition of commercially important fish and shellfish in Sri Lanka and found that fish from the Pacific and Indian oceans have higher proportions of fatty acids including both EPA and DHA. Herrings and Mackerel from both oceans had higher levels of EPA, DHA and n-3/n-6 ratios. The same authors concluded that the fish living in cold water (Japan) demonstrated higher levels of PUFA and MUFA and Sri Lankan fish had higher levels of saturated fatty acids than Japanese fish (Devadason et al., 2016).

Pelagic fish ordinarily known as sardines contain higher lipids and energy levels, although demersal species are generally contained with lower lipid and energy levels (Ball et al., 2007). Even though, seafood contains negligible amounts of saturated fats, some pelagic fish such as anchovy, bluefin tuna and different mackerels contain higher cholesterol levels that range up to 150 mg 100 $g^{-1}$of meat. Further, shellfish contains 170 mg, shrimp 95 mg and oyster 80 mg and clams 70 mg respectively. Suseno et al., 2014 showed that some small pelagic fish species contain palmitic acid as the major saturated fatty acid containing 15–20% of the total fatty acid content. Oleic acid and palmitoleic acids were ample mono-unsaturated fatty acids (5–6%). DHA is a PUFA available in fish as a percentage of approximately 12 - 22% (Suseno et al., 2014).

The edible seaweeds and kelp contain macronutrients, including polysaccharides (dietary fibre, alginate, carrageenan, agar, agarose) (Jaspars and Folmer, 2013), proteins (essential amino acids), and lipids (essential fatty acids, n-3 and n-6), and micronutrients, such as minerals and vitamins. These components have shown various health benefits, such as anti-inflammatory, anti-obesity, anticancer, antioxidant, and antibacterial (Quitral et al., 2022).

Several red seaweeds, such as *Gelidium*, *Gracilaria*, and *Neopyropia*, are used for agar and carrageenan production, and brown seaweeds are used for alginate production, which are commonly used as food additives and functional food ingredients in the food industry (Wang et al., 2022; Khandaker et al., 2021; Huang et al., 2021). Carrageenan and agar are also water-soluble polymers that can produce high-viscosity solutions widely used as food ingredients because of their unique functional properties, such as gelling, stabilization, emulsification, and thickening.

Benjama and Masniyom, (2012) reported that *Gracilaria,* a red seaweed, contains different essential amino acids including methionine, leucine, isoleucine, lysine, phenylalanine, tyrosine, arginine, threonine, and valine ranging from 3.43 to 8.96 mg 100 $mg^{-1}$of dry weight. *Gracilaria tenuistipitata* contains glutamic acid (2.13 mg 100 mg^{-1} DW), aspartic acid (1.9 mg 100 mg^{-1} DW) and leucine (1.51 mg 100 mg^{-1} DW). Large amounts of aspartic acid and glutamic acid are responsible for the special flavor and taste of these seaweeds.

The crude protein content of different red seaweeds is within 10-47% (Fleurence, 1999). The total protein content and the total free amino acid content of the green alga *Ulva rigida* were found to be 6.64% and 8.9%, respectively (Satpati and Pal, 2011). Research conducted with red seaweed species (*Gracilaria fisheri* and *G. tenuistipitata*) collected from Pattani bay, Southern Thailand recorded a protein content of *G. tenuistipitata* (21.6% db), i.e. significantly higher than that of G. *fisheri* (11.6% db)(Benjama and Masniyom, 2012).

Food derivatives of marine bioresources in relation to health promotion

Oceans are major reservoirs of bioactive compounds that have the potential to be applied in several stages of food processing, storage and fortification. Higher nutraceutical values of these resources have led to higher potency to excerpt functional ingredients such as omega-3 fatty acids, chitin, chitosan, fish protein hydrolysates, algal constituents, carotenoids, collagen, taurine and other bioactive compounds. Many of these food products are commercialized in several markets around the world including the United States, Japan and in some European countries (Kadam and Prabhasankar, 2010) as such extracts are virtually fat and calorie-free. Some abundantly used derivatives are given below in detail.

The macroalgae, *Sargassum* spp. are found to be ideal sources of dietary fibre and carotenoids with antioxidant activity, and hence they can prevent neurodegenerative diseases (Kadam and Prabhasankar, 2010). Usually, brown algae are enriched with typically complex polysaccharides, sugar and alcohols, thus many bioactive metabolites have been isolated in relation to different pharmacological activities such as cytotoxic, antitumor, nematocidal, antifungal, anti-inflammatory and antioxidant (Gamal, 2010). Soluble polysaccharides from algae have tremendous potential as dietary fibre for being evaluated as prebiotic compounds.

Sulphated fucans, such as fucoidans (osmoregulatory compounds) from brown algae, carrageenans from red algae and ulvans from green algae,

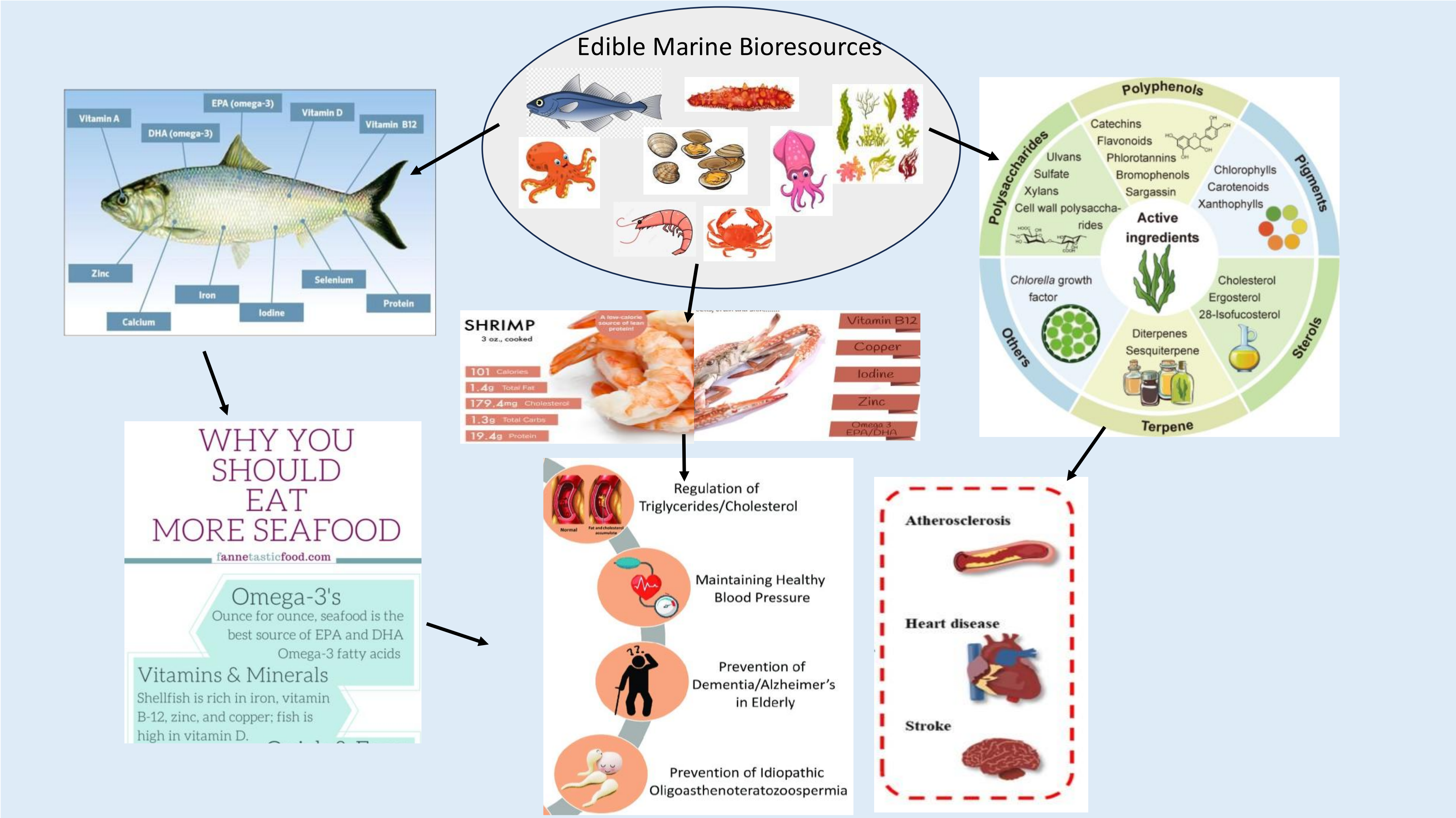

Figure 10.1: Nutritional values and health benefits of seafood consumption

have been known to act as modulators of coagulation as well as reveal antithrombotic, anti-inflammatory, antioxidant, anticancer and antidiabetic activities (Wijesekara et al., 2011). Algal products, such as agar and agarose and carrageenan, an algal derivative, used as a thickener in processed food are produced using novel technologies. In addition, bioactive compounds having a microalgal origin can be used to improve food nutritional profile due to the presence of PUFAs and pigments such as carotenoids and chlorophylls (Gamal, 2010).

Cyanobacteria are used for producing pigments such as chlorophyll a, phycocyanin, phycoerythrin, scytonemin, etc. Phycocyanin is a blue, light-harvesting pigment in cyanobacteria with antioxidant properties (Eriksen, 2008). Yellow–green pigment, scytonemin, is produced by *Nostoc* sp. as a defence mechanism against UV light and is reported to possess anti-inflammatory and antiproliferative mechanisms (Evans et al. 2021, Bennett and Soule 2022). Owing to their species specific, rich chemical composition, they can be used as nutritional supplements or natural food colorants after assuring their strong hepatotoxic or neurotoxic potential (Gamal, 2010). Masuda et al., 2008 stated that marine fungi (yeasts) can be used for producing high concentrations of γ-amino-butyric acid (GABA), a promising functional and healthy food ingredient.

Sustainable industries based on seaweed holobionts could become an integral part of the future bioeconomy, as they can provide more resource-efficient food, high-value chemicals and medical materials (Ren et al., 2022). The microbial communities associated with seaweeds contain a diverse assembly of organisms (including archaea, bacteria, fungi, microalgae, protozoa and viruses) on their surface and tissues. Such microorganisms often perform functions related to host growth and stress defence (van der Loos et al., 2019; Rosenberg et al., 2010). Consequently, the seaweed and associated microbial groups form a symbiotic relationship, which represents a single ecological unit with highly specialized interactions that are important for both the host and the symbiont (van der Loos et al., 2019).

The interaction types between seaweed and microorganisms can be basically divided into nutrient exchange, signal transduction and gene transfer (de Oliveira et al., 2012). Moreover, their specific functions include the production of molecules such as vitamins and other nutrients, converting organic matter and nitrate nitrogen to facilitate nutrient uptake of seaweeds and helping seaweed defend themselves by quorum sensing and secreting antifouling substances (Steinberg et al., 2011; Ihua et al., 2019; Wilkins et al., 2019). Many of the natural products, especially drugs and their precursors, are more likely to come from seaweed symbionts than from seaweeds themselves. For example, the complex bacterial community associated with *Ascophyllum nodosum* represents a potential source of novel hydrolases for use as functional foods, nutrition and biopharmaceuticals.

Functional foods associated with marine ingredients have been more successful in bakery and pasta products. The incorporation of edible seaweed "Wakame" (*Undaria pinnatifida*) abundantly found in temperate coasts of the northwestern Pacific Oceans having improved amounts of amino acids and fatty acid profiles is a very successful combination. Moreover, this seaweed is used in salads and sushi in Japanese cuisines with increased amounts of antioxidants and higher contents of fucoxanthin and fucosterol (Prabhasankar et al., 2009). Fucoxanthin, which was not affected by food processing, and its metabolites have been reported to have antioxidant, anticancer, anti-obesity and anti-inflammatory activities (Myashita and Hosokawa, 2008). Dietary ingestion of wakame has also been reported to reduce blood pressure (Chandini et al., 2008).

Enrichment of foods such as bread and other bakery products with fish oils is widely accepted around the world due to their increased content of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) leading to the reduction of cardiovascular diseases (Kadam and Prabhasankar, 2010). Verardo et al., (2009) and Iafelice et al., (2008) stated the recent designs of functional spaghetti made of seaweeds enriched with omega-3 fatty acids. In Japan, several foods (soybean paste, potato chips, and noodles) with added chitosan are available as cholesterol-lowering functional foods (Borderias et al., 2005).

Fish-derived bioactive ingredients: calcium from fish bones, fish oils rich in PUFAs extracted from fish livers; protein hydrolysates, peptides with antihypertensive activity and amino acids, such as taurine, which have antioxidant activity and positive effects on the cardiovascular system, vitamins, antioxidants and minerals (Kadam and Prabhasankar, 2010). Fish oils are said to prevent atherosclerosis, help in anti-aging and in brain development in premature infants.

Microbial polysaccharides including poly-β-hydroxyalkanoates (PHAs) with interesting chemical properties are produced by using deep-sea hydrothermal vent microorganisms. Chitosan, a chitin derivative produced from processing shells and bones from crabs, shrimps, cuttlefish etc., is a biodegradable and biocompatible polymer with antibacterial activity can be used as a food preservative. Its ability to absorb fat emphasizes its potential use as an anti-cholesterol agent (Hayes et al., 2008b).

Table 10.1: Main marine functional ingredients and their potential food applications

Bioresource	Functional ingredient	Functionality	Potential food application	Reference
Fish – salmon, sardines, tuna, herring, trout, catfish, cod, mackerel	Proteins – collagen, gelatine, albumin, bioactive peptides, amino acids	Anticoagulant activity Antioxidant activity Antibacterial activity Anti-hypertensive activity Blood pressure reduction	Stabilizing and thickness agents Protein replacements Gelling agents	Erbay and Yesilsu, 2021
	Lipids: omega-3 fatty acids	Cardiovascular disease reduction Arthritis and hypertension reduction Visual and neurological improvement	Fish oil capsules with potential use in other foods	Kadam and Prabhasankar,2010
Crustaceans- shrimp, prawn, crab, squid, lobster, cuttlefish	Chitin, chitosan Chitooligosaccharide	Reduction of lipid absorption Antitumor activity Antibacterial activity Antifungal activities Anti-Alzheimer's activity	Gelling agents Emulsifying agents Food preservatives Dietary fibre	Freitas *et al*., 2012; Hayes *et al*., 2008b

	Proteins: collagen, gelatine, albumin, Bioactive peptides Amino-acids: Taurine	Anticoagulant activity Antioxidant activity Antibacterial activity Anti-hypertensive activity Blood pressure reduction	Stabilizing and thickness agents Protein replacements Gelling agents	Ucak *et al*., 2021
Algae/ Seaweeds Red algae, brown algae,	Polysaccharides: algins, carrageenan, agar, fucans, exopolysaccharides	Anticoagulant activity Antibacterial, antiviral Antifungal activities Anti inflammatory	Gelling agents Stabilizers Emulsifying agents food gums	Kadam and Prabhasankar, 2010; Sarker *et al*., 2021; Wang *et al*., 2022; Khandaker *et al*., 2021
	Pigments: carotenoids (astaxanthin,lutein, fucoxanthin), Phenolic compounds: phlorotannins	Vitamin precursors Anti-carcinogenic activity Antioxidant Antiinflammatory	Food colorants Food antioxidants	Patel *et al*., 2022

Novel technological applications in food and nutrient production

Marine biotechnology is an important contributor to bioeconomy by inventing products and processes from marine organisms through the techniques of biotechnology, molecular and cell biology, and bioinformatics (Thakur and Thakur, 2005). It explores the oceans to develop novel chemical products, enzymes, pharmaceutical drugs and other industrial products and processes. Rotter et al., 2022 defined the term ‘Marine biotechnology’ as the identification of marine organisms and their compounds, extraction, isolation, characterization and use in various sectors ranging from food/feed to pharmaceutical and biomedical industries. Mostly the marine biodiscovery (from the water column, the seafloor, microbial biofilms, beach wrack, to side streams) are then developed as functional materials for the functional foods using possible extraction methods based on their characteristics such as heat resistance, solubility, molecular weights etc.

Almost 60% of the new marine natural products nowadays are derived from marine microorganisms (Carroll et al., 2020). There is a great interest in converting marine food by-products into valuable functional ingredients. Enzyme-mediated hydrolysis is an *in vitro* simple process that converts marine substrates into functional ingredients using enzymes at optimum pH and temperature conditions. Once enzymatic hydrolysis is completed, enzymes are inactivated and proceed through filtration steps in order to obtain the functional ingredient.

According to Rotter et al., 2022, High Throughput Sequencing (HTS) utilizes specific gene regions (barcodes) to provide genetic data on the various microbial communities with continuing improvements in data quality and bioinformatic analyses, leading to a better representation of the genetic-based taxonomic diversity of the sample. This method can detect both the most abundant community members and the rare species, which cannot be retrieved by traditional culture-dependent methods.

The isolation of DNA from the environmental samples, which is called eDNA is already well established in the field of marine monitoring (Diaz-Ferguson and Moyer, 2014; Pawlowski et al., 2018), especially for the characterization of bacterial communities in sediments and monitoring microbial populations in seawater samples (Kelly et al., 2017; Jeunen et al., 2019). In addition, quantitative Polymerase Chain Reaction (qPCR) assays have been implemented for targeted detection of organisms in seawater samples (Gargan et al., 2017). Although metagenomic data generated from eDNA samples can provide vast amounts of new information, datasets from complex communities, are difficult to process. Therefore, the use of functional metagenomic applications and tools (including metagenomics coupled with bioactivity screening/enzyme screening, meta transcriptomics, meta-proteomics, and meta-metabolomics) are used. One of the most used applications of functional metagenomics is the activity-based screening of metagenomics libraries. This has been largely applicable in the field of enzyme discovery, including marine enzymes (Hardeman and Sjoling, 2007; Di Donato et al., 2019).

According to Pace et al., 2023, innovative marine surveillance and monitoring technologies and the advances in ocean robotics, digitalization and artificial intelligence have enable scientists to better understand the state of the ocean. Such modelling data produce near real-time data on the state of the ocean and coastal resources and the ecosystem services they support, contributing to the growth of blue capital and blue carbon markets.

Challenges in achieving marine bioeconomy and potential solutions

The introduction of marine derivatives into human diet is always a complex subject due to several types of constraints such as diet type and habits that are related to cultural and ethnic aspects of a population. Consumer ideas and fears about marine pollution especially the bioaccumulation of heavy metals and microbial pathogens, may present a risk of chronic poisoning. As a simple example, though edible seaweeds are a product with a very long tradition in the human diet in Southeast Asia, some countries still present legal obstacles that may delay approval for the use of marine algae (Holdt and Kraan, 2011). Therefore, the consumer acceptance of new functional foods derived from marine bioresources with bioactive compounds will certainly be dependent on the balance between habits, traditions and their perception of the real health benefits. Still, there is a lack of adequate research in the application of functional/bioactive ingredients in foods as well as the scientific validation of the technological and biological feasibility.

The overexploitation of ocean bioresources, pollution, climate change, and other environmental factors can lead to the degradation of ocean ecosystems and biodiversity loss. This can have negative impacts on the long-term viability of the sustainable use of marine bioresources.

The regulation and governance of ocean resources can be complex, with overlapping jurisdictions and hence can create uncertainty and risk for businesses operating in the blue economy. Lack of adequate infrastructure facilities can be a significant barrier. The development of blue economy requires a skilled and knowledgeable workforce, particularly in areas such as marine science, technology, and engineering. However, there can be a need for more trained professionals in these fields. Also, there may be limited market access, particularly for small and medium-sized businesses in developing countries. This can limit their ability to compete and grow in the global blue economy.

The needed innovation capacity in the field of marine science can be achieved by establishing partnerships between academia, industry and government and by aligning priorities for research, technology development and commercialisation in the blue economy (McCormick and Kautto, 2013; Voyer et al., 2020; Kontovas et al., 2022). Exploring new markets and industrial service platforms to connect technologies and markets and link maritime industries with adequate financing for technology development is crucial for a successful blue economy (Wenhai et al., 2019).

Pace et al., 2023 mentioned integrated Food Production Systems. Technological advancements enhanced the energy efficiency in the production of food and feed, reducing waste and enhancing the quality and diversity of the fish produced. In Europe, seaweed and algae production for higher-value food and feed products is an emerging topic. Mass cultivation of algae and the use of algae as a source of protein may emphasise their potential to replace fish protein and lipids.

Since capture fisheries are stagnating in surplus, it is essential to move towards aquaculture, beyond extensive and semi-intensive systems. Introducing intensive marine fed aquaculture such as integrated multitrophic aquaculture (IMTA), which combines the cultivation of fed aquaculture species (e.g., finfish) with inorganic extractive aquaculture species (e.g., seaweed) and organic extractive aquaculture species (e.g., shellfish) for a balanced ecosystem management approach should be considered (Knowler et al., 2020). As an island nation, Sri Lanka has a higher potency to move towards IMTA and another intensive form of aquaculture with appropriate regulatory and policy frameworks, and financial tools for analysing the cost and benefits and environmental sustenance.

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Chapter 11

Working towards a circular and sustainable bioeconomy: The interlinkages with Sustainable Development Goals

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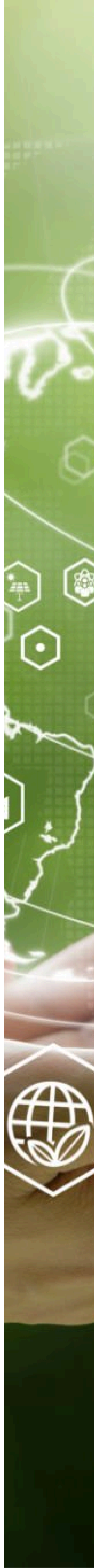

Abstract

Biobased economy or bioeconomy is economic activity involving the use of biotechnology and biomass in the production of goods, services, or energy. It is also considered as the part of the economy that is based on biology and biosciences. In recent times there has been a shift towards a definition that encompasses sustainability and circularity, with many countries now working towards a concept of a sustainable bioeconomy, which generally includes a progressive replacement of fossil-based raw materials in the economy. The link with sustainability connects the bioeconomy with the UN Sustainable Development Goals (SDGs), which are a range of goals pledged by world leaders in 2015 with the adoption of the 2030 Agenda for Sustainable Development. These 17 interlinked goals cover different aspects of sustainable development and aim to end extreme poverty, reduce inequality and protect the planet. This chapter looks at the relationship between a sustainable bioeconomy and the SDGs. In order to provide a holistic insight into this relationship, relevant literature and international policy are discussed. Principles formulated by the International Sustainable Bioeconomy Working Group that can be used as a guideline to achieve a sustainable bioeconomy are described. Finally, the status of achievement in Sri Lanka of relevant SDGs connected to the bioeconomy is brought in to look at the aforementioned relationship in a local context.

Keywords : Bioeconomy, Circular bioeconomy, SDGs, Sustainability, Sri Lanka

The Bioeconomy and Sustainable Development Goals

The bioeconomy concept is a developing field that has been given numerous interpretations by individual researchers as well as by regional and global bodies (Tan and Lamers, 2021). Some studies define it simply as the part of the economy that is based on biology and biosciences (El-Chichakli et al., 2016) while others state that while the bioeconomy rests on the idea of applying biological principles and processes in all sectors of the economy, it also includes progressive replacement of fossil-based raw materials with biogenic resources (Dietz et al., 2018).

The European Union has used evolving definitions over the years and one recent definition is that the bioeconomy 'includes and interlinks: land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources; and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy and services' (European Commission, 2018). The Global Advisory Council on Bioeconomy defines it in a holistic manner as 'the production, utilization, conservation, and regeneration of biological resources, including related knowledge, science, technology, and innovation, to provide sustainable solutions (information, products, processes and services) within and across all economic sectors and enable a transformation to a sustainable economy' (Global Bioeconomy Summit

Communiqué, 2018). This broad definition is widely used internationally and is used by certain United Nations (UN) bodies such as the Food and Agriculture Organization (FAO, 2021).

As can be seen in the recent definitions, the bioeconomy is connected and expected to provide opportunities that lead to greater sustainability.

However, it has also been debated whether the bioeconomy is intrinsically sustainable, especially with much of the bioeconomy policy focused on an industry centered approach rather than on moving away from fossil-based fuels to a sustainable circular flow economy based on renewables (Pfau et al, 2014; Gawel et al, 2019; Stegmann et al., 2020; Tan and Lamers, 2021).

Thus, the terms 'circular' and 'sustainability' are distinct though the definitions are connected to a certain degree. Under a circular economy the expectation is to have a regenerative system where the societal value of products, materials, and resources is maximized over time, leading to a better balance amongst the economy, the environment, and society (Meidl, 2021).Through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling, a circular economy looks to minimise resource input and waste, emission, and energy leakage by narrowing material and energy loops (Geissdoerfer et al., 2017). Sustainable development is a well-established concept in international law and its roots can be traced to the UN Stockholm Conference on the Human Environment of 1972. One of the most used definitions of sustainable development is "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). This definition comes from a UN report in 1987 which interestingly stressed that while economic growth must continue, it should adapt to accommodate certain ecological limits. In 2015, at a historic UN Sustainable Development summit, world leaders adopted the 2030 Agenda for Sustainable Development and pledged to achieve a set of goals by 2030 with the broad aim to end extreme poverty, reduce inequality and protect the planet (United Nations, 2015). These 17 Sustainable Development Goals (SDGs) as they are called, are defined in a list of 169 SDG Targets and the progress towards these are tracked by 247 Indicators. Each of these Indicators have a baseline value which is used to compare the progress made by each SDG.

In Sri Lanka, the government agency involved with monitoring and evaluation of the SDGs is the Sustainable Development Council of Sri Lanka (SDCSL) which was set up in 2018 under the Sri Lanka Sustainable Development Act No. 19 of 2017. Section 2 of the said Act provides that its objective is to ensure the preparation of a National Policy and Strategy on Sustainable Development which will provide the necessary legal framework for developing and implementing such a policy. Accordingly, a draft National Policy and Strategy on Sustainable Development (NPSSD) for a sustainably developed Sri Lanka was unveiled in 2020 and provides 17 policy goals which are aligned with the SDGs (SDCSL, 2021).

Over the years, numerous global studies on the bioeconomy have focused on how advancing the bioeconomy may be applied to achieving greater sustainability in the context of the SDG Targets (El-Chichak li*et al*., 2016; Deitz *et al*., 2018; Heimann, 2019;Ronzon and Sanjuan 2020). El-Chichakli *et al*. (2016) was one of the earliest studies that showed how bioeconomy principles could be applied for achieving individual SDGs. For example, innovations in bioeconomy such as use of bio-based materials in industries such as plastics processing, consumer goods, construction, pharmaceuticals and medical technology would help achieve SDG 12 (sustainable consumption) while SDG 7 (energy for all) may be achieved through decentralized solutions that combine bioenergy with other renewables. Other studies have highlighted the interlinkages amongst the SDGs and thus the need to be aware of trade-offs, synergies and possible perverse outcomes (Nilsson *et al*., 2016; Ronson and Sanjuan, 2020).The concept of a circular economy also links well with the SDGs as it seeks to minimize resource depletion, encourage regenerative practices, prevent the loss of natural resources and stimulate the reuse and recycling of by-products and wastes (Muscat *et al*., 2021).

In order to provide a holistic insight into the relationship between the bioeconomy and relevant SDGs' it is important to look at relevant literature and international policy guidelines. In the next section these interlinkages are examined with the overarching aim of understanding the steps necessary to work specifically towards a circular and sustainable bioeconomy. To this end a set of internationally accepted principles formulated by the UN Food and Agriculture Organization that can be used to move towards a sustainable bioeconomy in particular are presented. Furthermore, the Sri Lankan context is brought in by looking at the status of selected SDG indicators and the opportunities and challenges facing Sri Lanka in moving towards a circular and sustainable bioeconomy while achieving the pertinent SDGs.

Principles for a sustainable bioeconomy

The International Advisory Council on Global Bioeconomy emphasizes that the bioeconomy concept is not static, and that its definition is continually evolving (Global Bioeconomy Policy Report IV, 2020). As provided in the preceding section, in the recent past there has been a shift towards a definition that encompasses sustainability with many countries and regions now working towards a sustainable bioeconomy. However, it has also been noted that even in well-developed policy frameworks such as those in the European Union or developed nations such as Germany, the commitment to ensure a sustainable bioeconomy is often vague (Heimann, 2019). To address such issues and provide international support to nations to develop strategies and policies for a sustainable bioeconomy, the International Sustainable Bioeconomy

Working Group (ISBWG) was established in 2016. This multi stakeholder group facilitates international dialogue and provides a platform for sharing knowledge on sustainable bioeconomy innovations, technologies, practices, and policies. To further assist nations in transitioning to a sustainable bioeconomy, the ISBWG established the Aspirational Principles and Criteria for a Sustainable Bioeconomy which can be discussed under the broad themes of Environment, Economy, Governance and Society (Table 11.1). Consisting of 10 Principles and 24 Criteria, it emphasizes aspects that need to be considered for the transition to a greener, fairer, and more profitable economy, while enabling the achievement of SDGs (FAO, 2021).

Table 11.1: Overview of the Aspirational Principles and Criteria for a Sustainable Bioeconomy (FAO, 2021)

Broad target area	Principles	Relevant SDG
Economy	Principle 3: Sustainable bioeconomy should support competitive and inclusive economic growth	5, 7, 8
	Principle 7: Sustainable bioeconomy should make good use of existing relevant knowledge and proven sound technologies and good practices and, where appropriate, promote research and innovations	4, 9
	Principle 8: Sustainable bioeconomy should use and promote sustainable trade and market practices	10
Environment	Principle 2: Sustainable bioeconomy should ensure that natural resources are conserved, protected, and enhanced	14, 15
	Principle 5: Sustainable bioeconomy should rely on improved efficiency in the use of resources and biomass	6, 13
Governance	Principle 6: Responsible and effective governance mechanisms should underpin sustainable bioeconomy	16
	Principle 10: Sustainable bioeconomy should promote cooperation, collaboration and sharing between interested and concerned stakeholders in all relevant domains and at all relevant levels	17

Society	Principle 1: Sustainable bioeconomy development should support food security and nutrition at all levels	2, 3
	Principle 4: Sustainable bioeconomy should make communities healthier, more sustainable, and harness social and ecosystem resilience	1, 11
	Principle 9: Sustainable bioeconomy should address societal needs and encourage sustainable consumption	12

In the following sub-sections, the broad target areas of Economy, Environment, Governance and Society described in Table 11.1 are discussed based on the ISBWG's criteria for a sustainable bioeconomy (FAO, 2021). This section also includes the current national progress in achieving the related SDGs.

One of the challenges in reviewing Sri Lanka's progress with regard to the SDGs is the limitations in baseline data and this applies to both data availability and frequency of compilation. To resolve this problem the SDCSL set up a national SDG data portal and is involved in compilation and validation of data from government institutions. At present data is available for a total 156 out of the 247 SDG Indicators in the Global Framework (SDCSL, 2023). The national progress discussed herein is based mainly on data currently published by the SDCSL and country data from the Sustainable Development Report 2021 (Sachs *et al*., 2021), which complements official SDG indicators. It also provides SDG trends which estimate (based on historical data) how well a country has been progressing towards an SDG and determine whether this rate will be sufficient to achieve the SDG by 2030. The four SDG trends used in the above report include: on track or maintaining SDG achievement, moderately improving (score increasing at a rate above 50% of the required growth rate but below the rate needed to achieve the SDG by 2030), stagnating (score remains stagnant or increases at a rate below 50% of the growth rate needed to achieve the SDG by 2030) and decreasing score.

In 2022, Sri Lanka also submitted its second Voluntary National Review (VNR) on the SDGs to the High-level Political Forum (HLPF) of the United Nations. The information therein is also utilized as it reviews the SDGs in detail and provides an overview of the local context.

Economy

A safe and healthy business environment for producers and investors in biomass and bioproducts is necessary for the transition to a sustainable bioeconomy. Inclusion is a key component of the 2030 Agenda for Sustainable Development. Inclusive economic growth where all can contribute (irrespective of employment status or gender) to the development of the bioeconomy is important as it aligns with the concept of 'leaving nobody behind'. The Sri Lankan Constitution itself provides a foundation for inclusiveness as it entitles every Sri Lankan the fundamental rights to freedom of thought, conscience and religion; right to equality; and freedom of speech, assembly, association, occupation, movement (MoSDW&RD, 2018). It is also advised to strengthen the resilience of the rural and urban economy and develop rural-urban linkages. Diversification of rural economies and promoting local production and processing of food and non-food items is also important. According to Sachs *et al.* (2021), Sri Lanka has moderately improved regarding SDG 7 (affordable and clean energy) and SDG 8 (decent work and economic growth). The improvement in the former could be attributed in part to the high percentage of the population with access to electricity. The relatively lower unemployment rate (4.8% of the total labour force in 2019) would have contributed to the improvement in the latter.

The continued use of existing knowledge and technologies to sustainably produce food and non-food items from biological resources is also relevant to the economy theme. It also includes the promotion of research and innovation in this field, which can be encouraged through sound education. In general, Sri Lanka has a well-developed education system with free education available from primary to tertiary level since 1945. SDG 4 (quality education) is one of the few SDGs that Sri Lanka has already achieved according to Sachs *et al.* (2021). The completion rates of primary, lower secondary and upper secondary education in Sri Lanka are 90%, 87% and 81.3% respectively in 2020 while the completion rate of upper secondary education has increased from 75.89% in 2015 to 81.3% in 2020 (SDCSL, 2022). Sri Lanka also shows moderate improvement in SDG 9 (industry, innovation and infrastructure) which is an important sector for overall development in the bioeconomy. Learning lessons from the COVID-19 pandemic, the government further plans to diversify the economy and prevent overreliance on a handful of key industries (SDCSL, 2022).

Environment

In a sustainable bioeconomy it is imperative that natural resources and the environment is protected, while a circular bioeconomy emphasizes the circular flow of materials and the use of raw materials and energy through multiple phases (Yuan et al*.,* 2006). It recognises that sustainable production of food and goods depends on the conservation and sustainable use of biological diversity of plants, animals and microorganisms. It is also important to prevent degradation of natural environments and restore them where applicable. Through the replacement of fossil fuel-based production and sustainable use of resources, the bioeconomy can significantly contribute to climate change mitigation and adaptation both nationally and globally. Water scarcity and competition for its use in different sectors is becoming a reality in many parts of the world and it is important that the transition to a bioeconomy should not worsen this scenario. According to Sachs *et al*. (2021) SDGs related to life below water (SDG 14) and life on land (SDG 15) are facing major challenges in a Sri Lankan context. While SDG 14 shows a stagnating trend, SDG 15 is reported as showing a decreasing trend in terms of achieving the respective SDGs.

A bioeconomy that is circular and sustainable requires efficient use of natural resources such as plant biomass, animals, and microorganisms. The re-use and upgrading of by-products are encouraged as this would minimize the environmental impact of biomass production and may also reduce greenhouse gas emissions. These aspects could also help lessen global challenges such as accumulation of plastic waste and marine pollution due to litter. The SDGs related to these criteria are SDG 6 (clean water and sanitation) and SDG 13 (climate action). Sri Lanka shows a positive trend with regard to these SDGs with SDG 13 regarded as on track and SDG 6 showing moderate improvement as per Sachs et al. (2021). Sri Lanka has shown progress in SDG 6 in the past with around 88.8% of Sri Lankan households having access to safe drinking water and more than 50% of households in all districts having safe drinking water in 2016 (MoSDW&RD, 2018).

Governance

The bioeconomy is inherently cross-sectoral. Therefore, regulatory and institutional harmonization is necessary particularly with regard to existing legislation related to the different sectors connected to the bioeconomy. Inclusive consultation with stakeholders using both top-down and bottom-up development approaches as well as private, public, and civil society engagement in a transparent and equitable manner is important. In this regard an example from Sri Lanka is the multistakeholder consultation and validation process that was in operation for the draft National Policy and Strategy on Sustainable Development (NPSSD) as well as for the second VNR. Further, adequate monitoring and accountability systems should be in operation to evaluate the sustainability of the bioeconomy. In this regard too, the monitoring and evaluation framework proposed in the NPSSD will assess the effectiveness, efficiency, sustainability and the impact of each activity implemented in line with the different policy goals. Due to the unequal distribution of skills and resources in the sphere of bioeconomy, mutually beneficial knowledge sharing, and capacity building should be encouraged. In a Sri Lankan context, the related SDGs which are peace, justice and strong institutions (SDG 16) and partnerships for the goals (SDG 17) are both regarded to be showing a stagnating trend according to Sachs *et al*. (2021). It was noted in the second VNR that though significant steps had been taken by the Ministry of Justice for legal and procedural reforms, many are still in the pipeline (SDCSL, 2022)

Society

The bioeconomy should support and strengthen food security and nutrition. As global food consumption would increase in the future, sustainably increasing yield with limited land availability will be necessary. Sustainable management of the entire food system is important, and this would also require innovative bioeconomy policies and technologies to reduce health risks of unsustainable production systems and the health-related consequences of climate change and pollution. The principles further state that development of a sustainable bioeconomy should not be based on poor tenure security or inequitable rights to land, forests, water, and other resources, including traditional and indigenous knowledge systems. Instead, it should be used as a mode to further strengthen tenure security. Sachs *et al*. (2021) reports that Sri Lanka is moderately improving in the related SDGs which are zero hunger (SDG 2) and good health and wellbeing (SDG 3). The latter SDG is well supported by Sri Lanka's free health policy which provides healthcare without a charge at all Government hospitals (MoSDW & RD, 2018).

With increasing urbanization, it is important that sustainability of urban areas is enhanced. The resilience of biomass producers, rural communities and ecosystems should also be strengthened. These criteria are supported by SDG 1 (no poverty) and SDG 11 (sustainable cities and communities). According to Sachs *et al*. (2021), Sri Lanka is on track for the former though showing a stagnating trend with regard to achieving the latter SDG.

A shift towards sustainable consumption and production would be created through a sustainable bioeconomy. This would lead to use and conservation of biological resources both at national and global levels whilst finding alternative products or processes that would in turn minimize negative impacts of bioeconomy activities from one region or sector to another. It could also help reduce sustainability trade-offs. Ensuring policy coherence in the production and consumption of food and non-food items and enhancing synergies in the management of natural resources is also important due to the cross-sectoral nature of the bioeconomy.

Furthermore, it should be noted that trade-offs that occur between society and economy or related SDGs and environment related SDGs may have an overall bigger negative impact. For example, SDG 1 (no poverty), SDG 2 (zero hunger) or SDG 6 (clean water and sanitation) can negatively impact upon environment related SDGs such as life on land (SDG 15) and life below water (SDG 14).

Conclusion and future directions

As outlined in this chapter, the Aspirational Principles and Criteria for a Sustainable Bioeconomy (FAO, 2021) can be used as a guideline for the transition to the bioeconomy, while enabling the achievement of SDGs, under the broad themes of environment, economy, governance and society.

The Sustainable Development Report 2021 provides an overall score to countries based on its total progress towards achieving all 17 SDGs (percentage of SDG achievement) and Sri Lanka carries a country score of 68.1 while the regional score for East and South Asia is 65.7 (Sachs *et al*., 2021). As outlined, Sri Lanka shows a positive trend in achieving certain SDGs while more work is required in some. However, it should also be noted that the information used in the said report, is a complement to the official SDG indicators and voluntary country reviews. Therefore, certain discrepancies may be present in terms of the progress seen in the country reviews or other official SDG reports.

For those SDGs which appear to be lagging in terms of achievement, the positive synergies between the principles of sustainable bioeconomy and the SDGs can be used to progress towards these targets. However, as SDGs are interconnected and the bioeconomy itself is cross-sectoral, trade-offs can easily occur. The bioeconomy also has the potential to restrain rather than support the SDGs where there is a lack of appropriate regulations, policy and investments ensuring sustainability (Heimann, 2019). Hence, these should be considered, and appropriate action taken in order to achieve a circular and sustainable bioeconomy which in turn could support achieving the SDG targets.

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Chapter 12

The status of bioenergy in Sri Lanka: Challenges and opportunities

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Abstract

Bioenergy represents the main sub-sector of the overall bioeconomy. The evolution of bioenergy in Sri Lanka is initially linked with the use of biomass (firewood and forest residues) for domestic and industrial use until 20th century. Subsequently, the use of biomass for domestic purposes has been diminished with the introduction alternative energy sources. Nevertheless, one third of the energy requirement of the industry is yet fulfilled by biomass which is about 33%. Despite this dependency on non-renewable energy resource, Sri Lanka has made impressive strides in renewable energy development. However, the need for more sustainable energy management systems for domestic and industrial purposes demands the requirement of expansion of bioenergy in the future. Indeed, there is a research gap which needs to identify the potential and possibility of integrating the bioenergy into more localized/decentralized energy management system. This chapter may thus focus on, but are not limited to recent developments, applications, current trends and future prospects of bioenergy.

Keywords: Bioeconomy, Bioenergy, Biomass, Renewable energy, Sustainable practices

Introduction

Sri Lanka is on a journey towards sustainable energy to meet the power demands for tomorrow. Sri Lanka's focus on renewable energy sources highlights the country's commitment to reduce its carbon footprint and promote environmental stewardship. In this context, bioenergy plays a crucial role in the transition for the future. In fact, the existing energy requirement is shared by the non-renewable and renewable energy sources as around 60% and 40% respectively (Ministry of Power and Energy, 2022). Moreover, energy statistics revealed that thermal energy, primarily generated through oil and coal-fired power plants, contributes significantly to the national capacity, accounting for 37.9% or 1824 MW (CEB, 2023). This heavy reliance on fossil fuels emphasizes the urgent need of exploring other energy sources to ensure energy security and environmental sustainability.

Furthermore, the global economic crisis demonstrates the need for awareness of the finite nature of fossil raw materials and the impact of climate change. In fact, Sri Lanka has made impressive strides in renewable energy development. Wind and solar energy are also becoming more important and widely adopted as key components of Sri Lanka's renewable energy sources. Wind power accounts for 5.2% (248 MW) of the total capacity, while solar power contributes 2.7% (132 MW). These figures reflect the growing commitment to leveraging wind and solar resources to achieve a greener energy future. The need for a more sustainable energy management system for domestic and industrial purposes demands the expansion of bio-based economies in the future. Recent surveys evident that petroleum remained as the prominent energy supply source in the country (38%), followed by biomass (32%) (SLSEA, 2021).

However, there is a research gap which needs to identify the potential and possibility of integrating bioenergy in a more decentralized energy management system. This book chapter presents the evolution of the energy industry in Sri Lanka and the importance of transitioning to bioenergy with respect to the current context of energy usage. Meantime this chapter highlights the potential and limitations of different forms of bioenergy.

Nationally determined contributions (NDCs)

Sri Lanka's Nationally determined contributions (NDCs) outlined by Sri Lanka Sustainable Energy Authority, focus on reducing greenhouse gas (GHG) emissions in order to achieve sustainable development Goal 7. The country aims to achieve a significant reduction in carbon emissions and generate 70% of its electricity by enhancing energy efficiency and expanding the use of renewable energy sources, such as solar, wind, and hydropower and sustainable biomass which are abundant in the country. As part of the NDC plan, Sri Lanka aims to develop an additional capacity of 3,867 MW of renewable energy by 2030. (Sri Lanka Updated Nationally Determined Contributions, 2021) As the country is rich in renewable energy sources, Sri Lanka has the potential to meet this target.

According to the Energy balance 2018 from the Sri Lanka Sustainable Energy Authority, the industrial sector's energy supply is divided among biomass (33%), petroleum oil (34%), and electricity (33%). Biomass is used in tea and rubber factories, bakeries, tile and brick industries, and other small-scale enterprises. In the industrial sector, the NDCs propose a continued shift towards sustainable biomass energy and improved user efficiency across specific sub-sectors such as tea, rubber, apparel, hotel and tourism. Furthermore, as part of the NDCs for the period 2021-2030, Sri Lanka aims to manage biodegradable waste through biological treatments by adopting biogas technology in areas where composting is not feasible. These efforts are part of Sri Lanka's commitment to the Paris Agreement, to mitigate the impacts of climate change while promoting sustainable development.

Concept of renewable energy

Renewable energy is energy that can be used repeatedly, derived from natural sources that are replenished at a higher rate than they are consumed. Examples of renewable energy sources include solar power, wind power, bioenergy, tidal energy, hydroelectric power that are constantly replenished. Renewable energy plays a crucial role in achieving a sustainable and low carbon future by providing clean and reliable energy sources. And also, it enhances energy security by covering a portion of imported fossil fuel needs of the society. Additionally, it creates new job opportunities in renewable energy industries and related sectors.

The adoption of sustainable energy options is crucial for the Sri Lankan economy for several reasons. First, it ensures energy security by reducing dependence on imported fossil fuels. Currently, Sri Lanka imports nearly 40% of its energy needs, primarily in the form of petroleum products, making it vulnerable to global oil price fluctuations and supply disruptions. Second, shifting to renewables mitigates the environmental impact associated with fossil fuels. Third, the country's commitment to reducing greenhouse gas emissions, in line with international agreements such as the Paris Agreement, underscores the need for sustainable energy sources. Additionally, renewable energy can drive economic growth by creating green jobs and fostering technological innovation.

Biomass

Biomass is organic matter that comes from plants and animals and is a renewable source of energy originally sourced from the sun and derived from organic matter. It includes wood and wood waste, food waste, animal manure and human sewage, agricultural crop and waste materials. Biomass contains chemical energy stored from the sun, generated by plants through the process of photosynthesis. Biomass can be converted to energy using different methods such as direct combustion, thermochemical, chemical and biological conversion. Different types of energy can be created through several ways such as; direct firing, pyrolysis, anaerobic decomposition (Wasmi and Salih, 2021).

Biomass is consistently available and can be stored and utilized as needed. Sustainable management of biomass, such as growing crops and trees can offset carbon emissions during photosynthesis. Additionally, biomass has drawbacks also. Biomass has a lower energy density than fossil fuels and burning biomass can release pollutants, including carbon monoxide and nitrogen oxides, contributing air pollution unless these emissions are captured and managed properly.

The use of biomass-based products (firewood, forest residues) for energy has been a practice for eras in domestic as well as industrial set-up. The use of firewood for today's energy requirement for cooking and boiling purposes has been a common practice even today in the countryside of Sri Lanka. In addition, firewood is used to generate steam as a form of energy to cater to different industrial needs.

Bioenergy

Bioenergy is a form of renewable energy that can be produced from organic material known as biomass, which contains carbon absorbed by plants through photosynthesis. The development of bioenergy has the possibility to enhance long-term environmental and economic sustainability while also helping to reduce the climate impact of using fossil fuels.

Biomass can be converted into usable bioenergy through different processes. As biological processes, the fermentation of lignocellulosic and sugary materials for bioethanol production and the anaerobic digestion of organic waste for biogas production can be considered as key methods. In addition, fermentation is applied to produce bioethanol which is a substitute for gasoline. Bioenergy helps in recycling of waste materials, contributing to environmental conservation. It contributes to a more secure, sustainable and economically-sound future by providing clean domestic energy sources. As a versatile renewable energy source, bioenergy can be used for heating, electricity generation, and as biofuels for transportation purposes.

Evolution of Bioenergy industry in Sri Lanka

The energy industry in Sri Lanka has a long history, marked by moments of innovation and adaptation. Biomass in electrical generation involves utilizing wood, ideally harvested sustainably, as the primary fuel for energy or electricity production. Often termed as Dendro stemming from the Greek word for wood. It's rather relying on sustainable cultivation for fuel, ensures greener and more sustainable energy future. In July 1985, by the Institution of Engineers Sri Lanka (IESL), a pioneering proposal was presented to generate electricity from biomass, specifically through the cultivation of nitrogen-fixing trees like

Gliricidia. Ray Wijewardene is the person who tirelessly advocated for Dendro power using his influential positions. Ray's commitment extended to his own coconut estate, where he demonstrated practical applications by installing a 4kW biomass gasifier generator and a commercial project with 1 MW Dendro power plant in Walapane. This demonstration projects sparked private sector interest, leading to the formation of the Bio-Energy Association of Sri Lanka with Ray as its first president. Under his leadership, Dendro power was recognized as a viable option for meeting the national electricity demand, marking a significant step in the evolution of biomass energy in Sri Lanka. However, Dendro power plants that have recently been developed in Sri Lanka were not very successful. Many of them were reported as abandoned either temporarily or permanently.

Anaerobic digestion, also known as microbial fermentation, produces biogas when biodegradable wastes are broken down into a gas mixture in the absence of oxygen (Aworanti *et al*, 2018). In the 1970s, biogas technology was first introduced to Sri Lanka with the influence of China and India in order to test the microbial culture in local contexts (Musafer, 2005). About 25 years after introducing biogas to Sri Lanka, research on biogas was first conducted and documented in the latter 1990s. National Engineering Research & Development Center (NERD) created its batch processing biogas technology by utilising solid material that is anaerobically fermented as a batch rather than using animal faeces as in the case of Chinese and Indian models. The majority of the subsistence farmers who grow paddy found this technology to be very helpful, as its straw is used to charge the batch type biogas units (Musafer, 2005). In 2015, University of Moratuwa, studied the potential of plug flow digesters for biogas production for the Sri Lankan domestic context. The study came to the conclusion that plug flow digesters, especially when employing cow dung and kitchen trash as feedstock, can be a practical choice for producing biogas in Sri Lanka (Hasangika *et al*, 2015).

Although Sri Lanka has made significant strides in the research and development of biogas technology, the majority of studies have concentrated on addressing and comprehending the underlying difficulties with little emphasis on optimizing it for household use. Consequently, most of the already-installed biogas units were abandoned, primarily because of inadequate maintenance practices and occasionally because of technical difficulties.

Biofuels

Biofuel is a renewable energy source, unlike other natural resources such as petroleum, coal and nuclear fuels. It is derived from biomass, which includes animal waste, algae, or plant matter. Biofuels can be found in different states such as solid, liquid and gaseous. The most common biofuels are ethanol, biodiesel, and biogas, each containing unique characteristics and applications.

Biofuels can be grouped in “generations”, according to the type of technology they used and the type of biomass feedstocks they convert into fuel. First generation biofuels are produced from food crops such as food waste, oil crops and sugar. Bioethanol, biodiesel, and biogas are the most important first-generation biofuels. Second generation biofuels can be produced from a wider range of feedstocks, which are represented mainly by non-food crops. For instance, the whole plant biomass or waste streams that are rich in lignin and cellulose such as wheat straw, grass, or wood. Two main conversion pathways are used to break down this biomass: hydrolysis and thermochemical processes (Arumugam *et al*., 2007). Cellulosic bioethanol, algae-based fuels, represents the next generation advancement of biofuels. Other than that, bio-hydrogen, biobutanol, and syngas can be identified as second-generation biofuel types. While not fuel, biochar which is a by-product of biomass hydrolysis, production is linked to biofuels. Most biofuels can be used as transportation fuels, but they may also be used for heating and electricity generation.

Biogas

Anaerobic digestion (AD) is a multi-stage biochemical process involving complex interactions among diverse microbial communities to decompose organic matter into biogas. The process can be divided into four distinct stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, each facilitated by specific groups of microorganisms.

Hydrolysis is the initial stage where complex biopolymers such as carbohydrates, proteins, and lipids are broken down into simpler monomers like sugars, amino acids, and long- chain fatty acids. This stage is catalyzed by hydrolytic enzymes including amylase, cellulase, lipase, protease, and pectinase. Following hydrolysis, the acidogenesis stage involves the further breakdown of the monomers into volatile fatty acids (VFAs) such as acetic acid, propionic acid, formic acid, and lactic acid, along with alcohols like ethanol and methanol, and other byproducts including CO_2 , H_2 , and NH_3. (Haririchi *et al.,* 2022) In the acetogenesis stage, acetogenic bacteria convert the products of acidogenesis and some long-chain fatty acids from hydrolysis into acetate, CO_2, and H_2. This stage is not thermodynamically favorable unless the partial pressure of H_2 is kept low, a condition maintained by methanogenic bacteria that consume H_2. The final stage, methanogenesis, is strictly anaerobic and involves the conversion of acetate and hydrogen into methane (CH_4) and carbon dioxide by methanogenic archaea. There are two primary pathways: acetoclastic methanogenesis, where acetate is converted into methane and CO_2 (Kushkevych *et al.,* 2019).

The biogas production process not only produces methane-rich gas that can be used for electricity generation, heating and as a vehicle fuel, but also yields nutrient rich digestate, which can be used as a high-quality fertilizer. At present, biogas systems can be implemented at various scales, from small domestic digesters to large industrial plants, making them adaptable to different needs and contexts. By converting waste into energy, it promotes the circular economy.

There are key challenges and limitations hindering the widespread adoption and effective operation of biogas technology in Sri Lanka. Odor issues and corrosion of equipment caused by sulphur compounds like hydrogen sulphide in biogas emerged as a major problem. Technical limitations like lack of knowledge on appropriate feedstocks, crusting on digester slurry surface reducing gas production can be considered as challenges. According to a study conducted by Bekchanov *et al,* 2019 shows biogas technology adoption in Sri Lanka is hindered by a lack of awareness, high initial investment costs, limited access to finance, inadequate technical know-how, and social and cultural factors. The gap between recent advancements in biogas technology and the lack of proper implementation of domestic-scale biogas technology in Sri Lanka can be attributed to the challenges faced by urban populations. Insufficient research and development (R&D) funding is perceived as a significant obstacle, both in developing countries at industrial and domestic scales, specifically in Sri Lanka (Nevzorova and Kutcherov, 2019). Moreover, many universities and colleges in these countries do not adequately cover biogas technologies and their practical application in their engineering and technical curricula (Surendra et al., 2014).

Establishing decentralized biogas plants in rural areas can improve waste management, provide local energy sources, and enhance energy access. On a domestic scale, promoting household biogas systems can significantly reduce home energy costs by providing a renewable source of cooking gas and managing kitchen waste effectively. This reduction in household energy expenses can collectively contribute to the national economy by decreasing reliance on imported fuels and lowering overall energy costs. Government incentives, such as subsidies and favorable policies, can encourage private investments in biogas infrastructure.

Bioethanol

Bioethanol, biodegradable colorless liquid, is another type of biofuel produced from renewable biomass sources such as corn, sugarcane, wheat, and other plants rich in sugars or starches. Bioethanol is produced through the microbial fermentation process where sugars are converted into ethanol by yeast or bacteria. Lignocellulosic biomass, such as agricultural residues and wood also can be used as a feedstock, although it necessitates more complex processing. (Bibi *et al.,* 2017) Bioethanol if not ethyl alcohol, can be produced efficiently from a variety of feedstocks such as sugar cane, corn, sorghum, barley, sweet potatoes, cassava, wheat, several fruits and other biomasses and wastes.

The production process involves several steps. First, pre-treatment, which involves breaking down biomass into fermentable sugars using mechanical, chemical, or enzymatic methods. Next, during fermentation, microorganisms like yeast ferment the sugars into ethanol and carbon dioxide. The next step in the process of making ethanol is saccharification. This is the process of further hydrolysis of glucose monomers. Gluco-amylase enzyme is used during saccharification. Following this, distillation is employed to separate ethanol from the fermentation mixture. The distillation unit utilizes the differences in the boiling points of ethanol (78°C) and water (100°C) (Banu and Mahendran, 2019). Finally, dehydration purifies ethanol by removing water, producing anhydrous ethanol suitable for fuel (Bibi *et al.,* 2017).

Bioethanol is a renewable, biodegradable and non-toxic biofuel which contributes to both environmental sustainability and energy security. And it helps to reduce our dependence on crude oil by serving as an alternative transportation fuel. Additionally, bioethanol burns cleaner than gasoline, emitting fewer pollutants and helps maintain the air quality. Fuel-grade ethanol should be produced locally at least for partial replacement of petrol in Sri Lanka (Banu and Mahendran, 2019).

The production of bioethanol can also stimulate rural economies by creating job opportunities in agriculture, processing and distribution, providing new markets for crops. Furthermore, bioethanol can be mixed with gasoline and used in existing internal combustion engines without significant modifications, making it a practical and immediate solution for reducing fossil fuel use.

The main challenges of bioethanol industry are availability and the cost of feedstocks. The majority of bioethanol is currently produced from corn and sugarcane, which can be subjected to weather-related crop failures and price fluctuations. And also, the process of converting lignocellulosic biomass into fermentable sugars is complex and requires advanced technologies, which can be expensive and energy intensive. Additionally, the bioethanol production process indirectly contributes to a greenhouse gas emissions, and environmental pollution. R&D efforts should be focused on breeding high-yield, draught resistant crop varieties that are specifically suited to the local climate, reducing the need of water and fertilizers. Moreover, government support in the form of subsidies, tax incentives, and favorable policies can encourage investment in bioethanol infrastructure and technology. Strengthening partnerships between research institutions, industry stakeholders, and farmers can improve innovation and knowledge transfer.

Biodiesel

Biodiesel is another renewable and biodegradable fuel manufactured from biological sources such as vegetable oils, animal fats or recycled restaurant grease. Biodiesel is produced through transesterification, a chemical reaction that converts fats or oils into fatty acid methyl esters (FAME) and glycerol. The selection of feedstocks includes vegetable oils such as soybean, canola, and palm oil, as well as animal fats and used cooking oils. The production process involves several key steps: Initially, oil extraction is performed using mechanical pressing or solvent extraction methods. Subsequently, the transesterification process involves reacting to the extracted oil with an alcohol, typically methanol, in the presence of a catalyst such as sodium or potassium hydroxide, resulting in the formation of biodiesel and glycerol (Bashir *et al*., 2022). Finally, the biodiesel undergoes separation from glycerol and is further purified to remove any remaining impurities.

Biodiesel production faces several significant challenges that impact growth and viability. One major issue is the availability and the cost of feedstock, such as vegetable oils, animal fats which can affect production process efficiency. The high initial investment required for production facilities; technical challenges are also affected to the production. Additionally, while biodiesel can be used in many diesel engines it may require modifications or pose durability concerns in older engines.

Biodiesel produced from waste cooking oil appears to be a promising technique as it minimizes waste handling and disposal costs as well. Biodiesel can be used in diesel engines either pure or mixed with petroleum diesel in various proportions after proper modifications of the vehicle engines. Biodiesel has its environmental benefits, as it reduces greenhouse gas emissions, particulate matter, and other pollutants compared to conventional diesel. And also it offers energy security benefits by diversifying fuel sources and dependence on imported fossil fuels.

Other uses of bioenergy

Biochar

Biochar is generated from two main pathways. Either it can be generated directly from biomass pyrolysis or generated as an outcome of bioenergy processes. Biochar is the main byproduct in the process of biomass pyrolysis, which is carried out in temperature from 300-700 ^{0}C, with no presence of Oxygen. This process releases bio-oils and gases with at least 80% of element carbon, which is called biochar. By now, biochar has become a prominent substance in remediation approaches, due to high surface are, hydrophobicity, and low cost of production. (Shiran Pallewatta, 2023)

Biochar can be used for water treatment purposes which need high temperatures. Pesticide residues, pharmaceutical contaminants (glyphosate, carbofuran) can be treated better with biochar coming from the gasification process because it has very high surface area and fixed carbon due to the high temperature. In order to maintain the quality of biochar, higher temperatures should be maintained during the production process. It can be used as a quality enhancer of soil condition which is rich in phosphorus and overall reduce greenhouse gases. Additionally, it has qualities such as high water retention ability, improvement of the soil biology, enhancement of density, slow releasing ability of soil nutrients. Most of the orchid planting community are using biochar coming from pyrolysis. Basically, *Gliricidia* can be used as the raw material for this pyrolysis process due to the rapidly growing ability. Moreover, it helps to prevent fertilizer runoff and leaching, enabling the less use of fertilizer and it reduces the pollution of the surrounding environment. Furthermore, biochar has high absorbent capabilities of water and moisture. Therefore, it can be used as a material for dehumidification. And also it can be considered an odor absorbent.

Currently, there is a bioenergy plant in Mahiyanganaya area which generates biochar with a good quality after the gasification process. And also, there is another bioenergy plant in Rathnapura, Embilipitiya area which produces biochar as a byproduct of their gasification system. Cinnamon wood has the potential to produce value-added products like biochar which can be seen in Dambulla area, Sri Lanka.

There are several issues to improve the production of biochar as a byproduct of bioenergy. Addressing these challenges requires supportive policies and incentives to sustain biochar's role in sustainable agriculture and climate mitigation efforts. The reduction in tariff values for biochar poses several challenges for its production and adoption. The lowered tariff may deter investment in biochar production facilities, affecting supply chains and availability. This reduction could also impact on research and development efforts aimed at optimizing biochar's efficacy. Decreased tariffs might discourage farmers from integrating biochar into their agricultural practices.

Case studies

MAS Thulhiriya Fabric Park - biomass and industrial waste as a sustainable energy source.

Thulhiriya fabric park is the first privately owned apparel intensive free trade zone in Sri Lanka. It provides industrial services like centralized power, water and steam supply. Additionally, they have effluent treatment facilities. They use centralized hybrid boilers for steam generation and distribution. The Park provides 10 MVA medium voltage power supply through an underground distribution system. Treatment plant purify and supply a capacity of 9000 m^3 of water (daily), provide effluent treatment for 4000 m^3 of biological and chemical waste (daily), Sustainable biomass and dried industrial sludge were used in a 10:1 ratio as the raw materials for the boilers. They have 2 boilers in operation. Each boiler has a 17 ton/h capacity. To feed those they use 100 tons of rubber wood from plantations and 10 tons of dried sludge from controlled centralized effluent treatment plant. Industrial waste mainly comes from chemicals used in dye houses and treatment chemicals. Input chemical control programs have been established to monitor the incoming chemicals and hazardous particles. All input chemicals are treated with coagulant and flocculation processes and the output slurry sludge is treated with mechanical press to form wet sludge cake. Then dryers are used to make them ready to feed in boilers. Within the flame tube they maintain 1100 –1200 °C for 2-3 seconds as per environmental standards defined by the World Health Organization (WHO). The generated steam goes back to dye houses for the production process. This provides a clear example of how circularity is maintained within the premises and its economic benefit and potential.

Future opportunities

Syngas

Syngas, or synthesis gas is a gas mixture of predominantly Carbon monoxide (CO), in various ratios. It is produced through the gasification of carbon containing materials such as coal, biomass or municipal solid waste using the gasification technology. The gasification process uses high temperatures and controlled amounts of oxygen or steam. As a versatile fuel source, syngas can be used for internal combustion engines, turbines, or fuel cells to generate electricity. High efficiency and clean combustion can be identified as significant advantages of syngas.

In Sri Lanka, the development and utilization of syngas technology are still in the early stages. A few pilot projects have been initiated to demonstrate the feasibility of syngas production and utilization in Sri Lanka. For instance, HAITAI power manufacturers are doing a project using wood chips to generate syngas through biomass gasification. They generate 400 kW of power, which is connected to the grid for power generation. These projects often focus on small-scale gasification units that can convert agricultural residues, wood chips into syngas and that is important for the waste reduction process and as an alternative energy source (Weifang Haitai Power Machinery Co., Ltd., 2024). However, there is a need for more comprehensive policies, incentives and a regulatory framework.

The development of syngas technology in Sri Lanka faces several challenges, including the high capital costs, technical complexity. Additionally, raising awareness of its benefits and potential applications among stakeholders is crucial. Phased integration with existing systems rather than establishing large power plants all at once is a more realistic and manageable approach.

Biohydrogen

Biohydrogen, especially when produced using biomass or biogas, represents a promising future fuel for Sri Lanka. The potential of biohydrogen as a clean and versatile energy carrier is widely recognized, with significant opportunities for integration into various sectors such as transportation, industry, and power generation. One innovative approach to biohydrogen production involves the use of methane as a feedstock. Methanogenic bacteria can convert organic material into methane in anaerobic conditions, which can then be reformed to produce hydrogen. This biological process is gaining attention due to its potential for sustainable and low-carbon hydrogen production.

Biohydrogen production technologies are still in the developmental and demonstration stages worldwide. Research facilities and pilot projects in countries like Japan, Germany, and the USA are exploring the economic viability and scaling potential of these methods. For Sri Lanka, adopting these technologies requires addressing several challenges. These include the need for significant investment in research and infrastructure, establishing a proper regulatory framework, and developing local expertise.

Sri Lanka has great potential for biohydrogen production because of its abundant biomass resources and growing renewable energy sector. The government can support this transition by offering incentives for research and development, encouraging public-private partnerships, and seeking international collaboration. Although the initial investment in biohydrogen infrastructure is high, the long-term benefits include lower greenhouse gas emissions, improved energy security, and job creation. Environmentally, producing biohydrogen from biomass supports sustainable development goals by reducing the carbon footprint and promoting circular economy principles.

Other innovative approaches

Innovative approaches in biomass utilization, such as integrating biogas and bioethanol production offers a promising way to enhance biomass efficiency and sustainability. In this process, bioethanol production acts as a preliminary treatment for biogas production. In the bioethanol fermentation process, the primary byproduct is stillage, which has a high Chemical Oxygen Demand (COD) value. Higher COD means more production of methane. The byproduct from bioethanol production can therefore be used to produce biogas. By combining these, the overall efficiency of the biomass is increased and a lot of byproducts from bioethanol production can be used to generate more income (SAMAK, 2022). This approach contributes to waste reduction and environmental sustainability. Additionally, the nutrient rich digestate from biogas production can be used as a fertilizer, closing the loop in the biomass utilization cycle and promoting a circular economy.

Utilizing biochar from bioenergy plants in agriculture offers a practical approach to support petroleum use while promoting environmental sustainability. When managing a bioenergy plant that produces biochar as a byproduct, it is beneficial to collaborate with the agricultural sector to introduce biochar to farmers as an organomineral fertilizer. Ensuring a smooth supply chain and addressing policy issues are crucial steps in this process. The goal isn't to build a bioenergy plant to supply energy to the entire country, but rather to use bioenergy as a supportive energy source alongside petroleum. By maintaining small to medium-scale bioenergy plants we can reduce the reliance on petroleum to some extent.

Small scale bioenergy plants can be an excellent example of sustainable energy solutions. For example, tea waste can be utilized as raw material for these bioenergy plants. The byproduct, biochar can then be used to enhance soil quality in tea estates, promoting a cycle of sustainability. And, by combining resources from two or three Grama Niladhari Divisions, a community bioenergy plant can be established, making the community more self-sufficient. This approach provides a renewable source of energy, supports local agriculture, and strengthens community resilience.

Sri Lanka has immense potential to achieve a circular and sustainable bioeconomy. The abundant biomass resources distributed throughout Sri Lanka, paired with ongoing advancements in bioenergy technologies, offer a promising pathway for converting waste into valuable energy. By aligning bioenergy initiatives with national energy policies and emphasizing sustainable practices, Sri Lanka can significantly reduce its dependence on fossil fuels, decrease greenhouse gas emissions, and enhance energy security.

Additionally, fostering public-private partnerships, investing in research and development, and encouraging active community involvement are essential steps in this journey. As Sri Lanka continues to unlock the potential of bioenergy, it will pave the way for a more resilient and environmentally sustainable future, embracing the principles of a circular bioeconomy.

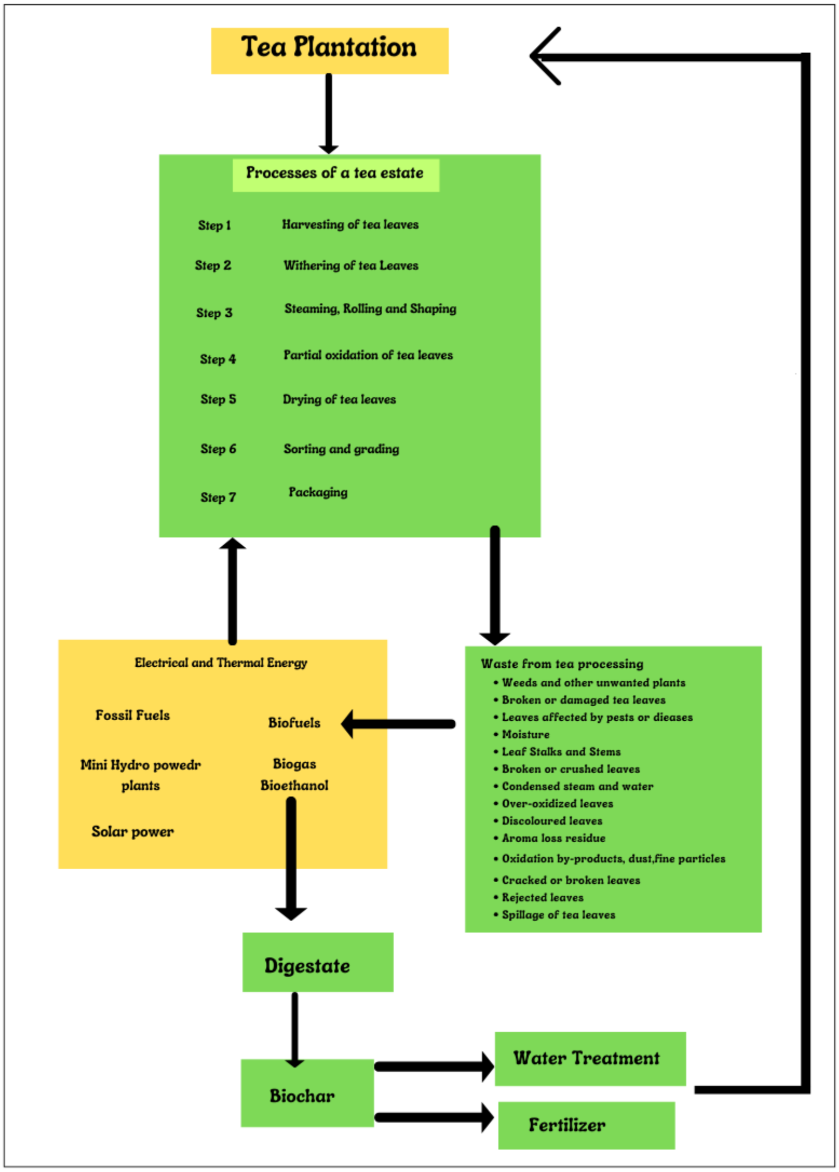

Figure 12.3: Transforming tea waste into renewable energy: A circular approach to sustainable bioenergy production

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Chapter 13

Dyes of fungal origin: Reshaping the dye industry with sustainable alternatives to synthetic dyes

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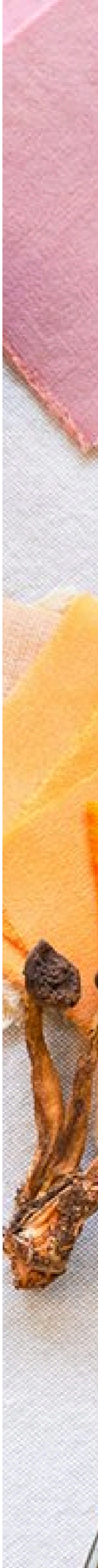

Abstract

Colors play crucial roles in various aspects of life on Earth. In addition to the inherent coloring capability of nature, synthetic dyes are being applied in almost every industry in the world. Based on top market analysis, the global market size for synthetic dyes was recorded at United States Dollars (USD) 6.3 billion in 2022 and is expected to grow to USD 8.7 billion by 2027. With the rising demand for artificial pigments, the manufacturing, processing, and utilization of synthetic colors have contributed to a wide array of environmental and health issues. Therefore, sustainable developmental goals in the field of the chemical industry have been specifically established to mitigate the potential environmental hazards. Interestingly, there is a significant demand for top-notch alternatives capable of effectively replacing synthetic dyes. When considering sustainable alternatives, dyes of fungal origin have been frequently highlighted in many recent research studies. Extensive research on fungal pigments has primarily focused on four genera: *Aspergillus, Penicillium, Paecilomyces,* and *Monascus*. These fungi have provided us with a wealth of knowledge regarding the production of pigments among fungal species. The notable fungal pigments can be broadly classified into four categories: carotenoids, polyketides, melanins, and azaphilones. Fungal pigments have gained significant attention in various industrial sectors in the world, including food, cosmetics, textiles, and pharmaceuticals. Therefore, the shifting from synthetic chemical dyes to dyes of fungal origin can be considered a remarkable milestone in achieving a sustainable bio-based circular economy.

Keywords: Bioeconomy, Environmental concerns, Fungal pigments, Synthetic dyes

The current necessity of natural-origin dyes

Colors represent a crucial part of our life. The most of organisms on our planet exhibit definite natural-colored shades through preferential absorption and refraction of particular wavelengths of visible light by chemical substances present in the tissues. Those chemical compounds are responsible for this light absorption and are considered natural pigments (Lin and Xu, 2020; Cordero and Casadevall, 2017). Natural pigments have an extensive historical lineage, tracing back to the advent of prehistoric civilizations in countries such as China, Egypt, and India. In these antiquated societies, an assortment of natural sources including plants, specific insects, and minerals such as malachite which produces green color, were harnessed for their ability to impregnate textiles with vibrant hues. These sources were also used to add color to culinary creations, adorn surfaces with paints, and even serve as ceremonial body pigments, among other applications (Chandler, 2001). However, the excessive cost of extraction, rapid color fastness when exposed to washing and sunlight, dull range of colors, and instability of the conventionally used natural pigments led to the invention of artificial dyes during the 1800s. The ground-breaking discovery of Perkin's mauve pigment by Sir William Henry Perkin in 1856 marked the advent of a revolutionary era in the field of synthetic organic dyes. This momentous achievement paved the way for the emergence of a diverse array of "coal-tar colors" derived from compounds such as aniline and various organic substances. Consequently, the commercial proliferation of synthetic pigments rapidly gained momentum, permeating numerous industries and leaving a persisting mark on sectors such as textiles, food coloring, pharmaceuticals, and cosmetics (Morris and Travis, 1992). Synthetic pigments, obtained through chemical reactions, impose significant environmental burdens. The textile dyeing and finishing industry is known as one of the most chemically intensive sectors globally (Kant, 2012), generating millions of gallons of effluents laden with hazardous toxic waste, comprising a plethora of vibrant colors and organic compounds. Moreover, synthetic pigments have been associated with various grave health risks, including toxicity, oncogenicity, and teratogenicity (Li and Tian, 2017).

In response to concerns raised in 2007 regarding the correlation between artificial colors and hyperactivity in children, regulations were implemented including the utilization of these dyes in food, textile, drugs, and cosmetics by the European Union, United States Food and Drug Administration, and World Health Organization (McCann et al., 2007). Therefore, there has been a significant demand for effective alternatives to synthetic pigments to mitigate their adverse effects. Consequently, intensive research into dyes of natural origin has commenced in recent years to address the issues associated with the excessive utilization of synthetic pigments (Mapari et al., 2010). In recent years, the global market for natural pigments has experienced rapid growth, driven by the heightened awareness of health among individuals and the exploration of modern pharmacological properties exhibited by numerous natural pigments such as carotenoids, flavonoids, and curcuminoids. However, the conventional methods of pigment production through plant-based materials heavily rely on the source material and often encounter limitations due to the low concentrations of target pigment compounds, hindering mass production on an industrial scale (Galaffu et al., 2015).

To address this challenge and facilitate large-scale industrial production, considerable efforts have been dedicated to enhancing pigment production with natural origin. This has involved the development of *in vitro* plant cell and tissue culture systems, as well as the optimization of microbial cultivation methods (Bhojwani and Dantu, 2013). Additionally, the emerging field of synthetic biology has revolutionized the production of pigments by enabling the design and reconstruction of novel biological modules that encompass microorganisms and other biological systems within bio-platforms (Osbourn et al., 2012). Through these approaches, it is now possible to achieve heterologous biosynthesis of pigments, where microorganisms are engineered to produce desired pigment compounds (Ganapathy et al., 2016). These innovative approaches not only address the limitations of conventional production methods but also offer the potential to generate a diverse range of pigments with enhanced yields. Ultimately, this bio-technological progress opens new avenues for meeting the rising global demand for natural pigments (Sen et al., 2019).

Fungal species as dye producers

Extensive research on fungal pigments has primarily focused on four genera: *Aspergillus, Penicillium, Paecilomyces,* and *Monascus* (Méndez et al., 2011; Lin and Xu, 2020). These fungi have provided us with a wealth of knowledge regarding the production of pigments among fungal species. The notable fungal pigments can be broadly classified into four categories: carotenoids, polyketides, melanins, and azaphilones (polyketide derivatives) (Celestino et al., 2014; Lin and Xu, 2020). The carotenoids exhibit distinct shades of orange and yellow colors. Polyketide pigments, including anthraquinones and hydroxyanthraquinones, display a wide array of colors, ranging from orange and bronze to maroon. Additionally, naphthoquinones (a type of polyketide pigment) are responsible for red, purple, or black shades. Azaphilones exhibit distinct hues of red and purple red. Melanin is responsible for grey and black shades.

In addition to the major strains of pigment-producing fungi, some non-dominant species are capable of producing vibrant hues. Many genera of the *Xylariaceae* family, such as *Daldinia*, *Hypoxylon, Jackrogersella*, etc., have a great capability to synthesize pigments of very diverse colors and hues (Lagashetti et al., 2019). The genera belonging to the family *Cordycipitaceae* such as *Torrubiella, Cordyceps, Beauveria,* *Hyperdermium*, and *Lecanicillium* have been revealed to be promising producers of bioactive pigments, e.g., tenellin and bassianin are reported from *Beauveria bassiana* and *Beauveria brongniartii* (Lagashetti et al., 2019).

Further, the red pigment production from the mangrove fungus *Penicillium sp*. and yellow pigment production from the marine sponge-associated fungus *Trichoderma parareesei* have been investigated (Sibero et al., 2016).

Applications of fungal dyes in various industries

Fungal pigments have gained significant attention in various industrial sectors, including food, cosmetics, textiles, and pharmaceuticals (Gmoser et al., 2017), due to the enormous advantages such as eco-friendly production, biodegradability, unique and vibrant color, color variation, lesser toxicity, safe and easy processing, and low resource requirement. Among the diverse fungal pigments, carotenoids derived from *Mucoromycota* species, particularly *Mucor circinelloides,* and *Blakeslea trispora*, have found extensive use in the agrochemical and pharmaceutical industries. Further, naphthoquinones, found in over 60 fungal species, exhibit various bioactivities, including antimicrobial and anticancer properties (Medentsev and Akimenko, 1998). However, only a few fungal pigments are currently produced at an industrial scale and commercially available due to the challenges in scaling up production. As an example for commercially reputed fungal pigment, the global market for carotenoids reached $1.5 billion in 2017 and, at a compound annual growth rate of 5.7%, it is projected to reach up to 2.0 billion by 2026*.

The textile industry plays a crucial role in the economy of any country. In developed countries, 1.3 million tons of synthetic dyes and dye precursors are used annually**. During the dyeing and finishing process, approximately 2 million tons of these dyes are wasted as effluent. These effluents mixed with wastewater persist for prolonged periods in the environment causing a vast range of environmental issues. To address these environmental issues, a remarkable interest is grown in finding eco-friendly dyes. Currently, natural pigments from fungi, with their many advantages over hazardous synthetic pigments, are proven to be a better alternative to synthetic dyes in the textile industry. Natural dyes derived from fungi are non-toxic and eco-friendly. Further, fungal dyes undergo easy degradation, high colorfastness, and high staining capability, etc.

Anthraquinones, produced by fungi such as *Cortinarius sanguineus* and *Fusarium oxysporum*, have been utilized as dyes for textiles due to their stability and lightfastness. The pigment from *Penicillium minioluteum* is

* Mordor Intelligence Research & Advisory. (2023, June). Pigments Market Size & Share Analysis - Growth Trends & Forecasts (2023 - 2028). Mordor Intelligence, (https://www.mordorintelligence.com/industry-reports/pigments-market), Retrieved July 17, 2023.

** Global synthetic dyes market size forecast, Synthetic dyes market by type (Acid dyes, reactive dyes, disperse dyes, direct dyes, solvent dyes, basic dyes), application, form (liquid, powder), structure (anionic, cationic, non-ionic), end-use industry, and region – global forecast to 2027, (Global Synthetic Dyes Market Size Forecast (marketsandmarkets.com)), published August 2022.

used to dye wet blue goat nappa leather, while the red pigment from *Talaromyces verruculosus* used to dye cotton fabric without any cytotoxic effect (Räisänen, 2018).

Natural and synthetic colors play a fundamental role in enhancing the visual appeal of industrial food products. However, synthetic pigments have been found to negatively impact health and food quality, prompting food processors to shift towards natural alternatives. Among microorganisms, fungi are notable for producing safe and efficient pigments for food processing.

In consideration the *Monascus* pigments which are widely used in East Asia as food colorants, have faced restrictions due to their nephrotoxicity and hepatotoxicity. Research has sought to develop citrinin-free *Monascus* strains, and *Talaromyces* species have shown promise as alternatives for red pigment production (Carvalho et al., 2005). Pink-red pigment from *Penicillium oxalicum*, astaxanthin from *Xanthophyllomyces dendrorhous*, β-carotene from *Blakeslea trispora*, riboflavin from *Ashbya gossypii*, and lycopene from *Erwinia uredovora* and *Fusarium sporotrichioides* are now widely utilized in the food processing industry.

The cosmetic industry is highly costly and continuously seeks novel and natural products. In ancient China and Japan, such compounds used in cosmetics were exclusively reserved for royal families. In addition, fungal pigments specifically have a marine origin are also finding applications in the cosmetic industry, with carotenoids and melanins serving as active ingredients in sunscreens, skin care products, and anti-aging facials/masks which represent an important future trend of fungal pigments as cosmeceuticals (Aggrawal et al., 2018).

Additionally, hydroxyanthraquinones have been explored as potential hair dyes (Meruvu and dos Santos, 2021). Use of fungal-pigmented wood for spalting is an emerging trend, offering sustainable and visually appealing wood products. Spalting is a technique in which specific fungi are intentionally introduced to the wood to create distinctive and attractive colors in the wood. Further, fungal melanin, known for its protective properties, has potential applications in engineering optoelectronic devices. Xylindein, a pigment derived from spalting fungi which are usually colonized in woods, has shown promise for organic semiconductor applications (Giesbers et al., 2019).

Several industries are at the forefront of utilizing fungal pigments for various industrial applications. For instance, Colorifix is a pioneering biotechnology firm originating in the United Kingdom, stands as the first company to harness engineered microorganisms for the production, deposition, and fixation of natural dyes onto textile.

Further, MycoWorks is an advanced platform originating in France that focuses on sustainable materials particularly those based on mycelium including fungal pigments. The incorporation of the extracted fungal dyes into their mycelium leather products is a fundamental step in enhancing the aesthetic appeal while promoting sustainability.

Special concerns in scaling up a fungal pigment industry

Fungal pigments show promise, but the large-scale production and extraction of these pigments from fungal cultures may pose challenges in terms of cost-effectiveness and industrial-scale feasibility. This aspect needs to be investigated further. The potential toxicity or side effects of fungal pigments, especially for human health and environmental applications, should be thoroughly evaluated before widespread use. For instance, the pigment extract of *Penicillium canescens* and *F. solani* exhibited strong antimicrobial activity against *Escherichia coli* and *Enterococcus aerogenes* and *Salmonella typhi*, *Staphylococcus aureus*, and *Bacillus cereus* at MIC values ranging from 1.5 to 2.5 mg/mL (Molelekoa et al*.,* 2023). However, certain levels of toxicity were observed for all pigment extracts at a concentration range of 3–5 mg/mL. Therefore, further toxicity tests must be done using molecular docking, albino mice, and cell linings (Molelekoa et al*.,* 2023).

Ensuring the safety and biocompatibility of these pigments is crucial. Developing standardized methods for consistent production, extraction, and characterization of fungal pigments are important to ensure batch-to-batch quality and reliability for commercial applications. Depending on the intended use (food, cosmetics, textile), the regulatory approval process for fungal dyes may need to be addressed, which could involve additional testing and documentation requirements.

The regulatory framework for approving fungal pigments in different industries

According to the regulations issued by the Minister of Healthcare and Nutrition in consultation with the Food Advisory Committee under section 32 of the Food Act, No. 26 of 1980, no person shall advertise or use any coloring substance as an ingredient in food preparation unless it is a permitted coloring substance. However, the current regulations do not explicitly prohibit the use of fungal pigments as food coloring agents. Additionally, under the National Environmental Act, No. 47 of 1980, industries involved in dye and dye intermediate manufacturing or formulation, as well as textile processing are required to obtain a license to operate. There is no specific mention in the law regarding the prohibition of dyes derived from fungal sources. Furthermore, there is no comprehensive international law specifically governing the use of fungal dyes in various industries.

Future directions

Fungal pigments represent a valuable resource, and exploration of untapped habitats, such as Antarctica and marine environments, holds promise for future bioprospecting endeavours. Development of fungal cell factories and improved cultivation and processing techniques will likely drive further advancements in fungal pigment production and applications in various industries.

Conclusion

Fungal pigments offer a promising and eco-friendly alternative to synthetic dyes which are associated with significant environmental and health hazards. Historical reliance on natural pigments emphasizes their value, yet modern technological advancements in biotechnology and synthetic biology have developed their potential for large-scale production. Extensive research into fungal genera such as *Aspergillus*, *Penicillum*, *Paecilomyces*, and *Monascus* has highlighted their capacity to produce a wide range of pigments with applications in food, textiles, cosmetics, and pharmaceuticals. The continuous exploration of untapped habitats and the development of advanced production techniques are set to drive future innovations, positioning fungal pigments as a sustainable and versatile resource for various industries.

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