THE INSTITUTE OF BIOLOGY SRI LANKA

BIOLOGICAL INNOVATIONS FOR ENVIRONMENTAL SUSTAINABILITY

THEMATIC PUBLICATION

2025

Biological Innovations for Environmental Sustainability

Published by

The Institute of Biology Sri Lanka

25th September, 2025

Citation: Name/s of chapter author/s (2025). 'Title of chapter', In: *Biological Innovations for Environmental Sustainability*. Colombo; Institute of Biology Sri Lanka, pp. x-y

Text by: K.V.N.T. De Silva, T.D.S. Ariyarathna, J.M.P.M. Jayasekara, W.M.J.Y. Bandara, C.C.D. Mendis, R.M.S.H. Disanayaka, W.M.D.N. Wijeyaratne, C.Y. Amarasinghe, C.M. Nanayakkara, A.A.D.N. Thathsarani, R.S. Rajakaruna, U.A. Jayawardena, V. T. Koggalage, R. Wimalasekera, S. Ramachandra, R. Liyanage, U. Kumarasinghe, A. U. Alahakoon, A.K.O.D. Amarasinghe, R.R.K. De Zoysa, K.D.A. Dulanjana, G. Rajapaksa, P.W. Samarasekere, K. C. T. Peiris, I. U. Kariyawasam, A.H.D. Athukorala, M.S.A. Banu, A.M.S.U.M. Attanayake, R.M.S.M.B. Rathnayaka, E.J. Eugene, A.A.A.P. Ishara, L.R.I.P.K. Wijerathne, K.A.S.H. Wijayasenarathne, R.T.K. Ariyawansha, R.M.A. Dilini, P.D.I. Imalka, D.D.N. Dissanayaka, R.M.S.M.B. Rathnayaka

Technical Editing: Dr. R. Wimalasekera and Prof. B.D. Rohitha Prasantha

Cover Page Design and Page Layout: Ms. N.T.M.S.N. Mindula

ISBN: 978-624-5998-06-7

Institute of Biology Sri Lanka (IOBSL)
'Vidya Mandiraya',
120/10, Wijerama Road, Colombo 07.
Email: iobslcouncil@gmail.com
Web: http://www.iobsl.org/

Biological Innovations for Environmental Sustainability

Authors

Chapter 1
Innovative Biological Strategies in Sponge Cities: Enhancing Climate Resilience and Environmental Sustainability
K.V.N.T. De Silva, T.D.S. Ariyarathna, J.M.P.M. Jayasekara, W.M.J.Y. Bandara, C.C.D. Mendis, R.M.S.H. Disanayaka and W.M.D.N. Wijeyaratne

Chapter 2
Microbial Strategies for Enhancing Soil Health and Sustainable Agriculture
C.Y. Amarasinghe and C.M. Nanayakkara

Chapter 3
Bioremediation for Restoring Microplastic-Contaminated Environments
A.A.D.N. Thathsarani, R.S. Rajakaruna and U.A. Jayawardena

Chapter 4
Lab-on-a-Chip (LoC) Technology for Sustainable Biological Ecotoxicity Assessment
V.T. Koggalage and R. Wimalasekera

Chapter 5
Environmental Sustainability through Insect Protein: Potential Feed and Food Applications in Sri Lanka
S. Ramachandra, R. Liyanage, U. Kumarasinghe and A.U. Alahakoon

Chapter 6
Microbial Enzymes - A Sustainable Biotechnological Approach to Environmental Challenges
A.K.O.D. Amarasinghe and C.M. Nanayakkara

Chapter 7
Plant-based Eco-friendly Approaches for Bisphenol A (BPA) Removal
R.R.K. De Zoysa, K.D.A. Dulanjana, G. Rajapaksa and P.W. Samarasekere

Chapter 8
From Ocean to Industry: Novel Bio-innovations with Marine Bacterial Pigments
K.C.T. Peiris and I.U. Kariyawasam

Chapter 9
Development of a Sustainable Biodegradable Packaging Material from Water Hyacinth and Guinea Grass
A.H.D. Athukorala, M.S.A. Banu, A.M.S.U.M. Attanayake and R.M.S.M.B. Rathnayaka

Chapter 10
Sustainable Biological Innovation in Healthcare: Biopharmaceuticals
E. J. Eugene

Chapter 11
Biological Approaches for the Remediation of Pharmaceutical Pollution in Aquatic Environments
A.A.A.P. Ishara, L.R.I.P.K. Wijerathne and G. Rajapaksa

Chapter 12
Biodegradable Plastics in Sri Lanka: A Review of Current Status, Challenges and Opportunities
K.A.S.H. Wijayasenarathne, R.T. K. Ariyawansha and R.M.A. Dilini

Chapter 13
Bio-Inspired Solutions for Water Conservation and Purification
P.D.I. Imalka and R. Wimalasekera

Chapter 14
Biological Approaches in the Sustainability of Medicinal Plant Production: Improving Resilience and Reducing Environmental Footprint
D.D.N. Dissanayaka and R.M.S.M.B. Rathnayaka

Published by

The Institute of Biology Sri Lanka

25th September 2025

Preface

Biological innovations signify the development, enhancement, and application of novel ideas, methods, technologies, or processes in the field of biology. These innovations encompass an extensive range of groundbreaking endeavours that harness biological processes and organisms to solve complex problems across various sectors, including healthcare, agriculture, and the environment. Biological innovations play a pivotal role in advancing environmental sustainability, addressing critical global challenges such as food security, climate change, biodiversity loss, and resource depletion. The integrative approach using modern technology and knowledge leverages natural processes and organisms to develop sustainable solutions across various sectors.

The Institute of Biology, Sri Lanka (IOBSL), as the premier professional body representing biologists in the country, is committed to advancing research, innovation, education, and public awareness in the field of environmental sustainability. In alignment with this mission, IOBSL continues to foster the development and dissemination of novel biological solutions that address the complex environmental challenges of our time. This thematic publication, titled Biological Innovations for Environmental Sustainability, showcases a range of innovative biological approaches that contribute to sustainable environmental practices. The insights presented here aim to inspire researchers, educators, policymakers, and all those with an interest in the transformative potential of biology to create a sustainable future.

We trust that this publication will serve as a valuable resource in promoting greater understanding and engagement with biological innovations that drive environmental sustainability.

Our sincere thanks go to the authors of the chapters, the reviewers, and the members of the council for their great support in producing this book.

Dr. R. Wimalasekera
Prof. B.D. Rohitha Prasantha
[Technical Editors]

25th September, 2025

Reviewers

Emeritus Prof. N. Salim
Department of Botany, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda, Sri Lanka.

Prof. S.A.C.N. Perera
Department of Agricultural Biology, Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka.

Emeritus Prof. N. Deshapriya
Department of Botany, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda, Sri Lanka.

Dr. S. Mapa
Department of Biosystems Technology, Faculty of Technology, University of Sri Jayewardenepura, Nugegoda, Sri Lanka.

Dr. W.M.N.M. Wijesundara
Department of Food Science and Technology, Faculty of Animal Science and Export Agriculture, Uva Wellassa University of Sri Lanka, Badulla, Sri Lanka.

Prof. P.N. Dasanayaka
Department of Botany, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda, Sri Lanka.

Dr. K.G.S.U. Ariyawansa
Department of Plant Sciences, Faculty of Science, University of Colombo, Colombo 03, Sri Lanka.

Dr. R. Wimalasekera
Department of Botany, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda, Sri Lanka.

Prof. H.L.D. Weerahewa
Department of Botany, Faculty of Natural Sciences, Open University of Sri Lanka, Nawala, Nugegoda, Sri Lanka.

Prof. D.H.H. Munasingha
Department of Botany, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda, Sri Lanka.

Emeritus Prof. B.F.A. Basnayake
Department of Agricultural Engineering, Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka.

Dr. A.U. Rajapaksha
Instrument Centre, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda, Sri Lanka.

Prof. P.N. Yapa
Department of Biological Sciences, Faculty of Applied Sciences, Rajarata University of Sri Lanka, Mihintale, Sri Lanka.

Dr. E.A.S. Edirisinghe
Department of Anatomy, Faculty of Medical Sciences, University of Sri Jayewardenepura, Nugegoda, Sri Lanka.

Prof. W.L.I. Wijesekara
Department of Food Science and Technology, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda, Sri Lanka.

Acknowledgements

The Institute of Biology Sri Lanka, would like to acknowledge the contribution of all those who have been involved in publishing this book. Their dedication and generous support have been instrumental in making this publication a reality.

- We sincerely appreciate the contribution from chapter authors for their willingness and commitment to share their expertise by composing a chapter in this book.

- We gratefully acknowledge the efforts of chapter reviewers for their valuable contribution in improving the quality, coherence, and content of the chapters.

- We extend our sincere thanks to Ms. N.T.M.S.N. Mindula for designing the cover page and title pages of the chapters.

Contents

Contents	**Page No.**
Authors	i
Preface	iii
Reviewers	iv
Acknowledgements	vi

Chapter 1:
Innovative Biological Strategies in Sponge Cities: Enhancing Climate Resilience and Environmental Sustainability 1
K.V.N.T. De Silva, T.D.S. Ariyarathna, J.M.P.M. Jayasekara, W.M.J.Y. Bandara, C.C.D. Mendis, R.M.S.H. Disanayaka and W.M.D.N. Wijeyaratne

Chapter 2:
Microbial Strategies for Enhancing Soil Health and Sustainable Agriculture 17
C.Y. Amarasinghe and C.M. Nanayakkara

Chapter 3:
Bioremediation for Restoring Microplastic-Contaminated Environments 32
A.A.D.N. Thathsarani, R.S. Rajakaruna and U.A. Jayawardena

Chapter 4:
Lab-on-a-Chip (LoC) Technology for Sustainable Biological Ecotoxicity Assessment 48
V.T. Koggalage and R. Wimalasekera

Chapter 5:
Environmental Sustainability through Insect Protein: Potential Feed and Food Applications in Sri Lanka 62
S. Ramachandra, R. Liyanage, U. Kumarasinghe and A. U. Alahakoon

Chapter 6:
Microbial Enzymes - A Sustainable Biotechnological Approach to Environmental Challenges 77
A.K.O.D. Amarasinghe and C.M. Nanayakkara

Chapter 7:
Plant-based Eco-friendly Approaches for Bisphenol A (BPA) Removal 91
R.R.K. De Zoysa, K.D.A. Dulanjana, G. Rajapaksa and P.W. Samarasekere

Chapter 8:
From Ocean to Industry: Novel Bio-innovations with Marine Bacterial Pigments 109
K.C.T. Peiris and I.U. Kariyawasam

Chapter 9:
Development of a Sustainable Biodegradable Packaging Material from Water Hyacinth and Guinea Grass 121
A.H.D. Athukorala, M.S.A. Banu, A.M.S.U.M. Attanayake and R.M.S.M.B. Rathnayaka

Chapter 10:
Sustainable Biological Innovation in Healthcare: Biopharmaceuticals 135
E. J. Eugene

Chapter 11:
Biological Approaches for the Remediation of Pharmaceutical Pollution in Aquatic Environments 147
A.A.A.P. Ishara, L.R.I.P.K. Wijerathne and G. Rajapaksa

Chapter 12:
Biodegradable Plastics in Sri Lanka: A Review of Current Status, Challenges and Opportunities 161
K.A.S.H. Wijayasenarathne, R.T. K. Ariyawansha and R.M.A. Dilini

Chapter 13:
Bio-Inspired Solutions for Water Conservation and Purification 179
P.D.I. Imalka and R. Wimalasekera

Chapter 14:
Biological Approaches in the Sustainability of Medicinal Plant Production: Improving Resilience and Reducing Environmental Footprint 197
D.D.N. Dissanayaka and R.M.S.M.B. Rathnayaka

CHAPTER 01

Innovative Biological Strategies in Sponge Cities: Enhancing Climate Resilience and Environmental Sustainability

K.V.N.T. De Silva, T.D.S. Ariyarathna, J.M.P.M. Jayasekara, W.M.J.Y. Bandara, C.C.D. Mendis, R.M.S.H. Disanayaka and W.M.D.N. Wijeyaratne*

Department of Zoology and Environmental Management,
University of Kelaniya, Sri Lanka
**dimuthu.wijeyaratne@kln.ac.lk*

Abstract

The concept of “Sponge cities” was introduced in China in the early 2000s as a solution for the increasing urban floods. A Sponge City is an urban development concept that integrates natural solutions to enhance water absorption, storage, and management within urban environments, aiming to reduce flooding, improve water quality, and enhance climate resilience by mimicking natural hydrological processes. This is generally achieved through green infrastructure like wetlands, rain gardens, and green rooftops etc. The biological aspects of Sponge Cities integrate with utilizing natural ecosystems and biological processes to manage urban water sustainably. It includes vegetation-based water management processes, soil and microbial systems, bioengineered water management systems, green infrastructure and urban biodiversity, algae-based water treatment, etc. The design retrofits used in sponge cities also help to reduce runoff and indirectly help urban cooling. When considering the Sri Lankan Scenario, rapid urbanization in Sri Lanka has led to increased flooding, water scarcity, and ecological degradation, which highlighted the need for sustainable urban water management strategies. The Sponge City concept, which integrates nature-based solutions to absorb, store, and reuse rainwater, presents a viable approach to enhance climate resilience and environmental sustainability through both physical and biological processes. While the Sponge City concept has achieved global recognition as a highly sustainable urban water management approach, its application in Sri Lanka remains unexplored. This chapter aims to explore innovative biological strategies to develop a framework suitable for Sri Lanka’s tropical urban landscapes, providing a sustainable and climate-resilient approach to urban water management.

Keywords: Biological Strategies, Climate Resilience, Nature-Based Solutions, Sponge Cities, Urban Water Management

Introduction

Among the most severe issues of the twenty-first century are urbanization and climate change, which require innovative solutions to promote environmental sustainability and urban resilience. Sponge Cities, a revolutionary approach that combines ecological principles with infrastructure development for urban planning, is identified as an important solution to address environmental problems associated with excessive flooding in expanding urban environments. Sponge cities are designed to address problems associated with flooding, water scarcity, and urban heat islands. Sponge cities are made to absorb, store, purify, and manage water in a way that closely resembles natural hydrological processes. This chapter discusses the cutting-edge biological techniques that support sponge cities, emphasizing how they promote innovative biological approaches, sustainable urban ecosystems, and climate resilience.

Planning and designing a Sponge City

Main components

The basic principles of the sponge city concept are derived from the blue-green infrastructure. In this concept, natural ecosystems integrate with urban development plans to manage stormwater. This approach helps to increase the ecological resilience and results in more livable cities. The components of a sponge city are presented in Figure 01. The establishment of sponge cities focuses on the green components that are beneficial in absorption, filtration, and the gradual release of water. Some of the beneficial components include rain gardens, green walls, green roofs, urban forests, permeable pavements, and bioswales. Blue components are used as conveyance, storage, and treatment units, including rivers, canals, wetlands, ponds, floodplains, and stormwater retention and detention systems (Liao et al., 2017).

The adaptive water management in the sponge cities is facilitated using smart monitoring systems, which include sensors and modeling tools to assess the real-time water flow and quality characteristics. Additionally, ecological designs are integrated with low-impact development (LID) strategies and gray infrastructure upgrades to allow cities to collect rainfall for irrigation, road cleaning, and domestic non-potable requirements. Ultimately, the confluence of digital technology, creative engineering, and ecological restoration is essential to achieve the sponge city's goals of sustainability, resilience, and enhanced urban quality of life (Gündel and Önaç, 2023).

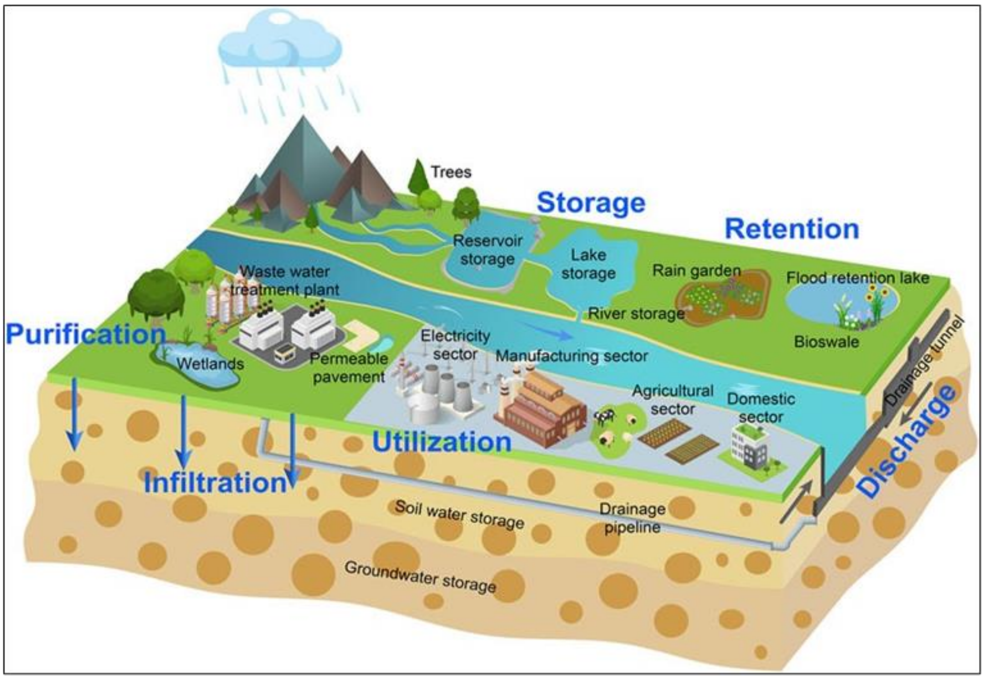


Figure 01. Components of a sponge city (Liu et al., 2022).

Land use planning

Land use planning is a crucial step in the development of sponge cities to balance ecological sustainability and urban development. Mainly, planners focus on optimizing urban areas to facilitate water absorption, storage, purification, and reuse. This includes avoiding artificial infrastructure such as concrete and asphalt while promoting water infiltration, water detention, and ecological restoration. For example, when planning the sponge city in Changde City in Jibu District, planners divided the land into several functional units, such as buildings, pavements, water systems, and greenbelts to allow infiltration and buffering of water during periods of heavy rainfall (Deng et al., 2022).

Some of the key aspects of land use planning include integration of water-sensitive urban design, maintaining natural floodplains and waterways, and adapting zoning regulations. In the integration of water-sensitive urban design, infrastructure and open areas are arranged to improve rainwater filtration and minimize runoff. In addition, multi-functional components are prioritized in this aspect. For instance, parks can be used as recreational areas in the dry period and as temporary water storage areas in rainy periods. Maintaining natural floodplains and waterways leads to reducing flood risks, preserving biodiversity, and preserving the ecological integrity of urban waterways by preventing urban expansion into ecologically delicate and flood-prone areas. In addition, the adaptation of zoning regulations is a crucial factor in the development of sponge cities. The rules and polices associated with urban planning should be updated to encourage the incorporation of green infrastructures such as rain gardens, green roofs, vegetated swales, and permeable pavements with the urban infrastructure (Wang et al., 2020).

Site selection

Infiltration potential, flood-prone zones, land availability, and the impact on communities are the key points to be considered during the site selection process for the establishment of sponge cities. Areas with permeable soil and low compaction are highly suitable for infiltration-based measures. In addition, the sites that frequently experience waterlogging can be used for stormwater detention and drainage. Public land, underutilized spaces, and redevelopment areas are ideal for large-scale interventions. Selected sites must connect to existing green-blue networks to enhance ecological and hydrological continuity. Additionally, accessibility, visibility, and integration with public amenities are crucial for promoting social acceptance and usage of these spaces (Deng et al., 2022).

Technological integration

Planning, implementing, and managing sponge cities depend on technological integration. Modern technologies can be used to improve the performance, flexibility, and efficiency of urban water systems. Smart monitoring technologies are among the important technological components. These modern tools enable adaptive stormwater management, flood forecasting, and early warning by monitoring rainfall intensity, water levels, soil moisture, and the operation of drainage and retention systems.

Additionally, mobile applications can be used to increase community engagement in sponge city projects. With these applications, the community can report flooding, increase awareness about nearby green infrastructure, and take part in upcoming projects. The incorporation of these emerging technologies guarantees that sponge cities are data-driven, resilient, and sensitive to urban issues (Shao et al., 2016).

Urban water management and ecosystem-based approaches

Urban water runoff and flooding control

Restoring the natural water balance improves the health of the associated ecosystems and enhances living conditions in urban areas. The concept of urban hydrology identifies the ecosystem-based methods to restore runoff and improve water quality regimes. However, the unpredictability of climate change has resulted in uncertainties associated with urban water management. Therefore, the rainwater management systems established in the sponge cities must be flexible and adaptable to changing environmental conditions (Saliba et al., 2020).

Green infrastructure for water absorption and retention

The use of plants, soil, and other natural systems to control water and make cities healthier is known as "green infrastructure." Green roofs, rain gardens, permeable pavements, vegetated swales, and constructed wetlands are some of the techniques used in this strategy. These measures increase infiltration, stimulate evapotranspiration, and slow down stormwater runoff.

One essential element of green infrastructure is bioretention systems. These artificially created green areas reduce flow volume, trap pollutants, and filter runoff. The effectiveness of deep-cut curb inlets for road bioretention systems was examined by Liu et al. (2022), who discovered that these alterations greatly enhance water capture and conveyance. This study demonstrated the additional benefits of improving landscape aesthetics and hydraulic performance. Green infrastructure is included in urban planning through the concept of 'Water Sensitive Urban Design (WSUD); concept. A multi-criteria decision analysis of WSUD options was carried out by Xu et al. (2025) at the "Parkville campus". The team assessed green infrastructure combinations according to social, economic, environmental, and functional criteria. Their findings supported the efficiency of integrated stormwater management strategies that also provided co-benefits such as enhanced biodiversity, air quality, and urban cooling (Zeleňáková, 2021).

Maintaining sustainable hydrological cycles

Urbanization increases surface runoff and decreases infiltration, disrupting the natural water cycle. Sustainable hydrological management aims to safeguard ecological balance, recharge aquifers, and restore natural flow channels. This requires a comprehensive knowledge of urban planning, hydrology, and land use.

Enhancing the layers of bioretention media is one of the major strategies for preserving sustainable hydrological cycles Yang et al. (2020) underlined the significance of each structural layer: drainage, transition, and filter to retain runoff and enhance water quality in the sponge cities. The results of their study showed that well-designed bioretention systems efficiently remove heavy metals and nutrients while also reducing peak flows (Yang et al., 2020).

Sustainable water management is further supported by the application of prediction models. Proactive decision-making is made possible by precise forecasting of runoff dynamics and rainfall patterns. The significance of high-resolution spatial rainfall data for comprehending urban hydrology and flood management was emphasized (Maier et al., 2020).

Biological aspects of Sponge Cities

Biological aspects of sponge cities concern the vegetation, trees, man-made green spaces, and bio-engineered water management systems. The technical terms which are used to express these biological aspects are often termed as green roofs, eco walls, rain gardens, constructed wetlands, permeable roads, bioswales and detention basins, rainwater harvesting, soil amendments and planting strategies, urban forest parks etc. in sponge city catalogues. The main components in sponge cities are summarized in Table 01.

Urban heat island mitigation is one of the most important achievements of sponge cities. The cities become significantly warmer than the surrounding rural areas because of the impervious surfaces (concrete), which hinder evapotranspiration. The sponge cities provide a successful solution to most cities with the urban heat island effect, and provide a more comfortable urban environment to residents. Urban forests, constructed wetlands, and green rooftops provide habitats for urban wildlife, including birds, small mammals, and insects, which help to increase biodiversity and ecosystem resilience (Knapp et al., 2019).

Table 01: Biological components of a sponge city

The green infrastructure	Description/ Importance	References
Eco walls	Different plants are used to cover the cement walls. They help to either evaporate rainwater through plants or infiltrate into the soil.	(Vashishta et al., 2024)
Rain gardens	They are depressions made in soil that help rainwater to infiltrate, by allowing replenishment of groundwater supplies.	(Orta-Ortiz and Geneletti, 2021)
Rainwater harvesting units	Modified tank-like structures, which are designed to capture and store rainwater using bioengineering techniques	(Ujma et al., 2023)
Constructed wetlands	Bio-engineered, artificially modified wetlands, which absorb excess water and runoff, and filter contaminants from water and plants to absorb excess nutrients	(Stefanakis, 2019)
Urban forests and green spaces	Bio-engineering system that helps to enhance the soil condition and the overall water absorption and retention capacity	(Palermo et al., 2023)

The health and well-being of the urban residents are also addressed by the biological aspects. The physical and mental health of the residents is directly connected with the surrounding environment. The sponge cities provide recreational opportunities and a better environment to exercise, relax, and connect with nature, improving the physical activities instead of the dull, dusty, hot, and monotonous concrete world in other cities. Therefore, the quality of life is higher in sponge cities, resulting in driving towards better social cohesion, mental relaxation, and reducing stress (Xu et al., 2025).

Sponge cities have higher aesthetic and cultural value compared to traditional urban landscapes. Vegetation in sponge cities improves the aesthetic value and makes it visually appealing. These cities become more attractive and appealing to live and work with higher aesthetic beauty and scenic spots, which improve the overall feeling of the city (Wang et al., 2022).

Carbon sequestration in the sponge cities is comparatively high compared to traditional cities. The sponge management plans could focus on the use of wetland and street trees with high carbon sequestration potential to enhance the amount of carbon removed from the urban atmosphere (Richter et al., 2024).

Global development of Sponge Cities

Integration of sponge city with modern technologies (IoT and AI)

The "Sponge City" concept has developed rapidly with the interaction of modern technology, revolutionizing how Sponge Cities are implemented and managed. The impact of IoT (Internet of Things) and AI (Artificial Intelligence) is important in the efficient management of sponge cities (Shao et al., 2016).

Real-time monitoring is an important aspect of IoT. It provides real-time monitoring of water levels in retention ponds, weather patterns in the vicinity of the sponge city, soil moisture, the condition of green roofs and permeable pavements, etc. Furthermore, IoT supports continuous and accurate data collection, which enables real-time adjustments and enhances adaptive urban planning in sponge city infrastructure. Implementation of smart drainage systems can help adjust the flow direction and capacity of the water inside the sponge city, especially during heavy rainfall events. These AI-powered drainage systems optimize the efficiency of drainage systems, ensuring that water is diverted efficiently and quickly to prevent floods (Qi et al., 2020).

Predictive flood modelling using AI and Geographic Information Systems (GIS) is highly popular in advanced sponge cities. Flood risks and the behaviour of stormwater are modelled using past and real-time data and are used to predict future trends associated with flood intensity and duration. In China, AI is used in pilot Sponge Cities of the "Wuhan flagship sponge city pilot project" to enhance the design of green infrastructure (Qi et al., 2020) and decrease urban flooding by 20% within 5 years. Some advanced algorithms were developed to manage urban water flows and identify optimum locations for sponge infrastructure. In Singapore, the smart water sensors and AI are incorporated to manage the "Active, Beautiful, Clean Waters (ABC Waters) program in the sponge cities (Neo et al., 2022).

Policy frameworks and governance

Robust governance bodies alongside comprehensive policy frameworks are vital for the success of Sponge Cities. Multidisciplinary approaches adopted by other countries are based on the specific contextual environment of the country, including socioeconomic factors, political standing, and other critical elements.

For instance, China endeavors to meet its targets on national policies as encapsulated by its National Sponge City Policy issued in 2015. This policy sets a deadline for 2030 to strive for 80% of urban areas to be capable of storing and reabsorbing a minimum of 70% of rainwater (Chikhi et al., 2024). These initiatives are often supported by large amounts of funding, reflecting the level of support such initiatives receive through the government and how directives at the national level are likely to be enforced in a controlled manner across multiple cities.

At the European Union, the Water Framework Directive emphasizes the importance of application of nature-based solutions as well as sustainable urban drainage systems (SUDS) to develop sponge cities. The governance in the EU tends to have a bottom-up approach and involves other major constituents, like local community members, in the planning and operational stages of water-sensitive urban designs (Zhou et al., 2019). In Copenhagen, Denmark, the action plan called the "Cloudburst Management Plan" was implemented to integrate blue-green infrastructure in sponge cities to handle storm events for the next 100 years effectively (Brears, 2023).

The approach is also adopted in the United States, in which the Environmental Protection Agency (EPA) is driving forward a Green Infrastructure Strategy to better manage stormwater in urban planning to promote the green city concept. In New York City, the "green infrastructure program" was initiated to manage stormwater and reduce Combined Sewer Overflows using rain gardens with real-time sensor-based monitoring systems (Nguyen et al., 2019). This involves the incorporation of green roofs, permeable pavements, and rain gardens that imitate floodplains.

Drawbacks of Sponge Cities

Integration of the sponge city features may also pose some challenges. Retrofitting and initial construction costs are quite prohibitive at first, especially in mid-developed countries or in densely populated areas. Maintenance is yet another challenge with infrastructure. Green solutions need active, regular care and effort if they are to function as intended. In some specific areas, a lack of technical knowledge stifles designing, monitoring, and managing sponge systems. In dense urban zones, there can also be issues concerning how the land is used.

Sri Lankan scenario

Flood management challenges and the need for sponge cities in Sri Lanka

Flooding is the most frequent natural disaster in Sri Lanka (Ali and Mannakkara, 2024), impacting a large percentage of the population, livelihoods, and property (UNDRR, 2019). Sri Lanka is highly vulnerable to floods due to its geographical location, tropical climate, monsoon seasons, and complex river systems (Dasandara et al., 2022). Most of the populated urban areas, especially in the Colombo District, are subjected to flood hazard-associated environmental and social risks. Impervious surfaces such as paved roads, concrete yards, and highways prevent the draining of water into the earth, causing flash floods over the cities in the past decades (Jayawardena and Van Roon, 2017; Nethmika and Mahanama, 2023). Illegal settlements constructed closer to the flood plain areas, and some modifications of the hydrological process make urban cities more vulnerable to floods (Dasandara et al., 2022).

Structural measures play a crucial role in flood management in Sri Lanka. Dams, improved levee designs, flood walls, seawalls, diversions, drainage systems and channel improvements, spillways, flap gates, pump stations, and flood tunnels are identified as some of the existing structural flood management measures in Sri Lanka (Sivakumar, 2015; Vijayarajah, 2023). However, presently, the performance of these measures has become slightly poor, increasing the impact of floods day by day due to many types of issues such as aging of structural measures, malfunctioning systems, water flow blockages, leakages, insufficient capacity, construction faults, etc. (Dasandara et al., 2022). The growing frequency and severity of flood events and issues with traditional grey structures emphasize the need for innovative, sustainable, and adaptive solutions in Sri Lanka. In this context, the sponge city concept (SCC) provides a better alternative to manage floods than traditional methods.

Potential for implementation of sponge cities in Sri Lanka

SCC is a nature-based, cost-effective climate change solution, and it provides more value than grey infrastructure (Nethmika and Mahanama, 2023). Hence, the application of the sponge city concept is particularly valuable for a country like Sri Lanka, which is facing a severe economic crisis and has a wealth of natural resources. This concept aligns with Sri Lanka's goals under frameworks like the Sendai Framework for Disaster Risk Reduction, the National Adaptation Plan (NAP), and the Sustainable Development Goals (SDGs), particularly SDG 11 on building sustainable cities and SDG 13 on climate action.

A study that was conducted by integrating sponge city elements with existing flood control projects in the Weras Ganga Basin to enhance flood resilience in Sri Lanka (Nethmika and Mahanama, 2023). In this study, key processes in SCC (infiltration, storage, bio-retention, detention, purification, and drainage systems) were implemented in the Weras Ganga Development Plan to control the flood in five flood-prone areas, namely, "Boralesgamuwa, Bellanwila, Rattanapitiya, Bokundara, and Delkanda". Implementation of SSC concepts in the study has proved to be successful in terms of the decreased flood level, duration, and exposure in the affected areas.

Advantages for the country

Adopting the SCC in Sri Lanka can offer a wide range of benefits. Flood mitigation by enhancing water absorption and storage is the major advantage, as it helps to reduce the damage to people, livelihoods, and property by decreasing flood severity and frequency. In addition to flood mitigation, permeable surfaces improve groundwater recharge, ensuring water availability by allowing more infiltration. Wetlands and lagoons naturally filter polluted water before releasing it into rivers, streams, and aquifers, thereby improving water availability. Creation of green spaces such as parks, green roofs, and rain gardens supports urban biodiversity, improves air quality, reduces urban heat, makes cities cooler, and offers recreational areas for communities. These nature-based approaches increase climate resilience to adaptability to extreme weather events such as heavy rains. As Sri Lanka faces financial limitations in implementing large-scale grey infrastructure, sponge cities offer a more affordable and environmentally sustainable solution in flood mitigation and control of associated environmental and health risks.

Challenges in adopting sponge city strategies

Although the SCC is a cost-effective solution in the long term, the initial investment required for planning and constructing large-scale green infrastructure projects can be challenging due to limited funding and high levels of debt in Sri Lanka. Furthermore, the limited awareness among policymakers, stakeholders, and the public regarding this concept is a challenge in the introduction and implementation of this relatively new concept in Sri Lanka. This limited understanding may hinder community support as well. A shortage of technical expertise and institutions for designing and maintaining green infrastructure can also be a challenge. However, these challenges can be successfully addressed through knowledge and funding collaborations with the developed countries who are successfully implementing the sponge city concept and by applying for funding from the donor organizations and potential investors, who are willing to conduct carbon offsetting projects in developing countries in South Asia.

References

Ali RA & Mannakkara S (2024). International Journal of Disaster Risk Reduction Phased post-disaster recovery challenges: 2016 – 2017 floods and landslides in Colombo and Kalutara, Sri Lanka. *International Journal of Disaster Risk Reduction* 111, 104728. https://doi.org/10.1016/j.ijdrr.2024.104728

Brears RC (2023). Amsterdam Becoming a Blue-Green City Through Blue-Green Infrastructure, in: Blue and Green Cities. Springer International Publishing, Cham, pp. 99–114. https://doi.org/10.1007/978-3-031-41393-3_5

Chikhi F, Li C, Ji Q & Zhou X (2024). Advancing Sponge City Implementation in China: The Quest for a Strategy Model. *Water Resources Management* 38, 2251–2277. https://doi.org/10.1007/s11269-024-03784-1

Dasandara M, Ernst R, Kulatunga U & Rathnasiri P (2022). Investigation of Issues in Structural Flood Management Measures in Sri Lanka. *Journal of Construction in Developing Countries* 27(1), 65–78. https://doi.org/10.21315/jcdc2022.27.1.4

Deng Y, Deng J & Zhang C (2022). Sponge City and Water Environment Planning and Construction in Jibu District in Changde City. *Sustainability* 15, 444. https://doi.org/10.3390/su15010444

Gündel H & Önaç AK (2023). Sponge City Based on Blue–Green Urbanism, in: 7th International Students Science Congress Proceedings Book. Presented at the 7th International Students' Science Congress, Izmir International Guest Students Association. https://doi.org/10.52460/issc.2023.053

Jayawardena HMIDP & Van Roon M (2017). Water sensitive planning and design as an ecologically inspired approach to delivering flood resilient urban environment in Sri Lanka. *Water Practice and Technology* 12, 964–977. https://doi.org/10.2166/wpt.2017.100

Knapp S, Schmauck S & Zehnsdorf A (2019). Biodiversity Impact of Green Roofs and Constructed Wetlands as Progressive Eco-Technologies in Urban Areas. *Sustainability* 11, 5846. https://doi.org/10.3390/su11205846

Liao KH, Deng S & Tan PY (2017). Blue-Green Infrastructure: New Frontier for Sustainable Urban Stormwater Management, in: Tan, P.Y., Jim, C.Y. (Eds.), Greening Cities, Advances in 21st Century Human Settlements. Springer Singapore, Singapore, pp. 203–226. https://doi.org/10.1007/978-981-10-4113-6_10

Liu Q, Cui W, Tian Z, Tang Y, Tillotson M & Liu J (2022). Stormwater Management Modeling in "Sponge City" Construction: Current State and Future Directions. *Front. Environ. Sci*. 9, 816093. https://doi.org/10.3389/fenvs.2021.816093

Maier R, Krebs G, Pichler M, Muschalla D & Gruber G (2020). Spatial Rainfall Variability in Urban Environments—High-Density Precipitation Measurements on a City-Scale. *Water* 12, 1157. https://doi.org/10.3390/w12041157

Neo TH, Xu D, Fowdar H, McCarthy T, Chen EY, Lee TM, Ong GS, Lim FY, Ong SL & Hu J (2022). Evaluation of Active, Beautiful, Clean Waters Design Features in Tropical Urban Cities: A Case Study in Singapore. *Water* 14, 468. https://doi.org/10.3390/w14030468

Nethmika TAT & Mahanama PKS (2023). Study on the applicability of sponge city concept to flood resilient in Sri Lankan cities: Boralesgamuwa and Sub Urban Areas. *FARU Journal* 10, 59–72. https://doi.org/10.4038/faruj.v10i1.192

Nguyen TT, Ngo HH, Guo W, Wang XC, Ren N, Li G, Ding J & Liang H (2019). Implementation of a specific urban water management - Sponge City. *Science of The Total Environment* 652, 147–162. https://doi.org/10.1016/j.scitotenv.2018.10.168

Orta-Ortiz MS & Geneletti D (2021). Reviewing the Performance of Nature-Based Solutions for Stormwater Management in Urban Areas, in: La Rosa, D., Privitera, R. (Eds.), Innovation in Urban and Regional Planning, Lecture Notes in Civil Engineering. Springer International Publishing, Cham, pp. 15–22. https://doi.org/10.1007/978-3-030-68824-0_2

Palermo SA, Turco M, Pirouz B, Presta L, Falco S, De Stefano A, Frega F & Piro P (2023). Nature-based solutions for urban stormwater management: an overview. IOP Conf. Ser.: Earth Environ. Sci. 1196, 012027. https://doi.org/10.1088/1755-1315/1196/1/012027

Qi Y, Chan FKS, Thorne C, O'Donnell E, Quagliolo C, Comino E, Pezzoli A, Li L, Griffiths J, Sang Y & Feng M (2020). Addressing Challenges of Urban Water Management in Chinese Sponge Cities via Nature-Based Solutions. *Water* 12, 2788. https://doi.org/10.3390/w12102788

Richter M, Heinemann K, Meiser N & Dickhaut W (2024). Trees in Sponge Cities—A Systematic Review of Trees as a Component of Blue-Green Infrastructure, Vegetation Engineering Principles, and Stormwater Management. *Water* 16, 655. https://doi.org/10.3390/w16050655

Saliba SM, Bowes BD, Adams S, Beling PA & Goodall JL (2020). Deep Reinforcement Learning with Uncertain Data for Real-Time Stormwater System Control and Flood Mitigation. *Water* 12, 3222. https://doi.org/10.3390/w12113222

Shao W, Zhang H, Liu J, Yang G, Chen X, Yang Z & Huang H (2016). Data Integration and its Application in the Sponge City Construction of CHINA. *Procedia Engineering* 154, 779–786. https://doi.org/10.1016/j.proeng.2016.07.583

Sivakumar SS (2015). Flood Mitigation Strategies Adopted in Sri Lanka A Review. *International Journal of Scientific & Engineering Research* 6.

Stefanakis A (2019). The Role of Constructed Wetlands as Green Infrastructure for Sustainable Urban Water Management. *Sustainability* 11, 6981. https://doi.org/10.3390/su11246981

Ujma A, Iremashvili I & Tsutsqiridze M (2023). The Need To Connect Buildings With The Natural Environment and Rainwater Retention in Modern Construction.

UNDRR (2019). Disaster Risk Reduction in Sri Lanka.

Vashishta N, Gupta H & Bhargava B (2024). Green Walls, Green Roofs, and Urban City Landscapes as Nature-Based Ecological Solutions, in: Bhargava, B., Kumar, P., Verma, V. (Eds.), Ornamental Horticulture: Latest Cultivation Practices and Breeding Technologies. Springer Nature Singapore, Singapore, pp. 275–293. https://doi.org/10.1007/978-981-97-4028-4_15

Vijayarajah S (2023). Flood risk management adaptation strategies in sri lanka, in: Regional Symposium on Disaster Risk Management-2021.

Wang R, Wu H & Chiles R (2022). Ecosystem Benefits Provision of Green Stormwater Infrastructure in Chinese Sponge Cities. *Environmental Management* 69, 558–575. https://doi.org/10.1007/s00267-021-01565-9

Wang Z, Lou Y, Zhang B & Shi B (2020). Thoughts and Strategies of Sponge City Construction Planning: A Case Study of Pingxiang, Jiangxi Province. *OJCE* 10, 43–54. https://doi.org/10.4236/ojce.2020.101005

Xu Z, Marini S, Mauro M, Maietta Latessa P, Grigoletto A & Toselli S (2025). Associations Between Urban Green Space Quality and Mental Wellbeing: Systematic Review. *Land* 14, 381. https://doi.org/10.3390/land14020381

Yang F, Fu D, Liu S, Zevenbergen C & Singh RP (2020). Hydrologic and Pollutant Removal Performance of Media Layers in Bioretention. *Water* 12, 921. https://doi.org/10.3390/w12030921

Zeleňáková M (2021). Urban Rainwater and Flood Management. *Water* 13, 974. https://doi.org/10.3390/w13070974

Zhou M, Köster S, Zuo J, Che W & Wang X (2019). Cross-boundary Evolution of Urban Planning and Urban Drainage Towards the Water Sensitive "Sponge City," in: Köster, S., Reese, M., Zuo, Jian'e (Eds.), Urban Water Management for Future Cities, Future City. Springer International Publishing, Cham, pp. 303–329. https://doi.org/10.1007/978-3-030-01488-9_14

CHAPTER 02

Microbial Strategies for Enhancing Soil Health and Sustainable Agriculture

C.Y. Amarasinghe* and C.M. Nanayakkara

Department of Plant Sciences, Faculty of Science,
University of Colombo, Colombo 03, Sri Lanka.
** Chalani.yashodya@gmail.com*

Abstract

There is an estimated number of >450,000 species of land plants on earth and their life primarily depends on soil for nutrient and water supply. Additionally, soil provides other services such as shaping the rhizosphere microbial diversity, aerating the roots, sequestering soil carbon, etc. Hence, soil health is an integrated aspect of plant health. Soil health is described as its ability to support sustainable plant growth, maintain or enhance soil water and air, and sustain a healthy soil microbiome. Healthy soil is considered as a stable living environment that enables all essential biological processes through maintaining a diverse community of soil organisms, known as soil microbiome, that mediate nutrient cycling, control plant pathogens, pests, and weeds, and form beneficial symbiotic associations with plant roots. Further, soil microbiome contributes to improving soil physical and chemical characteristics, facilitating plant growth. The current world population of 8.2 billion is projected to reach 9.6 billion in 2050, making food security a prime goal for world economies. Soil degradation is recognized as a silent global crisis that jeopardizes global agriculture. To address this, microbial strategies such as bioremediation, biofertilizers, biocontrol agents, and bioaugmentation are increasingly important. These approaches degrade contaminants, restore fertility, and alleviate stresses such as heavy metal toxicity, pesticide residues, and salinity, while reinforcing soil microbial diversity. In this chapter, we highlight the role of such microbial innovations in sustaining soil health for long-term agricultural productivity.

Keywords: Biofertilizer, Bioremediation, Soil health, Soil microbial activity

Introduction

Soil health forms the foundation of terrestrial life and is pivotal for maintaining the integrity of agroecosystems. Healthy soil is characterized by its ability to function as a living ecosystem that sustains plants, animals, and humans. It supports plant growth, facilitates efficient nutrient cycling, stores and filters water, resists erosion, suppresses plant diseases, and buffers against environmental stressors (NRCS, 2021). However, in recent decades, soil health has been critically undermined by unsustainable agricultural practices such as excessive tillage, monoculture cropping, overuse of chemical inputs, and inadequate organic matter replenishment (FAO, 2015). In response to the growing challenges of soil degradation, biodiversity loss, and the environmental impact of conventional farming, sustainable agriculture has emerged as a universal approach that seeks to optimize productivity while preserving environmental quality and enhancing the use of natural resources (FAO, 2015).

A range of microbial-based strategies such as nitrogen-fixing bacteria, phosphate and potassium solubilizing microbes, mycorrhizal fungi, lactic acid bacteria, and plant growth-promoting rhizobacteria (PGPR), etc. have gained prominence as ecologically sound solutions for restoring and maintaining soil health. Beyond biofertilizers, these include biocontrol agents, composting microbes, and bioremediation technologies (Bhardwaj et al., 2014). Such innovations harness the capabilities of beneficial microorganisms such as nitrogen-fixing bacteria, phosphate and potassium solubilizing microbes, mycorrhizal fungi, lactic acid bacteria, and plant growth-promoting rhizobacteria (PGPR) to improve nutrient availability, suppress pathogens, enhance soil structure, and increase plant resilience.

Soil health

Soil health is the continued capacity of soil to function as a vital, living ecosystem that sustains plants, animals, and humans, making it a foundational element in sustainable agriculture (USDA NRCS, 2024). It encompasses a range of physical, chemical, and biological properties that collectively determine how well soil can support life and ecosystem services. Healthy soil regulates water by influencing infiltration and reducing runoff, sustains diverse plant and animal life through its nutrient and microbial networks, filters and buffers potential pollutants via mineral and microbial interactions, cycles essential nutrients such as carbon, nitrogen, and phosphorus, and provides physical stability for plant roots and human infrastructure (USDA NRCS, 2024).

However, poor agricultural practices like excessive tillage, compaction, and salinization can degrade soil health and reduce its capacity to function (Baumhardt et al., 2015). These actions disrupt microbial networks, diminish soil structure, and lead to nutrient imbalances, which ultimately threaten crop yields and ecosystem integrity. Therefore, maintaining and restoring soil health is not only essential for food security and agricultural productivity but also for environmental sustainability and the long-term well-being of both natural and human systems (USDA NRCS, 2024).

Sustainable agriculture

Sustainable agriculture is a general approach to farming that aims to meet current food and fiber demands without compromising the ability of future generations to meet their own needs (Doval, 2023). This approach is underlined by a set of interrelated practices designed to maintain and improve soil health, increase productivity, and reduce negative environmental impacts (SARE, 2025). Crop rotation enhances soil structure and nutrient supply while breaking the cycles of pests and diseases. Integrated pest management (IPM) combines biological control methods, cultural practices, and minimal use of chemical pesticides to manage pests sustainably (Angon et al., 2023). Cover cropping with non-cash crops enhances soil organic matter, prevents erosion, and suppresses weeds. No-till or reduced tillage practices minimize soil disturbance, conserving moisture and supporting microbial diversity. Water conservation techniques such as drip irrigation, mulching, and rainwater harvesting are employed to optimize water use (FAO, 2021). At the same time, reduced reliance on synthetic fertilizers and pesticides limits environmental pollution and promotes beneficial soil organisms.

Bridging soil health and sustainable agriculture

Sustainable agriculture and soil health are deeply interconnected and mutually reinforcing components of a resilient land management system. While sustainable agriculture provides a comprehensive framework for managing land in ways that are environmentally sound, socially responsible, and economically viable, soil health represents the ecological backbone that enables these goals to be achieved across diverse landscapes and purposes, not just in food production (FAO, 2020). Healthy soils perform critical ecosystem functions, including regulating water flow, enhancing groundwater recharge, sequestering atmospheric carbon, recycling organic matter and nutrients, filtering pollutants, and sustaining rich biodiversity (van Leeuwen et al., 2017). By placing soil health at the center of sustainable agriculture and land stewardship strategies, we move toward systems that not only sustain productivity but also regenerate ecological functions (Kibblewhite et al., 2008).

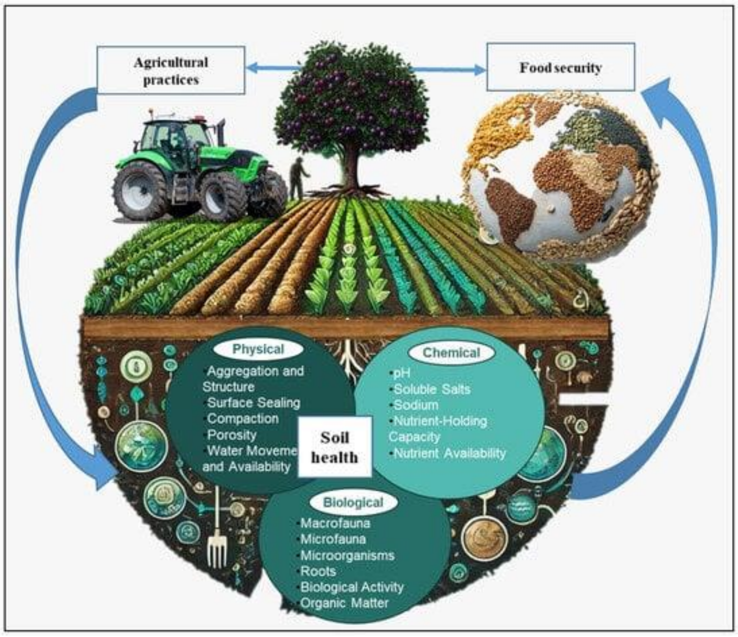


Figure 01. Interconnections between soil health, agricultural practices, and food security.

(Source: Țopa et al., 2025)

Soil microbiome: The living engine of soil

The soil microbiome is the diverse community of microorganisms; bacteria, fungi, archaea, protozoa, and actinomycetes that inhabits the soil environment and plays a pivotal role in sustaining life on Earth (Fierer, 2017). This complex and dynamic ecosystem underpins soil health and plant productivity by driving essential ecological functions such as nutrient cycling, organic matter decomposition, soil structure maintenance, and disease suppression (Delgado-Baquerizo et al., 2018).

Among the key functions of the soil microbiome is nutrient cycling. Nitrogen-fixing bacteria such as *Rhizobium, Azospirillum*, and *Azotobacter* convert atmospheric nitrogen into ammonia, making this vital nutrient available to plants (Kuypers et al., 2018). Meanwhile, phosphate-solubilizing genera like *Bacillus* and *Pseudomonas* mobilize insoluble phosphorus compounds, increasing their bioavailability to crops (Sharma et al., 2013). Fungi and actinomycetes contribute by breaking down complex organic molecules such as lignin and cellulose, thereby promoting humus formation and carbon recycling in the soil (Singh & Satyanarayana, 2011). In addition, certain soil microbes produce extracellular polymeric substances (EPS), which aid in the aggregation of soil particles, improving porosity, water retention, and overall soil structure (Costa et al., 2018).

The rhizosphere, enriched by root exudates, the rhizosphere supports intense microbial activity and interaction, with the highest microbial diversity typically found near the rhizoplane (the root surface) (Berendsen et al., 2012). Here, microbial populations thrive and engage in nutrient exchange, signaling, and symbiosis, directly impacting plant health. Arbuscular mycorrhizal fungi (AMF), for instance, form symbiotic relationships with plant roots that significantly enhance water and nutrient uptake, particularly phosphorus, and boost resistance to biotic and abiotic stressors (Smith & Read, 2008). Species like *Bacillus subtilis* produce antimicrobial compounds such as iturins and surfactins that suppress pathogenic organisms, while competitive exclusion in the rhizosphere limits the establishment of harmful microbes (Ongena & Jacques, 2008). Long-term maintenance of such practices by plants leads to the development of a soil that resists pathogen colonization, a phenomenon depicted as disease-suppressive soils (Mendes et al., 2011).

Microbial strategies for enhancing soil health

Soil microbes play essential roles in nutrient cycling, disease suppression, organic matter decomposition, and pollutant breakdown. By using specific microbial strategies, we can support and restore the natural functions of soil ecosystems in sustainable ways.

Biofertilizers

Biofertilizers are formulations containing live or latent strains of beneficial microorganisms that promote plant growth by enhancing nutrient availability and stimulating root development (Yashavantha Rao et al., 2020). These microbial inoculants offer an environmentally friendly alternative to synthetic chemical fertilizers, contributing to long-term soil fertility and agricultural sustainability. The primary groups of plant growth-promoting rhizomicroorganisms (PGPR) used as biofertilizers include species from genera such as *Azospirillum*, *Bacillus*, *Rhizobium*, *Paenibacillus*, and *Streptomyces*, which exhibit a wide array of functional traits. One of the most vital functions of these microorganisms is nitrogen fixation (Sharma et al., 2020). For instance, symbiotic bacteria such as *Rhizobium* and *Frankia* form root nodules with higher plants supply fixed nitrogen to the soil and plants. Endophytic and rhizospheric bacteria such as *Azotobacter*, *Azospirillum, Burkholderia, Herbaspirillum,* etc. readily assimilate nitrogen in plants and soil (Douglas, 2009; Elbeltagy et al., 2001).

In addition to nitrogen fixation, many biofertilizer strains improve phosphorus availability through the solubilization of insoluble phosphates. Microorganisms such as *Bacillus* and *Pseudomonas* produce organic acids and enzymes that convert insoluble forms of phosphorus into soluble forms absorbable by plants (Pradhan et al., 2025). Further, soil microbes also produce siderophores, the iron-chelating compounds, which enhance iron uptake and suppress pathogens by depriving them of essential micronutrients (Zang et al., 2023). Another vital contribution is the production of phytohormones like auxins, cytokinins, and gibberellins, which stimulate seed germination, root elongation, and overall plant vigor (Sharma et al., 2020).

Biofertilizers have proven to be effective in significantly reducing reliance on synthetic chemical fertilizers while maintaining crop productivity. In Sri Lanka, a microbial biofilm-based fertilizer, comprising *Azorhizobium caulinodans*, *Aspergillus* spp., and the flavonoid naringenin, enabled a 50% reduction in urea application for rice cultivation without any yield loss (Perera, 2017).

Table 01. Latest commercial biofertilizer products available in 2025

Product Name	Microorganism	Type	Application	Manufacturer
Bulkagrochem Biofertilizers	Rhizobium, Azotobacter, PSB, Mycorrhiza, NPK, KMB	Powder (Water Soluble & Insoluble), Liquid	Soil & Seed Treatment	Bulkagrochem
Symborg's Symbionts	Various (e.g., Azospirillum, Bacillus)	Liquid & Granular	Foliar Spray, Soil Application	Symborg Inc.
Koppert Biological Systems	Various (e.g., Rhizobium, Azotobacter, Trichoderma)	Liquid & Granular	Soil & Seed Treatment	Koppert Biological Systems
Lallemand Plant Care	Various (e.g., Rhizobium, Azospirillum)	Liquid & Granular	Soil & Seed Treatment	Lallemand Inc.
Novozymes BioAg	Various (e.g., Rhizobium, Azotobacter)	Liquid & Granular	Soil & Seed Treatment	Novozymes
AgriLife Biofertilizers	Various (e.g., Rhizobium, Azotobacter)	Liquid & Granular	Soil & Seed Treatment	AgriLife
Suståne Natural Fertilizer	Various (e.g., Rhizobium, Azotobacter)	Granular	Soil Application	Suståne Natural Fertilizer Inc.
Indogulf BioAg	Various (e.g., Rhizobium, Azotobacter)	Liquid & Granular	Soil & Seed Treatment	Indogulf BioAg LLC
Kula Bio	Various (e.g., Rhizobium, Azotobacter)	Liquid & Granular	Soil & Seed Treatment	Kula Bio Inc.
Rizobacter	Various (e.g., Rhizobium, Azotobacter)	Liquid & Granular	Soil & Seed Treatment	Rizobacter

Biocontrol agents

Biocontrol agents are beneficial microorganisms that protect plants from soil-borne diseases and pathogens through various mechanisms. Prominent biocontrol agents include bacteria such as *Bacillus subtilis* and *Pseudomonas fluorescens*, and fungi like *Trichoderma harzianum*. These organisms suppress plant pathogens through antibiosis, competition, induced resistance, and direct parasitism (Choudhaker et al. 2024).

In antibiosis, microbes produce bioactive compounds that inhibit or kill pathogens. For example, *Bacillus subtilis* secretes lipopeptides like fengycins and surfactins, while *Pseudomonas fluorescens* produces phenazines and pyoluteorin that inhibit fungal and bacterial invaders (Triasih et al., 2021). Competition for space and nutrients is another important mechanism: effective colonization of root surfaces by beneficial microbes prevents the establishment of pathogenic species by occupying available niches and consuming limiting nutrients (Waghunde et al., 2021). Biocontrol agents also induce systemic resistance (ISR) in plants, enhancing their innate immune responses. For example, *Bacillus amyloliquefaciens* triggers the expression of defense-related genes in host plants, preparing them to respond more effectively to pathogen attacks.
In addition to controlling plant diseases, biocontrol agents, referred to as plant probiotics, significantly enhance plant growth and productivity (Dimopoulou et al., 2019; Harutyunyan et al., 2022). These beneficial microorganisms promote nutrient uptake, improve root architecture, and stimulate favorable interactions within the rhizosphere. As plant probiotics, they help maintain a balanced soil microbiome, reduce dependency on chemical pesticides, and minimize the accumulation of harmful residues in soil and water. Hence, their integration into crop management strategies supports the development of sustainable and ecologically resilient farming systems (Kaur et al., 2017)

Bioremediation and bioaugmentation

Bioremediation is a strategy that employs living organisms, primarily microorganisms and plants, to detoxify, degrade, or immobilize pollutants in contaminated soils. This approach is widely used to address pollutants such as heavy metals, pesticides, hydrocarbons, and industrial chemicals. Microorganisms play a central role in microbial bioremediation. *Pseudomonas putida* is known for its exceptional metabolic versatility, allowing it to degrade a wide array of xenobiotics including petroleum-based compounds and synthetic pesticides (Upadhyay et al., 2020). Fungi such as *Aspergillus niger* also contribute to soil remediation by binding and immobilizing heavy metals like cadmium (Cd), lead (Pb), and arsenic (As) through biosorption and bioaccumulation processes (Upadhyay et al., 2020).

Bioaugmentation is a technique that specifically involves the deliberate addition of effective microbial strains, either native or genetically engineered, into contaminated environments (Omokhagbor et al., 2020). These strains are either selected or engineered to make them highly efficient in degrading or detoxifying specific pollutants. Bioaugmentation has been successfully applied in sites impacted by oil spills, industrial effluents, and excessive agrochemical use (Upadhyay et al., 2020).

Composting for organic waste management

Microorganisms, particularly thermophilic bacteria and saprophytic fungi are essential agents in composting processes that convert organic waste into stable, nutrient-rich compost. During aerobic composting, microbes break down complex organic materials like kitchen waste, crop residues, and animal manure into the humus, a stable organic material that improves soil texture, water retention, and nutrient availability (Waqas et al., 2023). Thermophilic bacteria such as *Bacillus* spp. thrive at high temperatures during the active phase of composting, rapidly degrading proteins, fats, and cellulose. Fungi, including *Aspergillus* and *Trichoderma* spp., specialize in breaking down lignin and other recalcitrant compounds, facilitating the decomposition of tougher plant materials (Rawool et al., 2020). The incorporation of Effective Microorganisms (EM), a mixed culture of beneficial microbes including *Lactobacillus*, *Saccharomyces*, and photosynthetic bacteria, has been found to significantly accelerate the composting process. These microbes improve the fermentation of organic matter, reduce foul odors, and enrich the compost with bioactive compounds that support soil and plant health (Rawool et al., 2020).

Emerging technologies and approaches

Advancements in biotechnology and computational sciences have introduced innovative tools for optimizing microbial applications in soil health management. One such advancement is the development of custom-made microbial consortia for the augmentation of the soil microbiome. These are carefully designed communities of complementary microbial strains, often including nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and biocontrol agents. Unlike single-strain inoculants, mixed-designed microbial consortia leverage microbial synergy to perform multiple functions simultaneously, such as nutrient mobilization, pathogen suppression, and plant growth promotion (Santoyo et al., 2021). Co-inoculation strategies involving such consortia have shown enhanced rhizosphere colonization, improved nutrient bioavailability, and greater resilience to environmental fluctuations (Kumar et al., 2023).

Gene editing tools such as CRISPR have opened new frontiers in microbial biotechnology. By enabling precise editing of microbial genomes, researchers can enhance traits such as stress tolerance, biosynthesis of antimicrobial compounds, and metabolic efficiency (Dudeja et al., 2025). For example, CRISPR-Cas systems have been employed to engineer *Pseudomonas fluorescens* for the overproduction of phenazines, compounds known to suppress root pathogens (Singh et al., 2024). Artificial intelligence (AI) and machine learning (ML) technologies are also being integrated into soil microbiology to model and predict complex microbial interactions. By analyzing vast datasets from omics studies and field trials, AI algorithms can identify optimal microbial combinations, forecast their behavior in different soils, and guide precision applications (Zhang and Li, 2024).

Merging traditional knowledge and indigenous microbes for innovative practices

To effectively merge traditional wisdom with contemporary microbiological techniques, systematic documentation of these practices is essential. This involves examining integration strategies, determining how these inputs are applied in the field, assessing their application frequency and compatibility with crops, and evaluating the resulting agronomic outcomes (Deshmukh et al., 2021), conducting scientific validation of these traditional inputs through microbial profiling and nutrient analysis to assess their impacts on soil health and crop productivity (Chen et al., 2023). Developing integrated protocols that combine these traditional approaches with modern bioformulations to create region-specific, ecologically sound solutions is a timely action (Lee et al., 2021).

Conclusion

Microbial strategies are no longer optional enhancements in agriculture, they are fundamental to building farming systems that are resilient, efficient, and environmentally sustainable. Beneficial soil microbes play indispensable roles in supporting plant health, from making nutrients more available and protecting against diseases to help reclaim degraded land and improve crop resilience under stress. Thanks to advances in biotechnology, omics-based research, and precision agriculture tools like artificial intelligence, our understanding of soil microbes has reached unprecedented levels. These technologies now allow us to not only explore microbial communities in great detail but also to design and apply tailored microbial formulations with greater accuracy and purpose. At the same time, traditional agricultural knowledge continues to offer valuable, cost-effective, and environmentally friendly

References

Angon PB, Rahman MA, Chowdhury MAH, Hasan MK, Roy DC, Ahmed M, Hoque MM, Mahmud MS, Rahman MA, Rahman M, Sultana S, Hossain MF & Rahman MM (2023). Integrated pest management (IPM) in agriculture and its role in maintaining ecological balance and biodiversity, *Advances in Agriculture*, pp. 1–19.

Baumhardt R, Stewart B & Sainju U (2015). North American soil degradation: processes, practices, and mitigating strategies. *Sustainability*, 7(3), pp. 2936–2960.

Berendsen RL, Pieterse CMJ & Bakker PAHM (2012). The rhizosphere microbiome and plant health. *Trends in Plant Science*, 17(8), pp. 478–486.

Bhardwaj D, Ansari MW, Sahoo RK & Tuteja N (2014). Biofertilizers function as key players in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. *Microbial Cell Factories*, 13(1), p. 66.

Chen L, Wang J & Zhao Q (2023). Evaluating traditional bioinputs through microbial and nutrient profiling. *Journal of Agricultural Microbiology*, 67(3), pp. 199–211.

Choudhaker M, Sharma S & Singh R (2024). Evaluation of bacterial biocontrol agents for disease suppression and plant growth promotion. *Frontiers in Microbiology*, 15, p. 1419547.

Costa OYA, Raaijmakers JM & Kuramae EE (2018). Microbial extracellular polymeric substances: ecological function and impact on soil aggregation. *Frontiers in Microbiology*, 9, p. 1636.

Delgado-Baquerizo M, Oliverio AM, Brewer TE, Benavent-González A, Eldridge DJ, Bardgett RD, Maestre FT, Singh BK & Fierer N (2018). A global atlas of the dominant bacteria found in soil. *Science*, 359(6373), pp. 320–325.

Deshmukh P, Rao S & Iyer M (2021). Documenting traditional microbial practices in agriculture: a roadmap to sustainable farming. *Agricultural Heritage Studies*, 9(1), pp. 45–58.

Dimopoulou A, Theologidis I, Typas MA & Karpouzas DG (2019). Bacillus amyloliquefaciens MBI600 differentially induces tomato defense signaling pathways depending on plant part and dose of application. *Scientific Reports*, 9(1), p. 3433.

Douglas AE (2009). Endosymbionts and intracellular parasites. *Encyclopedia of Microbiology*, pp. 128–141.

Doval, C.Y. (2023) What is sustainable agriculture?, *Sustainable Agriculture Research & Education Program.* Available at: https://sarep.ucdavis.edu/sustainable-ag

Dudeja C, Singh N, Mehra S, Ran, R, Saini R, Bhatia R, Beniwal V, Ghosh R, Yadav AN, Yadav N, Choudhary D, Kumar S, Tuteja N & Prabha R (2025). Microbial genome editing with CRISPR–Cas9: recent advances and emerging applications across sectors. *Fermentation*, 11(7), p. 410.

Elbeltagy A, Nishioka K, Suzuk H, Sato T, Sato YI, Morisaki H, Mitsui H & Minamisawa K (2001). Endophytic colonization and in planta nitrogen fixation by a *Herbaspirillum* sp. isolated from wild rice species. *Applied and Environmental Microbiology*, 67(11), pp. 5285–5293.

FAO (2015). *Status of the world's soil resources: main report*, Food and Agriculture Organization of the United Nations.

FAO (2020). *The state of food and agriculture 2020: overcoming water challenges in agriculture*, Food and Agriculture Organization of the United Nations.

FAO (2021). *The state of food and agriculture 2021: making agrifood systems more resilient to shocks and stresses*, Food and Agriculture Organization of the United Nations.

Fierer N (2017). Embracing the unknown: disentangling the complexities of the soil microbiome. *Nature Reviews Microbiology*, 15(10), pp. 579–590.

Harutyunyan N, Ghazaryan K, Ghazaryan S, Hovhannisyan A, Ghazaryan L, Hakobyan A & Sahakyan N (2022). One Health probiotics as biocontrol agents: One Health tomato probiotics. *Plants*, 11(10), p. 1334.

Kaur G, Reddy MS & Meena VS (2017). Plant probiotics: microbial inoculants for sustainable agriculture and environmental safety. In *Plant–Microbe Interactions in Agro-Ecological Perspectives*, Springer, pp. 37–62.

Kibblewhite MG, Ritz K & Swift MJ (2008). Soil health in agricultural systems, *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1492), pp. 685–701.

Kumar R, Sharma V & Patel A (2023). Synthetic microbial consortia: A strategy for improved rhizosphere colonization and plant growth promotion. *Journal of Soil Biology*, 59(2), 112–125.

Kuypers MMM, Marchant HK & Kartal B (2018). The microbial nitrogen-cycling network. *Nature Reviews Microbiology*, 16, pp. 263–276.

Lee D, Fernando N & Yadav B (2021). Integrating indigenous knowledge and modern microbiology for low-input farming systems. *Ecological Agriculture*, 14(2), pp. 77–90.

Mendes R, Garbeva P & Raaijmakers JM (2011). The rhizosphere microbiome: significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms. *FEMS Microbiology Reviews*, 37(5), pp. 634–663.

NRCS (2021). *Soil health*, United States Department of Agriculture Natural Resources Conservation Service.

NRCS (2024). *Soil health*, United States Department of Agriculture Natural Resources Conservation Service.

Ongena M & Jacques P (2008). Bacillus lipopeptides: versatile weapons for plant disease biocontrol. *Trends in Microbiology*, 16(3), pp. 115–125.

Omokhagbor Adams G, Osemwengie O, Eguavoen I, Omoregie E & Egbe C (2020). Bioremediation, biostimulation and bioaugmentation: a review', *International Journal of Environmental Bioremediation & Biodegradation*, 3(1), pp. 28–39.

Perera TA, Tirimanne ST, Seneviratne G & Kulasooriya SA (2017). *Azorhizobium caulinodans* ORS 571–Aspergillus spp. biofilm in the presence of flavonoid naringenin: an extremely effective association for rice root colonization with a definite future as a nitrogen bio-fertilizer. *Indian Journal of Biochemistry and Biophysics*, 54(5), pp. 214–222.

Pradhan N, Rana A, Kumari S, Kumar R, Behera,D, Yadav AN, Kumar A, Rajawat M, Saxena AK, Ramesh A & Singh A (2025). A review on microbe–mineral transformations and their impact on plant growth. *Frontiers in Microbiology*, p. 1549022.

Rawool DB, Nimbalkar AS & Giri AP (2020). Effective microorganisms (EM) and their role in sustainable agriculture and waste management. *Environmental Sustainability*, 3(4), pp. 373–382.

Santoyo G, Moreno-Hagelsieb G, Orozco-Mosqueda MDC & Glick BR (2021). Plant growth stimulation by microbial consortia. *Agronomy*, 11(2), p. 219.

Sharma A, Johri BN & Sharma S (2020). Biofertilizers for sustainable agriculture: from production to application. *International Journal of Current Microbiology and Applied Sciences*, 9(2), pp. 2333–2346.

Sharma SB, Sayyed RZ, Trivedi MH & Gobi TA (2013). Phosphate solubilizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils. *SpringerPlus*, 2(1), p. 587.

Singh, A & Satyanarayana T (2011). Biodegradation of lignin and cellulose by fungi: potential for biomass utilization. *Applied Microbiology and Biotechnology*, 91, pp. 1007–1018.

Singh A, Mehta R & Kapoor D (2024). CRISPR-Cas mediated engineering of Pseudomonas fluorescens for enhanced biocontrol potential. *Microbial Biotechnology*, 17(1), pp. 33–45.

Smith SE & Read DJ (2008). *Mycorrhizal symbiosis*, 3rd edn, Academic Press, London.

Sustainable Agriculture Research and Education Program (2025) SARE. Available at: https://www.sare.org/

Țopa D-C, Căpșună S, Calistru A-E & Ailincăi C (2025). Sustainable Practices for Enhancing Soil Health and Crop Quality in Modern Agriculture: A Review. *Agriculture*, 15(9):998.

Triasih U, Nugroho YA & Widyaningsih S (2021). Antimicrobial activity of *Pseudomonas fluorescens* and *Bacillus subtilis* on different dilution concentrations against various citrus post-harvest pathogens. *Atlantis Press*.

Upadhyay S, Singh KP & Sharma R (2020). Bioremediation and bioaugmentation of contaminated soil: microbial approaches. *Applied Microbiology and Biotechnology*, 104, pp. 1233–1247.

UC Sustainable Agriculture Research and Education Program 2022, 'UC SAREP sustainable agriculture & food systems 2023–24 small grants program', *UC SAREP*.

Van Leeuwen JP, van der Putten WH, de Groot WJ & de Ruiter PC (2017). Gap assessment in current soil monitoring networks across Europe for measuring soil functions. *Environmental Research Letters*, 12(12), p. 124003.

Waghunde RR, Shelake RM, Sabalpara AN, Patel P & Malviya MK (2021). Application of cereal and vegetable endophytes in plant health management. *Microbiomes and Plant Health*, pp. 29–51.

Waqas M, Ahmad I, Hussain A, Khan A, Rehman A, Farooq A, Hassan M & Shahzad A (2023). Composting processes for agricultural waste management: a comprehensive review. *Processes*, 11(3), p. 731.

Yashavantha Rao HC, Chandra Mohana N & Satish S (2020). Biocommercial aspects of microbial endophytes for sustainable agriculture. *Microbial Endophytes*, pp. 323–347.

Zhang S, Li J, Wang Y, Chen Y, Liu H, Zhou X & Huang X (2023). Significance of soil siderophore-producing bacteria in evaluation and elevation of crop yield. *Horticulturae*, 9(3), p. 313.

Zhang Y & Li H (2024). Artificial intelligence in precision soil microbiology: modelling microbial interactions for sustainable agriculture. *Computational Agriculture*, 12(4), pp. 210–224.

CHAPTER 03

Bioremediation for Restoring Microplastic-Contaminated Environments

A.A.D.N. Thathsarani[1], R.S. Rajakaruna[2] and U.A. Jayawardena[1]*

Department of Zoology, Faculty of Natural Science,
The Open University of Nawala, Sri Lanka.[1]
Department of Zoology, Faculty of Science, University of Peradeniya,
Peradeniya, Sri Lanka.[2]
**uajay@ou.ac.lk*

Abstract

Microplastic (MP) pollution is a major environmental challenge, especially in aquatic ecosystems, where it threatens biodiversity and human health. Bioremediation offers a sustainable and eco-friendly solution for mitigating MP contamination, utilizing various biological agents such as seaweeds, freshwater macrophytes (duckweeds, mosquito fern, and water hyacinth, etc.), and micro-organisms. This chapter discusses the potential of these biological agents in the perseverance of MP pollution in aquatic environments, utilising both in-situ and ex-situ remedial techniques. Phytoremediation for MP is highly focused on utilizing aquatic plants, such as seaweeds and duckweeds. Seaweeds act as natural bio-filters as well, with extensive surface areas and bio-adhesive properties, thus trapping and aggregating MPs for more efficient removal. Freshwater macrophytes offer bioremediation strategies by decontaminating water polluted with MPs as it's an aquatic plant that grows fast, and it traps MPs on their root surface, also boosting the microbial activity in the polluted waters. Microorganisms, including bacteria and fungi, also play a significant role in MP degradation. Bacteria such as *Pseudomonas* and *Rhodococcus* exhibit enzymatic activity capable of breaking down polymer structures, while fungi like *Aspergillus* and *Penicillium* secrete extracellular enzymes that fragment_plastics into smaller toxic components. Combined actions of these organisms create a promising pathway for remediating MP-contaminated waters. However, a deeper understanding of their mechanisms, interactions, and limitations is needed for large-scale applications. This chapter highlights recent advances in bioremediation, identifies challenges to broader implementation, and outlines future strategies for enhancing biological solutions to restore aquatic environments impacted by MP pollution.

Keywords: Aquatic, Bioremediation, Environment, Microplastic, Phytoremediation

Introduction

Microplastic (MP) pollution has become a critical global concern due to its pervasive presence in ecosystems, impacting marine biodiversity, food webs, and human health (Thushari and Senevirathna, 2020). MPs are defined as plastic particles smaller than 5 mm and greater than 1 μm (Masura et al., 2005) and have been detected in water bodies, sediments, and organisms. They are categorized into primary MPs, intentionally manufactured and used in products, and secondary MPs, formed through the degradation of larger plastics (Masura et al., 2005). Secondary MPs dominate natural environments, largely from fragmentation, thereby intensifying the problem (Hettiarachchi and Meegoda, 2023). Their documented ecotoxicological effects underscore the urgency of developing effective remediation strategies.

MP remediation is particularly vital for aquatic-based industries that support livelihoods and human health, as long-term contamination can disrupt biological processes (Bidashimwa et al., 2023). Conventional remediation methods include physical approaches such as thermal degradation, grinding, filtration, and photo oxidation, and chemical treatments such as coagulation, precipitation, oxidation reduction, and pH adjustment (Ugrina and Juric, 2023). However, these approaches face limitations of efficiency, cost, and environmental safety. In contrast, bioremediation the use of organisms or enzymes to degrade, transform, or remove pollutants offers a more sustainable solution (Yuan et al., 2020).

Bioremediation uses microorganisms, fungi, or plants to restore polluted ecosystems by reducing contaminants to acceptable levels (Sardrood et al., 2012; Azubuike et al., 2016;). While biodegradation is one mechanism, bioremediation encompasses broader strategies, with effectiveness depending on pollution type, site conditions, and cost (Azubuike et al., 2016). Its sustainability compared to conventional methods makes it attractive for long-term restoration (Das et al., 2023). This chapter highlights MP bioremediation using plants, algae, and microorganisms, with particular focus on phytoremediation. Aquatic plants and seaweeds act as natural bio-filters, utilizing their large surface areas and adhesive properties to trap and aggregate MPs (Tang, 2023). Their applications and scientific validations are discussed to provide a comprehensive review.

Bioremediation techniques for microplastic pollution

Various types of bioremediation techniques can be applied to reduction of MP pollution, depending on the site of application. Bioremediation techniques are broadly categorized into two main categories: the location of treatment and the type of organism employed.

Based on Location

In situ bioremediation

This involves treating the contamination at the site itself, without removing the polluted material. It is generally more cost-effective and less disruptive to the environment. (Azubuike et al., 2016). Bioventing, biosparging and biostimulation could be recognized as examples of *in situ* bioremediation. When soil, freshwater or marine environments are contaminated with MPs, they can be treated using in-situ bioremediation techniques, by using microorganisms like bacteria, fungi, algae, or enzymes to break down or eliminate the particles without excavating. After colonizing plastic surfaces, these organisms release enzymes that break down polymer chains into smaller molecules, which can subsequently be used as sources of energy or carbon (Kumar et al., 2021). However, in-situ, bioremediation presents a promising option for reestablishing MP-contaminated ecosystems with little disruption to the environment.

Ex situ bioremediation

Ex-situ bioremediation involves treating contaminated materials such as soil, sediment, or water by using biological agents in a controlled environment. That is, these materials have been removed from their original location. This approach allows for the optimisation of key conditions such as temperature, pH, nutrient availability and aeration which can significantly enhance the activity of microorganisms or enzymes involved in breaking down plastics (Vidali, 2001). In the context of MP pollution, ex-situ methods commonly rely on microbial groups or specific microbial strains applied in bioreactors, composting systems, or slurry phase setups to accelerate the degradation of synthetic polymers like polyethylene (PE), polypropylene (PP), and polystyrene (PS) (Restrepo Florez et al., 2014). Although ex situ bioremediation offers better control and often faster degradation rates than in situ techniques, it can be much more expensive and logistically complex. Because excavation, transport, and specialised treatment facilities are required extensively for ex-situ bioremediation (Williams, 2006). Techniques such as enzymatic degradation, fungal pelletisation, and biochar application are prominent examples of this method, offering efficient and environmentally friendly solutions to combat MP pollution, particularly in aquatic environments.

Based on organisms/mechanism used

Although this categorization is the main way to categorise bioremediation, still the specific organisms or biological processes involved can also serve as a basis for classification. These categories often overlap with the more commonly used *in situ* and ex-situ approaches.

Microbial remediation

This method primarily uses microorganisms specially bacteria and fungi to break down and transform pollutants (Sardrood et al., 2012; Jain et al., 2020). Among bacteria, Pseudomonas and Bacillus species are frequently reported for their ability to degrade plastic materials (Quintella et al., 2019). Algae indirectly contribute to the process, either by directly interacting with pollutants or by supporting microbial communities. Even though microbial bioremediation is generally considered cost-effective and environmentally friendly, it has limitations. These include relatively slow degradation rates, a dependence on optimal environmental conditions, and the risk of incomplete breakdown, which can result in MP fragments or harmful byproducts (Shah et al., 2008). Among bacterial species, *Pseudomonas putida* has shown particular effectiveness in degrading polyethylene (PE) and polystyrene (PS), largely due to its flexible metabolism and ability to produce relevant enzymes (Muhonja et al., 2018). Similarly, *Bacillus subtilis* and *Bacillus cereus* have been found to break down low-density polyethylene (LDPE) in aquatic systems by releasing extracellular depolymerases (Auta et al., 2017). Microorganisms can also form biofilms on MP surfaces, which enhances degradation through increased microbial interaction and enzymatic activity (Zettler et al., 2013). Studies have shown that biofilm-forming bacteria also degrade polyethylene MPs more efficiently than free-floating, planktonic samples. This indicates that encouraging bio film development could be a promising strategy to accelerate MP bioremediation in aquatic environments (Jiao et al., 2024).

Mycoremediation

Fungal bioremediation specifically involves the use of fungi to degrade or remove pollutants, including MPs. Species such as A*spergillus* and *Penicillium* have shown promising potential in breaking down various types of plastics (Quintella et al., 2019; Sardrood et al., 2012). In particular, *Aspergillus niger* and Aspergillus tubingensis have been reported to degrade materials like polyester and PE (Khan et al., 2017). Similarly, *Penicillium chrysogenum* has been studied for its ability to form biofilms on MP surfaces, which facilitates both fragmentation and microbial colonisation in aquatic environments (Yousif and Haddad, 2013). These fungal strains are considered strong candidates for in-situ bioremediation strategies aimed at reducing MP pollution in water bodies. One emerging technique in this field is fungal pelletisation, where certain fungi form dense pellets that can aggregate and extract MPs from water. White rot fungi, known for their high enzymatic activity, have demonstrated the ability to bind and potentially degrade MPs such as PP and polymethyl methacrylate (PMMA), aiding their removal from aquatic systems (Wang et al., 2023). This approach not only assists in physically capturing MPs but also supports their biological degradation, offering a dual benefit in managing these persistent environmental contaminants.

Enzyme-based remediation

Enzymatic bioremediation involves the use of specific enzymes either extracted from organisms or produced through commercial processes to break down pollutants (Quintella et al., 2019). In laboratory studies, microbial strains such as *Aspergillus niger*, *Bacillus subtilis*, and *Pseudomonas putida* have been shown to enzymatically degrade plastic polymers by breaking them into smaller, less harmful molecules (Urbanek et al., 2018). Recent advancements in enzyme engineering have also led to the development of specialised enzymes capable of degrading polyethylene terephthalate (PET), even under the harsh conditions typically found in wastewater treatment systems. These enzymes work by converting PET into simpler compounds that are more easily absorbed and processed by microorganisms, thereby helping reduce MP concentrations in treated wastewater (Qui et al., 2024). Enzymatic approaches offer a targeted and efficient strategy for addressing MP pollution, particularly in controlled environments such as sewage and wastewater treatment facilities.

Phytoremediation

Phytoremediation involves the use of plants to trap, absorb, or degrade pollutants. In the context of MP remediation, aquatic plants interact with MPs through surface adhesion, root uptake, and microbial-assisted degradation (Besseling et al., 2017). Phytoremediation influences the natural capabilities of plants to sequester, accumulate, or degrade pollutants. In aquatic environments, certain plants can trap MPs through root entanglement or surface adhesion, facilitating their removal from the water column. Recent advancements have focused on enhancing these natural processes to improve remediation efficiency (Besseling et al., 2017). The fundamental mechanisms of phytoremediation are depicted in Figure 1.

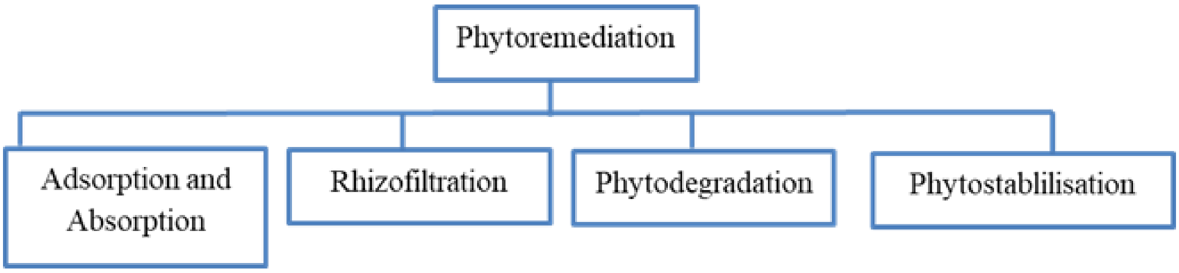


Figure 01. Classification of phytoremediation methods employed in MP remediation

Role of seaweeds

Seaweeds, particularly macroalgae, have demonstrated strong potential for MP remediation, largely due to their rapid growth rates and extensive surface areas. Research has shown that certain seaweed species can adsorb MPs, helping to reduce their concentration in marine environments (Gutow et al., 2016). In addition to direct adsorption, seaweeds also contribute to the development of biofilms on their surfaces, which can support microbial communities involved in the degradation of trapped MPs. This dual role as both natural filters and enhancers of microbial activity places seaweeds as effective agents in integrated bioremediation strategies.

Recent studies reinforce the value of seaweeds in both natural and controlled settings. For instance, Stabili et al. (2024) investigated Chaetomorpha linum grown in an integrated multitrophic aquaculture (IMTA) system and found it to be highly effective at capturing MP fibres, accounting for more than 97% of the MPs recovered from nearby waters. Remarkably, these particles were easily removed using a hypersaline wash, allowing the seaweed biomass to be reused. In a complementary study, Lotfigolsefidi et al. (2025) assessed the potential of *Chlorella vulgaris* biomass to remove polystyrene MP under laboratory conditions. They achieved removal efficiencies of up to 73% by optimising variables such as pH, contact time, and algal concentration. Together, these findings highlight the promise of seaweed-based systems in both aquaculture and experimental settings as targeted, sustainable approaches to MP remediation.

Field-based research also confirms seaweeds' natural capacity to accumulate MPs. Bhuyan et al. (2025) conducted an extensive survey of edible seaweeds, including *Fucus*, *Ulva*, and *Gracilaria* harvested from coastal areas, revealing widespread contamination by MP fibres, fragments, and films. These findings raise important concerns not only for environmental health but also for food safety. In a related study, Xiao et al. (2024) examined farmed *Saccharina japonica* (kelp) and *Pyropia yezoensis* (nori) in East Asian aquaculture systems, reporting that these species accounted for nearly 45% of estimated dietary MP fibre intake in the region. While these studies did not directly test the use of seaweeds for remediation, they demonstrate seaweeds' intrinsic capacity to bind MPs to their thalli. This ability holds great potential to be more effectively utilised in structured bioremediation systems, especially as research and innovation in the field continue to advance.

Role of freshwater macrophytes

Freshwater plants have shown considerable potential in MP remediation, with Eichhornia crassipes (water hyacinth), *Pistia stratiotes*, *Lemna minor*, and *Azolla* spp. receiving most attention. Among these, water hyacinth stands out due to its rapid growth, extensive root systems, and tolerance to pollutants including heavy metals and antibiotics (Yin et al., 2025). It doubles its biomass within 7–10 days and achieves MP removal efficiencies of 55.3%–69.1% within 48 hours, primarily through root surface adsorption (1,060–1,426 mg/g). While smaller MPs (0.5 mm) penetrate through root cracks, the vascular ring in stems blocks further translocation, maintaining plant health (Yin et al., 2025). Additionally, water hyacinth acts as a natural plastic aggregator. In the Saigon River, hyacinth patches retained 54%–77% of floating plastics, up to 32 times higher than open waters, with efficiency peaking in larger patches and dry seasons (Schreyers et al., 2024). These findings rank water hyacinth as an effective trap for plastics in addition to MPs.

Duckweeds also demonstrate strong phytoremediation potential. Lemna minor removed up to 76% of MPs in experiments (Rozman et al., 2023) and maintained stable growth and chlorophyll content even under high MP concentrations (Rozman et al., 2022). Short-term exposure reduced root length depending on MP type, with fragments and fibres causing more damage than spheres, although plants later acclimatised. Biochemical responses, such as antioxidant capacity and respiration, showed minimal stress, while adhesion tests revealed approximately 6.5% strong and 75% weak MP retention, influenced by particle shape (Rozman et al., 2022). This physical adhesion supports removal but may also promote trophic transfer when herbivores feed on contaminated fronds (Tan et al., 2023). Chronic exposure studies with *Lemna minuta* reported reduced growth and chlorophyll under higher concentrations, highlighting long-term risks (Ceschin et al., 2023).

Azolla spp. also contributes significantly. A. filiculoides adsorbed polypropylene MPs and secreted enzymes such as esterase and lipase, enhancing degradation of complex plastics (Chen et al., 2023 a,b; Liu et al., 2023). Root mats further stabilised MPs in sediments, reducing mobility by up to 50% (Zhang et al., 2023). With added ecological benefits, Azolla is recommended as a low-cost nature-based remediation agent (Nyein and Iwai, 2025). Other aquatic macrophytes, including water lettuce, also employ phytoaccumulation, phytostabilisation, and phytofiltration mechanisms to reduce MPs in water and soil (Lu et al., 2023; Sharma et al., 2024). Overall, aquatic plants remediate MPs rapidly through surface trapping, while enzymatic degradation, though slower, ensures deeper breakdown (Figure 3). These mechanisms underline the role of floating macrophytes in integrated MP management strategies. The following Figure 2, depicts the most frequently used water plants in MP remediation. Figure 3 depicts the minimum average duration for the microplastic remediation by different bioremedial agents. The values were calculated as per the durations given in the above-mentioned references. Given the graph, aquatic macrophytes remediate MPs within a very short duration comparative to the other biological agents. This is basically done through trapping of MPs thereby by removing them from the water column and surface. But when degradation is focused, the most effective is the enzymatic remediation even though it costs more days for MPs degradation (Figure 3).

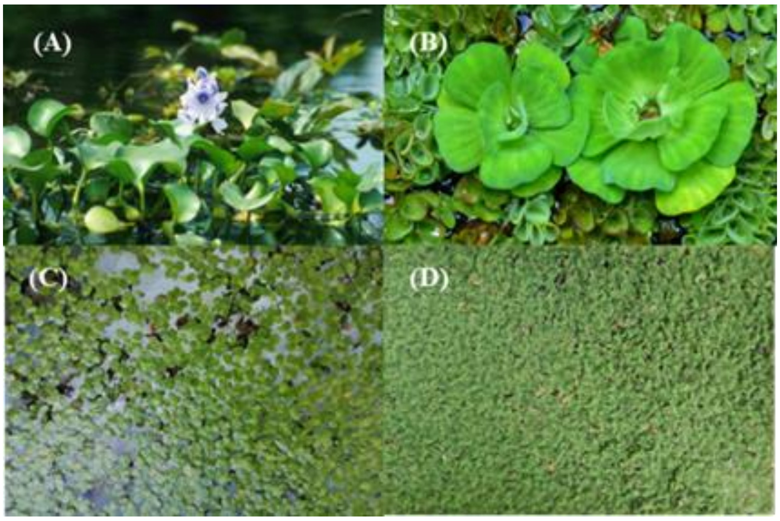


Figure 02. Freshwater plants frequently used in bioremediation of MPs. *Eichhornia crassipes* (A), *Pistia stratiotes* (B)(Source:https://www.bing.com/images/s), *Lemnar minor* (C) and *Azolla pinnata* (D).

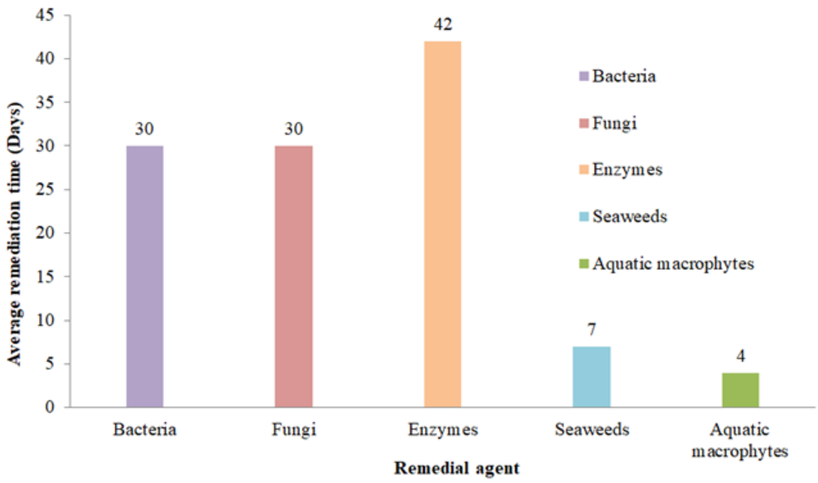


Figure 03. The minimum average duration for the microplastic remediation by different bioremedial agents. Results interpreted from the cited references of the current manuscript (Gutow et al (2016), Kalcikova et al (2017), Sundbaek et al (2018), Tan et al., 2023), Mateos-Cardenas et al (2019), Alkimin et al (2019), Liao et al (2021), Kalcikova (2020), Rozman et al (2022), Rozman and Kalcikova (2022), Tang et al (2022), Rozman et al (2023), Ceschin et al (2023), Chen et al (2023), Liu et al (2023), Zhang et al (2023), Lu et al (2023), Schreyers et al (2024), Sharma et al (2024), Yin et al (2025), and Nyein and Iwai (2025)).

Importance of bioremediation for microplastic pollution

Bioremediation is increasingly recognised as a practical and sustainable solution to MP pollution. Conventional methods such as filtration, incineration, and chemical treatments are often costly, energy-intensive, and harmful to ecosystems. In contrast, bioremediation uses natural biological processes to degrade or transform MPs without generating toxic byproducts.

Bioremediation helps maintain ecological balance, protect biodiversity, and minimise long-term environmental harm through biological processes that degrade or remove MP particles. Among the different bioremediation approaches, phytoremediation the use of plants has shown a particularly strong possible technique for managing MP pollution in aquatic ecosystems. Aquatic plants such as seaweeds, duckweeds, mosquito ferns, and water hyacinths have demonstrated the ability to trap, absorb, and in some instances break down MPs. These are widely available, easy to cultivate, and cause minimal disruption to natural habitats, making them practical candidates for use in a variety of aquatic backgrounds. Compared to microbial remediation, phytoremediation offers several advantages: it is simpler to implement, easier to monitor, and often allows for the reuse or recycling of plant biomass. Importantly, MPs are known to absorb and transport toxic substances, including heavy metals and persistent organic pollutants (POPs), which pose additional risks to ecosystems and human health. If aquatic plants can effectively capture and retain MPs, they may also be capable of assimilating or stabilising the harmful chemicals attached to them. This added function enhances the ecological value of phytoremediation and highlights its potential as a comprehensive tool for contaminant elimination. Combining plants with microbial communities could further enhance MP removal, but more research is needed to test their performance under real environmental conditions and to evaluate long-term scalability. With continued innovation, phytoremediation has strong potential to become a leading strategy for managing MP pollution and restoring aquatic ecosystem health.

References

Alkimin GD, Cardoso CM, de Medeiros GA, Domingues RR, Gonçalves RR & Barbosa FJR (2019). Antioxidant responses and photosynthetic pigment contents in aquatic macrophytes exposed to heavy metals. Environmental Science and Pollution Research, 26(23), 23894–23905.

Auta HS, Emenike CU & Fauziah SH (2017). Distribution and importance of microplastics in the marine environment: A review of the sources, fate, effects, and potential solutions. *Environment International, 102*, 165–176.

Azubuike CC, Chikere CB & Okpokwasili GC (2016). Bioremediation techniques–classification based on site of application: principles, advantages, limitations and prospects. *World Journal of Microbiology and Biotechnology*, 32, 1-18.

Besseling E, Wang B, Lurling M & Koelmans AA (2017). Nanoplastic affects growth of *S. obliquus* and reproduction of *D. magna*. *Environmental Science and Technology*, 51(9), 5274-5281.

Bhuyan MS, Senapathi V, Karthikeyan S, Kunda M, Islam MT, Iheanacho S & Choudhury A K (2025). Microplastics contamination in seaweed: impacts on human health and mitigation approaches. *Discover Oceans*, 2(1), 2.

Bidashimwa D, Hoke T, Huynh TB, Narkpitaks N, Priyonugroho K, Ha TT & Weissman A (2023). Plastic pollution: how can the global health community fight the growing problem?. *BMJ Global Health*, 8(Suppl 3), e012140.

Ceschin S, Mariani F, Di Lernia D, Venditti I, Pelella E & Iannelli MA (2023). Effects of microplastic contamination on the aquatic plant *Lemna minuta* (least duckweed). *Plants*, *12*(1), 207.

Chen X, Liu Y & Zhang Z (2023). Adsorption of polypropylene microplastics by *Azolla filiculoides*: Influence of exposure time and particle size. *Environmental Pollution*, 292, 118345.

Chen Y & Liu Z (2023a). Enzymatic degradation of polyethylene microplastics by duckweeds (*Lemna minor*): Role of laccase and peroxidase. *Journal of Hazardous Materials*, 424, 127532.

Chen Y, Liu Z & Li H (2023b). Integrating phytoremediation with microbial remediation for enhanced microplastic removal: A review. *Journal of Environmental Management*, 330, 117123.

Das S, Sultana KW, Ndhlala AR, Mondal M & Chandra I (2023). Heavy metal pollution in the environment and its impact on health: exploring green technology for remediation. *Environmental health insights*, 17.

Gutow L, Eckerlebe A, Gimenez L & Saborowski R (2016). Experimental evaluation of seaweeds as a vector for microplastics into marine food webs. *Environmental Science and Technology*, 50(2), 915-923.

Hettiarachchi H & Meegoda JN (2023). Microplastic pollution prevention: the need for robust policy interventions to close the loopholes in current waste management practices. *International journal of environmental research and public health*, 20(14), 6434.

Jain D, Kour R, Bhojiya AA, Meena RH, Singh A, Mohanty, SR & Ameta KD (2020). Zinc tolerant plant growth promoting bacteria alleviates phytotoxic effects of zinc on maize through zinc immobilization. *Scientific reports*, 10(1), 13865.

Jiao Y, Zhou A, Zhang D, Chen M & Wan L (2024). Distinct microbial community structures formed on the biofilms of PLA and PP, influenced by physicochemical factors of sediment and polymer types in a 60-day indoor study. *Frontiers in Environmental Science*, 12, 1452523.

Kalcikova G (2020). Electrostatic interactions and surface properties as key factors governing microplastic adherence to aquatic plants. *Environmental Chemistry Letters*, 18(5), 1711–1720.

Kalcikova G, Van Gestel CAM & Gagkaeva TY (2017). Influence of polyethylene microplastics on root growth of aquatic plants. *Science of the Total Environment*, 607–608, 811–819.

Khan S, Nadir S, Shah Z, Shah AA, Karunarathna SC, Xu J & Hasan F (2017). Biodegradation of polyester polyurethane by *Aspergillus tubingensis*. *Environmental Pollution, 225*, 469–480. https://doi.org/10.1016/j.envpol.2017.03.005

Kumar S, Sharma J & Bhoi PR (2021). Microbial degradation of microplastics: Current status and future perspectives. *Environmental Pollution, 283*, 117070.

Liao L, Li J, Chen, Q, Wu C & Zhao Y (2021). Antioxidant responses in aquatic plants exposed to environmental stress: A critical review. *Aquatic Botany*, 170, 103338.

Liu Z, Chen X & Li H (2023). Enzymatic degradation of polyvinyl chloride (PVC) microplastics by *Azolla filiculoides*: Role of esterase and lipase. *Journal of Environmental Management*, 325, 116532.

Lotfigolsefidi F, Davoudi M, Sarkhosh M & Bonyadi Z (2025). Removal of microplastics by algal biomass from aqueous solutions: performance, optimization, and modeling. *Scientific Reports*, 15(1), 501.

Lu Y, Li MC, Lee J, Liu C & Mei C (2023). Microplastic remediation technologies in water and wastewater treatment processes: Current status and future perspectives. *Science of the Total Environment*, 868, 161618.

Masura J, Baker JE, Foster GD, Arthur C & Herring C (2015). Laboratory methods for the analysis of microplastics in the marine environment: recommendations for quantifying synthetic particles in waters and sediments.

Mateos-Cardenas A, Scott DT, Seitmaganbetova G, van Pelt FNAM & O'Halloran J (2019). Adsorption and ingestion of microplastics by freshwater plant Lemna minor. *Environmental Pollution*, 252, 467–475.

Muhonja CN, Makonde H, Hensel O & Onyango MS (2018). Microbial biodegradation of low-density polyethylene and polypropylene: A review on existing literature. *International Journal of Environmental Research and Public Health, 15*(7), 1456.

Nyein N & Iwai CB (2025). Investigating Azolla microphylla in Domestic Wastewater Treatment and Its Potential for Biological Carbon Capturing. *Environment Asia*, 18.

Qiu J, Chen Y, Zhang L, Wu J, Zeng X, Shi X & Chen J (2024). A comprehensive review on enzymatic biodegradation of polyethylene terephthalate. Environmental Research, 240, 117427.

Quintella CM, Mata AM & Lima LC (2019). Overview of bioremediation with technology assessment and emphasis on fungal bioremediation of oil contaminated soils. *Journal of environmental management*, 241, 156-166.

Restrepo-Flórez JM, Bassi A & Thompson MR (2014). Microbial degradation and deterioration of polyethylene – A review. *International Biodeterioration & Biodegradation, 88*, 83–90.

Rozman U & Kalcikova G (2022). Fragmented versus spherical microplastics: Different shapes, different risks. *Environmental Toxicology and Chemistry*, 41(1), 12–23.

Rozman U, Blazic A & Kalcíkova G (2023). Phytoremediation: A promising approach to remove microplastics from the aquatic environment. *Environmental Pollution*, 338, 122690.

Rozman U, Kokalj AJ, Dolar A, Drobne D & Kalcikova G (2022). Long-term interactions between microplastics and floating macrophyte Lemna minor: The potential for phytoremediation of microplastics in the aquatic environment. *Science of the Total Environment*, 831, 154866.

Sardrood BP, Goltapeh EM & Varma A (2012). An introduction to bioremediation. In Fungi as bioremediators (pp. 3-27).

Schreyers LJ, van Emmerik TH, Bui TKL, Biermann L, Uijlenhoet R, Nguyen HQ & van der Ploeg M (2024). Water hyacinths retain river plastics. *Environmental Pollution, 356*, 124118

Shah AA, Hasan F, Hameed A & Ahmed S (2008). Biological degradation of plastics: A comprehensive review. *Biotechnology Advances, 26*(3), 246–265.

Sharma R, Patel M & Gupta N (2024). Aquatic plant-mediated microplastic removal: A comprehensive review. *Environmental Science and Pollution Research*, 31, 15432-15445.

Stabili L, Quarta E & Giotta L (2024). The seaweed Chaetomorpha linum cultivated in an integrated multitrophic aquaculture system: A new tool for microplastic bioremediation?. *Science of the Total Environment*, 954, 176262.

Sundbek KB, Nielsen TG & Hansen BW (2018). Seaweed as a sink for microplastics? Adhesion and removal efficiency on Fucus vesiculosus. *Marine Pollution Bulletin*, 133, 138–145.

Tan J W, Tong R J, Tang Z, Lee C Z, Yong CL & Todd PA (2023). Leaf morphology affects microplastic entrapment efficiency in freshwater macrophytes. Marine and Freshwater Research, 74(7), 641-650.

Tang FH, Maggi F & Schmidt J (2022). Duckweed: A potential phytoremediator for microplastic pollution. *Science of the Total Environment*, 815, 152912.

Tang KHD (2023). Phytoremediation of microplastics: A perspective on its practicality. *Industrial and Domestic Waste Management*, 3(2), 90-102.

Thushari GGN & Senevirathna JDM (2020). Plastic pollution in the marine environment. *Heliyon*, 6(8).

Ugrina M & Juric A (2023). Current trends and future perspectives in the remediation of polluted water, soil and air- A review. *Processes*, 11(12), 3270.

Urbanek AK, Rymowicz W & Mironczuk AM (2018). Degradation of plastics and plastic-degrading bacteria in cold marine habitats. *Applied Microbiology and Biotechnology, 102*(18), 7669–7678.

Vidali M (2001). Bioremediation. An overview. *Pure and Applied Chemistry, 73*(7), 1163 1172.

Wang J, Li X & Zhang Y (2023). Scaling up phytoremediation of microplastics: Challenges and opportunities. *Environmental Science and Technology*, 57(8), 3456-3465.

Wang X, Zhang Y & Li J (2023). Rhizofiltration of microplastics by duckweeds (Lemna minor): Efficiency and mechanisms. *Water Research*, 215, 118234.

Williams J (2006). Bioremediation of contaminated soils: a comparison of in situ and *ex situ* techniques. Engineering Biology.

Xiao X, Liu S, Li L, Li R, Zhao X, Yin N & Luo Y (2024). Seaweeds as a major source of dietary microplastics exposure in East Asia. *Food Chemistry*, 450, 139317.

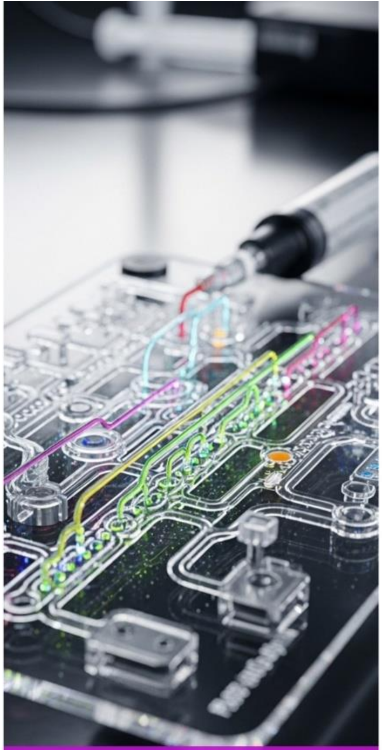
Yin J, Zhu T, Li X, Wang F & Xu, G. (2025). Phytoremediation of microplastics by water hyacinth. *Environmental Science and Ecotechnology, 24*, 100540.

Yousif E & Haddad R. (2013). Photodegradation and photostabilization of polymers, especially polystyrene: Review. *SpringerPlus, 2*, 398.

Yuan J, Ma J, Sun Y, Zhou T, Zhao Y & Yu F (2020). Microbial degradation and other environmental aspects of microplastics/plastics. *Science of the Total Environment*, 715, 136968.

Zettler ER, Mincer TJ & Amaral-Zettler LA (2013). Life in the "Plastisphere": Microbial communities on plastic marine debris. *Environmental Science and Technology*, 47(13) 7137-7146.

Zhang Y, Wang X & Li J (2023). Phytostabilization of microplastics in sediment by *Azolla filiculoides*: Mechanisms and efficiency. *Science of the Total Environment*, 856, 159123.



CHAPTER 04

Lab-on-a-Chip (LoC) Technology for Sustainable Biological Ecotoxicity Assessment

V. T. Koggalage and R. Wimalasekera*

Department of Botany, University of Sri Jayewardenepura,
Gangodawila, Nugegoda, Sri Lanka.

**rinukshi@sci.sjp.ac.lk*

Abstract

Ecotoxicology plays a critical role in assessing the environmental impact of pollutants through diverse toxicity evaluations. Conventional toxicological assessments offer essential insights into the ecological effects of environmental contaminants. However, they typically demand substantial sample volumes, extended testing durations, and result in considerable biological and chemical waste. These limitations have prompted the advancement of more efficient and sustainable testing solutions. Among them, Lab-on-a-Chip (LoC) technology can be considered a groundbreaking innovation. Multiple laboratory functions, including sample preparation, mixing, reaction, and detection, are integrated onto a miniaturized microfluidic device by LoC technology. These platforms enable rapid, automated, and resource-efficient analyses by significantly minimizing reagent use, waste generation, and processing time. This chapter outlines the fundamental principles, key components, and fabrication techniques, including photolithography, soft lithography, and 3D printing, which are utilized in LoC systems. Further, sustainable aspects of LoC technology in ecotoxicity assessments, such as the use of biodegradable materials and minimal energy consumption, are described. A diverse array of biological models and organ-on-chip are assessed for their suitability and efficiency in LoC-based toxicity testing platforms. Adopting LoC platforms in ecotoxicology is explored in detail through water quality monitoring, wastewater surveillance, soil, and nano-contaminant toxicity assessments. Moreover, this chapter explores technical challenges and operational limitations of LoC along with possible future approaches, highlighting the potential of automation, artificial intelligence, and regulatory standardization. Broadening LoC applications to include community-level testing and multi-species interactions offers promising opportunities for next-generation ecotoxicological assessment.

Keywords: Ecotoxicology, Environmental Monitoring, Lab-on-a-Chip (LoC), Microfluidics, Toxicity Testing

Introduction

Ecotoxicology underpins evidence-based decision-making by assessing the potential ecological risks posed by chemical substances and effluents. It consists of laboratory ecotoxicity tests of various types to explore relationships between exposure and effect under controlled laboratory conditions, as well as studies investigating the effects of chemicals or effluents in complex field ecosystems under diverse ecological conditions (Chapman, 1995). Those tests measure the toxicity of substances found in the environment by exposing standard living organisms to them. There are various types of ecotoxicological assays, such as behavioral tests (avoidance tests), acute and chronic toxicity tests (Gainer et al., 2019).

When considering conventional ecotoxicity testing, though they carry significantly important roles in environmental protection, conventional ecotoxicological assays require large sample volumes, are time-consuming, and generate considerable waste (Huang et al., 2016). As an example, chronic toxicity tests may be lengthy and laborious, as sometimes they range from 4 to 7 weeks (Loureiro et al., 2005).

The emergence of the ‘Lab-on-a-Chip (LoC) technology’ represents a significant advancement in this regard. A Lab-on-a-Chip is a miniature device that can integrate one or several laboratory functions on a single integrated circuit, which is known as a ‘chip’ (Volpatti and Yetisen, 2014).

These chips act as fluidic integrated circuits, where liquid samples flow through microchannels etched into the devices, and they allow for mixing and separating fluids, facilitating chemical reactions and analyzing substances. LoCs are portable and convenient, and commonly used for medical diagnostics, point-of-care testing, and environmental monitoring. Moreover, this platform integrates microfluidics with biosensors, fluorescence imaging, and microelectrodes for precise toxicity monitoring.

This chapter emphasizes the role of LoC as a sustainable alternative for conventional ecotoxicity assessments, offering rapid, precise, and eco-friendly solutions for monitoring pollution and protecting biodiversity.

Principles and components of Lab-on-a-Chip (LoC) systems

Fundamental principles of LoC systems are miniaturization, microfluidics, integration, automation, speed, and portability. The functional components are the injector, transporter, preparator, mixer, reactor, separator, detector, controller, and power supply.

Through miniaturization, traditional lab processes have been shrunk into micro-scale dimensions in LoC systems. Microfluidics is considered a multidisciplinary field, and it investigates the behavior and manipulation of small amounts of fluids with characteristic length scales from nanometers to hundreds of micrometers (Chen et al., 2010). From a technological point of view, microfluidics requires low fluid volumes. Also, short assay time, low power consumption, rapid generation of small liquid compartments and a high degree of parallelization are significant features (Sista et al., 2008). In the integration of LoC systems, sample preparation, reaction, separation, and detection are combined and performed in a single platform. Because of automation, reproducibility is enhanced, and human error is reduced. Speed and portability of LoC platforms emphasize quick analysis and use in real-time monitoring.

There are various fabrication techniques in the development of complex LoC architectures with high reproducibility, and the choice of technique depends on the intended purpose, whether for research or commercial application (Ren et al., 2013). Photolithography, soft lithography, multilayer lithography (MSL), hot embossing, injection molding, laser ablation, 3D printing, and etching have emerged as significant fabrication techniques (Mathew et al., 2024).

When considering chip manufacturing for laboratory research, chip materials generally need to compromise between the ease of prototyping and the performance of the device. In contrast, in commercialization, cost of production, ease, and reliability are the major concerns (Ren et al., 2013). Paper, glass (Figure 01), silicon, thermosets, hydrogel, thermoplastics, and elastomers are various chip materials that are highly utilized in LoC technology (Mathew et al., 2024).

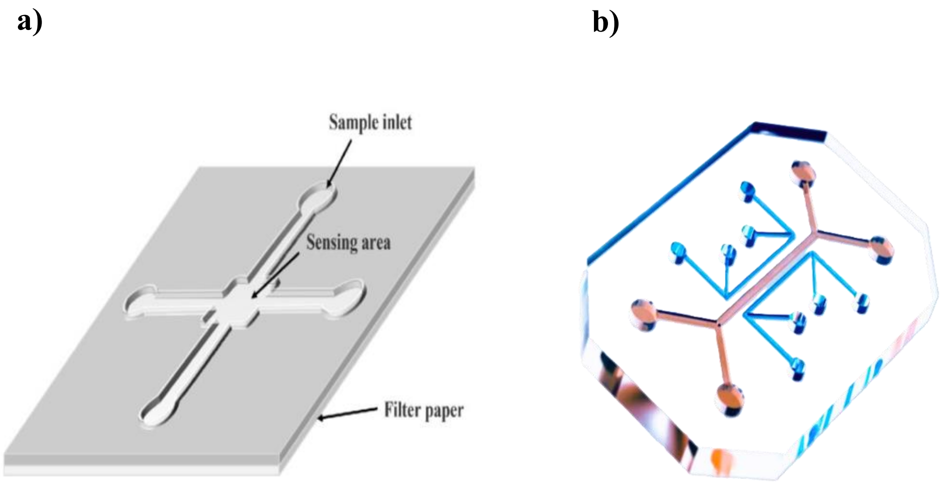


Figure 01. **a)** Paper-based microfluidic chip, **b)** Glass chip.
[Images were adapted from Wang et al. (2022)]

Core components of LoC systems are microfluidic channels, pumps and valves, mixers, reactors, sensors, detectors, and input and output ports. Integration of sensors and detectors further enhances their enabling real-time monitoring and analytical capabilities of biological responses (Melin and Quake, 2007).

When fluids are loaded into a lab-on-a-chip cartridge to be analyzed, they are processed by onboard components such as valves, pumps, and sensors due to their movement through a network of microchannels etched into the chip. Actuators pull the liquid through the device, where it undergoes a serial dilution phase, and this step introduces a series of inputs, like reagents, that test and chemically react with the sample fluid (Shakeri et al., 2021).

Sustainability aspects of LoC technology in ecotoxicity testing

Sustainability can be considered a driving force behind the adoption of LoC technologies in environmental science. Most of the chips are made from biodegradable and recyclable materials. In both biomedical and environmental applications, bio-derived and biodegradable polymers such as polylactide (PLA), shellac, and silk fibroin have been successfully used (Lausecker et al., 2016). Gelatin has also been utilized as a bio-based and biodegradable microfluidic platform in cell culture, and wood has been introduced in microfabrication processes (Lausecker et al., 2016).

Reduction in sample and reagent volumes is a significant benefit of LoCs. Moreover, packaging material, compared to equivalent macroscale analytical processes, is another distinct advantage. Importantly, LoCs allow automation, and they enable accessibility of researchers and users to harness benefits arising from higher reproducibility and reducing the number of analyses required in optimization processes (Keçili and Hussain, 2021).

Conventional ecotoxicity experiments are energy-intensive and produce high levels of chemical and hazardous waste (Lopez et al., 2017). Nevertheless, LoC technology addresses these challenges by minimizing waste and optimizing energy use, and as a result, ecotoxicity tests can be performed in a resource-efficient and cost-effective way (Campana and Wlodkowic, 2018).

Biological models in LoC-based ecotoxicity assessment

A wide range of biological models, like microorganisms, invertebrates, plant-based systems, cell cultures, and organ-on-chip models, have been adapted in LoC-based ecotoxicity research.

Microorganisms such as *E. coli* and algae are used for their sensitivity to pollutants and ease of culture. As quantifiable endpoints, bacterial bioluminescence or algal chlorophyll fluorescence can serve (Azizipour et al., 2020). Campana and Wlodkowic, (2018) mentioned that ecotoxicity assay protocols with small model organisms can offer a great advantage over *in vitro* research protocols as they allow for assessing effects of stressors under the physiological status of an intact organism.

For the most recent examples of aquatic ecotoxicology biotests, microfluidic systems that facilitate automated fish embryo toxicity (FET) biotests on zebrafish embryos and tests using invertebrates like the marine amphipod *Allorchestes compressa* can be included (Huang et al., 2016). Moreover, as an emerging area of research, integrating plant-based systems with LoC technology in ecotoxicity assays can be a promising tool, but they are still in their infancy in environmental monitoring (Cartlidge et al., 2015). For example, using *Lemna minor* or *Allium cepa* roots, miniature phytotoxicity can be assessed based on growth inhibition or chromosomal aberrations. Other biological models in ecotoxicity assays are organ-on-chip models and cell culture models. Kim et al. (2020) reported that the ecotoxicity of leaf extract of *Curcuma longa*, which is widely applied as a functional food material and for many cosmetic products, was tested by using a pumpless skin-on-chip.

Applications of LoC in ecotoxicological testing

LoC devices have been used in diverse applications within ecotoxicology. Integration of LoC technology for water quality monitoring, wastewater surveillance, assessing nano contaminants, and soil ecotoxicity testing can be seen as novel applications of eco toxicity testing.

Water quality monitoring

In water quality monitoring, heavy metals, pesticides, and pharmaceuticals in drinking and surface water can be detected using LoC devices. By employing genetically modified organisms, different microfluidic chips were developed. Buffi et al. (2011) reported that *Saccharomyces cerevisiae* and *E. coli* cells were genetically modified to produce green fluorescence by expressing green fluorescent protein (GFP) in response to the presence of arsenite, arsenate, Cd^{2+}, and Pb^{2+} ions to detect DNA damage.

Zhao and Dong (2013) exploited the natural light-emission ability of the marine bacterium *Vibrio fisheri* to fabricate a real-time screening LOC system, which was tailored to a rapid bioluminescence-based test conforming to the ISO 11384 standard, enabling the monitoring of heavy metal ions and phenol in drinking water in a continuous mode.

Wastewater surveillance

Using LoC platforms, industrial effluents and urban runoff for acute and chronic toxicity can be assessed in wastewater treatment. Ecotoxicological studies on wastewater surveillance are employing aquatic protozoa in microfluidics. A well-investigated ciliate species in environmental toxicology, *Paramecium tetraurelia* was used to treat wastewater because of its important role in activated sludge (Illing et al., 2016). They presented a microfluidic system that can isolate single cells of *P. tetraurelia* for further monitoring of their viability after exposure to different concentrations of silver nitrate in wastewater.

A more sophisticated design was developed by Zhang et al. (2014) to evaluate the effect of manganese ions on wastewater on the motility of *Caenorhabditis elegans*. The chip-based device incorporated a worm counter that operated on electric impedance sensing principles, which enabled automated loading of the exact number of worms into the microchannel network. Subsequently, the automated delivery of a range of stepwise toxicant concentrations was allowed by a disk-shaped concentration gradient generator. Then, the on-chip fluorescent microscopy unit further improved the device's analytical capabilities by measuring the green fluorescence emitted by different GFP-tagged *E. coli* strains, which were genetically modified to glow in response to dopaminergic neurotoxicity and oxidative stress. By feeding GFP-tagged *E. coli* to *C. elegans*, the neuron damage or the stress of *C. elegans*, caused by manganese in wastewater, can be determined.

Assessing nano-contaminants

Nowadays, there is great concern about the increasing presence of nanoparticles as an emerging contaminant in aquatic ecosystems, and due to the lack of knowledge about the underpinning mechanisms behind their toxicity and the lack of efficient methods to detect them represents a challenge for environmental risk assessment (Özel et al., 2014). To solve this problem, Kim et al. (2017) developed a novel microfluidic device, and the chip was designed to efficiently visualize the uptake and toxicity of silver nanoparticles (AgNPs) in *C. elegans*. Then it was demonstrated for *in situ* and *in vivo* monitoring of nanomaterials, and the system was fabricated by photolithography. The worms were loaded through the inlet reservoir to an exposure chamber and integrated with an immobilizing clamp channel that allowed for imaging acquisition following incubation with AgNPs.

Soil ecotoxicity testing

To assess soil health, detect contaminants, and provide insights into soil-organism interactions can be achieved through LoC platforms. The concept of 'Soil-on-chip' can simulate the environmental soil conditions and allow for controlled studies of organismal responses to soil contaminants (Stanley et al., 2016).

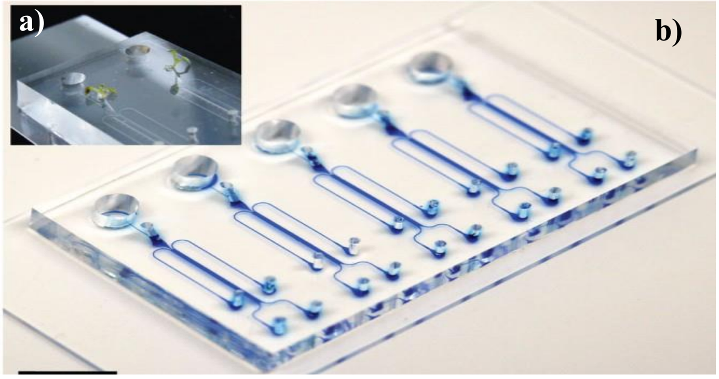


Figure 02. RootChip, **a)** Image of 9-day-old *Arabidopsis* plants cultured into the root inlet of the Bi-directional dual-flow-RootChip, **b)** Image of epoxy dye (blue) filled microchannels for visualization of *Arabidopsis* roots, observation chambers, and micromechanical valves (Scale bar: 10 mm). [Adapted from Allan et al. 2023]

Using microfluidic devices and on-chip cultivation of model plants, plant growth in various soil conditions can be analysed. A study by Grossmann et al. (2011) reported that the 'RootChip' consists of separate chambers for primary roots of seedlings of the model plant *Arabidopsis* (Figure 02). Each chamber is linked to an on-chip perfusion system, which is equipped with micromechanical valves, enabling precise pulsed perfusion of individual chambers. The RootChip system has been used in studies that involve fluorescent sensors for measuring flux kinetics of small molecules. Moreover, to study the calcium signaling during fertilization in *Arabidopsis* and dynamic imaging of cytosolic zinc in *Arabidopsis* roots, RootChip system has been used (Lanquar et al., 2014; Allan et al., 2023).

In the study of Busch et al. (2012), another microfluidic perfusion system named the 'RootArray', was conceived as a large-scale gene expression analysis platform. In this system, within a single large observation chamber, 64 roots were grown and imaged. By using various *Arabidopsis* lines carrying various promoter-GFP constructs and automated image acquisition, gene expression patterns were recorded in response to changing conditions that can mimic the soil conditions in the environment within the observation chamber.

Challenges and limitations of LoC for ecotoxicology

Environmental monitoring and ecotoxicological testing have been transformed by LoC platforms as they enable miniaturized, rapid, and sensitive analyses. However, their widespread adoption and functionality can be hindered by several challenges and limitations.

Miniature size of the chips prevents their applications with larger model organisms such as vascular plants and macro-invertebrates. Moreover, for processing large sample volumes, chip-based systems are usually not particularly suitable as they are smaller in size. Even though special parallel processing capabilities can address this issue, the added complexity may outweigh any cost or analytical benefits compared to conventional methods (Campana and Wlodkowic, 2018).

Microfluidic systems feature extremely high surface area to volume ratios, which can lead to significant losses of tested toxicants because of surface adsorption. Therefore, the substrata used to fabricate chip-based systems should be carefully considered, and stringent monitoring of the toxicant concentrations inside the device might be needed to avoid introducing analytical biases. When trying to limit the loss of sample through adsorption, certain chemical and physical surface treatments that change wettability properties of the inner walls of the microfluidic channels should be considered (Campana and Wlodkowic, 2018). Hence, certain distinct disadvantages and limitations in LoC technology need consideration by scientists.

Future perspectives

Automation achieved in combination with wireless integration, enhanced multi-organism, multi-analyte frameworks, and other advanced peripherals would provide LoC frameworks in ecotoxicology with a wider scope. The integration of Artificial Intelligence and advanced material science would improve device sensitivity, analyzable data, and provide more accurate predictive algorithms.

Moreover, new vistas for high-throughput ecotoxicological screening can be provided by microfluidic technologies that are difficult to achieve using existing, conventional approaches (Huang et al., 2016).

In the future, regulatory integration and standardization of the LoC ecotoxicity assays can be achieved by developing standard protocols and validation methods, as no effort has been made yet towards standardization of chip-enabled bioassays, nor have demonstrations been made in larger environmental monitoring studies (Campana and Wlodkowic, 2018).

Moreover, in most studies, low complexity and homogeneous water samples have been used for the demonstration, but by developing microsystems applicable for analysis of complex and heterogeneous environmental samples, whole sediment ecotoxicity tests can be done (Stanley et al., 2016).

Furthermore, fascinating prospects of LoC-based systems in multi-species interactions studies, such as predator-prey and host-pathogen interactions, community testing, and microcosm analysis, need further exploration in ecotoxicity assessments (Ren et al., 2013).

Finally, the primary goal currently is to develop highly automated, user-friendly, portable, and cost-effective systems with many technological advances made in the field of miniaturization, additive 3D manufacturing, and electronics, and that will open new analytical capabilities for ecotoxicity assays and environmental monitoring (Campana and Wlodkowic, 2018).

Conclusion

LoC technology can be considered the most sustainable and promising alternative for traditional ecotoxicity testing. It enables the analyses to be conducted in real time with less resource investment, thus supporting LoC practices along with equal access to environmentally important toxicity data. Standardization and continued innovation of LoC platforms in ecotoxicity assessments will unlock their full potential related to environmental conservation and public health.

References

Allan C, Tayagui A, Hornung R, Nock V & Meisrimler CN (2023). A dual-flow RootChip enables quantification of bi-directional calcium signaling in primary roots. *Frontiers in plant science*, 13, p.1040117.

Azizipour N, Avazpour R, Rosenzweig DH, Sawan M & Ajji A (2020). Evolution of biochip technology: A review from lab-on-a-chip to organ-on-a-chip. *Micromachines*, 11(6), p.599.

Buffi N, Merulla D, Beutier J, Barbaud F, Beggah S, Van Lintel H, Renaud P & van der Meer, JR (2011). Miniaturized bacterial biosensor system for arsenic detection holds great promise for making integrated measurement device. *Bioengineered bugs*, 2(5), pp.296-298.

Busch W, Moore BT, Martsberger B, Mace DL, Twigg RW, Jung J, Pruteanu-Malinici I, Kennedy SJ, Fricke GK, Clark RL & Ohler U (2012). A microfluidic device and computational platform for high-throughput live imaging of gene expression. *Nature methods*, 9(11), pp.1101-1106.

Campana O & Wlodkowic D (2018). The undiscovered country: Ecotoxicology meets microfluidics. *Sensors and Actuators B: Chemical*, 257, pp.692-704.

Cartlidge R, Nugegoda D & Wlodkowic D (2015). GammarusChip: innovative lab-on-a-chip technology for ecotoxicological testing using marine amphipod *Allorchestes compressa*. In *Bio-Mems and Medical Microdevices* 9518, pp. 210-218.

Chapman PM (1995). Ecotoxicology and pollution—Key issues. *Marine Pollution Bulletin*, 31(4-12), pp.167-177.

Chen CH, Lu Y, Sin ML, Mach KE, Zhang DD, Gau V, Liao JC & Wong, PK (2010). Antimicrobial susceptibility testing using high surface-to-volume ratio microchannels. *Analytical chemistry*, 82(3), pp.1012-1019.

Gainer A, Hogan N & Siciliano SD (2019). Soil invertebrate avoidance behavior identifies petroleum hydrocarbon-contaminated soils toxic to sensitive plant species. *Journal of Hazardous Materials*, 361, pp.338-347.

Grossmann G, Guo WJ, Ehrhardt DW, Frommer WB, Sit RV, Quake SR & Meier M (2011). The RootChip: an integrated microfluidic chip for plant science. *The plant cell*, 23(12), pp.4234-4240.

Huang Y, Persoone G, Nugegoda D & Wlodkowic D (2016). Enabling sub-lethal behavioral ecotoxicity biotests using microfluidic Lab-on-a-Chip technology. *Sensors and Actuators B: Chemical*, 226, pp.289-298.

Illing R, Burkart C, Pfitzner D, Jungmann D, Baraban L & Cuniberti G (2016). Ecotoxicity assessment using ciliate cells in millifluidic droplets. *Biomicrofluidics*, 10(2).

Keçili R & Hussain CM (2021). Green micro total analysis systems (GµTAS) for environmental samples. *Trends in Environmental Analytical Chemistry*, 31, p.e00128.

Kim JH, Lee SH, Cha YJ, Hong SJ, Chung SK, Park TH & Choi SS (2017). *C. elegans*-on-a-chip for *in situ* and *in vivo* Ag nanoparticles' uptake and toxicity assay. *Scientific Reports*, 7(1), p.40225.

Kim K, Jeon HM, Choi KC & Sung GY (2020). Testing the effectiveness of *Curcuma longa* leaf extract on a skin equivalent using a pumpless skin-on-a-chip model. *International journal of molecular sciences*, 21(11), p.3898.

Lanquar V, Grossmann G, Vinkenborg JL, Merkx M, Thomine S & Frommer WB (2014). Dynamic imaging of cytosolic zinc in *Arabidopsis* roots combining FRET sensors and RootChip technology. *New Phytologist*, 202(1), pp.198-208.

Lausecker R, Badilita V, Gleißner U & Wallrabe U (2016). Introducing natural thermoplastic shellac to microfluidics: A green fabrication method for point-of-care devices. *Biomicrofluidics*, 10(4).

Lopez JB, Jackson D, Gammie A & Badrick T (2017). Reducing the environmental impact of clinical laboratories. *The Clinical Biochemist Reviews*, 38(1), p.3.

Loureiro S, Soares AM & Nogueira AJ (2005). Terrestrial avoidance behaviour tests as screening tool to assess soil contamination. *Environmental pollution*, 138(1), pp.121-131.

Mathew A, Liu D, Yu M, Haasbroek P, Wang X, Guan T, Zaki S, Su Q, Li J, Jagannath A & Chen Y (2024). Lab-on-a-chip: From Prototyping to Scale-up Production. In Lab-on-a-chip Devices for Advanced Biomedicine, pp.505-559.

Melin J & Quake SR (2007). Microfluidic large-scale integration: the evolution of design rules for biological automation. *Annu. Rev. Biophys. Biomol. Struct.*, 36(1), pp.213-231.

Özel RE, Liu X, Alkasir RS & Andreescu S (2014). Electrochemical methods for nanotoxicity assessment. *TrAC Trends in Analytical Chemistry*, 59, pp.112-120.

Ren K, Zhou, J & Wu, H (2013). Materials for microfluidic chip fabrication. *Accounts of chemical research*, 46(11), pp.2396-2406.

Shakeri A, Khan S & Didar, TF (2021). Conventional and emerging strategies for the fabrication and functionalization of PDMS-based microfluidic devices. *Lab on a Chip*, 21(16), pp.3053-3075.

Sista R, Hua Z, Thwar P, Sudarsan A, Srinivasan V, Eckhardt A, Pollack M & Pamula V (2008). Development of a digital microfluidic platform for point of care testing. *Lab on a Chip*, 8(12), pp.2091-2104.

Stanley CE, Grossmann G, Solvas XC & deMello AJ (2016). Soil-on-a-Chip: microfluidic platforms for environmental organismal studies. *Lab on a Chip*, 16(2), pp.228-241.

Volpatti LR & Yetisen AK (2014). Commercialization of microfluidic devices. *Trends in biotechnology*, *32*(7), pp.347-350.

Wang K, Wang M, Ma T, Li W & Zhang H (2022). Review on the selection of aptamers and application in paper-based sensors. *Biosensors*, 13(1), p.39.

Zhang B, Li Y, He Q, Qin J, Yu Y, Li X, Zhang L, Yao M, Liu J & Chen Z (2014). Microfluidic platform integrated with worm-counting setup for assessing manganese toxicity. *Biomicrofluidics*, *8*(5).

Zhao X & Dong T (2013). A microfluidic device for continuous sensing of systemic acute toxicants in drinking water. *International journal of environmental research and public health*, 10(12), pp.6748-6763.

CHAPTER 05

Environmental Sustainability through Insect Protein: Potential Feed and Food Applications in Sri Lanka

S. Ramachandra[1*], R. Liyanage[2], U. Kumarasinghe[2] and A. U. Alahakoon[2]

[1]Department of Agricultural Technology, Faculty of Technology,
Sri Lanka Technology Campus, Ingiriya, Padukka. Sri Lanka.
[2]Department of Biosystems Technology, Faculty of Technology,
University of Sri Jayewardenepura,Mahenwatte,
Pitipana North, Homagama. Sri Lanka.
*sisithar@sltc.ac.lk

Abstract

Traditional animal farming for food is often resource-intensive and creates considerable environmental concerns, such as greenhouse gas emissions, deforestation, and land and water pollution. Consequently, there is an increasing interest in alternative protein sources, such as insect protein, to mitigate these impacts by providing a more sustainable alternative. This book chapter explores how insect protein can be a sustainable solution to address the environmental concerns related to human food and animal feed production in Sri Lanka. As insects can be grown in organic waste, they can efficiently convert organic waste into premium protein, requiring significantly fewer resources like land, water, and feed compared to traditional livestock. Additionally, insects serve as a valuable source of essential amino acids, favourable fats, vitamins, and macro and micro minerals. As a traditional food source in many cultures, there is increasing interest in incorporating insects into global diets. They can be transformed into different food items, including flour, cookies, and snacks, offering a sustainable, nutritious substitute for traditional animal protein sources. However, designing attractive insect food products and publicizing their benefits is necessary to improve consumer acceptance. Another major application of insect protein is replacing traditional animal feed ingredients, such as soybean meals or fishmeal. This can reduce the environmental footprint of livestock production by lowering the demand for resource-intensive feed crops such as corn, wheat, and soybeans. Consequently, the introduction of insect proteins for the nourishment of humans and animals can be regarded as a sustainable option.

Keywords: Animal feed, Food, Insect proteins, Sri Lanka, Sustainability

Introduction

There is a global requirement to develop sustainable protein sources for both livestock feed and direct human consumption. The increasing global population has a considerable effect on global food systems, particularly animal-derived proteins for human diets. Traditional livestock production for dairy, meat, egg, and aqua products is the primary protein source for humans; however, it is considered a resource-intensive protein production, demanding a large land area and a significant amount of water (Lange and Nakamura, 2023). Livestock farming has contributed to greenhouse gas emissions, land degradation through overgrazing, water pollution through nutrient runoff from animal manure, etc. In addition, many countries face significant challenges in finding sustainable and cost-effective raw materials for animal feed (Ishag, 2024). Traditional feed materials to fulfill the protein requirement of the animals, such as fishmeal and soybean, have now become expensive sources while considered environmentally unsustainable options.

These unsustainable sources for human food and animal feed production necessitate the exploration and adoption of alternative and sustainable protein sources to ensure environmental sustainability. In this context, insect protein is emerging as a promising and sustainable alternative in the world to address these challenges (Kröger et al., 2022). Insect consumption is traditionally practiced in many parts of the world. Edible insects are considered one of the healthier and more nutritious foods that can be used as an alternative protein source for both animal feed and the human diet (Van Huis, 2016). Insects are rich in protein, fat, minerals, vitamins, and energy (Rumpold and Schlüter, 2013), whereas the nutrition profiles of these insects vary depending on the species (Lange and Nakamura, 2021). These insects provide greater amounts of protein, essential amino acids, omega-3 and omega-6 fatty acids, vitamins, and significant amounts of micronutrients such as iron, magnesium, manganese, copper, phosphorus, and selenium (Rumpold and Schlüter, 2013).

Apart from the exceptional nutritional benefits, insect farming provides substantial environmental advantages. Insect farming requires considerably less land area and water compared to traditional livestock production, while exerting less greenhouse gas effect. Most importantly, it can efficiently convert various organic wastes, such as household food waste, agricultural residues, into high-quality protein. This ability can be used to utilize waste streams effectively in order to rear insects (Van Huis and Oonincx, 2017).

Certain edible insect species can grow on a wide range of organic waste materials such as food waste, kitchen waste, market waste, garden waste, and agricultural residues. Therefore, production processes of edible insects for human food and animal feed can create new market opportunities (Lange and Nakamura, 2023). The insect farming industry helps to generate employment opportunities in various sectors, including insect farming, food processing, distribution, and quality control. While the production of animal feed using insect protein may not be much challenging, the widespread adoption of insect-based human food may face considerable barriers. Unfamiliarity and the lack of understanding regarding consumer perception, nutritional functionality, functionality in food matrices, and the overall sustainability of insect-based food products may contribute to their limited market entrance. Furthermore, cultural acceptance, regulatory challenges, and gaps in scientific research may be challenging, and those need to be appropriately addressed.

This chapter aims to discuss the potential of edible insects as a sustainable protein source for animal feed and human food in Sri Lanka while exploring their significant nutritional value and environmental benefits.

Environmental benefits of insect proteins

The adoption of insect proteins into human meals contains significant environmental benefits. As the primary advantages, the reduced greenhouse gas emissions, lower land and water use, efficient waste recycling, and decreased pressure on traditional feed resources can be highlighted. These environmental benefits, in several ways, will create a potential platform, making them a viable and sustainable alternative to conventional protein sources. Figure 01 summarizes the comprehensive summary of the potential environmental benefits that can be achieved through insect protein initiatives.

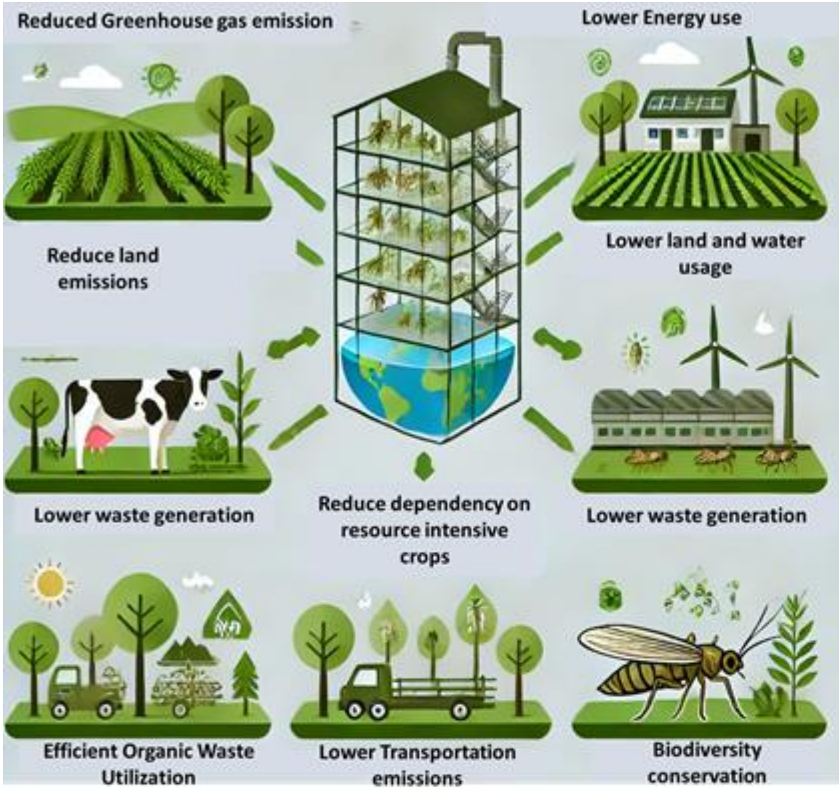


Figure 01. Potential environmental benefits of insect protein initiatives

Compared to insect farming, traditional livestock farming is a major contributor to greenhouse gas (GHG) emissions, particularly methane (CH_4) and nitrous oxide (N_2O), which have high global warming potentials. However, in insect farming, it generates significantly lower emissions. Several studies indicate that insect production releases fewer greenhouse gases per kilogram of protein compared to cattle, pigs, and poultry. Thus, this reduction in emissions contributes to mitigating climate change and achieving sustainability goals (Van Huis and Oonincx, 2017).

The potential of waste circulation through insect farming is interesting. This has been identified as one of the most environmentally beneficial aspects of insect farming. This has huge potential to convert organic waste into high-quality protein. Insects, such as black soldier fly larvae (*Hermetia illucens*), can efficiently break down agricultural and food waste, reducing the amount of organic matter that would otherwise contribute to landfill accumulation and methane production. Thus, by utilizing organic waste as feedstock for insect farming, the waste can be diverted to a meaningful approach without being sent to landfills. This circular economy model enhances resource efficiency and sustainability. On the other hand, insect farming generates significantly less waste compared to traditional livestock farming. Conventional livestock production results in large volumes of manure and organic waste, which can contribute to soil and water pollution through nutrient runoff and methane emissions. Insect farming, however, produces minimal waste, as nearly all parts of the insect can be used for food and animal feed. Thus, this makes insect farming a more resource-efficient and environmentally friendly alternative in this era (Lisboa et al., 2024).

Further, land and water requirements per production of one kg of protein are significantly lower than those of conventional livestock farming. Insect farming requires considerably less space and water. Large-scale production of livestock, such as cattle and poultry, requires extensive areas of land for grazing and crop cultivation for feed production. The land required by conventional livestock farming leads to deforestation and habitat destruction, finally affecting the biodiversity of ecosystems. However, compared to these, insects can be reared in compact, vertical farming systems by minimizing land use. Production of conventional animal feed also results in vast carbon and water footprints. During farming of feeding materials such as soybeans, corn, and wheat, the carbon emission is high due to several factors such as chemical inputs and energy inputs, which also contribute to soil degradation and water pollution. The livestock-based water pollution has become a silent eco-threat in many regions of the globe. As farming contributes to significant water pollution through nutrient runoff, antibiotics, and chemical inputs, it contaminates freshwater sources. However, insect farming produces minimal wastewater and does not require antibiotics or hormones to sustain production. Thus, these environmentally friendly approaches used in insect farming reduce the risk of antimicrobial resistance, which is a growing global concern. Additionally, insect farming minimizes nitrogen and phosphorus runoff, preventing eutrophication. Furthermore, insects have a lower water footprint, as they obtain much of their moisture from their diet, reducing the need for freshwater resources that are otherwise extensively used in conventional livestock farming (Smetana et al., 2023).

Moreover, reduced transportation and storage emissions are a major benefit of insect farming. Traditional meat production emits extensive amounts of carbon during the transportation of feed, live animals, and final meat products. However, insects can be locally farmed in smaller spaces by reducing transportation distances. Additionally, insect protein products, such as dried insect meals and insect-based flour, have a longer shelf life and require less refrigeration compared to fresh meat. These practices also lead to lower energy use and emissions associated with cold storage and distribution.

Admitting all these environmental benefits, ensuring safe farming practices is critical to prevent unintended ecological and health risks. Thus, insects should be reared in controlled and hygienic conditions to prevent contamination, disease outbreaks, and the spread of invasive species. Proper waste management and biosecurity measures are essential to maintain sustainable production without harming surrounding ecosystems. Additionally, the potential use of genetic modification in insect farming raises both opportunities and concerns. Even though genetic modification can enhance insect growth rates, protein content, and disease resistance, it may also lead to unforeseen ecological consequences if modified insects escape into the wild. The impact of genetically modified insects on biodiversity, food safety, and regulatory frameworks must be thoroughly assessed before large-scale implementation (Li et al., 2023).

Insect protein for animal feed in Sri Lanka

Insect-derived protein offers a promising alternative protein source for animal feed production, addressing the increasing global demand for animal feeds. It is considered an environmentally friendly and resource-efficient substitute for traditional feed sources. Traditional feed sources face several challenges, including the increasing cost of raw materials such as corn, soybeans, and fishmeal. This increasing cost is attributed to factors like climate change and growing competition emerging from the human food and biofuel industries (Van Huis, & Oonincx, 2017). Moreover, the excessive use of water and land for feed crop production has exacerbated the issue of limiting available resources. To reduce this environmental burden, the animal feed industry actively seeks alternative feed sources with similar nutritional profiles, such as underutilized cereals and legumes, food wastes, and insect proteins. The agricultural sector in Sri Lanka also faces significant challenges in the animal feed industry, especially for poultry feeds, including rising costs of conventional protein sources and increasing environmental concerns related to feed crop production.

The most promising insects in animal feeds include Larvae of the black soldier fly, Maggot, and pupae of the common housefly (*Musca domestica*), yellow mealworm larvae (*Tenebrio* *molitor*), Larvae of the beetle (*Coleoptera*), termites (*Isoptera*), grasshoppers (*Caelifera*), crickets (*Gryllidae*) (Ghaly and Alkoaik, 2009; Fu et al., 2025).

Insects have been recognized as a promising substitute for animal feed (poultry, swine, and fish) due to several reasons, including their nutritional value, sustainability, economic viability, and benefits for waste management. The protein content of edible insects ranges from 35–60% dry weight basis, often exceeding the protein content of conventional plant protein sources (Kim et al., 2019). Interestingly, their crude protein is enriched with an excellent amino acid profile, consisting of high levels of lysine, methionine, and threonine, which are generally limiting amino acids in conventional plant-based feeds. These insects provide significant amounts of essential micronutrients, including iron, zinc, copper, and vitamin B complex.

Being a complete protein with all the essential amino acids has made insect protein more suitable for meeting the amino acid requirements of rapidly growing poultry. The digestibility of amino acids in insect meals prepared for poultry is high compared to other concentrated feeds (Slimen et al., 2023). Further, several studies have demonstrated that incorporating insect protein into poultry feed can improve their growth performance and feed conversion efficiency compared to the poultry fed with traditional protein sources such as soybean meals or fishmeal. As shown by Krishnan et al. 2011, feeding poultry with insect-based feed can be considered the best option to replace soybean meal in poultry feed. Veldkamp et al. (2012) showed that a poultry diet formulated with insect protein can potentially substitute a wide range of feed ingredients such as cassava peels, sorghum, fish meal, maize, and soy meal. Several studies have demonstrated that when insects are included in poultry feed, the carcass quality, breast muscle portions, feed consumption, weight gain, feed efficiency, and sensory properties of meat are better at a recommended level of inclusion (Slimen et al., 2023). In addition, the chitin present in insect exoskeletons has shown prebiotic effects in certain monogastric animals. This effect can potentially be used to support gut health and the immune function of livestock animals. The prebiotic effects of chitin and the presence of bioactive peptides in insects can potentially be beneficial for disease resistance while reducing the use of antibiotics for poultry (Slimen et al., 2023). However, the presence of chitin may slightly influence nutrient digestibility at very high inclusion rates, which can be minimized by certain processing methods such as heat treatment and enzymatic hydrolysis to enhance nutrient bioavailability. In addition, recent high demand and consequent prices for fishmeal, together with increasing production pressure on aquaculture, have led to the undertaking of research into the development of insect proteins for fish and making insects more cost-effective dietary fishmeal substitutes. Insect meals have demonstrated high protein digestibility in many fish species, such as rainbow trout; European sea bass, compared to traditional protein sources. Moreover, the naturally occurring chitin in insect meals has demonstrated immune-stimulatory effects in several aquaculture species, which may be potentially used to reduce disease susceptibility and antibiotic usage in aquaculture operations in Sri Lanka (Rodríguez-Rodríguez et al., 2024).

Considering these facts, the introduction of insects into animal feeds in Sri Lanka provides a transformative step towards a more sustainable livestock and aquaculture industry (Bashura et al., 2023). However, continued research is required to find out optimal inclusion levels, profitable processing techniques, and large-scale production methods in order to successfully apply these techniques in countries like Sri Lanka.

Insect protein for human consumption in Sri Lanka

Increasing global population and changing dietary patterns have created a global demand for diverse and novel protein sources. Edible insects have emerged as a highly promising alternative to animal-derived protein, which comes through conventional livestock, offering significant nutritional and environmental advantages. In comparison with major animal protein sources for human consumption, such as dairy, meat, fish, and seafood, edible insects can provide high-quality nutrients, including complete protein with essential amino acids, fiber, mono- and polyunsaturated fats, vitamins, and minerals (Rumpold and Schlüter, 2013). Moreover, edible insects are rich sources of functional properties such as antioxidants, antihypertensive, anti-inflammatory, and antimicrobial activities due to the presence of certain bioactive compounds (phenolic compounds, chitin, chitosan, fatty acids, and bioactive peptides). In addition, they are also rich in various micronutrients, including iron, zinc, calcium, magnesium, and B vitamins (eg, B12, riboflavin, biotin, folic acid), which could help to mitigate common dietary deficiencies.

Insect consumption, which is also known as entomophagy, has emerged in many parts of the world a long time ago; however, it has not yet been considered as a mainstream food source due to several reasons, such as changes in local availability, cultural preferences, traditional knowledge on consumption and processing, etc. In Sri Lanka, although certain traditional practices exist, widespread consumption of insect or insect protein is not practiced; therefore, it still presents opportunities for integration into the national diet.

Potential edible insect species can include mealworms, palm weevil larvae (*Rhynchophorus spp.*), silkworm pupae (*Bombyx mori*), bamboo worms (*Omphisa fuscidentalis*), ants (Weaver ants, leaf-cutter ants), bee larvae (*Apis mellifera*), crickets (*Acheta domesticus),* winged termites (*Macrotermes spp.*), larvae of the black soldier fly (*Hermetia illucens*) (Edible insect statistics, 2025).

However, adoption of insects for human consumption is still challenging due to cultural and psychological barriers, and unfamiliarity and unpleasant feelings about insect consumption. These challenges can be overcome by introducing these insect proteins more acceptably and appealingly through processing insects into less identifiable forms, such as flour, protein concentrates, or isolates. Then these forms can be incorporated into daily consumed food systems such as protein bars, bakery products, cookies, snacks, or even for extruded food products (Kröger et al., 2022).

However, there is a necessity to conduct rigorous sensory evaluation for these food products with the participation of local panellists to correctly evaluate the taste preferences and acceptance levels. Along with that, guidelines, regulations, and policies should be established for insect farming, harvesting, processing, storage, packaging, consumption, and marketing. That will build trust between the consumer and the producer while providing non-toxic, safe food products to the consumers. Consumer awareness is a main challenge for the introduction of this kind of non-traditional food source. Therefore, public awareness and education programs should be implemented within Sri Lanka, highlighting the nutritional and environmental benefits of entomophagy. Other indirect benefits also should be highlighted, such as new economic opportunities through insect farming, particularly in rural areas, job opportunities for farming, and processing.

As Sri Lanka faces challenges related to micronutrient deficiencies and the rising cost of conventional protein sources, the integration of insect protein into the human diet in Sri Lanka presents an opportunity to address nutritional security and promote sustainable food systems within the country. Species like crickets and mealworms, and black soldier flies could be studied for their adaptability to local rearing conditions in Sri Lanka using a wide range of organic waste as growth media, to use them as potential protein sources for human food to combat the food security issues within the country.

Challenges and opportunities

There are many opportunities present for the introduction of insect proteins for both animal feed and human food production within Sri Lanka. Since insect protein serves as an excellent source of nutrients for animal feed, there is a high potential of including in poultry, swine, and fish feeds. For example, Sri Lanka's poultry sector is a leading livestock industry; however, it is still highly dependent on imported feed resources such as soybean meals, maize-like ingredients. Insect meal, such as black soldier fly larvae, can locally produce a protein source that can partially or wholly replace the imported feed sources.

Since Sri Lanka generates a substantial amount of organic waste, such as household organic waste, agricultural wastes, restaurant waste, etc., there is a great opportunity to utilize such diverse organic waste streams to produce protein-rich larvae or insects. This action will reduce the waste management burden within the country while reducing the pressure on landfills and environmental pollution. The current burden of waste management can be transformed into a revenue-generating process by producing insect protein to fulfill the local protein requirements for both animal feed and human food production.

Sri Lanka has a rich insect biodiversity, which again offers opportunities to identify potential edible insects to be used. However, research should be conducted to identify locally available, nutritious, and safe insect species that can be reared sustainably. The development of efficient insect production systems suitable for local climate and resource availability remains a challenge. Small-scale insect rearing farms can be established across various regions of the country, mainly focusing on Northern and Eastern provinces as well. These farms may primarily use less technological approaches with manual handling, whereas semi-automated/automated systems can be gradually introduced to improve efficiency.

The development of appropriate processing technologies should be carefully carried out for scaling insect protein production in Sri Lanka. Energy-efficient processing methods, such as drying methods, should be optimized while maintaining protein quality. Optimal storage conditions for preserving the nutritional quality of insect meals should also be investigated in Sri Lanka in order to improve the shelf life of products. Through microbial safety assessments in insect production systems, substrate management and post-harvest processing can be determined to eliminate potential pathogen risks. Heavy metal accumulation can be a concern when insects are reared on certain waste streams; therefore, substrates should be effectively managed to comply with the international safety standards.

Insect protein production in Sri Lanka presents valuable opportunities for further research and innovation, too. For example, genetic improvement programs can be initiated to develop various edible insect species adapted to local conditions. Novel feed formulation strategies by integrating insect proteins along with conventional feed sources can be investigated to optimize amino acid profiles and functional properties for specific animals and their life stages.

The major challenge for introducing insect-derived protein for human consumption is the unpleasant feeling or lower consumer acceptance. To overcome this unpleasant feeling, awareness campaigns, public education programs, and the development of more appealing food products from insects are required. Insects can be processed into various forms, such as protein powders, flours, or extracts, and then those can be integrated into products such as cookies, protein bars, snacks, etc. This approach can create a new market for value-added food products within Sri Lanka, which may be used for local consumption and export purposes.

Certain insects are not safe to use in animal feed or human food as they cause allergic reactions or food poisoning. Therefore, research should be conducted to identify unsafe insect species or ways to mitigate these toxicities. Some of these health risks can be prevented by using recommended insect species that are reared on pollutant-free media.

The regulatory landscape for insect protein in animal feed and human food remains untouched in Sri Lanka. Therefore, necessary actions have to be taken to develop preliminary guidelines for insect meal inclusion in animal feed and human food. To avoid the potential risks associated with insect farming, processing, consumption, and marketing, regulations should be established for the maintenance of proper hygienic practices throughout the production chain. Moreover, there is a need to conduct environmental risk assessments when rearing non-native insect species that are not indigenous to Sri Lanka for commercial purposes within the country. Most importantly, with the participation of the Central Environmental Authority of Sri Lanka, waste management guidelines have to be established to be used in insect production facilities to address any concerns related to hygiene and safety of the rearing media.

Conclusion

The integration of insect-derived proteins into animal feed and human food within Sri Lanka offers a promising technique toward food security and improved environmental sustainability. There is a potential application of converting locally available organic waste, such as agricultural by-products, household waste, into a high-value protein source. However, the collective effort and contribution of research scientists/institutions, regulatory bodies, and private sector stakeholders are required to overcome any implementation barriers. Priority should be given to developing certain strategies to increase consumer perception and their awareness towards insect protein consumption, establishing regulatory frameworks, and developing locally appropriate rearing systems and processing facilities. With such support and strategic planning, insect farming can be introduced to Sri Lanka as another successful industry to achieve sustainable protein production for local requirements, contributing to both economic development and environmental sustainability.

References

Bashura UGB, Ramachandra S & Alahakoon AU (2023). Effective Utilization of Black Soldier Flies Larvae (*Hermetia illucens*) as a poultry feed: a review', paper presented at the International Research Conference of Sri Lanka Technology Campus, Sri Lanka Technology Campus, Colombo, Sri Lanka, 14-15 December.

Fu C, Cheema WA, Mobashar M, Shah AA & Alqahtani MM (2025). Insects as Sustainable Feed: Enhancing Animal Nutrition and Reducing Livestock Environmental Impression. *Journal of Animal Physiology and Animal Nutrition*, 109, pp. 280-290. doi: 10.1111/jpn.14055.

Ghaly AE & Alkoaik FN (2009). The Yellow Mealworm as a Novel Source of Protein. *American Journal of Agricultural and Biological Sciences*, 4(4), 319-331. https://doi.org/10.3844/ajabssp.2009.319.331

Ishag K 2024. Animal Feed Business Risk Assessment Quantification COVID-19 and Supply Chains Disruptions Losses. *Journal of Mathematical Finance*, 14, pp. 337-355. doi: 10.4236/jmf.2024.143019.

Kim TK, Yong HI, Kim YB, Kim HW & Choi YS (2019). Edible Insects as a Protein Source: A Review of Public Perception, Processing Technology, and Research Trends. *Food Science of Animal Resources*, 39(4), pp. 521-540. doi: 10.5851/kosfa.2019.e53.

Kröger T, Dupont J, Büsing L & Fiebelkorn F (2022). Acceptance of insect-based food products in western societies: a systematic review. *Frontiers in Nutrition*, 8, pp. 759885.

Lange KW & Nakamura Y (2021). Edible insects as future food: chances and challenges. *Journal of Future Foods*, 1(1), pp. 38-46.

Lange KW & Nakamura Y (2023). Potential contribution of edible insects to sustainable consumption and production. *Frontiers in Sustainability*, 4, pp. 1112950.

Li M, Mao C, Li X, Jiang L, Zhang W, Li M, Liu H, Fang Y, Liu S, Yang G & Hou X (2023). Edible Insects: A New Sustainable Nutritional Resource Worth Promoting. *Foods*, 12(22), pp. 1–23. doi: 10.3390/foods12224073.

Lisboa HM, Nascimento A, Arruda A, Sarinho A, Lima J, Batista L, Dantas MF & Andrade R (2024). Unlocking the Potential of Insect-Based Proteins: Sustainable Solutions for Global Food Security and Nutrition, *Foods*, 13(12). pp. 1846. doi: 10.3390/foods13121846.

Edible Insects Statistics and Facts 2025. Available at: https://media.market.us/edible-insects-statistics/ (Accessed: 28 May 2025).

Rodríguez-Rodríguez M, Sánchez-Muros MJ, Vargas-García MC, Varga AT, Fabrikov D. & Barroso FG (2024). Evaluation of *in vitro* Protein Hydrolysis in Seven Insects Approved by the EU for Use as a Protein Alternative in Aquaculture', *Animals*, 14(1), pp. 96. doi.org/10.3390/ani14010096.

Rumpold BA & Schlüter OK (2013). Nutritional composition and safety aspects of edible insects. *Molecular Nutrition & Food Research*, 57(5), pp. 802-823.

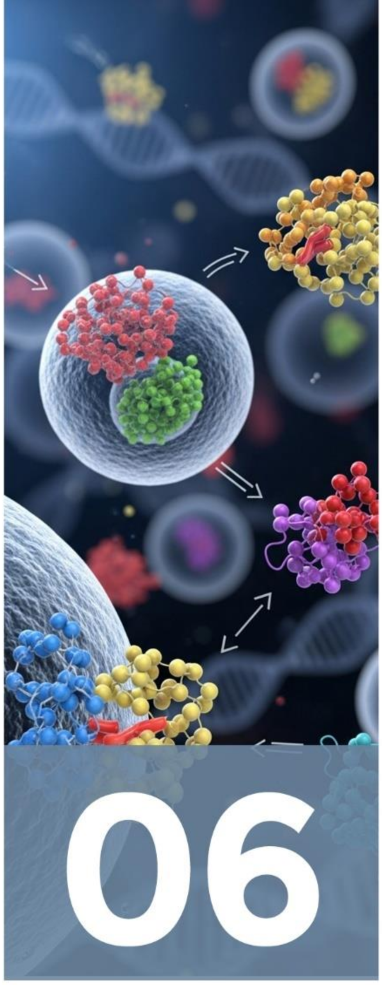
Slimen IB, Yerou H, Ben Larbi M, M'Hamdi N & Najar T (2023). Insects as an alternative protein source for poultry nutrition: a review. *Frontiers in Veterinary Science*, 10, pp. 1200031. doi.org/10.3389/fvets.2023.1200031.

Smetana S, Bhatia A, Batta U, Mouhrim N & Tonda A (2023). Environmental impact potential of insect production chains for food and feed in Europe. *Anim Front.* 13(4), pp 112-120. doi: 10.1093/af/vfad033.

Van Huis A (2016). Edible insects are the future?. *Proceedings of the Nutrition Society*, 75(3), pp. 294-305.

Van Huis A & Oonincx DGAB (2017). The environmental sustainability of insects as food and feed. A review, *Agronomy for Sustainable Development*, 37(5). doi: 10.1007/s13593-017-0452-8.

Veldkamp T & Bosch G (2015). Insects: a protein-rich feed ingredient in pig and poultry diets. *Animal Frontiers*, 5 (2) pp. 45–50. https://doi.org/10.2527/af.2015-0019.



CHAPTER 06

Microbial Enzymes - A Sustainable Biotechnological Approach to Environmental Challenges

A.K.O.D. Amarasinghe and C.M. Nanayakkara*

Department of Plant Sciences, Faculty of Science,
University of Colombo, Colombo 03, Sri Lanka.
**chandi@pts.cmb.ac.lk*

Abstract

Microbial enzymes have gained increasing attention as sustainable and efficient biocatalysts for mitigating diverse environmental challenges. Derived from bacteria, fungi, actinomycetes, and algae, these enzymes facilitate the transformation or degradation of persistent pollutants through highly specific and environmentally benign mechanisms. This chapter provides a comprehensive overview of microbial enzyme applications in environmental biotechnology, focusing on bioremediation, biofuel production, and plastic waste degradation. In bioremediation, enzymes such as laccases, peroxidases, and oxygenases enable the breakdown of hydrocarbons, synthetic dyes, pesticides, and metal-organic complexes, offering a low-impact alternative to conventional remediation technologies. Meanwhile, cellulases and lipases contribute to sustainable energy production by enabling the processing of lignocellulosic feedstocks and waste oils into bioethanol and biodiesel. Enzyme-based approaches are increasingly being explored as alternatives to conventional chemical methods, offering benefits such as reduced toxicity, energy savings, and biodegradability. The discovery of plastic-degrading enzymes, such as PETase, has further expanded the scope of microbial enzyme applications, demonstrating potential for biologically based recycling strategies. Recent advances in enzyme engineering, synthetic biology, and immobilization technologies have significantly improved catalytic efficiency, operational stability, and production scalability. Although challenges remain regarding cost, regulatory approval, and environmental performance, continued innovation is steadily addressing these limitations. Microbial enzymes, with their versatility and environmental compatibility, are poised to become integral to future strategies in waste management, clean energy generation, and ecological restoration.

Keywords: Biodegradation, Biofuel, Bioremediation, Microbial enzymes, Sustainability

Introduction

With rapid industrial growth and an increasing global population, the world is facing serious environmental problems like pollution, waste buildup, and heavy reliance on fossil fuels. These issues show up in the form of polluted water and soil, overcrowded landfills, and rising greenhouse gas emissions that contribute to climate change. Traditional methods of dealing with these problems, like physical or chemical treatments, can be expensive and sometimes cause more harm than good. That's where microbial enzymes come in. These are natural proteins made by microorganisms such as bacteria and fungi, and they have the ability to break down pollutants, convert waste into biofuels, and even help degrade plastics. What makes them really useful is that they work under mild conditions, are biodegradable, and can act specifically on certain substances without affecting the environment much. Because of these advantages, microbial enzymes are gaining attention as eco-friendly tools in biotechnology. This chapter provides an overview of how microbial enzymes are being used globally for environmental applications, especially in areas like bioremediation, biofuel production, and plastic degradation, and how they could play a key role in building a more sustainable future.

Types and sources of microbial enzymes

Microorganisms, including archaea, bacteria, fungi, actinomycetes, yeasts, and algae, are capable of producing a wide variety of enzymes, many of which play significant roles in addressing environmental challenges. These enzymes belong to different classes, such as oxidoreductases and hydrolases, and are involved in breaking down complex compounds into simpler, less harmful forms (Kuhad et al., 2011). In industrial enzyme production, fungi and yeasts are the major contributors (about 50%), followed by bacteria (around 35%), with the remaining coming from other sources like algae (Nigam, 2013). Given below are some of the most common microbial enzymes used in environmental biotechnology, along with their typical sources and roles:

- **Laccases:** These are copper-containing oxidase enzymes mainly found in white-rot fungi like *Trametes* and *Phanerochaete*, but they are also present in some bacteria and plants (Baldrian, 2006). Laccases can oxidize a wide range of phenolic and aromatic compounds using oxygen, and the only by-product is water. They are especially useful in breaking down lignin in plant material and degrading stubborn pollutants like synthetic dyes and phenols (Strong and Claus, 2011). Laccases are widely used in wastewater treatment, especially for removing color from dye-contaminated water (Strong and Claus, 2011).

- **Peroxidases:** Peroxidases (including lignin peroxidase and manganese peroxidase) come mainly from white-rot fungi (Wong, 2009). These enzymes use hydrogen peroxide to oxidize and break down complex pollutants like industrial dyes, phenolic compounds, and some hydrocarbons (Wong, 2009).
- **Cellulases:** Cellulases break down cellulose, the main component of plant biomass, into simple sugars. Fungi like *Trichoderma reesei* and *Aspergillus* species are major producers of cellulases, as are bacteria like *Clostridium* and *Cellulomonas* (Lynd et al., 2002). In nature, these enzymes help decompose plant material, while in biotechnology, they are essential for converting agricultural waste into fermentable sugars for bioethanol production (Lynd et al., 2002). Actinomycetes like *Streptomyces* also produce cellulases and help recycle organic matter in soil (Gupta et al., 2002).
- **Lipases:** Lipases break down fats and oils into fatty acids and glycerol. They are produced by various microbes, including *Bacillus* and *Pseudomonas*, and *Candida* and *Rhizopus* (Sharma et al., 2001). In environmental applications, microbial lipases are used to degrade oil spills and grease in wastewater. They also play a major role in biodiesel production by catalyzing the transesterification of oils into fatty acid methyl esters under mild and eco-friendly conditions (Hasan et al., 2006).
- **Proteases:** These enzymes degrade proteins into smaller peptides and amino acids. Proteases are widely produced by bacteria such as *Bacillus* species and various fungi (Joo et al., 2004). Apart from their industrial use in products like detergents and food processing, microbial proteases help break down protein-rich waste like animal by-products or decaying plant matter (Joo et al., 2004). Some alkaline proteases are particularly useful for treating wastewater under harsh conditions because they remain stable at high pH and temperature (Jaouadi et al., 2010).

These examples show the diversity of microbial enzymes and how they have evolved to break down complex molecules in the environment. By identifying the right enzymes or combinations of them, scientists can design targeted and efficient approaches to tackle specific types of pollution. The next sections will look at how these enzymes are applied in real-world environmental solutions.

Applications in bioremediation

Bioremediation involves the use of living organisms or their enzymatic products to detoxify or remove environmental pollutants. Microbial enzymes are central to many bioremediation strategies due to their ability to chemically transform harmful compounds into less toxic or non-toxic forms (Ghosal et al., 2016). These transformations often occur through oxidation, reduction, or enzymatic cleavage of complex molecular structures, facilitating the breakdown or removal of pollutants (Figure 01) (Das and Chandran, 2011).

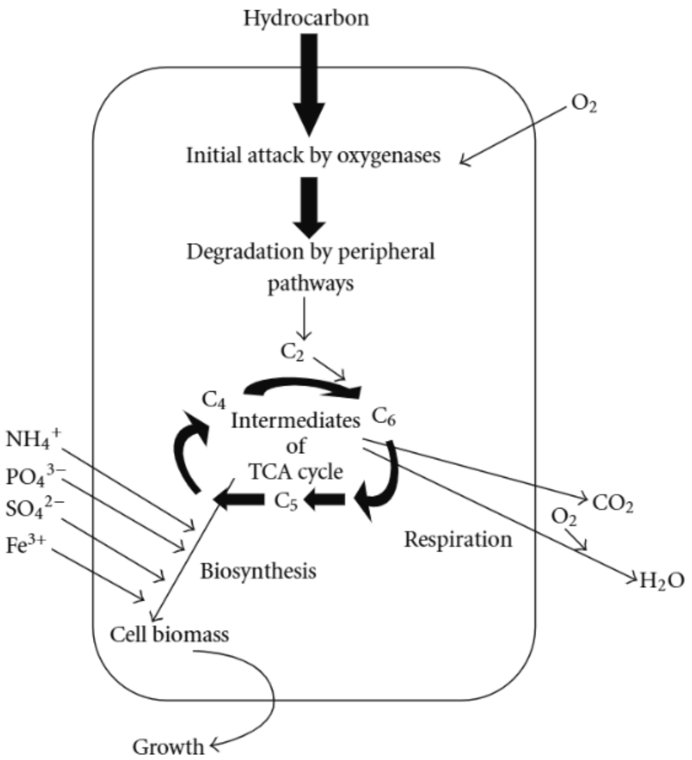


Figure 01. Main principle of aerobic degradation of hydrocarbons by microorganisms [source: Das and Chandran, 2011]

Environmental pollution caused by hydrocarbons, dyes, pesticides, and heavy metals poses significant threats to ecosystems and human health. For example, the International Tanker Owners Pollution Federation (ITOPF, 2023) reports that over 1.3 million tonnes of oil are released into the marine environment annually due to industrial activities such as offshore drilling, transport, and storage. Oil spills and petroleum contamination severely impact aquatic life and soil ecosystems. Microbial enzymes such as oxygenases and dehydrogenases play a major role in degrading petroleum hydrocarbons. Under aerobic conditions, monooxygenases and dioxygenases incorporate oxygen atoms into hydrocarbon molecules, initiating their breakdown into smaller, more bioavailable intermediates (Van Hamme et al., 2003) demonstrated that *Pseudomonas aeruginosa* and *Bacillus* spp. isolated from oil-contaminated soils were capable of degrading Assam crude oil, achieving over 90% petroleum hydrocarbon reduction in controlled experiments. Additionally, extremophiles, microorganisms adapted to thrive in high salinity, pressure, and temperature conditions typical of deep-sea and marine oil spill sites, are increasingly recognized for their robust enzymatic activity. These extremozymes, often derived from halophilic or thermophilic archaea and bacteria, remain active under harsh marine conditions, making them valuable agents for in situ bioremediation of oil-contaminated marine environments (Raddadi et al., 2012). Similarly, Head et al. (2006) reported that such enzymatic processes can convert complex, water-insoluble hydrocarbons into smaller metabolites that microbes eventually mineralize into carbon dioxide and water. This mechanism allows microbes to effectively "digest" oil and polycyclic aromatic hydrocarbons (PAHs) in contaminated environments. Pesticides represent another class of persistent pollutants, with more than 3.7 million tonnes applied globally each year (FAO, 2021). Many synthetic pesticides, especially organophosphates and chlorinated compounds, are stable and resistant to degradation. Microbial enzymes such as dehalogenases and organophosphorus hydrolases are capable of breaking these molecules down. For example, dehalogenases remove halogen atoms from chlorinated solvents and herbicides, while phosphotriesterases hydrolyze organophosphate pesticides into non-toxic forms (Mulbry and Karns, 1989). Soil bacteria and actinomycetes naturally produce these enzymes, making them ideal for the bioremediation of pesticide-contaminated environments. Textile industries release large volumes of dye and phenolic waste, estimated at 280,000 tonnes of synthetic dyes per year (Verma et al., 2012). Fungal enzymes, particularly laccases and peroxidases from white-rot fungi like *Trametes villosa*, are highly effective in breaking down these aromatic pollutants (Wesenberg et al., 2003). Laccases oxidize dye molecules and phenolic compounds, transforming them into smaller, less toxic fragments. Zille et al. (2005) demonstrated that laccase from *T. villosa* could degrade a range of azo dyes under oxidative conditions, avoiding the formation of toxic aromatic amines. In addition, laccase-producing bacteria such as *Bacillus* spp. have been reported to decolorize over 90% of synthetic textile dyes within a few hours (Kim et al., 2022). Heavy metals, although elemental and non-degradable, can be detoxified or immobilized using microbial enzymes. For example, chromate reductases can reduce carcinogenic hexavalent chromium (Cr^{6+}) to its less toxic trivalent form (Cr^{3+}), effectively lowering its mobility and bioavailability (Hossan et al., 2020). Other microbial enzymes such as cyanide hydrolases and ureases assist in degrading metal-organic complexes or fertilizers (Dash et al., 2009). Although the enzymes do not remove the metals themselves, these transformations greatly reduce their environmental impact. Globally, soil and water contamination by heavy metals such as lead, mercury, and cadmium remain a critical issue, with an estimated 800,000 tonnes of lead and 30,000 tonnes of chromium released between 1950 and 2000 (McLaughlin et al., 2000). Enzyme-based bioremediation is already being practiced in various parts of the world, particularly in cleaning up oil spills and dye-contaminated sites using microbial consortia or enzyme-augmented bioreactors (Riser-Roberts, 1998). These systems are valued for being environmentally safe, operational *in situ*, and effective under mild conditions. However, enzyme stability and cost-efficiency remain challenges, especially under extreme field conditions. To address this, strategies such as enzyme immobilization and protein engineering are being employed to improve their stability, reusability, and field applicability (Sheldon, 2007).

Role in biofuel production

Microbial enzymes play a vital role in the production of renewable biofuels such as bioethanol and biodiesel by converting agricultural residues and waste oils into cleaner energy sources through environmentally friendly processes (Chandel et al., 2012). In bioethanol production, second-generation methods use lignocellulosic biomass like crop residues and wood. These materials are rich in cellulose and hemicellulose, which are broken down into fermentable sugars by microbial enzymes such as cellulases and hemicellulases produced by organisms like *Trichoderma reesei, Aspergillus niger*, and various bacteria (Lynd et al., 2002). Advances in enzyme engineering have improved their efficiency and stability, making commercial production more feasible in countries including the USA and Brazil (Bischof et al., 2016). In biodiesel production, microbial lipases from species such as *Pseudomonas cepacia* and *Candida antarctica* catalyze the transesterification of oils under mild conditions, offering a cleaner alternative to chemical catalysts (Sharma et al., 2001; Hasan et al., 2006). These enzymes are effective even with low-quality feedstocks like used cooking oil, which helps mitigate environmental pollution. Immobilization techniques and genetic modifications have further enhanced lipase stability and reusability for industrial use (Verma et al., 2012). Importantly, bio fuels produced using microbial enzymes are less environmentally persistent than fossil fuels. Bioethanol, for example, is highly volatile and readily biodegradable. If released into the environment, it evaporates quickly or is easily broken down by microbes, reducing long-term contamination risks in soil and water (Jeswani et al., 2020). Therefore, microbial enzyme-based biofuel production contributes to both clean energy generation and environmental protection.

Microbial enzymes in plastic degradation

Plastic pollution is one of the most persistent environmental problems we face today. Synthetic plastics like polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) are highly durable, which is useful for their everyday applications but problematic when they end up as waste. Because these materials don't break down easily in nature, they accumulate in landfills, oceans, biomass and even remote ecosystems. However, in in the early 2000s, microbial enzymes have shown exciting potential for breaking down certain plastics, offering new hope for biological recycling and plastic waste management (Singh and Sharma 2008). Most enzymes that can degrade plastic belong to the hydrolase class. These enzymes work by breaking the bonds in plastic polymers, turning them into smaller, more manageable molecules. Some plastics, like polyurethanes and polyesters, are more susceptible to enzymatic breakdown, especially by enzymes like cutinases and lipases that can target the ester bonds in their structure (Wei and Zimmermann 2017). One of the most remarkable discoveries in this area came in 2016, when researchers in Japan identified a bacterium called *Ideonella sakaiensis* that can actually "eat" PET; a plastic commonly used in drink bottles and clothing (Yoshida et al. 2016). This bacterium produces two enzymes: polyethylene terephthalate hydrolase (PETase), which breaks PET down into smaller molecules called mono(2-hydroxyethyl) terephthalate (MHET), and MHETase, which further degrades MHET into the building blocks terephthalic acid and ethylene glycol. These are the same raw materials used to make PET, so this process could theoretically allow complete recycling of PET back into new plastic (Yoshida et al. 2016). Since the discovery of *I.sakaiensis*, PETase has become a major focus of enzyme engineering. Although the natural version of PETase works best at around 30°C and is relatively slow, researchers have developed modified "fast PETases" that are more thermostable and can break down even crystalline PET (the more rigid form used in bottles) much more quickly sometimes in just a few days at 50°C. These engineered enzymes make it possible to imagine a future where waste PET could be broken down enzymatically, then reused to make new plastic closing the loop in a circular economy. Although this area of research is still developing, the progress so far is encouraging. Scientists have found plastic-degrading microbes not just in landfills, but in compost heaps, marine environments, and even on plastic waste itself (Urbanek et al. 2018). The ultimate goal is to create enzyme-based treatments that can be used in recycling plants or even sprayed on landfill sites to help break down plastics without needing high heat or harsh chemicals. Of course, challenges remain. Many of these enzymes still need to be optimized for industrial-scale use, especially in terms of speed, cost, and stability. But with continued research, microbial enzymes like PETase, along with extremozymes such as thermophilic cutinases and lipases from *Thermobifida fusca* or *Ideonella sakaiensis* could become a central part of how we manage plastic waste in the future making plastic not just recyclable, but biologically degradable.

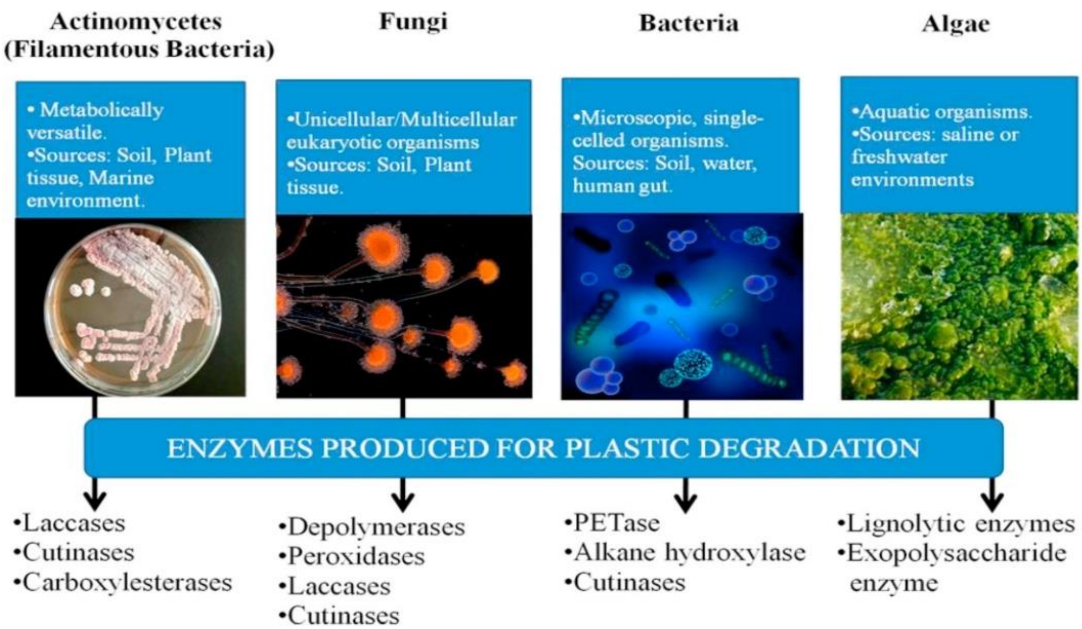


Figure 02. Critical enzymes for plastic degradation from different microorganisms.
[source: Kaushal et al., 2021]

Challenges and future prospects

Despite their vast potential in environmental biotechnology, microbial enzymes face challenges related to cost, scalability, and stability. Producing purified enzymes in large quantities remains expensive, and their activity can decline under harsh field conditions, limiting effectiveness during urgent interventions like oil spills. To address this, researchers are improving enzyme yields through better fermentation, genetic engineering, and immobilization techniques that enhance stability and reusability (Sheldon, 2007). The use of whole microbes as *in situ* enzyme producers is also gaining attention, particularly as a cost-effective alternative to pure enzyme applications. However, regulatory concerns arise when using genetically modified organisms, requiring strict biosafety oversight (Chaturvedi and Verma, 2016). While most microbial enzymes are biodegradable and generally recognized as safe (Dvořák et al., 2017), environmental impact assessments remain essential. Looking ahead, enzyme-based solutions align well with sustainability goals, supporting waste-to-value processes, renewable energy, and pollution control. Emerging tools such as synthetic biology, nanotechnology, and machine learning are expected to enhance enzyme design and broaden their application to complex pollutants like microplastics and pharmaceuticals (Mazurenko et al., 2020). As ongoing research continues to overcome current barriers, microbial enzymes are poised to play a central role in building a cleaner, more sustainable future.

Conclusion

Microbial enzymes are becoming increasingly important in tackling some of the most pressing environmental challenges of our time. As highlighted throughout this chapter, these naturally occurring biocatalysts can break down harmful pollutants in bioremediation, transform plant waste into renewable biofuels, and even help us manage plastic pollution more sustainably. What sets microbial enzymes apart is their eco-friendly and highly specific nature. Unlike many chemical treatments, enzymes can carry out complex reactions under mild conditions, often with fewer side effects or by-products. And with current advances in biotechnology, enzymes can now be produced in large quantities making it possible to treat wastewater at the industrial scale or convert tons of agricultural residues into clean energy. The applications discussed in this chapter clearly show that enzyme-based technologies can either replace or improve conventional methods. They allow us to clean up pollution without relying on harsh chemicals, create energy from waste instead of fossil fuels, and recycle materials that would otherwise persist in the environment for years or decades. The reach of microbial enzymes is also globally significant. Whether it's a small-scale composting initiative in a rural community or a large-scale biofuel production facility in a major city, enzyme technologies are making a positive impact across different settings. They also align directly with sustainability goals, helping to close the loop in waste management and reduce the overall environmental footprint of industrial processes.

Looking ahead, the potential of microbial enzymes will only grow. With rapid progress in areas like protein engineering, synthetic biology, and systems design, we're likely to see the development of next-generation enzymes that are even more efficient, cost-effective, and specialized. These innovations could open the door to solving tough problems like breaking down synthetic chemicals or creating fully circular systems for materials and energy. Microbial enzymes represent a powerful example of how we can work with nature to protect and restore the environment. Their use not only reflects the strength of modern biotechnology but also supports a more harmonious relationship between human activity and the natural world. With continued investment in research and practical deployment, microbial enzymes are set to play a vital role in creating a cleaner, greener, and more sustainable future for all.

References

Baldrian P (2006). Fungal laccases – occurrence and properties. *FEMS Microbiology Reviews*, 30(2), 215–242.

Bischof RH, Ramoni J & Seiboth B (2016). Cellulases and beyond: the first 70 years of the enzyme producer *Trichoderma reesei*. *Microbial Cell Factories*, 15(1), 106.

Chandel AK, Silva SS & Singh OV (2012). Detoxification of lignocellulosic hydrolysates for improved bioethanol production. *BioEnergy Research*, 5(2), 318–338.

Chaturvedi V & Verma P (2016). Regulatory aspects of genetically modified microorganisms used in industrial applications. *Journal of Biosafety & Health Education*, 4, 1.

Das N & Chandran P (2011). Microbial degradation of petroleum hydrocarbon contaminants: An overview. *Biotechnology Research International*, 2011, 941810.

Dash RR, Gaur A & Balomajumder C (2009). Cyanide in industrial wastewaters and its removal: A review on biotreatment. *Journal of Hazardous Materials*, 163(1), 1–11.

Dvořák P, Nikel P I, Damborský J & de Lorenzo V (2017). Bioremediation 3.0: Engineering pollutant-removing bacteria in the times of systemic biology. Biotechnology Advances, 35(7), 845–866. https://doi.org/10.1016/j.biotechadv.2017.08.001

FAO (2021). Pesticide Use. Food and Agriculture Organization. https://www.fao.org

Ghosal D, Ghosh S, Dutta TK, & Ahn Y (2016). Current State of Knowledge in Microbial Degradation of Polycyclic Aromatic Hydrocarbons (PAHs): A Review. Frontiers in Microbiology, 7, 1369. https://doi.org/10.3389/fmicb.2016.01369

Gupta R, Beg QK & Lorenz P (2002). Bacterial alkaline proteases: molecular approaches and industrial applications. *Applied Microbiology and Biotechnology*, 59(1), 15–32.

Hasan F, Shah AA & Hameed A (2006). Industrial applications of microbial lipases. *Enzyme and Microbial Technology*, 39(2), 235–251.

Head IM, Jones DM & Röling WFM (2006). Marine microorganisms make a meal of oil. *Nature Reviews Microbiology*, 4(3), 173–182.

ITOPF (2023). Oil Tanker Spill Statistics. International Tanker Owners Pollution Federation. https://www.itopf.org

Jaouadi B, Abdelmalek B, Fodil D, Ferradji FZ, Rekik H, Zaraî N, & Bejar S (2010). Purification and characterization of a thermostable keratinolytic serine alkaline proteinase from Streptomyces sp. Strain AB1 with high stability in organic solvents. Bioresource Technology, 101(21), 8361–8369.

Jeswani HK, Chilvers A & Azapagic A (2020). Environmental sustainability of biofuels: A review. Proceedings. Mathematical, Physical, and Engineering Sciences, 476(2243), 20200351. https://doi.org/10.1098/rspa.2020.0351

Joo HS, Chang CS, & Kim KK (2004). Alkaline protease from a newly isolated *Bacillus clausii* I-52: production and some properties. *Process Biochemistry*, 39(8), 1445–1451.

Kaushal J, Khatri M & Arya SK (2021). Recent insight into enzymatic degradation of plastics prevalent in the environment: A mini - review. Cleaner Engineering and Technology, 2, 100083. https://doi.org/10.1016/j.clet.2021.100083

Kim W, Jeong Y, Back S, Kim S, & Kim J (2022). Decolorization of Textile Dye by Spore Surface Displayed Small Laccase for the Enhanced Thermal Stability and Robust Repeated Reaction. Biotechnology and Bioprocess Engineering, 27(6), 930–937. https://doi.org/10.1007/s12257-022-0317-0

Kuhad RC, Gupta R, & Singh A (2011). Microbial cellulases and their industrial applications. *Enzyme Research*, 2011, Article ID 280696.

Lynd LR, Weimer PJ, van Zyl WH & Pretorius IS (2002). Microbial cellulose utilization: Fundamentals and biotechnology. *Microbiology and Molecular Biology Reviews*, 66(3), 506–577.

Mazurenko S, Prokop Z & Damborsky J (2020). Machine learning in enzyme engineering. *ACS Catalysis*, 10(2), 1210–1223.

McLaughlin MJ, Parker DR & Clarke JM (2000). Metals and micronutrients – food safety issues. *Field Crops Research*, 60(1–2), 143–163.

Mulbry WW & Karns JS (1989). Purification and characterization of three parathion hydrolases from gram-negative bacterial strains. *Journal of Bacteriology*, 171(12), 6740–6746.

Nigam PS (2013). Microbial enzymes with special characteristics for biotechnological applications. *Biomolecules*, 3(3), 597–611.

Raddadi N, Cherif A, Daffonchio D, Neifar M, & Fava F (2015). Biotechnological applications of extremophiles, extremozymes and extremolytes. Applied Microbiology and Biotechnology, 99.

Riser-Roberts E (1998). *Remediation of petroleum-contaminated soils: biological, physical, and chemical processes*. CRC Press.

Sharma R, Chisti Y & Banerjee UC (2001). Production, purification, characterization, and applications of lipases. *Biotechnology Advances*, 19(8), 627–662.

Sheldon RA (2007). Enzyme immobilization: The quest for optimum performance. *Advanced Synthesis & Catalysis*, 349(8-9), 1289–1307.

Singh B & Sharma N (2008). Mechanistic implications of plastic degradation. *Polymer Degradation and Stability*, 93(3), 561–584.

Strong PJ & Claus H (2011). Laccase: a review of its past and future applications. *Environmental Technology*, Critical Reviews in Environmental Science and Technology 41:373–434.

Urbanek AK, Rymowicz W & Mironczuk AM (2018). Degradation of plastics and plastic-degrading bacteria in cold marine habitats. *Applied Microbiology and Biotechnology*, 102(18), 7669–7678.

Van Hamme JD, Singh A & Ward OP (2003). Recent advances in petroleum microbiology. *Microbiology and Molecular Biology Reviews*, 67(4), 503–549.

Verma A K, Dash RR & Bhunia P (2012). A review on chemical coagulation/flocculation technologies for removal of colour from textile wastewaters. *Journal of Environmental Management*, 93(1), 154–168.

Hossan S, Hossain S, Islam MR, Kabir MH, Ali S, Islam MS, Imran KM, Moniruzzaman M, Mou TJ, Parvez AK, & Mahmud ZH (2020). Bioremediation of Hexavalent Chromium by Chromium Resistant Bacteria Reduces Phytotoxicity. International Journal of Environmental Research and Public Health, 17(17), 6013. https://doi.org/10.3390/ijerph17176013

Wei R & Zimmermann W (2017). Biocatalysis as a green method to recycle polyethylene terephthalate. *Microbial Biotechnology*, 10(6), 1302–1307.

Wesenberg D, Kyriakides I & Agathos SN (2003). White-rot fungi and their enzymes for the treatment of industrial dye effluents. *Biotechnology Advances*, 22(1-2), 161–187.

Wong DWS (2009). Structure and action mechanism of ligninolytic enzymes. *Applied Biochemistry and Biotechnology*, 157, 174–209.

Yoshida S, Hiraga K, Takehana T, Taniguchi I, Yamaji H, Maeda Y, Toyohara K, Miyamoto K. Kimura Y, & Oda K (2016). A bacterium that degrades and assimilates poly (ethylene terephthalate). *Science* (New York, N.Y.), 351(6278), 1196–1199. https://doi.org/10.1126/science.aad6359

Zille A, Gornacka B, Rehorek A & Cavaco-Paulo A (2005). Degradation of azo dyes by Trametes villosa laccase over long periods of oxidative conditions. *Applied and Environmental Microbiology*, 71(11), 6711–6718.

CHAPTER 07

Plant-Based Eco-Friendly Approaches for Bisphenol A (BPA) Removal

R.R.K. De Zoysa, K.D.A. Dulanjana, G. Rajapaksa* and P.W. Samarasekere

Department of Zoology and Environment Management,
University of Kelaniya
**gayani@kln.ac.lk*

Abstract

Bisphenol A (BPA) is a chemical widely used in the production of polycarbonate plastics and epoxy resins. Extensive use of this endocrine disruptor has made it a ubiquitous environmental contaminant, making its exposure inevitable for all living organisms. BPA can leach into surface water through industrial effluents, household wastewater, and landfill leachates. The accumulation of BPA in the environment, especially in aquatic ecosystems, can affect wild populations living in those habitats. Thus, removal of BPA from surface water has gained significant attention, and numerous physicochemical methods for BPA removal have been introduced. Chemical methods have been reported with adverse consequences like secondary pollution due to disposed materials and byproducts, high energy usage, carbon emission etc. Environmental concerns associated with physiochemical methods have necessitated sustainable and eco-friendly approaches to remove BPA. Use of plants for the removal of BPA or phytoremediation is one such environmental-friendly method as plants absorbs, accumulate, and detoxify harmful chemicals through roots and shoots. Phytoremediation presents a cost-effective, environmentally friendly, and sustainable approach to wastewater treatment. Unlike conventional chemical methods, it minimizes secondary pollution, promotes ecosystem restoration, and provides habitats for aquatic organisms. Moreover, it contributes to carbon sequestration and improves water quality, making it a promising approach for reducing the impact of BPA and other environmental pollutants. Various plant-based studies have shown the potential of aquatic plants, including *Ceratophyllum demersum, Hydrilla verticillata,* and *Potamogeton oxyphyllus,* plants near water bodies such as *Panicum virgatum* and *Portulaca oleracea,* and ornamental plants such as *Dracaena sanderiana*, *Dracaena fragrans*, and *Salvia* in the remediation of BPA. Additionally, certain crops such as soybeans, wheat, lettuce and collards have also been found to absorb BPA. The ability of certain plants to remove BPA appears to be an eco-friendly approach to remove a ubiquitous environmental contaminant.

Keywords: Bisphenol, Phytoremediation

Introduction

Bisphenol A (BPA) is an industrial raw material widely used in the production of polycarbonate plastics, epoxy resins, and thermal papers. BPA is commonly found in items such as plastic water bottles, food containers, beverage can linings, baby feeding bottles, medical devices (including dental sealants, contact lenses), cosmetic products, plastic toys, water pipes, and jar cap coatings etc (Corrales et al., 2015). According to the BPA-global strategic business report 2024, the estimated global market for BPA was 6.4 million tons in 2023 and is predicted to reach around 9.3 million tons by 2030.

BPA enters the environment through both direct and indirect pathways, including domestic and industrial solid waste, industrial and wastewater treatment plant effluents discharged into aquatic systems. Landfill leachate is another significant source of BPA contamination. Improperly disposed plastic items can undergo chemical degradation under elevated temperatures, acidic, or alkaline conditions, leading to the leaching of BPA into the surrounding soil and water (Im & Löffler, 2016). Due to the widespread nature of BPA usage, BPA continuously enters the natural environment, making it a pervasive chemical. It can accumulate in surface and groundwater, sediments, and even in biota, causing long-term risks to aquatic ecosystems and potentially entering the food chain.

Occurrence of BPA in the environment

Numerous environmental samples, such as soil, sediments, water, sewage effluents, and sludge, contain BPA. BPA ranging from 120-6500 ng g^{-1} has been detected in municipal sewage sludge in Norway (Janda et al., 2021). Industrial wastewater contained a higher amount of BPA compared to municipal wastewater in Northern Serbia. The lowest BPA concentration was detected in rural drinking water samples, while the urban drinking water ranged between 2.5-36.5 ng L^{-1} (Čelić et al., 2020). According to recent research, 12 states of India, which include the Yamuna River, have reported the environmental occurrence of BPA (Lalwani et al., 2020). BPA concentrations in water samples collected from Bolgoda Lake, Sri Lanka, influenced by leachate from the Karadiyana solid waste open dump, has ranged from 3.3 to 29.2 µg/L during the rainy period and from 1.0 to 1.2 µg/L during the dry period (Matharage et al., 2021). Graziani et al. (2019) reported that atmospheric BPA concentrations were highest in industrial areas of Córdoba, Argentina, and gradually decreased with increasing distance from the industrial zone. Furthermore, meteorological parameters, including wind speed, temperature, humidity, and atmospheric pressure, can alter the concentration of BPA.

Exposure to BPA and its effects

Major exposure routes of BPA are through diet, inhalation, and dermal contact. Once ingested, BPA can be absorbed through the gastrointestinal tract of humans and other animals. BPA dust can enter through inhalation. Direct contact with skin, particularly when handling receipts printed on thermal paper, can cause dermal exposure to BPA (Liu & Martin, 2017). A considerable amount of BPA is released from food containers and cans (Lorber et al., 2015). Food and beverage containers and dental sealants release BPA due to inadequate polymerization and breakdown of the polymers due to exposure to higher temperatures (Almeida et al., 2018). Improper disposal of end-of-use plastics, solid waste accumulation, and incineration are major pathways of BPA release. Acidic soil or water conditions, high temperature, and UV-radiation can increase the migration rate of BPA into the environment (Almeida et al., 2018). BPA has been shown to transfer through the food chain owing to its moderate solubility in fat tissue. Since BPA is an endocrine disruptor, it perturbs hormone signalling pathways, including estrogen, androgen, and thyroid hormones. Deregulation of hormone signalling affects the growth, development, and behaviour of living organisms (Amir et al., 2021)

Effects on animals

Numerous experimental studies have investigated the effect of BPA on animals. Richter et al. (2007) reported that BPA exposure impacts the brain, male reproductive system, and metabolic processes of rodents. Another study demonstrated that tumor formation in the mammary glands in rats exposed to BPA (Acevedo et al., 2013). The genotoxicity and cytogenetic effects of BPA have been investigated using hamster ovary cells (Xin et al., 2015). Baralla and colleagues have observed alterations in oxidative stress and cellular deformations in sheep red blood cells (Baralla et al., 2021). In rats, BPA exposure had lowered the levels of glutathione and increased the levels of lipid peroxidation in their livers. In zebrafish, BPA has been shown to alter growth, sex differentiation, organ development, and swimming behavior. Changes in population sex ratio, growth, and development can negatively affect the aquatic ecosystem health (Pathirajage & Rajapaksa, 2024).

Effects on humans

BPA is metabolized primarily in the liver of humans (Völkel et al., 2002) It undergoes conjugation with glucuronic acid to form BPA-glucuronide, a more water-soluble compound that can be excreted in urine. About 90% of the absorbed BPA is excreted via urine within six hours (Völkel et al., 2002). Emerging findings suggest that BPA has the potential to damage neuronal activity and fertility in humans (Santoro et al., 2019). Alterations in the reproductive system, metabolic activity, and development processes have also been widely investigated. Shankar and Teppala (2011) identified a correlation between urinary BPA and diabetes mellitus in humans. BPA has raised health concerns due to its ability to mimic estrogen, causing potential disruption in endocrine function (Lü et al., 2024). In addition, BPA can also disrupt the function of thyroxin by acting as an antagonist and can interfere with androgen receptors (Kim & Park, 2019). These interactions contribute to obesity, fertility issues, miscarriages, and polycystic ovary syndrome-like conditions in women. In men, BPA affects sperm quality, fertility, and sexual function (Tian et al., 2018). There is evidence that BPA can cause hypertension, cardiovascular diseases, and hormone-dependent cancers (Han and Hong, 2016). Furthermore, BPA has been shown to induce DNA breaks in human cells, primarily through oxidative DNA damage and also It acts on erythrocytes, causing hemolysis, lipid peroxidation, oxidative stress, and reduction in antioxidant enzymes (Maćczak et al., 2015).

Given the wide range of adverse health effects associated with BPA, there is an urgent need for researchers and policymakers to develop and implement effective strategies to mitigate the environmental occurrence of BPA.

Conventional BPA removal techniques

Widely used methods for BPA removal involve a range of physiochemical methods, including adsorption methods, advanced oxidation processes (AOPs), membrane filtration technologies, chemical precipitation, coagulation, photocatalysis, biodegradation etc.

Adsorption involves the accumulation of BPA molecules on the surface of an adsorbent. This technique is considered a cost-effective, easy-to-operate method with minimal environmental impact. Common adsorbents include activated carbon, graphene, functional/biopolymers, and metal-organic frameworks (Dehghani et al., 2015)

Advanced oxidation processes (AOPs)

AOPs are techniques such as Fenton oxidation, photolysis, photocatalysis, and ozonation. These processes operate by producing hydroxyl radicals that degrade BPA. While AOPs are effective in degrading BPA into less harmful substances, they are often expensive and energy-intensive (Sharma et al., 2016). Fenton reaction is the most common chemical method used to coagulate and precipitate the BPA from wastewater using Fe^{2+}, H_2O_2 in acidic media. This method can produce OH• to facilitate BPA degradation. It has certain drawbacks, such as ferric hydroxide precipitation and a requirement for an acidic environment for the process. (Abu Hasan et al., 2023).

Membrane separation

Membrane separation techniques, including nanofiltration, reverse osmosis, ultrafiltration, and microfiltration, offer high separation efficiency. The performance of these techniques depends on membrane properties such as hydrophobicity, permeability, and surface charge. (Godiya & Park, 2022).

Biodegradation

Biodegradation refers to the microbial breakdown of BPA into water and carbon dioxide using bacteria, fungi, microalgae, and enzymes like laccase. This method is applied in systems including activated sludge systems, trickling filters, nitrification and biofilm reactors (Chen et al., 2022).

Each method has its own advantages and limitations. Such that, membrane separation is identified as a promising BPA removal technique, yet the challenges, such as membrane pore clogging, insufficient separation, limited half-life of membranes, and difficulties in concentrated treatments have been identified in hindering large-scale applications. Similarly, eco-friendly approaches such as bioremediation limit large-scale applications owing to a narrow range of environmental tolerance and slow growth of microbes (Razia et al., 2024). These limitations encourage a combination of techniques for effective BPA removal. While these methods are effective to varying degrees, they are often associated with high operational costs, significant energy consumption, and the risk of secondary pollution from chemical byproducts (Godiya & Park, 2022). These limitations highlight the urgent need for eco-friendly and sustainable solutions.

Phytoremediation

Phytoremediation is an eco-friendly and cost-effective biotechnology that utilizes plants to absorb, accumulate, and detoxify a wide range of environmental pollutants from soil, water, and air (Lee et al., 2020). This method capitalizes on the natural ability of certain plant species to uptake contaminants through their roots and either store, degrade, or transform them within plant tissues. Plants used in phytoremediation are capable of absorbing organic pollutants such as petroleum hydrocarbons, pharmaceutical residues, pesticides, and dyes, and also inorganic pollutants such as heavy metals as the roots absorb water and nutrients, pollutants are also absorbed and transported through the plant system, where they are accumulated, transformed, or volatilized depending on the specific remediation mechanism involved (Campos et al., 2008).

Common phytoremediation mechanisms include phytoextraction, phytodegradation, phytovolatilization, phytostabilization, phytostimulation, and rhizofiltration (Issac et al., 2024). However, the pollutants uptake can sometimes affect plant growth. While certain contaminants may stimulate root activity or adaptive responses, others can hinder growth by disrupting physiological processes. Therefore, selecting suitable plant species is essential. Ideal candidates for phytoremediation should exhibit traits such as fast growth to ensure high biomass production, extensive root systems to maximize soil and water contact, high transpiration and respiration rates to facilitate uptake and transport of pollutants, tolerance to toxic substances to survive and function effectively in contaminated environments.

Table 01. Methods of phytoremediation

Method	Reference	Description	Examples
Phytoextraction	Salt et al., 1998	Plants absorb contaminants (e.g., heavy metals, organic pollutants) from soil or water and store them in above-ground parts, which are later harvested.	Sunflower, Indian mustard
Phytostabilization	Ali et al., 2013	Plants immobilize contaminants in the root zone, reducing their mobility and preventing leaching or erosion.	Vetiver grass, Poplar
Phytodegradation	Zazouli et al., 2014	Plants degrade organic pollutants internally or through secreted enzymes.	*Azolla filiculoides* (removes >95% of BPA), willow
Phytovolatilization	Pilon-Smits & Freeman, 2006	Plants absorb and convert pollutants into volatile forms, which are released into the atmosphere through transpiration.	*Brassica juncea* (for selenium), Poplar
Rhizodegradation	Susarla et al., 2002	Root exudates stimulate microbial activity in the rhizosphere, leading to the breakdown of organic pollutants.	Grasses, legumes
Rhizofiltration	Dushenkov et al., 1995	Roots absorb, concentrate, or filter out pollutants from water; microbes may assist in degradation.	Sunflower, Indian mustard

Biosorption of BPA using biomaterials

The use of biomaterials in adsorption processes is commonly referred to as biosorption. It is gaining significant interest due to its environmentally friendly characteristics and cost-effectiveness. Various biomaterials, including bacteria, fungi, algae, and plant-based substances, have been explored for the removal of BPA from contaminated water sources (Şenol et al., 2020). These biosorbents may be derived from plant materials such as leaves, barks, shells, and peels, either in raw form or after treating with acids, bases or other chemicals to enhance their adsorption capacity.

The removal of BPA via biosorption primarily involves two mechanisms, namely, chemisorption and physisorption. Physisorption is a process that occurs at the heterogeneous surfaces of adsorbents, where BPA molecules adsorb and adhere due to weak intermolecular forces such as van der Waals forces and electrostatic interactions. It is characterized by the fact that the adsorption process does not involve any chemical bonding, which allows the adsorbed molecules to be easily desorbed under certain conditions (Agboola et al., 2021). Chemisorption involves the formation of strong chemical bonds between the adsorbate and the adsorbent surface. This mechanism is characterized by molecular bonding, leading to more stable and often irreversible interactions under normal environmental conditions (Alkhaldi et al., 2024). The predominant mechanism for the biosorption, whether the physisorption or chemisorption depends on factors such as the chemical composition of the biosorbent, surface functional groups, treatment methods, and environmental conditions.

Research on biosorption

Several studies have demonstrated the effectiveness of different plant-based biosorbents for BPA removal. Lazim et al (2015) reported that coir pith, coconut shell, and durian peel, exhibited BPA removal efficiencies and adsorption capacities of 72% (4.308 mg/g), 69% (4.159 mg/g), and 70% (4.178 mg/g), respectively. Pretreatments of these materials significantly increase their pore size and surface area, enhancing the adsorption capacity. Balarak et al. (2019) investigated the use of dried rice husk as a BPA absorbent, and a maximum removal of 99.1% was achieved. The study highlighted the involvement of the hydronium ions enveloping the absorbent surface and confirmed that the adsorption process followed the Langmuir isotherm model, indicating monolayer chemisorption. In a study by Şenol et al. (2020), untreated lichen biomass (*Pseudoevernia furfuracea*) was used as a biosorbent, achieving the maximum BPA removal of 80% with a sorbent concentration of 20 g/L. The removal process was found to be primarily chemisorption facilitated by hydrogen bonding between the hydroxyl groups of BPA and the phenolic and carboxylic functional groups in the lichen surface. These studies present the promising potential of biosorbents for BPA removal.

Use of plants for BPA removal

Recent studies have demonstrated that photosynthetic organisms including bacteria possess the ability to remove BPA from aqueous environments. For instance, water velvet achieved approximately 80% of BPA removal within 20 days, while Spirogyra and Duckweed achieved removal efficiencies about 95% and 96% respectively over the same period (Garcia-Rodríguezet al., 2015). Switchgrass (*Panicum virgatum*), a terrestrial grass species native to the United States, has been studied for BPA removal from water, showing a reduction of BPA by about 40-46% over three months (Phouthavong-Murphy et al., 2020). Portulaca oleracea has also shown the capacity of remove endocrine-disrupting chemicals, including BPA, within 24 hours at concentrations up to 250 μmol/L (Imai et al., 2007). Aquatic plants are particularly advantageous for water-based phytoremediation due to their direct interaction with contaminated water. Key examples include *Eichhornia crassipes* (Water Hyacinth), a fast-growing floating plant with a high capacity for absorbing both heavy metals and organic pollutants, including BPA. Submerged macrophytes such as *Ceratophyllum demersum*, *Hydrilla verticillata*, and *Potamogeton oxyphyllus* also offer significant potential for BPA removal due to their widespread surface area for absorption and associated microbial activity around root zones. Apart, several terrestrial and semi-aquatic species have been studied for their BPA removal potential. Ornamental species such as *Dracaena sanderiana*, *Dracaena fragran,* and *Salvia* have gained attention for their potential applications in both indoor air purification and wastewater treatment (Saiyood et al., 2010).

Agricultural crops and BPA absorption

Interestingly, certain agricultural crops such as soybeans, lettuce, collards, and wheat have demonstrated BPA uptake in controlled studies. Lettuce has been shown to accumulate BPA significantly, with concentrations ranging from 144 to 195 μg/kg in leaves, depending on whether the exposure occurred via root or leaves, indicating BPA's relative mobility within the plant (Lu et al., 2015). Soybean plants have also shown BPA accumulation in roots, stems, and leaves, causing abnormalities in root growth, seed germination, growth in early stages, number of leaves, etc. BPA can inhibit or promote those effects depending on the concentration (Kim et al., 2023). Wheat has exhibited BPA uptake and metabolism during its growth. Nearly all the parts of wheat contain BPA, and roots contained the highest concentration (0.029–0.20 mg kg-1) (Wang et al., 2018). While this finding suggests the potential of agricultural plants for phytoremediation, it simultaneously raises food safety concerns when such crops are grown in contaminated environments.

Published works in Sri Lanka

Somaratne and Weerakoon (2012) discovered that Sri Lankan mustard has the potential to absorb significant amounts of Mn, Pb, and Co. The roots absorbed a higher amount than shoot and seeds. According to a study conducted by Amarakoon et al. (2022) *Salvinia* spp. showed a significant textile dye removal efficiency from batik industry effluent.

Anupama et al. (2024) have conducted a study focused on using three semi-aquatic plants; *Commelina diffusa*, *Amaranthus viridis,* and *Ipomoea aquatica* to improve water quality in Diyawanna Oya, Sri Lanka. Their results showed that Ipomoea aquatica was the most effective in reducing pollution, especially in lowering chemical oxygen demand and electrical conductivity. Secondly, *Commelina diffusa* showed notable efficiency, while *Amaranthus viridis* has been shown to be favourable in reducing water turbidity. Overall, their study suggests that these plants, especially Ipomoea aquatica, can be useful for cleaning polluted water in Sri Lanka. So far, there are no studies on BPA removal.

Applications of phytoremediation in the world

Mostly, phytoremediation has been used to remove heavy metals. In early 2000, homeowners of Washington, DC used brake fern (genus: Pteris) to remove arsenic and to detoxify soil which was contaminated by World War weapon testing (Beans, 2017). Another well-known incident was the planting of sunflowers near ponds and lakes to absorb Cesium-137 and Strontium-90 from contaminated soil and water after the Chernobyl disaster (Achmad, 2018).

Some countries use phytoremediation in wastewater treatment. France has successfully integrated reed beds composed of Phragmites australis into urban wastewater treatment systems since 2000. Not only France many countries in Europe use this technique in waste wastewater treatment of rural areas and in domestic wastewater treatment.

Phytoremediation could help clean up around 30,000 polluted waste sites in the US, according to the Environmental Protection Agency (Sharma & Pandey, 2014).

Future directions and innovations

Plant-based remediation is expected to integrate with advanced technologies such as, remote monitoring of plant health using sensors and drones to assess water quality and plant performance in real-time, biotechnological advances with the development of super-accumulator or transgenic plant species specifically engineered for enhanced pollutant and chemical uptake and degradation, community scale implementation in urban infrastructures such as rooftop wetlands and green walls, for decentralized and sustainable water treatment solutions (Mondal et al., 2022). Furthermore, the successful adoption of phytoremediation also depends on supportive environmental regulations, policies, and active public engagement. Regulatory bodies must recognize phytoremediation as a viable method for pollution control, and community awareness campaigns are essential to inform the general public about the ecological and public health benefits (Sharma & Pandey, 2014).

Several strategies have been proposed to enhance the efficiency and applicability of phytoremediation. The genetic engineering approaches such as introducing genes for higher tolerance or enzymatic degradation of BPA, is an option to enhance phytoremediation approaches. Another approach is combining plants with pollutant-degrading microbes in the rhizosphere to enhance microbial communities that can degrade BPA synergistically. Controlled systems utilizing hydroponic systems enable better management of plant exposure to BPA and optimize treatment conditions (Isaac et al., 2024).

Other approaches include engineered ecosystems such as constructed wetlands designed to mimic natural environments to enhance phytoremediation processes and use of more than one spp. in a system.

Conclusion

Phytoremediation presents a low-cost, sustainable and environmental-friendly approach to pollution mitigation. However, when using edible plant species for phytoremediation, caution must be exercised as the risk of bioaccumulation in organisms possess a potential food safety hazard. Thus, continued research is essential to identify and optimize non-edible plant species for use in phytoremediation applications. Overall, phytoremediation offers a sustainable remediation strategy that combines environmental restoration with aesthetic value and ecological benefits, making it as a promising solution for the managing BPA and other environmental contaminants.

References

Abu Hasan H, Muhamad MH, Budi Kurniawan S, Buhari J & Husain Abuzeyad O (2023). Managing Bisphenol A Contamination: Advances in Removal Technologies and Future Prospects. Water 15(20), p.3573.

Acevedo N, Davis B, Schaeberle CM, Sonnenschein C & Soto AM (2013). Perinatally administered bisphenol a as a potential mammary gland carcinogen in rats. Environmental health perspectives, 121(9), pp.1040-1046.

Achmad CAA (2018). Root uptake and distribution of radionuclides 134Cs and 60Co in sunflower plants (Helianthus annuus. L). In E3S Web of Conferences (Vol. 73, p. 05027). EDP Sciences.

Agboola OD & Benson NU (2021). Physisorption and chemisorption mechanisms influencing micro (nano) plastics-organic chemical contaminants interactions: a review. *Frontiers in Environmental Science*, *9*, p.678574.

Ali H, Khan E & Sajad MA (2013). Phytoremediation of heavy metals—concepts and applications. *Chemosphere*, *91*(7), pp.869-881.

Alkhaldi H, Alharthi S, Alharthi S, AlGhamdi HA, AlZahrani YM, Mahmoud SA, Amin LG, Al-Shaalan NH, Boraie WE, Attia MS & Al-Gahtany SA (2024). Sustainable polymeric adsorbents for adsorption-based water remediation and pathogen deactivation: a review. *RSC advances*, *14*(45), pp.33143-33190.

Almeida S, Raposo A, Almeida-González M, Carrascosa C & Bisphenol A (2018). Food Exposure and Impact on Human Health. Compr Rev Food Sci Food Saf. 17(6):1503-1517.

Amarakoon AMIM, Maithreepala RA & Jayasinghe UAD (2022). Applicatıon of Selected Floating Aquatic Plants for Phytoremediation of Textile Dye Effluent from Batik Industry.

Amir S, Shah STA, Mamoulakis C, Docea AO, Kalantzi OI, Zachariou A, Calina D, Carvalho F, Sofikitis N, Makrigiannakis A & Tsatsakis A (2021). Endocrine disruptors acting on estrogen and androgen pathways cause reproductive disorders through multiple mechanisms: a review. International journal of environmental research and public health, 18(4), p.1464.

Anupama Y A, Dissanayake D, Jinasena N & Gunawardena A (2024). Efficacy of Three Selected Semi-Aquatic Plants as Natural Water Quality Treatments in Sri Lanka.

Balarak D, Ansari H, Dashtizadeh M & Bazi M (2019). Synthesis of Graphene Oxide as an Adsorbent for the Removal of Bisphenol A. *Journal of Human Environment and Health Promotion*, *5*(3), pp.98-103.

Baralla E, Demontis MP, Varoni MV & Pasciu V (2021). Bisphenol A and Bisphenol S Oxidative Effects in Sheep Red Blood Cells: An In Vitro Study. Biomed Res Int. 24.

Beans C (2017). Phytoremediation advances in the lab but lags in the field. *Proceedings of the National Academy of Sciences*, *114*(29), pp.7475-7477.

Campos V, Merino I, Casado R & Gómez L (2008). Phytoremediation of organic pollutants: a review. Spanish Journal of Agricultural Research, 6(S1), 38-47.

Čelić M (2020). Target analysis and suspect screening of wastewater-derived contaminants in receiving riverine and coastal areas and assessment of environmental

Chen Y, Sun K, Sun H, Yang Y, Li Y, Gao B & Xing B (2022). Photodegradation of pyrogenic dissolved organic matter increases bioavailability: Novel insight into bioalteration, microbial community succession, and C and N dynamics. *Chemical Geology*, *605*, p.120964.

Chen ZH, Liu Z, Hu JQ, Cai QW, Li XY, Wang W, Faraj Y, Ju XJ, Xie R & Chu LY (2020). β-Cyclodextrin-modified graphene oxide membranes with large adsorption capacity and high flux for efficient removal of bisphenol A from water. Journal of Membrane Science, 595, p.117510.

Corrales J, Kristofco LA, Steele WB, Yates BS, Breed CS, Williams ES & Brooks BW (2015). Global assessment of bisphenol A in the environment: review and analysis of its occurrence and bioaccumulation. Dose-response, 13(3), p.1559325815598308.

Dehghani MH, Mahvi AH, Rastkari N, Saeedi R, Nazmara S & Iravani E (2015). Adsorption of bisphenol A (BPA) from aqueous solutions by carbon nanotubes: kinetic and equilibrium studies. Desalination and Water Treatment, 54(1), pp.84-92.

Dushenkov V, Kumar PN, Motto H & Raskin I (1995). Rhizofiltration: the use of plants to remove heavy metals from aqueous streams. *Environmental science & technology*, *29*(5), pp.1239-1245.

Garcia-Rodríguez A, Matamoros V, Fontàs C & Salvadó V (2015). The influence of Lemna sp. and Spirogyra sp. on the removal of pharmaceuticals and endocrine disruptors in treated wastewaters. *International Journal of Environmental Science and Technology*, *12*(7), pp.2327-2338.

Godiya CB & Park BJ (2022). Removal of bisphenol A from wastewater by physical, chemical and biological remediation techniques. A review," Environmental Chemistry Letters. Springer Science and Business Media Deutschland GmbH, pp. 1801–1837. Available at: https://doi.org/10.1007/s10311-021-01378-6.

Graziani N, Carreras H & Wannaz E (2019). Atmospheric levels of BPA associated with particulate matter in an urban environment. Heliyon, 5, p. e01419.

Han C & Hong YC (2016). Bisphenol A, hypertension, and cardiovascular diseases: epidemiological, laboratory, and clinical trial evidence. Current hypertension reports, 18(2), p.11.

Im J & Löffler FE (2016). Fate of bisphenol A in terrestrial and aquatic environments. *Environmental science & technology*, *50*(16), pp.8403-8416.

Imai S, Shiraishi A, Gamo K, Watanabe I, Okuhata H, Miyasaka H, Ikeda K, Bamba T & Hirata K (2007). Removal of phenolic endocrine disruptors by Portulaca oleracea. Journal of bioscience and bioengineering, 103(5), pp.420-426.

Issac PK, Ravindiran G, Velumani K, Jayaseelan A, Greff B, Mani R, Chang SW, Ravindran B & Awasthi MK (2024). Futuristic advancements in phytoremediation of endocrine disruptor Bisphenol A: A step towards sustainable pollutant degradation for rehabilitated environment. Waste Management, 179, pp.216-233.

Janda R, Ukić Š, Mikulec N & Vitale K (2021). Bisphenol A–an environmental and human threat. *Agriculturae Conspectus Scientificus*, *86*(4), pp.295-304.

Kim E, Song M, Ramu AG & Choi D (2023). Analysis of impacts of exogenous pollutant bisphenol-A penetration on soybeans roots and their biological growth. *RSC advances*, *13*(15), pp.9781-9787.

Kim MJ & Park YJ (2019). Bisphenols and thyroid hormone. Endocrinology and Metabolism, 34(4), pp.340-348.

Lalwani D, Ruan Y, Taniyasu S, Yamazaki E, Kumar NJ, Lam PK, Wang X & Yamashita N (2020). Nationwide distribution and potential risk of bisphenol analogues in Indian waters. Ecotoxicology and environmental safety, 200, p.110718.

Lazim ZM, Hadibarata T, Puteh MH & Yusop Z (2015). Adsorption characteristics of bisphenol A onto low-cost modified phyto-waste material in aqueous solution. *Water, Air, & Soil Pollution*, *226*(3), p.34.

Lee BXY, Hadibarata T & Yuniarto A (2020). Phytoremediation mechanisms in air pollution control: a review. *Water, Air, & Soil Pollution*, *231*(8), p.437.

Liu J & Martin JW (2017). Prolonged Exposure to Bisphenol A from Single Dermal Contact Events. Environmental Science and Technology, 51(17), pp. 9940–9949. Available at: https://doi.org/10.1021/acs.est.7b03093.

Lorber M, Schecter A, Paepke O, Shropshire W, Christensen K & Birnbaum L (2015). Exposure assessment of adult intake of bisphenol A (BPA) with emphasis on canned food dietary exposures. Environment international, 77, pp.55-62.

Lu J, Wu J, Stoffella PJ & Wilson PC (2015). Uptake and distribution of bisphenol A and nonylphenol in vegetable crops irrigated with reclaimed water. *Journal of Hazardous Materials*, *283*, pp.865-870.

Maćczak A, Bukowska B & Michałowicz J (2015). Comparative study of the effect of BPA and its selected analogues on hemoglobin oxidation, morphological alterations and hemolytic changes in human erythrocytes. Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology, 176, pp.62-70.

Matharage H, Jayaweera M, Bandara N & Gunawardana B (2021) December. Occurrence of bisphenol A in Bolgoda lake receiving leachate from a solid waste open dump: a silent killer of a healthy ecosystem. In 2021 From Innovation To Impact (FITI) (Vol. 1, pp. 1-5). IEEE.

Mondal BP, Sahoo RN, Das B, Paul P, Chattopadhyay A & Devi S (2022). Monitoring Phytoremediation of Metal-Contaminated Soil Using Remote Sensing. In Advances in Bioremediation and Phytoremediation for Sustainable Soil Management: Principles, Monitoring and Remediation (pp. 399-415). Cham: Springer International Publishing.

Pathirajage SK & Rajapaksa G (2024). Long-term exposure to environmentally relevant Bisphenol-A levels affects growth, swimming, condition factor, sex ratio and histology of juvenile zebrafish. Scientific Reports, 14(1). Available at: https://doi.org/10.1038/s41598-024-73538-x.

Phouthavong-Murphy JC, Merrill AK, Zamule S, Giacherio D, Brown B, Roote C & Das P (2020). Phytoremediation potential of switchgrass (Panicum virgatum), two United States native varieties, to remove bisphenol-A (BPA) from aqueous media. *Scientific reports*, *10*(1), p.835.

Pilon-Smits EA & Freeman JL (2006). Environmental cleanup using plants: biotechnological advances and ecological considerations. Frontiers in Ecology and the Environment, 4(4), pp.203-210.

Razia S, Hadibarata T & Lau SY (2024). A review on biodegradation of Bisphenol A (BPA) with bacteria and fungi under laboratory conditions. International Biodeterioration and Biodegradation. Elsevier Ltd. Available at: https://doi.org/10.1016/j.ibiod.2024.105893.

Richter CA, Taylor JA, Ruhlen RL, Welshons WV & Vom Saal FS (2007). Estradiol and bisphenol A stimulate androgen receptor and estrogen receptor gene expression in fetal mouse prostate mesenchyme cells. Environmental health perspectives, 115(6), pp.902-908.

Saiyood S, Vangnai AS, Thiravetyan P & Inthorn D (2010). Bisphenol A removal by the Dracaena plant and the role of plant-associating bacteria. Journal of Hazardous Materials, 178(1-3), pp.777-785.

Salt DE, Smith RD & Raskin I (1998). Phytoremediation. Annual Review of Plant Physiology and Plant Molecular Biology, 49, pp. 643–668, DOI:10.1146/annurev.arplant.49.1.643

Santoro A, Chianese R, Troisi J, Richards S, Nori SL, Fasano S, Guida M, Plunk E, Viggiano A, Pierantoni R & Meccariello R (2019). Neuro-toxic and reproductive effects of BPA. Current neuropharmacology, 17(12), pp.1109-1132.

Şenol ZM, Gül ÜD & Gürkan R (2020). Bio-sorption of bisphenol a by the dried- and inactivated-lichen (Pseudoevernia furfuracea) biomass from aqueous solutions. Journal of Environmental Health Science and Engineering, 18(2), pp. 853–864. Available at: https://doi.org/10.1007/s40201-020-00508-6.

Shankar A & Teppala S (2011). Relationship between urinary bisphenol A levels and diabetes mellitus. The Journal of Clinical Endocrinology & Metabolism, 96(12), pp.3822-3826.

Sharma J, Mishra IM & Kumar V (2016). Mechanistic study of photo-oxidation of Bisphenol-A (BPA) with hydrogen peroxide (H2O2) and sodium persulfate (SPS). Journal of environmental management, 166, pp.12-22.

Sharma P & Pandey S (2014). Status of phytoremediation in world scenario. International Journal of Environmental Bioremediation & Biodegradation, 2(4), pp.178-191.

Somaratne S & Weerakoon SR (2012). A Comprehensive Study on Phytoextractive Potential of Sri Lankan Mustard (Brassica Juncea (L.) Czern. & Coss) Genotypes. *International Journal of Agricultural and Biosystems Engineering*, *6*(1), pp.25-29.

Susarla S, Medina VF & Mccutcheon SC (2002). Phytoremediation: An ecological solution to organic chemical contamination, Ecological Engineering. Available at: www.elsevier.com/locate/ecoleng.

Tian Y, Zhou X, Miao M, Li DK, Wang Z, Li R, Liang H & Yuan W (2018). Association of bisphenol A exposure with LINE-1 hydroxymethylation in human semen. International Journal of Environmental Research and Public Health, 15(8), p.1770.

Völkel W, Colnot T, Csanády GA, Filser JG & Dekant W (2002). Metabolism and kinetics of bisphenol A in humans at low doses following oral administration. Chemical research in toxicology, 15(10), pp.1281-1287.

Wang S, Liu F, Wu W, Hu Y, Liao R, Chen G, Wang J & Li J (2018). Migration and health risks of nonylphenol and bisphenol a in soil-winter wheat systems with long-term reclaimed water irrigation. Ecotoxicology and Environmental Safety, 158, pp.28-36.

Xin L, Lin Y, Wang A, Zhu W, Liang Y, Su X, Hong C, Wan J, Wang Y & Tian H (2015). Cytogenetic evaluation for the genotoxicity of bisphenol-A in Chinese hamster ovary cells. Environmental toxicology and pharmacology, 40(2), pp.524-529.

Yang L, Wang J, Yang Y, Li S, Wang T, Oleksak P, Chrienova Z, Wu Q, Nepovimova E, Zhang X & Kuca K (2022). Phytoremediation of heavy metal pollution: Hotspots and future prospects. Ecotoxicology and Environmental Safety, 234, p.113403.

Zaborowska M, Wyszkowska J, Borowik A & Kucharski J (2021). Bisphenol A—A dangerous pollutant distorting the biological properties of soil. International journal of molecular sciences, 22(23), p.12753.

Zazouli MA, Mahdavi Y, Bazrafshan E & Balarak D (2014). Phytodegradation potential of bisphenolA from aqueous solution by Azolla Filiculoides. *Journal of Environmental Health Science and Engineering*, *12*(1), p.66.

CHAPTER 08

From ocean to industry: Novel bio-innovations with marine bacterial pigments

K. C. T. Peiris and I. U. Kariyawasam*

Department of Botany, University of Sri Jayewardenepura,
Gangodawila, Nugegoda, Sri Lanka.
**isurufasi@sjp.ac.lk*

Abstract

Marine environments are one of the most significant ecosystems of our earth that are yet to be explored to understand their full potential. They contain undiscovered mysterious black boxes holding colossal information that is to be decoded scientifically and exploited for the benefit of mankind. Currently, the marine bacteria are being explored for their production of clinically and industrially important secondary metabolites. The pigments produced by marine bacteria as a consequence of quorum sensing are of current interest due to their anti-microbial, anti-cancer, photo-protective, anti-parasitic, and immunosuppressive activities. The main categories of pigments that are produced by the marine bacteria are carotene, melanin, phenazine, pyrrole, violacein, and quinones. The prime goal of this chapter is to explore the potential utilization of marine bacterial pigments for novel bio-innovations such as biocompatible quantum dots, eco-friendly UV-filters, bioelectricity generation, and climate-resilient biosensors.

Keywords: Biocompatible, Bioinnovations, Marine bacteria, Pigments, Quantum dots, Secondary metabolites

Introduction

The majority of marine bacteria are associated with marine seaweeds, which have recently gained significant interest among the scientific community. These microbial communities can be seen on both phycoplanes and inside the seaweed cytosol. The phycoplane is the living surface of the marine seaweeds, and it harbors highly diverse microbial communities, including pigmented bacteria, which are ecologically important and with their significant bioactive pigment profiles (Soliev et al., 2011). These seaweed-associated bacteria play vital roles in the growth and development of seaweeds, especially by providing key nutrients such as CO_2, nitrogen from nitrogen fixation, vitamins, phytohormones, and thiamin derivatives. Further, the morphogenesis of seaweeds, particularly in *Ulva* species and in *Monostroma oxyspermum*, nutrient cycling, induction of spore liberation in *Acrochaetium*, and zoospores settlement of *Ulva* species are strictly modulated through the activity of seaweed-associated bacteria. Marine pigmented bacteria have diverse pigment profiles with vibrant to dull colors ranging from red, violet, yellow, brown, black, etc. (Velmurugan et al., 2020). The bioactive marine bacterial pigments contribute significantly to the structural and functional stability of phycoplane and ambient micro-ecosystems and also facilitate seaweed health, growth, and development of their bioactive properties. Additionally, these pigmented bacteria contribute to nutrient and organic matter cycling and also serve as indicators of environmental changes in marine ecosystems (Thompson and Polz, 2014).

Among prodiginine pigments, undecylprodigiosin, cycloprodigiosin, and heptyl prodigiosin, found in strains like *Streptomyces*, *Pseudoalteromonas*, and α-Proteobacteria exhibit anticancer, immunosuppressive, antimalarial, and antiplasmodial activities (Hamada and Mohamed, 2024). Prodigiosin, a prominent red pigment from diverse marine bacteria including *Pseudoalteromonas rubra*, *Hahella chejuensis*, and *Serratia rubidaea*, displays broad-spectrum bioactivity, such as antibacterial, anticancer, cytotoxic, anti-inflammatory, antiviral, algicidal, and UV-protective effects. Carotenoids like astaxanthin, zeaxanthin, lycopene, and various xanthins derived from *Agrobacterium*, *Arthrobacter*, *Brevundimonas*, and *Rhodopirellula* species possess strong antioxidant, anticancer, and radical scavenging properties (Nawaz et al., 2020). Violacein, a deep violet pigment from *Pseudoalteromonas* and *Chromobacterium*, offers antimicrobial, antiprotozoan, anticancer, and UV-shielding potential. Phenazine derivatives, produced by *Pseudomonas*, *Bacillus*, and *Streptomyces*, act as potent antibiotics, antivirals, anticancer, and insecticidal agents. Other notable compounds include melanins with UV-protective, antioxidant, antibacterial, and anti-quorum-sensing activities, and quinones such as fridamycins, mersaquinone, and streptoanthraquinone, which show promising anticancer, antibacterial, antiviral, and antitrypanosomal properties. Additionally, compounds like scytonemin from cyanobacteria and tryptanthrin from *Cytophaga* further enhance the therapeutic repertoire of marine bacterial pigments, highlighting their significance in drug discovery and sustainable biotechnology (Nawaz et al., 2020).

Eco-friendly UV filters

UV filters play a crucial role in protecting human skin from harmful ultraviolet (UV) radiation, mitigating risks such as premature aging, DNA damage, and skin cancer (Brenner and Hearing, 2008). However, conventional synthetic UV filters, such as oxybenzone and octinoxate, have raised significant environmental concerns due to their role in coral bleaching, bioaccumulation, and toxicity to marine ecosystems (Downs et al., 2016). In contrast, marine bacteria, thriving in high-UV environments, have evolved sophisticated defense mechanisms, producing UV-resistant pigments that absorb, scatter, or neutralize harmful radiation. For instance, scytonemin acts as a passive UV shield by absorbing UVA (315–400 nm) through its indole-derived structure, dissipating energy as heat without generating free radicals (Gao and Garcia-Pichel, 2011). Similarly, carotenoids and melanin-like pigments quench reactive oxygen species (ROS) induced by UV exposure, preventing oxidative damage to bacterial cells, while mycosporine-like amino acids (MAAs) absorb UVB (280–315 nm) and short-wave UVA, converting radiation into harmless thermal energy (Brenner and Hearing, 2008). Recognizing these advantages, several forward-thinking companies have begun integrating bacterial pigments into commercial products. In considering the real-world examples that are currently utilizing bacterial pigments in their production process, Helioguard 365, a natural UV-screening active ingredient, originates from Switzerland, derived from *Rhodococcus* bacteria, and is used in sunscreens by brands like La Roche-Posay and Biotherm for its broad-spectrum UV protection (Grether-Beck et al., 2014). Unlike synthetic filters, these pigment-based solutions are biodegradable, non-toxic, and sustainable, aligning with global regulations phasing out harmful chemicals (Downs et al., 2016). As consumer demand for eco-friendly alternatives grows, marine bacterial pigments are poised to redefine the future of UV protection across cosmetics, textiles, and coatings.

Bioelectricity generation

Bioelectricity is the harnessing of electrical energy from biological systems, representing a transformative approach to renewable energy, with microbial fuel cells (MFCs) emerging as a promising platform. At the heart of this technology lie exoelectrogenic marine bacteria, which uniquely transfer extracellular electrons during metabolic processes, converting organic substrates into electricity (Lovley, 2012). These bacteria thrive in extreme marine environments (e.g., high salinity, pressure), endowing them with exceptional resilience for bioenergy applications. Critically, their native pigments, such as phenazines, melanin, and violacein, act as redox mediators, bridging electron transfer between bacterial cells and MFC electrodes to enhance power output (Rabaey et al., 2005). For instance, *Shewanella oneidensis* employs phenazine-derived pigments to shuttle electrons, while melanin's semiconductor-like properties amplify conductivity under light, enabling light-assisted MFCs (Turick et al., 2011). These natural pigments offer unparalleled advantages: biodegradability, stability in harsh conditions, and compatibility with hybrid solar-microbial systems. Pioneering industries are already capitalizing on this potential. Cambrian Innovation's BioVolt™ employs marine exoelectrogens for wastewater treatment with concurrent energy recovery (Kumar et al., 2024). Despite challenges in pigment yield and MFC scalability, synthetic biology approaches, such as CRISPR-engineered *Pseudomonas* for enhanced phenazine production (Zhang et al., 2018), signal a future where marine bacterial pigments drive sustainable energy grids, aligning with circular bioeconomy principles.

Climate-resilient biosensors

Biosensors are analytical devices coupling biological recognition elements with physicochemical transducers, playing a pivotal role in environmental monitoring by detecting pollutants, toxins, and climate-induced stressors with high specificity (Turner, 2013). However, conventional biosensors often fail under extreme environmental conditions (e.g., Salinity fluctuations, temperature extremes, or pH shifts), highlighting the urgent need for climate-resilient alternatives. Marine bacterial pigments, evolved to withstand harsh oceanic environments, offer an elegant solution. Pigments such as melanin (radiation-resistant), violacein (pH-stable), and carotenoids (thermotolerant) serve dual roles in biosensors: as redox mediators for electrochemical detection and as optical reporters for colorimetric/fluorescent signaling. For instance, violacein's structural plasticity enables selective binding to heavy metals, triggering measurable color changes, while melanin's semiconductor properties enhance electron transfer in graphene-based biosensor electrodes (Hsu et al., 2024). These pigments are not only biodegradable but also reduce reliance on synthetic dyes, aligning with green chemistry principles.

In recent studies, *Pseudodalteromonas*-derived melanin was utilized in its marine toxin biosensors for aquaculture (Tang et al., 2023), promising to unlock scalable, climate-adaptive biosensors for planetary health monitoring.

Role in carbon sequestration

Carbon sequestration is the long-term storage of atmospheric CO_2, a critical strategy for mitigating climate change, with biological processes in oceans, forests, and soils accounting for nearly 50% of annual carbon uptake. Among these, marine microorganisms serve as unsung heroes of the oceanic carbon cycle, which constitutes Earth's largest active carbon sink (Falkowski et al., 2008). Pigmented marine bacteria, particularly those producing melanin, carotenoids, or scytonemin, contribute through multifaceted mechanisms: photosynthetic cyanobacteria employ chlorophyll a and phycobiliproteins to fix CO_2 *via* the Calvin cycle (Flombaum et al., 2013), while chemolithoautotrophs like purple sulfur bacteria utilize rhodopsins to drive carbon fixation in aphotic zones. Beyond photosynthesis, these bacteria enhance sequestration through biomineralization (e.g., carbonic anhydrase-mediated $CaCO_3$ precipitation in *Bacillus* spp. (Zaidi et al., 2022) and by producing stable carbon reservoirs like exopolysaccharide-rich biofilms that sediment at rates of 0.5–2 Gt C/year. Remarkably, pigment-derived UV resistance allows these microbes to maintain metabolic activity in climate-vulnerable zones like polar seas and sunlit surface waters (Garcia-Pichel et al., 2018). Biotechnological applications are already emerging; companies like LanzaTech engineer pigment-producing *Clostridium* strains to convert industrial emissions into carbon-negative biofuels. Challenges persist in quantifying species-specific contributions and scaling cultivation, yet advances in metagenomics and synthetic biology (e.g., CRISPR-enhanced RuBisCO expression) promise to unlock these microorganisms' full potential as climate-regulating powerhouses (Zhao et al., 2024).

Applications in sustainable agriculture

Sustainable agriculture is defined as farming systems that maintain ecological balance while meeting present food demands, and increasingly relies on microbial solutions to enhance soil health and crop resilience (Pretty and Bharucha, 2018). Marine pigmented bacteria, evolved under extreme oceanic conditions, offer unique agricultural advantages through their stress-tolerant phenotypes and bioactive metabolites. Strains like *Chromobacterium violaceum* (violacein-producing) and *Serratia marcescens* (prodigiosin-synthesizing) serve dual roles: as plant growth promoters through nitrogen fixation and indole-3-acetic acid (IAA) production (Kulkova et al., 2024), and as biocontrol agents against fungal pathogens like *Fusarium via* pigment-mediated membrane disruption. Their pigments (e.g., carotenoids, melanin) also mitigate abiotic stresses in melanin-rich *Pseudomonas* spp. reduce oxidative damage in crops under drought by scavenging ROS (Khalimi et al., 2024). Companies are already commercializing these benefits: Indigo Agriculture employs marine bacterial consortia in their seed coatings to enhance salinity tolerance, expanding their role in climate-smart agriculture.

Advances in biomedicine

Marine pigmented bacteria represent an underexplored treasure trove of bioactive compounds, having evolved unique pigments including violacein, prodigiosin, melanin, scytonemin, and carotenoids to thrive in extreme oceanic environments (Zhang et al., 2018). These pigments exhibit remarkable therapeutic properties: violacein and prodigiosin induce apoptosis in cancer cells by disrupting mitochondrial membranes and activating caspase pathways (Lu et al., 2024), while melanin's ROS-scavenging ability shows promise for treating neurodegenerative diseases like Alzheimer's (Caldas et al., 2020). Their antimicrobial efficacy against drug-resistant pathogens, such as *Candida auris*, has spurred interest as alternatives to conventional antibiotics. The pharmaceutical industry is increasingly leveraging these natural compounds. PharmaMar commercialized the anticancer drug Aplidin® (derived from the marine bacterium *Symploca*) (Depenbrock et al., 1998). Similarly, Melanotech specializes in microbial melanin for radiation protection and wound-healing dressings (Cordero et al., 2017). Advances in nanoparticle encapsulation (e.g., liposomal prodigiosin by Marinova Pty Ltd) enhance drug delivery precision (Jiang et al., 2023). CRISPR-based metabolic engineering and sustainable fermentation methods position marine bacterial pigments as next-generation therapeutics aligning.

Biocompatible Quantum Dots

Semiconducting nanoparticles, more commonly known as quantum dots (QDs), possess unique size and shape-dependent optoelectronic properties. In recent years, these unique properties have attracted much attention in the biomedical field to enable real-time tissue imaging (bioimaging), diagnostics, single-molecule probes, and drug delivery, among many other areas. The optical properties of QDs can be tuned by size and composition, and their high brightness, resistance to photobleaching, multiplexing capacity, and high surface-to-volume ratio make them excellent candidates for intracellular tracking, diagnostics, *in vivo* imaging, and therapeutic delivery (Wagner et al., 2019). The anti-microbial properties of marine bacterial pigments significantly contribute to the stability of QDs by preventing microbial colonization and biofilm formation, which can degrade QDs over time. These pigments, such as prodigiosin and violacein, possess inherent antibacterial activity that disrupts bacterial membranes and inhibits microbial growth. When used as capping agents or stabilizers for QDs, their functional groups (e.g., amines, carboxylates) not only facilitate nanoparticle synthesis but also enhance the antimicrobial efficiency of the QDs. For instance, QDs functionalized with these pigments can generate ROS under light exposure, damaging bacterial DNA and proteins, thereby suppressing microbial proliferation and ensuring the long-term stability of the QDs. Furthermore, these pigments create a physical barrier that hinders bacterial adhesion to the QD surface, reducing corrosion and maintaining the optical and structural integrity of the nanomaterials. This dual role in stabilizing QDs chemically while protecting them biologically makes marine bacterial pigments highly effective in enhancing the durability and functionality of quantum dots in diverse applications (Rajendiran et al., 2019; Liu et al., 2024).

Conclusion

Marine bacterial pigments, such as melanin, carotenoids, violacein, and prodigiosin, offer a sustainable and versatile platform for innovation across multiple sectors. Their unique properties, ranging from photoprotection and antimicrobial activity to redox mediation and biocompatibility, enable applications in biocompatible quantum dots, eco-friendly UV filters, bioelectricity generation, climate-resilient biosensors, carbon sequestration, sustainable agriculture, and advanced biomedicine. These pigments not only provide functional benefits but also align with environmental sustainability goals, as they are biodegradable, non-toxic, and can be produced efficiently in saline environments with minimal ecological impact. Advancements in synthetic biology and fermentation technologies are further enhancing the scalability and efficacy of these pigments, positioning marine bacterial pigments as key contributors to a sustainable bioeconomy.

References

Brenner M & Hearing VJ (2008). The protective role of melanin against UV damage in human skin. *Photochemistry and photobiology*, 84(3), pp. 539–549.

Caldas M, Santos AC, Veiga F, Rebelo R, Reis RL & Correlo VM (2020). Melanin nanoparticles as a promising tool for biomedical applications - a review. *Acta biomaterialia*, 105, pp. 26–43.

Cordero RJB, Vij R & Casadevall A (2017). Microbial melanins for radioprotection and bioremediation. *Microbial Biotechnology, 10*(5), pp. 1186–1190.

Depenbrock H, Peter R, Faircloth GT, Manzanares I, Jimeno J & Hanauske AR (1998). *In vitro* activity of aplidine, a new marine-derived anti-cancer compound, on freshly explanted clonogenic human tumour cells and haematopoietic precursor cells. *British Journal of Cancer, 78*(6), pp. 739–744.

Downs CA, Kramarsky WE, Segal R, Fauth J, Knutson S, Bronstein O, Ciner FR, Jeger R, Lichtenfeld Y, Woodley CM, Pennington P, Cadenas K, Kushmaro A & Loya Y (2016). Toxico pathological Effects of the Sunscreen UV Filter, Oxybenzone (Benzophenone-3), on Coral Planulae and Cultured Primary Cells and Its Environmental Contamination in Hawaii and the U.S. Virgin Islands. *Archives of environmental contamination and toxicology*, *70*(2), pp. 265–288.

Falkowski PG, Fenchel T & Delong EF (2008). The microbial engines that drive Earth's biogeochemical cycles. *Science (New York, N.Y.)*, 320(5879), pp. 1034–1039.

Flombaum JL, Gallegos RA, Gordillo J, Rincón LL, Zabala N, Jiao DM, Karl WKW, Li MW, Lomas D, Veneziano CS, Vera JA, Vrugt & Martiny AC (2013). Present and future global distributions of the marine Cyanobacteria *Prochlorococcus* and *Synechococcus*, *Proc. Natl. Acad. Sci. U.S.A*. 110 (24) pp. 9824-9829,

Gao Q & Garcia-Pichel F (2011). Microbial ultraviolet sunscreens. *Nature Reviews Microbiology, 9*(11), pp. 791–802.

Garcia-Pichel F, Bebout BM & Castenholz RW (2018). Multiple Strategies for Light-Harvesting, Photoprotection, and Carbon Flow in Microbial Mats of High Arctic Lakes. *Frontiers in Microbiology*, 9, pp. 2881.

Grether-Beck S, Marini A, Jaenicke T & Krutmann J (2014). Photoprotection of human skin beyond ultraviolet radiation. *Photodermatology, photoimmunology & photomedicine*, 30(2-3), pp. 167–174.

Hamada MA & Mohamed ET (2024). Characterization of *Serratia marcescens* (OK482790)' prodigiosin along with *in vitro* and *in silico* validation for its medicinal bioactivities. *BMC microbiology*, 24(1), pp. 495.

Hsu CY, Saleh RO, Pallathadka H, Kumar A, Mansouri S, Bhupathi P, Ali SHJ, Al-Mashhadani ZI, Alzubaid LH & Hizamm MM (2024). Advances in electrochemical-optical dual-mode biosensors for detection of environmental pathogens. *Analytical Methods*, Advance online publication.

Jiang Y, Li W, Wang Z & Lu J (2023). Lipid-Based Nanotechnology: Liposome. *Pharmaceutics*, 16(1), pp. 34.

Khalimi K, Pranatayana IBG & Batin CB (2024). Harnessing *Serratia marcescens*: A dual role as biocontrol agent against *Fusarium oxysporum* f.sp. *melongenae* and heteroauxin producer. *International Journal of Biosciences and Biotechnology, 11* (2), pp. 1–11.

Kulkova I, Wróbel B & Dobrzyński J (2024). *Serratia spp.* as plant growth-promoting bacteria alleviating salinity, drought, and nutrient imbalance stresses. *Frontiers in Microbiology, 14*, Article 1342331.

Kumar S, Shenode NR, Jeph Y & Kudale R (2024). Microbial Fuel Cells for Bioelectricity Generation – Current Innovations and Challenges. *International Journal for Research in Applied Science & Engineering Technology.*

Liu S, Wu D, Zheng J, Han B, Qi J , Meng F, Li J & Liu D (2024). New Strategy for Microbial Corrosion Protection: Photocatalytic Antimicrobial Quantum Dots. *Nanomaterials (Basel, Switzerland), 15*(1), pp. 2.

Lu Y, Liu D, Jiang R, Li Z & Gao X (2024). Prodigiosin: unveiling the crimson wonder a comprehensive journey from diverse bioactivity to synthesis and yield enhancement. *Frontiers in microbiology*, 15, 1412776.

Lovley DR (2012). Electromicrobiology. *Annual Review of Microbiology, 66*, pp. 391–409.

Nawaz A, Chaudhary R, Shah Z, Dufossé L, Fouillaud M, Mukhtar H & Haq IU (2020). An Overview on Industrial and Medical Applications of Bio-Pigments Synthesized by Marine Bacteria. *Microorganisms*, 9(1), pp. 11.

Pretty J & Bharucha ZP (2018). *Sustainable Intensification of Agriculture: Greening the World's Food Economy* (1st ed.), Routledge.

Rabaey K, Boon N, Höfte M & Verstraete W (2005). Microbial phenazine production enhances electron transfer in biofuel cells. *Nature Biotechnology, 23*(4), pp. 451–456.

Rajendiran K, Zhao Z, Pei DS & Fu A (2019). Antimicrobial Activity and Mechanism of Functionalized Quantum Dots. *Polymers, 11*(10), 1670.

Soliev AB, Hosokawa K & Enomoto K (2011). Bioactive pigments from marine bacteria: applications and physiological roles. *Evidence-based complementary and alternative medicine: eCAM*, 670349.

Tang X, Zuo J, Yang C, Jiang J, Zhang Q, Ping J & Li P (2023). Current trends in biosensors for biotoxins (mycotoxins, marine toxins, and bacterial food toxins): Principles, application, and perspective. *Trends in Analytical Chemistry*.

Thompson JR & Polz MF (2014). Dynamics of Vibrio populations and their role in environmental nutrient cycling, *The biology of Vibrios*, pp. 190–203.

Turner APF (2013). Biosensors: Sense and sensibility. *Chemical Society Reviews, 42*(8), pp. 3184–3196.

Turick CE, Ekechukwu AA, Milliken CE, Casadevall A & Dadachova E (2011). Gamma radiation interacts with melanin to alter its oxidation–reduction potential and results in electric current production. *Bioelectrochemistry*, 82(1), pp. 69-73.

Velmurugan P, Venil CK, Ravi AV & Dufossé L (2020). Marine bacteria is the cell factory to produce bioactive pigments: A prospective pigment source in the ocean. *Frontiers in Sustainable Food Systems, 4*, 589655.

Wagner AM, Knipe JM, Orive G & Peppas NA (2019). Quantum dots in biomedical applications. *Acta Biomaterialia, 94*, pp. 44–63.

Zaidi S, Srivastava N & Kumar Khare S (2022). Microbial carbonic anhydrase mediated carbon capture, sequestration & utilization: A sustainable approach to delivering bio-renewables. *Bioresource technology*, 365, pp. 128174.

Zhang T, Gannon SM, Nevin KP, Franks AE & Lovley DR (2018). Improved electrical conductivity in biofilms using synthetic biology for sustainable bioelectrical energy generation. *Frontiers in Microbiology*, 9, pp. 2633.

Zhao L, Cai Z, Li Y & Zhang Y (2024). Engineering Rubisco to enhance CO_2 utilization. *Synthetic and Systems Biotechnology,* 9(1), pp. 55-68.

CHAPTER 09

Development of a Sustainable Biodegradable Packaging Material from Water Hyacinth and Guinea Grass

A.H. D. Athukorala[1], M. S. A. Banu[1], A. M. S. U. M. Attanayake[1] and R. M. S. M. B. Rathnayaka[2]*

[1]The Faculty of Engineering, The Open University of Sri Lanka, Nawala, Sri Lanka
[2]Faculty of Technology, Sri Lanka Technology Campus, Padukka, Sri Lanka
*sangeethr@sltc.lk

Abstract

The increasing demand for sustainable and biodegradable packaging materials has necessitated the development of eco-friendly alternatives to conventional plastic-based packaging. This study explores the potential of a novel bio-based packaging material derived from water hyacinth (*Eichhornia crassipes*) and guinea grass (*Megathyrsus maximus*), both of which are fast-growing and highly regenerative plant species. In Sri Lanka, water hyacinth is an invasive species that disrupts aquatic ecosystems; thus, its utilization in packaging presents an effective strategy for environmental management. The incorporation of turmeric (*Curcuma longa*) and activated carbon further enhances the functional properties of the composite material. Turmeric contributes natural antimicrobial and disinfectant properties, effectively inhibiting pathogenic microorganisms and improving packaging safety. Meanwhile, activated carbon functions as a potent adsorbent, neutralizing undesirable odors and contaminants to maintain packaging quality and freshness. This study evaluates the physicochemical properties, biodegradability, and antimicrobial efficacy of the developed material to assess its suitability as an alternative to plastic-based packaging. The findings underscore the potential of agricultural by-products in addressing environmental challenges, reducing plastic pollution, and promoting sustainable packaging solutions. By repurposing invasive water hyacinth, this research not only mitigates ecological concerns but also fosters the advancement of biodegradable packaging, thereby contributing to global sustainability efforts in the biodegradable packaging material sector.

Keywords: Antimicrobial properties, Biodegradable packaging, Guinea Grass, Sustainable Material, Water hyacinth

Introduction to sustainable packaging

The biodegradable packaging industry faces criticism as petroleum-based plastics have historically dominated the market. These conventional plastics contribute significantly to environmental pollution, with packaging materials accounting for approximately 36% of global plastic production. A large portion of this waste ends up in landfills or the oceans, highlighting the urgent need for sustainable alternatives (Rhodes, 2019). About 45% of landfill waste stems from biodegradable packaging material according to the U.S. Environmental Protection Agency, which demonstrates the necessity for sustainable alternative solutions. Biodegradable packaging material with sustainability features exists as a multi-disciplinary solution to environmental concerns without impacting packaging safety or quality.

Sustainable biodegradable packaging material utilizes renewable, biodegradable, and recyclable materials in energy-efficient production processes. Nature-based films made from biopolymers, including polylactic acid (PLA), starch, and cellulose derivatives, are finding broader applications as sustainable alternatives to synthetic polymers because of their lower environmental impact (Rhim et al., 2013). PLA, made from fermented plant starch, is one example and can function much like conventional plastics, except it has 50-70% lower greenhouse gas emissions during production (Leal Filho et al., 2021). Another innovation is Waste-free edible packaging, which is coatings made from proteins, lipids or polysaccharides that have shelf-life extension capabilities. Han et al. (2014) support the above statements by showing that the application of chitosan-based, edible films prevents microbial growth on fresh, perishable packaging and decreases packaging spoilage by as much as 40%.

Most bioplastics need industrial composting to break down, and thus composting facilities are still rare worldwide (Peelman et al., 2013). Plus, bio-based materials tend to have inferior mechanical properties, like tensile strength or moisture resistance, when compared with conventional plastics, which require the use of additives or multilayering techniques that complicate recycling (Mishra et al., 2020). A second barrier is consumer acceptance, stemming from the fact that consumers have misconceptions about the price and the durability of the products (Steenis et al., 2017).

Figure 01. Biodegradable packaging made from Water hyacinth and Guinea grass

The importance of eco-friendly packaging alternatives

Environmental conservation through alternative sustainable packaging material selection occurs under rising market demands and regulatory requirements. Working with conventional packaging materials and especially single-use plastics functions as a main driver of environmental pollution while causing increased resource extraction and climate change effects. The transition to sustainable materials like biodegradable or recyclable substances, along with compostable materials, permits the attainment of circular economic objectives.

Environmental impact reduction

Almost 40% of these conventional plastics are used for plastic packaging, and 8 million metric tons of plastic packaging leak into the oceans each year, threatening marine ecosystems (Jambeck et al., 2015). Bioplastics, such as polylactic acid (PLA), made from cornstarch, break down within months under industrial composting conditions, while petroleum-based plastics can take hundreds of years to break down (Song et al., 2009). In a life cycle assessment study, Song et al., (2009) concluded that the use of PLA results in 60% less greenhouse gas emissions than traditional plastics, thus lowering climate change.

Water hyacinth ***(Eichhornia crassipes)***

Water hyacinth (*Eichhornia crassipe*) is a free-floating, perennial aquatic species indigenous to the Amazon basin in South America. This species is characterized by having glossy, ovate to rounded leaves (5-15 cm diameter) arranged in rosettes, thick spongy petioles containing bulbous air-filled structures for buoyancy, and striking lavender flowers (Villamagna and Murphy 2010). Its fibrous, hanging root system is nutrient-absorbing and a habitat for microorganisms.

Growth habitat

The ideal conditions for water hyacinth growth are freshwater environments such as lakes, rivers, and wetlands, as well as temperatures between 25–30°C, which are more common in tropical and subtropical areas. It favors eutrophic conditions, thriving under high sunlight and N-P availability, and is common in nutrient-rich waters (Patel, 2012). It is capable of exponential growth, depending on environmental conditions capable of doubling its biomass within two weeks through stolons, seeds or fragmentation reproduction. This trait enables it to form dense mats, often taking over whole water surfaces.

Ecological and socio-economic impact

Though the plant extracts heavy metals such as lead and mercury, as well as nutrients, making it useful for phytoremediation purposes (Malik, 2007), when growing out of control, it can be disruptive to ecosystems. Mats shade out light and deplete dissolved oxygen while outcompeting native species, resulting in a loss of biodiversity.

Environmental impact and invasiveness of water hyacinth (Eichhornia crassipes)

The water hyacinth plant is one of the world's ten most noxious aquatic plants and is problematic in freshwater ecosystems. It is originally from South America, but has invaded over 50 countries within tropical and subtropical areas where it outcompetes local species due to its fast growth and adaptability to varying conditions (Villamagna and Murphy, 2010). This plant forms dense floating mats that prevent light from penetrating, and thus photosynthesis by submerged plants and phytoplankton is prevented, disrupting aquatic packaging chains. This mat can also choke the life out of fish and other aquatic organisms as it decays, and "microbial decomposition depletes dissolved oxygen, resulting in hypoxia" (Patel, 2012). This oxygen depletion has also caused large fish kills, reduced biodiversity, and jeopardized fisheries among other problems (Malik, 2007).

Water hyacinth is an invasive species due to its high rate of reproduction. Seeds are produced in thousands every year and have a viability of up to 20 years, and vegetative reproduction through stolons permits rapid spread (Villamagna and Murphy, 2010). Nutrient water from agricultural runoff also contributes to high growth rates, with a biomass doubling in under two weeks (Patel, 2012). These mats also block water movement, causing sedimentation and flooding problems, and also constitute a breeding ground for vectors of disease, such as mosquitoes and snails, increasing the incidence of malaria and schistosomiasis (Malik, 2007).

Infestations interfere with irrigation, fishing and navigation and result in management and lost livelihood costs on the order of millions of USD each year. Water hyacinth does have applications in phytoremediation, absorbing heavy metals and other contaminants, and in biofuel production, mitigating its ecological cost somewhat (Patel, 2012). Yet, the use of herbicides must be avoided, as they pose secondary ecological risks and thus sustained control will need to rely also on integrative strategies like those offered by biological control with Neochetina weevils or even mechanical control methods (Villamagna & Murphy, 2010).

Chemical composition of water hyacinth

Water hyacinth is a high-growth-rate plant and is known for its complex and variable chemical composition, which differs by morphological part and environmental setting. It is composed mainly of cellulose (20-30%), hemicellulose (33-50%), and lignin (5-15%), and thus is a potentially useful lignocellulosic substrate for biofuels (Malik, 2007; Rezania et al., 2015). Lignin content is also lower in younger plants; on top of that, stems contain a higher cellulose percentage (30%) than leaves (15-20%), which increases their suitability for enzymatic hydrolysis in the bioethanol production process (Rezania et al., 2015). On top of that, because of its ability to phytoremediate, the plant also stores high levels of minerals and heavy metals, such as Lead (Pb), Cadmium (Cd) and Chromium (Cr), with the strongest correlation between the metal concentrations being found in areas surrounding contaminated water bodies (Mishra and Tripathi, 2008).

Guineagrass (*Megathyrsus maximus*)

Guineagrass has established itself throughout the tropical and sub-tropical regions (Perrin and Brereton-Stiles, 1999; Muir et al., 2004). Guinea grass undergoes wider climatic adaptations throughout its native African range. Studies indicate guineagrass occurs more frequently in natural habitats than in managed grasslands across annual rainfall zones with under 600 mm annual precipitation (J.P. Muir, personal observation, 1995). Guinea grass belongs to the family Poaceae, subfamily Panicoideae. Guinea grass is variable in size and indumentum of culms, leaves, and panicles.

Potential uses of biodegradable packaging materials

Bioplastics, such as polylactic acid (PLA), starch, cellulose, and polyhydroxyalkanoates (PHAs), have been proposed as non-fossil fuel-based, sustainable replacements for plastics and other products in a variety of sectors. PLA and starch-based films decrease plastic waste and help preserve packaging by offering antimicrobial properties and barriers to moisture and oxygen, which is urgent given that 8 million tons of plastics end up in the oceans each year (Jambeck et al., 2015; Siracusa, 2019). Mulch films from polybutylene adipate terephthalate (PBAT) or PHA, which are biodegradable and decompose in soil, are employed in agriculture, thus leading to less microplastic pollution and higher productivity (Kasirajan and Ngouajio, 2012). Chitosan or alginate are examples of biomaterials that are used in healthcare applications for dissolvable sutures and drug delivery systems because of their biodegradability in biological settings (Prasad et al., 2021). Products for consumption, like compostable bags and containers made of cellulose, are following the circular economy model, which minimizes what goes to the landfill (Song et al., 2009). Although they may have benefits such as reduced carbon footprint or certification fulfilling certain standards (e.g., ASTM D6400, EN 13432), they still face issues in the aspects of cost-competitiveness and mechanical performance compared to synthetic polymers (Rudnik, 2019). Chemical modifications as well as the development of nano-reinforced bio-composites are geared toward overcoming these limitations to expand to industrial levels of production (Peelman et al., 2013). Biodegradable packaging, therefore, connects ecological values with functional needs and can serve the global agenda of sustainable development to reduce pollution and reliance on fossil fuels, as long as the necessary large-scale production and disposal infrastructure also develops in conjunction.

The production of water hyacinth into packaging materials

Water hyacinth (*Eichhornia crassipes*) functions as a major source in biodegradable packaging production because of its cellulose (20–30%) and hemicellulose (33–50%) composition and its sustainable polymer alternative. Water hyacinth processing begins with pretreatment using mechanical grinding or chemical delignification to obtain cellulose fibers that integrate with binders such as starch, chitosan, or polyvinyl alcohol to shape films or composites, according to (2017). Cells treated with NaOH-based alkali removal achieve tensile strengths between 15–25 MPa, which matches low-density polyethylene materials according to Rezania et al. (2015). Research shows that compression molding and solvent casting improve material consistency by producing packaging films with 10–20% elongation at break, which makes them appropriate for use in lightweight containers and protecting wraps (Mishra and Tripathi, 2009). The processing costs need to decrease for large-scale production while mechanical resistance under moisture exposure requires improvement that plasticizers (e.g., glycerol) and nanofillers (cellulose nanocrystals) help address (Gunnarsson and Petersen, 2008). The environmental impact of using bio-plastic materials is shown by life-cycle assessments to result in a 40–60% decrease in carbon emissions below standard plastics, according to Malik (2007). Water hyacinth-based packaging stands as a two-fold solution to control invasive species while advancing sustainable materials through its yearly production of over 350 million tons of plastic waste yet, it depends on processing standardization and regulatory support from industries.

Process

I. The water hyacinth specimens from local water areas and guinea grass were collected.

II. Clean-up procedures removed all types of dirt while getting rid of insects and impurities from the raw materials.

III. The personnel processed the clean water hyacinth and guinea grasses into small pieces using appropriate instruments.

IV. After adding activated carbon and turmeric to enhance natural antimicrobial and disinfectant properties, effectively inhibiting pathogenic microorganisms.

IV. A solution of water and 5% NaOH per one litter should be added and started boiling. Temperature should be 100^0C for 60 min to obtain unbleached pulp (Goswami and Saikia, 1994).

V. The processing continued with blending the soft material through mechanical beater systems to produce a fibrous slurry.

VI. A uniform fiber mixture resulted from filtering pulp to eliminate its excess water composition.

VII. Natural latex along with gum arabic and starch was blended with the pulp to boost its bonding capability.

VIII. The blended pulp received molds for the formation of sheets or mesh screens for the creation of specific sheets at targeted dimensions and densities.

IX. The pressing process applied manual force on the sheets to eliminate moisture while achieving better sheet density.

X. The sheets underwent air-drying under regulated conditions to ensure the completion of the drying process.

XI. The sheets went through processing for shaping into final packaged forms.

Environmental and economic benefits of reducing plastic waste

The substantial yearly plastic production of more than 400 million tons leads to acute ecological damage and economic loss on a global scale. The adoption of sustainable replacements alongside better waste management approaches reduces environmental damage while creating parallel advantages for nature and the economy.

Environmental benefits

Reduced pollution and ecosystem protection

The 80% of marine debris comes from plastic waste including single-use products resulting in deadly hazards for marine organisms through both ingestion and trapping. Microplastics measuring smaller than 5mm have spread throughout isolated ecosystems where they damage ecosystems together with their underlying biodiversity and packaging system relationships.

Lower greenhouse gas emissions

The manufacturing process of plastic depends on fossil fuel resources which consume between 4 and 8 percent of worldwide oil consumption while producing annual CO_2 emissions of 1.8 billion tons of pollution. The use of bio-derived materials along with recycled plastics leads to greenhouse gas emission reductions from 25–40% which helps countries achieve their climate targets.

Restoration of aquatic systems

When water hyacinth invasive species are gathered for bioplastic production, it leads to improved water passageways, which uses the procedure to enhance water quality and restore fish populations.

Economic benefits

Cost savings in waste management

All governments allocate $40 billion annually to handle their plastic waste management costs starting from cleanups to landfills expenses.

Properties of packing material

Physical properties

The packaging material derived from water-hygiene plants has a lightweight and fibrous structure, with a porous texture. The density typically ranges between 0.25–0.40 g/cm^3, making it suitable for cushioning applications. The material can be molded into various thicknesses (2–10 mm), and while it retains a mild plant-based odor, proper processing reduces its natural smell.

Mechanical properties

The material exhibits moderate strength compared to conventional plastics. Its tensile strength ranges between 2–6 MPa, which is sufficient for light packaging. The compressive strength falls between 50–150 kPa, allowing it to provide protection for fragile items. While the material offers some flexural strength, it tends to be brittle and can break under repeated bending.

Barrier properties

Due to its hydrophilic nature, the material absorbs 40–70% of its weight in water, making it less resistant to moisture. Without surface treatment, water resistance remains low. However, the porous structure allows for good air permeability and provides natural breathability. Additionally, it offers reasonable thermal insulation comparable to other natural fiber-based materials.

Biodegradability

The developed material is fully biodegradable under soil or composting conditions, typically decomposing within 30–45 days. During decomposition, it leaves behind organic matter without toxic residues, making it safe for soil enrichment. Utilizing invasive water-hygiene plants also reduces their harmful environmental impact.

Thermal properties

The material remains stable up to temperatures of about 120 °C. Its thermal conductivity is low (~0.03–0.05 W/mK), providing good insulation. Like most plant-based materials, it is flammable, but flame retardancy can be improved with surface treatments.

Conclusion

Water hyacinth-based biodegradable packaging material combines dual environmental benefits because it solves two pressing problems through its waste management of invasive species and plastic waste reduction. This renewable packaging material decomposes easily in nature while it biodegrades completely without producing any microplastics which helps lower landfills and prevent marine pollution. Water hyacinth control enables the growing of this invasive water plant to create packaging materials that help protect natural habitats while purifying water ecosystems. Businesses can use water hyacinth as an invasive plant material to generate sustainable job opportunities, which converts environmental hazards into usable resources for industrial production. The plant has both limited growth costs and inexpensive cultivation methods, which create an affordable PET plastic alternative yet support worldwide circular economy frameworks. The implementation of water hyacinth packaging allows business to strengthen their environmental image through green branding, which increases their market competitiveness. The alternative use of water hyacinth for snack pouches and bakery wraps, and produce containers specifically prevents 40% of global plastic packaging from ending up as waste. The weight efficiency of this material decreases delivery emissions, and its organic insulation characteristics lower the need for cold storage energy usage. The powerful advantages unite to establish water hyacinth as a disruptive solution that trains ecological preservation to work alongside waste management and promotes inclusive financial advancement.

References

Abdelhamid AM & Gabr AA (1991). Evaluation of water hyacinth as a feed for ruminants. *Archiv für Tierernaehrung*, *41*(7-8), pp.745-756.

Forcinio H (2023). Market for Packaging Continues to Expand: Interest grows in AI, digitalization, robotics, and sustainability. *Pharmaceutical Technology*, *47*(11), pp.22-24.

Gaurav GK, Mehmood T, Cheng L, Klemeš JJ & Shrivastava DK (2020). Water hyacinth as a biomass: A review. *Journal of Cleaner Production*, *277*, p.122214.

Goswami T & Saikia CN (1994). Water hyacinth—a potential source of raw material for greaseproof paper. *Bioresource technology*, *50*(3), pp.235-238

Goswami, T. & Saikia, C. N. (1994). *Water hyacinth — a potential source of raw material for greaseproof paper*. Bioresource Technology, 50(3), 235-238. DOI: 10.1016/0960-8524(94)90095-7

Gunnarsson, C. C. & Petersen, C. M. (2007). *Water hyacinths as a resource in agriculture and energy production: A literature review*. Waste Management, 27(1), 117-129. DOI: 10.1016/j.wasman.2005.12.011

Han JH (2014). Edible films and coatings: a review. Innovations in biodegradable packaging material, pp.213-255.

Herbes C, Beuthner C & Ramme I (2018). Consumer attitudes towards biobased packaging–A cross-cultural comparative study. *Journal of cleaner production*, *194*, pp.203-218.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., & Law, K.L. (2015). *Plastic waste inputs from land into the ocean*. Science, 347(6223), 768–771. Available at: https://doi.org/10.1126/science.1260352

Kasirajan, S., & Ngouajio, M. (2012). Polyethylene and biodegradable mulches for agricultural applications: A review. *Agronomy for Sustainable Development*, 32(2), 501–529. Available at: https://doi.org/10.1007/s13593-011-0068-3

Khalil HA, Bhat AH & Yusra AI (2012). Green composites from sustainable cellulose nanofibrils: A review. *Carbohydrate polymers*, *87*(2), pp.963-979

Malik A (2007). Environmental challenge vis-à-vis opportunity: the case of water hyacinth. *Environment International*, 33(1), pp.122-138.

Mishra UN, Das S & Kandali R (2020). Bioremediation of synthetic polymers: present and future prospects of plastic biodegradation. *Int J Curr Microbiol App Sci*, *9*(12), pp.1234-1247.

Mishra VK & Tripathi BD (2008). Concurrent removal and accumulation of heavy metals by the three aquatic macrophytes. *Bioresource technology*, *99*(15), pp.7091-7097.

Muir JP & Jank, L (2004). Guineagrass. *Warm-season (C4) grasses*, *45*, pp.589-621.

Peelman N & Ragaert P & De Meulenaer B & Adons D & Peeters R & Cardon L & … & Devlieghere F (2013). Application of bioplastics for food packaging. *Trends in Food Science & Technology*, 32(2), pp.128–141.

Patel S (2012). Threats, management and envisaged utilizations of aquatic weed *Eichhornia crassipes*: an overview. *Reviews in Environmental Science and Biotechnology*, 11(3), pp.249–259.

Penfound, W T & Earle, T. T. (1948). The biology of the water hyacinth. *Ecological Monographs*, 447-472.

Purcarea T, Ioan-Franc V, Ionescu ȘA, Purcărea IM, Purcărea VL, Purcărea I, Mateescu-Soare MC, Platon OE & Orzan AO (2022). Major shifts in sustainable consumer behavior in Romania and retailers' priorities in agilely adapting to it. *Sustainability*, *14*(3), p.1627.

Perrin MR & Brereton-Stiles R (1999). Habitat use and feeding behaviour of the buffalo and the white rhinoceros in the Hluhluwe-Umfolozi Game Reserve. *South African Journal of Wildlife Research*, 29(1), pp.1–9.

Prasad, C., Thambiliyagodage, C., & Jayasinghe, U. (2021). A fibrous mat of chitosan blended with polycaprolactone (PCL) was prepared by Prasad et al. for potential applications in wound healing. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, 109(3), 505–515. Available at: https://doi.org/10.1002/jbm.b.34732

Rezania S, Ponraj M, Talaiekhozani A, Mohamad SE, Din MFM, Taib SM, Sabbagh F & Sairan FM (2015). Perspectives of phytoremediation using water hyacinth for removal of heavy metals, organic and inorganic pollutants in wastewater. *Journal of environmental management*, *163*, pp.125-133.

Rhim JW & Park HM, & Ha CS (2013). Bio-nanocomposites for food packaging applications. *Progress in Polymer Science*, 38(10-11), pp.1629-1652. DOI:10.1016/j.progpolymsci.2013.05.008

Rhodes, C. J. (2019). Solving the plastic problem: From cradle to grave. *Science Progress*, 102(2), 003685041984228. Available at: https://doi.org/10.1177/003685041984228

Robertson GL (2005). *Biodegradable packaging material: principles and practice*. CRC Press.

Rudnik E (2019). *Compostable polymer materials*. Newnes.

Setyaningsih, L., Satria, E., Khoironi, H., Dwisari, M., Setyowati, G., Rachmawati, N., Kusuma, R., & Anggraeni, J. (2019). Cellulose extracted from water hyacinth and the application in hydrogel. *IOP Conference Series: Materials Science and Engineering*, 673, 012017. Available at: https://doi.org/10.1088/1757-899X/673/1/012017

Siracusa V (2019). Microbial degradation of synthetic biopolymers waste. *Polymers*, *11*(6), p.1066

Song JH & Murphy RJ & Narayan R & Davies GB (2009). Biodegradable and compostable alternatives to conventional plastics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1526), pp.2127–2139. DOI: 10.1098/rstb.2008.0311

Steenis ND & van Herpen E & van der Lans IA & Ligthart TN & van Trijp HCM (2017). Consumer response to packaging design: the role of packaging materials and graphics in sustainability perceptions and product evaluations. *Journal of Cleaner Production*, 162, pp.286-298. DOI: 10.1016/j.jclepro.2017.06.036 29

Villamagna AM & Murphy BR (2010). Ecological and socio-economic impacts of invasive water hyacinth. *Environmental Management*, 45(2), 189–199.

CHAPTER 10

Sustainable Biological Innovation in Healthcare: Biopharmaceuticals

E. J. Eugene*

Department of Biomedical Science, School of Sports and Health Science,
Cardiff Metropolitan University, UK Campus,
International College of Business and Technology, Colombo, Sri Lanka.
**mcjeugene@yahoo.com*

Abstract

Healthcare ensures the well-being and health practices of individuals and communities. A less efficient use of resources in healthcare leads to a severe environmental impact and consequently endangers the health of people. Therefore, it is vital to understand how sustainable development is applied to healthcare processes. Sustainability in healthcare should be embraced as a guiding principle that recognizes the interconnectedness between human and environmental health. Biopharmaceuticals, developed through biological systems, offer enhanced biodegradability, resulting in a reduced environmental footprint. As such, biopharmaceuticals represent an eco-friendly option toward sustainable healthcare practices.

Keywords: Biopharmaceuticals, Healthcare, Innovation, Sustainability

Introduction

Healthcare ensures the well-being and health practices of individuals and communities. The primary objective of the healthcare sector is the diagnosis, treatment, and prevention of diseases; however, an inefficient use of resources leads to a severe environmental impact and consequently endangers the health of people. Therefore, it is vital to understand how sustainable development is applied to healthcare processes. Sustainability in healthcare should be embraced as a principle that recognizes the interconnectedness of human and environmental health (Small 2007; Pande et al., 2025). Focusing on sustainability criteria like poverty reduction, waste reduction, fair distribution, pollution prevention, clean technology, transparency-related business practices, and product management is the key to sustainable development. The evolution of innovation as the shift of the unit of innovation from the individual innovator to companies and the shift of the object of innovation from technological innovation to business management model (Stuss, 2023).

Biopharmaceuticals (biologics or biologicals) are medicinal products derived from biological sources such as cells, tissues, or entire organisms. These compounds encompass a broad range of substances, including viruses, therapeutic serums, toxins, antitoxins, vaccines, blood and its derivatives, allergenic proteins, and analogous products. Unlike traditional pharmaceuticals, which are chemically synthesized, biopharmaceuticals are produced using advanced biological processes. They are employed for the prevention, diagnosis (*in vivo*), treatment, or cure of various diseases and medical conditions in humans. Examples of these innovative biopharmaceutical products include vaccines, blood-derived products (hormones, growth factors, thrombolytic agents), biosimilars, monoclonal antibodies, recombinant proteins, gene therapies, and CAR-T cell therapies. These products are characterized by their structural complexity, target specificity, greater precision, and effective and personalized treatment for diseases. Biopharmaceuticals have significantly improved therapeutic efficacy across a range of conditions. However, they face drawbacks such as extended development times, limited patent protection, and the possibility of biosimilar challenges (Pande et al., 2025).

Table 1: Sources of pharmaceuticals (Chen et al., 2018)

Source Item	**Extracted from living systems**	**Produced by recombinant DNA**
Characteristic	1. Extracted from animals or humans 2. Extracted from animals and currently produced using biotechnologies. Examples: Therapeutic insulin from porcine pancreatic islets	Biopharmaceuticals produced by recombinant DNA technologies are usually one of the following three types: 1. Substances that are almost identical to the body's own key signalling proteins. 2. Monoclonal antibodies are similar to antibodies produced by the human immune system against microbes. 3. Receptor constructs based on naturally occurring receptors linked to the immunoglobulin frame.
Example	Whole blood and blood components and tissue transplants, stem cells, antibodies for passive immunization, fecal microbiota, human breast milk, human reproductive cells	Blood factors, blood plasminogen factors, hormones, hematopoietic growth factors, interferons, interleukin-based products, vaccines, monoclonal antibodies, tumor necrosis factor, therapeutic enzymes

Genetic technology in healthcare: Recombinant proteins

The biological and societal realities could be altered by genetic technology. All living organisms are impacted by their creation and use. Currently, microorganisms, plants, and animals are being genetically modified to produce food, medications, and industrial goods.

By enabling the expression of proteins in a variety of host systems, genetic engineering opens the door for novel therapies and technologies. Proteins created artificially by combining sequences from different sources using recombinant DNA are known as recombinant proteins. The host organism subsequently receives this genetic material and expresses the protein. The procedure makes it possible to create proteins that are either identical to those found in nature or have unique features. Recombinant proteins are employed in medications like diabetes (insulin), hemophilia (factor VIII), and multiple sclerosis (interferon-beta). These are useful for researching the functions, interactions, and structures of proteins. The steps involved in making recombinant proteins are as follows: The gene that codes for the target protein is cloned by inserting it into a plasmid vector, which is then introduced into a host cell. The plasmid is delivered into host cells (bacteria, yeast, insect, or mammalian cells) *via* methods such as heat shock, electroporation, or viral transduction. This is referred to as transfection or transformation. The recombinant protein is produced in the host cells by growing them in conditions that promote its expression. The protein is extracted from the host cells and purified using methods such as affinity chromatography and ion exchange. Characterization is then done to verify that the purified protein satisfies the necessary quality and functional criteria, and it is then analyzed (Izutsu, 2024).

Most gene therapies currently exist in basic research facilities, and their clinical use is still being tested. To achieve a therapeutic benefit, therapeutic components must be delivered to specific cells. Consequently, the delivery method is essential for delivering drugs to target cells, and it is critical to choose a suitable delivery method that is specific, effective, safe, and cost-effective. As a result, their safety must be confirmed in preliminary tests. The development and study of delivery instruments is likely to be challenging, expensive, and time-consuming (Chen and Yen, 2018).

Ensuring that the recombinant protein is soluble and properly folded remains one of the primary challenges. Inclusion bodies, which are collections of insoluble misfolded proteins, can be formed by proteins produced in bacteria or yeast. Additionally, selecting the right expression system is essential for proteins that need particular post-translational modifications, like glycosylation. Increasing production while controlling expenses and preserving protein quality is a difficult task. Large-scale production can be expensive and calls for sophisticated bioreactor equipment. Production capacities are being improved by innovations such as enhanced mammalian cell lines and cell-free protein synthesis. Creating scalable and adaptable production systems that may be tailored to particular needs is a key component of personalized medicine. Recombinant protein is an example of efforts to reduce waste, optimize resource utilization, and develop greener production processes with a sustainable orientation (Izutsu, 2024).

Innovative vaccines

Vaccination remains the most cost-effective public health intervention after access to clean water, where the benefits outweigh the associated costs. One of the best methods for controlling diseases is vaccination, which involves administering an antigenic substance (vaccine). The primary benefits of vaccination are long-term immunity and prevention; the drawbacks include complicated immunization schedules, stringent storage requirements, and limited administration routes (Chen and Yen, 2018). The potential advancements in disease prevention can be maximized by properly developing and delivering vaccinations.

The effort required to meet the increasing need for next-generation and novel vaccines created for new indications and emerging pathogens is only achievable under a sustainable business model. Improving international cooperation and the ongoing innovation of technologies accelerate the creation, development, and production of vaccines. Nevertheless, these procedures must be backed by a well-balanced project portfolio and the judicious management of sustainable vaccine procurement practices for various market categories. Together, this will permit a gradual transition to a more efficient and lucrative vaccine manufacture, which can make a significant contribution to the global endeavour to influence global health (Rappuoli and Hanon 2018).

There are many modern vaccines for example mRNA vaccines; a small portion of the virus genetic information is used in mRNA vaccines to elicit an immunological response, Viral vector vaccines; vaccines against viral vectors work by modifying a virus to introduce genetic material from the specific pathogen into the body, DNA vaccines; genetically modified DNA is used in DNA vaccines to elicit an immunological response, Nanoparticle-based vaccines; vaccines based on nanoparticles work by delivering antigens to the immune system via nanoparticles, Plant-based vaccines; plants are used as bioreactors to manufacture vaccine antigens (Abdaal et al., 2024).

One of the successful methods of producing novel vaccines is the use of nanotechnology. By using nanoparticles, vaccinations can be administered by interchangeable routes, controlled release at a specific site, and remain stable at ambient temperature. Biopharmaceuticals lead to the creation of painless, secure, efficient, and reasonably priced goods. Furthermore, biotechnologies including reverse vaccinology, recombinant subunit vaccination, recombinant protein vaccination, DNA vaccination, and RNA vaccination have the potential to develop therapeutic vaccines for both infectious and noninfectious disorders. Complicated immunization schedules are the main obstacle. Since biotechnology-based vaccinations typically only include fragments of microbes (DNA, RNA, or protein), several doses are necessary (Chen and Yen, 2018).

Biosimilars: An innovation of excellence

The first group of biopharmaceutical items produced using recombinant technologies has paved the way for the creation of "generic" alternatives for original biologics, referred to in this article as biosimilars. Cells in culture or entire animals produce biologics, which are naturally more variable than chemical synthesis techniques. Consequently, it is impossible to replicate an innovative product exactly, as opposed to generic pharmaceuticals. As a result, the area of biosimilars has several significant challenges, such as i) confirming the similarity, ii) the interchangeability of biosimilars and innovative products, iii) the potential need for unique nomenclature to distinguish the various biopharmaceutical products, iv) the regulatory environment, v) commercial prospects and guidelines to support manufacturers in product development, vi) intellectual property rights, and vii) public safety (Sekhon, and Saluja, 2011).

For biosimilar companies, this information gap on sustainable innovation represents a significant obstacle and is essential in explaining the variations in regulatory routes. It is necessary to prove biosimilarity and guarantee that the modification in the manufacturing process has no impact on efficacy or safety. The degree of change is typically a crucial determinant of the analysis needed to assess the quality. Thus, it is necessary to make sure that the modifications do not affect the safety and effectiveness of biosimilars. After their patent protection expires, some biopharmaceuticals might be replaced by less expensive biosimilars. Biosimilars are finally being developed as a result of the financial success of biopharmaceutical therapies and the expiration of their patents. Ultimately, biosimilars play a beneficial role in the healthcare system (Chen and Yen, 2018).

Innovative thrombolytic agents

The discovery of streptokinase and urokinase and second-generation plasminogen activators, paved the way for the use of these enzymes as thrombolytic agents to break down the fibrin network, which resulted in systemic bleeding. The third-generation molecules, primarily t-PA modifications, exhibited advantageous features such as increased stability, safety, and effectiveness along with greater fibrin specificity: exhibiting features expected in a sustainable innovation, with targeted delivery of these medications utilizing liposome technology, plasmin variants are produced as direct fibrinolytic agents (Adivitiya and Khasa, 2017).

Numerous carriers have been evaluated for the controlled release of thrombolytic agents, such as mesoporous silica, liposomes, magnetic nanoparticles, and dendrimers. Membrane coating coats nanoparticles by using the cell membranes of the natural thrombus constituents, primarily platelets and red blood cells. Physical responsive nano-drug delivery systems encompass magnetic targeting, ultrasound-mediated thrombolytic therapy, and platelet-like biomimetic particles activated by shear stress. However, magnetic nanoparticles face challenges, including inadequate dispersion and solubility in water. Although ultrasound treatment will cause the thrombus to change structure, it may also raise the chance of thrombus shedding, which could obstruct and ischemia adjacent veins. Membrane coating nanoparticles by using the cell membranes of the natural thrombus constituents, primarily platelets and red blood cells. This method enables nanoparticles to preserve nearly all of the cell membrane's original constituents while preserving the proteins' complete functioning. However, the use of antibody/ligand modification techniques holds great promise for enhancing targeting and extending half-life, proving an ideal technique for innovative and sustainable products (Shen et al., 2021).

Using a range of thrombotic and stroke animal models, scientists have developed a potent fibrinolytic enhancer, Db-TCK26D6x33H1F7, that exhibits strong *in vivo* performance. The diabody has potential clinical uses in treating thrombotic disorders, including (i) preventing venous thromboembolism, (ii) treating brain ischemia/reperfusion injury, and (iii) thrombolytically treating fibrin-rich and platelet-rich clots in ischemic stroke, according to our findings. In mice stroke models, this innovative profibrinolytic method seems to be both safer and more successful than the existing tPA treatment. These findings suggest that this diabody could be a promising candidate for clinical research on thrombotic diseases (Wyseure et al.,2014).

Innovative monoclonal antibodies

Biopharmaceuticals represent groundbreaking solutions that have transformed the management of significant chronic illnesses and cancers. The authorization of biosimilar products has evolved into a complicated and equitable process, with drug versions demonstrating confirmed biosimilarity that can provide a more affordable treatment choice for patients. The findings indicate that advancements in targeted therapies utilizing monoclonal antibodies have sparked considerable interest for many years. These medications have turned into crucial tools in combating major illnesses, including cancer and autoimmune disorders. Consequently, it is thought that the introduction of these drugs could aid in the prevention and management of diseases through the application of monoclonal antibody therapy (Santos-Neto et al., 2021).

Monoclonal antibodies (mAbs) have emerged as potent therapeutic agents, revolutionizing the landscape of modern medicine. Therapeutic applications across various medical disciplines, including cancer treatment, autoimmune diseases, and infectious diseases, are examined. Furthermore, it has many challenges and opportunities in manufacturing scalability, cost-effectiveness, and access to therapies on the innovative route. Research also emphasizes the potential for next-generation mAbs, personalized medicine, and integration with emerging modalities such as immunotherapy and gene therapy. In conclusion, the evolution of monoclonal antibodies underscores their transformative impact on healthcare and their continued promise to advance the frontiers of medicine innovatively and sustainably (Kothari et al., 2024).

Sustainable innovation using CAR-T cell therapies

Chimeric antigen receptor (CAR-T) therapy has transformed the management of certain blood cancers, specifically acute lymphoblastic leukemia and large B-cell lymphomas. Currently, two CAR-T cell therapies, Tisagenlecleucel and Axicabtagene ciloleucel, have received FDA approval. This treatment process entails the extraction of T cells, which are then genetically engineered to produce an antigen receptor that is typically absent, leading to the formation of a chimeric molecule, a T cell that possesses the dual specificity of an antibody (Ahmad, 2020).

In recent years, there has been a growing emphasis on promoting CAR-T cell treatment as an adoptive immunotherapy. Individual T cells are genetically modified as the basis for its preparation. The development of the functioning intracellular signaling domain, a crucial component of genetically modified T cells, has taken a long time and produced numerous advancements in the efficacy and safety of CAR-T cells. Numerous international clinical trials have shown that CAR-T cell treatment has strong and enormous applicability potential. The technology's promise is found in CAR-T cell engineering, which can withstand harsh environments and stimulate an endogenous tumor response (Ahmad, 2021).

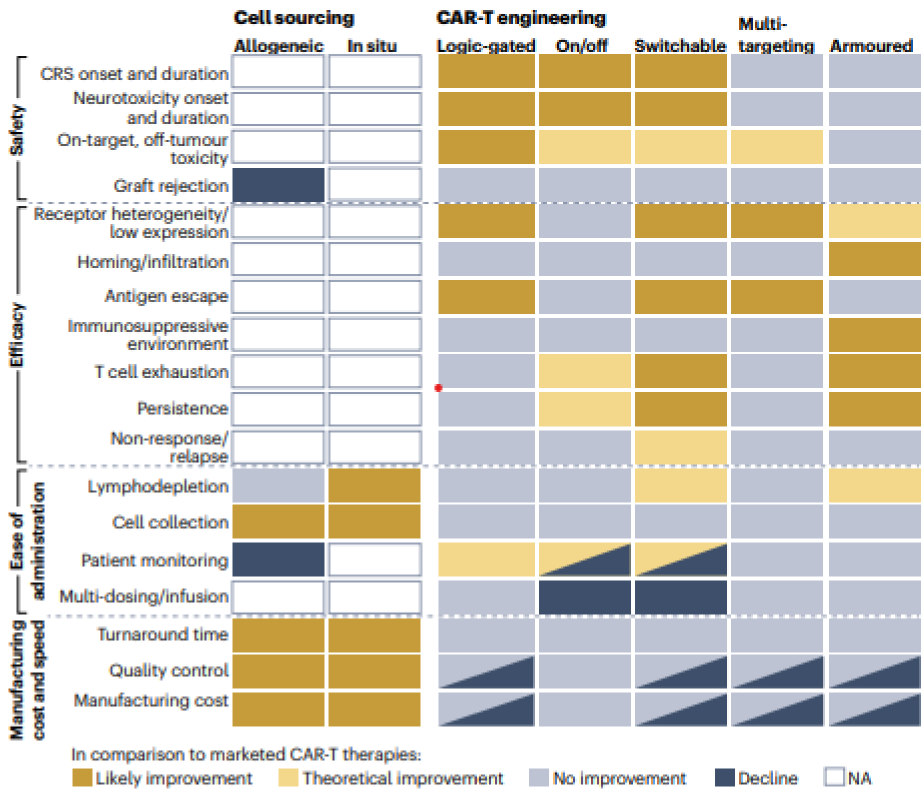


Figure 01. Impact of CAR-T therapy innovations (Verma et al., 2023)

The potential of this strategy is found in CAR-T cell engineering, which can suppress aggressive TMEs and promote an endogenous tumor response, as seen in figure 01 above. The final prerequisites for researchers in this field are to conduct clinical trials and secure the required funding. More successful cases of cancer eradication are reported as this treatment develops.

Conclusion

The creation of biopharmaceuticals is constantly evolving and carries significant implications for therapy, diagnostics, and research. By utilizing various expression systems and tackling related challenges, researchers and engineers are constantly pushing the boundaries of these products' capabilities and applications. As technology evolves and new approaches are introduced, the future of biopharmaceutical production holds the promise of improved efficiency, increased scalability, and creative solutions to intricate medical and research problems. The continuous advancement and enhancement of production methods will be crucial in determining the future of the biopharmaceutical sector and its impact on global health outcomes (Izutsu, 2024).

References

Abdaal K, Batool A, Navid M, Ahmed S, Qazi A, Safdar W, Ali H, Rashid M & Rafaqat S (2024). Advancements in Vaccination Strategies: From Historical Milestones to Modern Innovations in Viral Disease Prevention and Public Health. *Research Journal for Veterinary Practitioners*. 12. 10.17582/journal.rjvp/2024/12.1.11.21.

Adivitiya & Khasa YP (2017). The evolution of recombinant thrombolytics: Current status and future directions, *Bioengineer*, 8:4, pp.331-358.

Ahmad A (2020). CAR-T Cell Therapy. *International Journal of Molecular Sciences*, *21*(12), 4303. https://doi.org/10.3390/ijms21124303.

Ahmad A (2021). CAR-T cell therapy: current advances and future research possibilities. *Journal of Scientific Research in Medical and Biological Sciences,* 2(2), doi: https://doi.org/10.47631/jsrmbs.v2i2. 234.

Chen Y-C & Yen M-K (2018). Introductory Chapter: Biopharmaceuticals. In Biopharmaceuticals, IntechOpen 79194.

Izutsu K-I (2024). Production of Recombinant Proteins: Techniques, challenges and future Directions. *Pharm. Bioprocess,* 12(5), DOI: 10.37532/2048-9145.2024.12(5), pp. 232-233.

Kothari M, Wanjari A, Acharya S, Karwa V, Chavhan R, Kumar S, Kadu A & Patil R (2024). A comprehensive review of monoclonal antibodies in modern medicine: Tracing the evolution of a revolutionary therapeutic approach. *Cureus.* 9;16(6):e61983. doi: 10.7759/cureus.61983.

Pande AH, Prasad YR & Anakha J (2025). What are biopharmaceuticals? *Explor Drug Sci,*3:100880. doi.org/10.37349/eds.2025.100880.

Rappuoli R & Hanon E (2018). Sustainable vaccine development: a vaccine manufacturer's perspective. *Current Opinion in Immunology,* 53, pp.111–118.

Santos-Neto JF, Oliveira FO, Hodel KVS, Fonseca LMS, Badaro´ R & Machado BA (2021). Technological advancements in monoclonal antibodies, *Scientific world journal,* doi.org/10.1155/2021/6663708.

Sekhon BS & Saluja V (2011). Biosimilars: An overview. *Biosimilars,* 1, pp.1-11. doi:10.2147/BS.S16120.

Shen W, Hu L & Xing C (2021). Thrombolytic Agents: Nanocarriers in Targeted Release. *Molecules,* 26, 6776. https://doi.org/10.3390/ molecules26226776.

Small B (2007). Sustainable development and technology: Genetic engineering, social sustainability, and empirical ethics. *International Journal of Sustainable Development,* doi: 10.1504/IJSD.2007.

Stuss MM (2023). The role of innovation in sustainable development. In Organizing Sustainable Development. doi: 10.4324/9781003379409-21.

Verma M, Obergfell K, Topp S, Panier V & Wu J (2023). The next-generation CAR-T therapy landscape. *Nat Rev Drug Discov.* 22(10):776-777. doi: 10.1038/d41573-023-00140-7.

Wyseure T, Rubio M, Denorme F, Lizarrondo, MS, Peeters M, Gils A, De Meyer S, Vivien D, & Declerck P (2014). Innovative thrombolytic strategy using a heterodimer diabody against TAFI and PAI-1 in mouse models of thrombosis and stroke. *Blood*. 125. 10.1182/blood-2014-07-588319.

CHAPTER 11

Biological Approaches for the Remediation of Pharmaceutical Pollution in Aquatic Environments

A.A.A.P. Ishara, L.R.I.P.K. Wijerathne and G. Rajapaksa*

Department of Zoology and Environment Management, Faculty of Science,
University of Kelaniya, Sri Lanka.
**gayani@kln.ac.lk*

Abstract

Pharmaceutical pollution is an increasing concern in freshwater ecosystems. The active pharmaceutical compounds' high stability and low degradability make pharmaceutical pollution more threatening to non-target organisms, necessitating effective removal strategies. The treatment methods vary from physical to chemical processes, including adsorption, membrane filtration, electrochemical treatment to ozonation, chlorination, and Fenton reaction. However, these approaches often lead to unintentional environmental consequences, such as toxic byproduct formation, high energy consumption, and incomplete degradation of complex pharmaceutical compounds. The accumulation of transformation products with unknown toxicity has raised concerns about the long-term viability of these chemical methods. In response, biological processes are emerging as a sustainable and eco-friendly solution. Bioremediation utilizes bacteria and fungi to metabolize pharmaceuticals, while phytoremediation relies on algae and plants such as *Lemna minor* for contaminant uptake and transformation. Fungi such as *Pleurotus ostreatus* and *Trametes versicolor*, along with enzymes like laccases and peroxidases, are also used for the degradation process.

These approaches ensure higher levels of degradation, reduce energy usage, and prevent toxic byproduct formation. Further, wetland construction integrating plant-microbe interactions and biochar-assisted microbial degradation has gained attention as a cost-effective and eco-friendly approach. Advancements in synthetic biology and genetic engineering have enhanced microbial efficiency, with genetically modified bacteria and fungi improving the efficiency of degradation. These strategies align with global sustainability goals, emphasizing the need to prioritize their large-scale implementation in wastewater treatment systems. Thus, biological approaches emerge as effective methods for removing pharmaceutical contaminants, ensuring environmental integrity and public health.

Keywords: Bioremediation, Environmental sustainability, Pharmaceutical Pollutant

Introduction

"Today's medicines are tomorrow's pollutants if we do not handle them responsibly."

With the growing human population and rising healthcare needs, global demand for pharmaceuticals continues to increase. Heavy production and usage coupled with improper disposal and inadequate removal from wastewater facilities have given rise to an "emerging environmental concern of pharmaceutical pollution" (Agarwal, 2022). From analgesics, antibiotics, to hormones and psychiatric drugs, a wide range of pharmaceuticals have been detected, from the nanogram to the microgram scale, in water bodies (David and Pancharatna, 2009). The lower degradability and higher stability of active pharmaceutical ingredients lead to accumulation in water, causing impacts such as endocrine disruption, growth abnormalities, and toxicity to non-target organisms, and antimicrobial resistance in microbial populations (De Oliveira et al., 2016). Since these effects are sub-lethal and chronic instead of immediate mortality, they will silently reduce the population's resilience. Conventional treatment methods often fall short in removing pharmaceutical microcontaminants from water. This has led to growing interest in sustainable and eco-friendly alternatives. This chapter examines the sources and impacts of pharmaceutical pollution, the limitations of current treatments, and highlights promising biological approaches for remediation.

Sources and fate of pharmaceuticals in aquatic environments

Pharmaceuticals reach the natural environment via three major pathways.

- From wastewater effluents of pharmaceutical industries and hospitals,
- From human excretory products, and
- Due to improper disposal of unused or expired medications.

Once in aquatic ecosystems, the environmental fate of pharmaceuticals is governed by properties such as aqueous solubility, biodegradability, adsorption to sediments, hydrolysis, and photodegradation. For example, some compounds, such as diclofenac or carbamazepine, are highly persistent, remaining active for weeks or even months in surface waters. Commonly detected pharmaceutical pollutants include carbamazepine, caffeine, metformin, sulfamethoxazole, trimethoprim, diclofenac, and acetaminophen, at concentrations ranging from nanograms to micrograms per liter in surface and groundwater, sediments, and even in drinking water. A study carried out by Wilkinson et al., (2022) has reported that over 43% of sampled sites across 104 countries contained at least one pharmaceutical compound, emphasizing the global scale and pervasiveness of this contamination.

Environmental and ecotoxicological impacts

The studies highlight that upon chronic exposure, even low concentrations of pharmaceuticals can cause significant changes in biochemical and physiological parameters in non-target organisms, including oxidative stress and metabolic alterations (De Oliveira et al., 2016). For instance, exposure to 1–5 ng/L of 17α-ethinylestradiol causes reproductive disruption in fish. Pharmaceuticals like acetaminophen and diclofenac have been linked to reproductive toxicity, hepatotoxicity, renal damage, and endocrine disruption in aquatic life, even at low concentrations. These compounds have been shown to bioaccumulate and undergo trophic transfer; thus, effective removal of pharmaceutical pollutants from global aquatic ecosystems has become a necessity.

Conventional treatment methods for pharmaceutical removal

Conventional wastewater treatment plants (WWTPs) are designed primarily for the removal of organic matter, nutrients, and pathogens, not specifically for pharmaceuticals. These conventional methods are inadequate for complete removal, which necessitates the need for more sustainable approaches (Verlicchi et al., 2012). Current removal methods are generally categorized into three main stages:

Primary treatment

This stage involves physical processes such as screening, grit removal, and sedimentation to eliminate large solids and suspended particles. Since this is not a specific method for the pharmaceuticals, most pharmaceuticals remain in the aqueous phase without being removed, while only a small fraction of hydrophobic pharmaceuticals are eliminated.

Secondary treatment - Activated sludge process

The most widely used method in this stage is the activated sludge process, which is an aerobic treatment that uses microbial communities to metabolize organic pollutants. Wastewater is aerated to ensure the optimum mixing and to promote microbial activity. The resulting activated sludge consists of flocs (aggregations of microorganisms) that are mixed with incoming wastewater to form a slurry. This mixture is then transferred to a clarifier, where the sludge settles and separates from the treated water, which moves on for further treatment. Compared to other conventional methods, this is more effective in removing biodegradable pharmaceuticals such as acetaminophen (up to 90% removal) and ibuprofen (up to 95% removal) (Jelic et al., 2011). Despite the high efficiencies, there are some drawbacks, such as the difficulty in removing chemically stable compounds such as carbamazepine, sulfamethoxazole, and diclofenac. Another drawback is the long hydraulic retention time required for pharmaceuticals, leading to the buildup of pharmaceutical residues, which will eventually find their way back into the environment when the sludge is used on land.

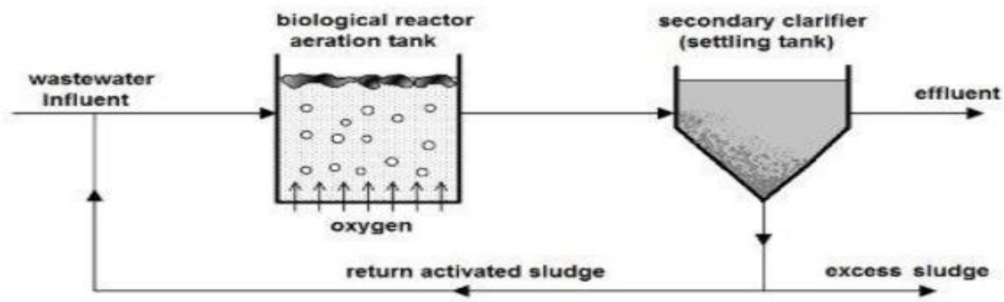


Figure 01. Schematic drawing of the activated sludge process
(Source: De Cazes et al., 2014)

Tertiary method

Activated carbon adsorption

Activated carbon, in the form of granular or powdered carbon, is widely used for adsorbing non-polar or hydrophobic pharmaceuticals such as naproxen, ibuprofen, and estrogens. These compounds adhere to the carbon via van der Waals forces and hydrophobic interactions (Karungamye, 2020). Rather than degradation of pharmaceuticals, this approach transfers contaminants from the aqueous phase to the solid carbon matrix. Therefore, saturation of the solid matrix requires regeneration, through high-temperature or chemical treatments, both energy-intensive and environmentally hazardous (Kumar et al., 2021). Furthermore, disposal of saturated matrix poses risks of secondary pollution through incineration or landfill leachate (Michael et al., 2013). These highlight concerns about environmental safety.

Membrane filtration (physical treatment)

Key membrane processes like ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) rely on semi-permeable membranes that act as physical barriers, separating dissolved substances from water based on size and charge (Luo et al., 2014). Among these, RO is effective at removing pharmaceutical compounds, including carbamazepine, diclofenac, and antibiotics (Naghdi et al., 2018). Despite their effectiveness, membrane filtration methods come with environmental drawbacks. The high energy and pressure requirements contribute to a large carbon footprint (Ahmed et al., 2020). Membrane fouling is another issue, demanding frequent chemical cleaning or membrane replacement, generating chemical waste, and adding to environmental concerns.

Advanced Oxidation Processes (AOPs)

AOPs involve highly reactive species, like hydroxyl radicals (•OH), produced through ozone (O_3), hydrogen peroxide (H_2O_2), and ultraviolet (UV) radiation to break down complex organic pollutants and pharmaceutical compounds, including hormones, antibiotics, analgesics, and anti-inflammatories (Ahmed et al., 2020). However, despite their effectiveness, incomplete degradation can lead to the formation of toxic or persistent by-products, which may still pose environmental and health risks.

Biological methods

Biological methods exploit natural metabolic and enzymatic processes to convert harmful pharmaceutical compounds into less toxic or harmless byproducts, thereby reducing their ecological and health risks (Rivera-Utrilla et al., 2013). Biological systems are particularly effective for purifying wastewater, especially wastewater containing emerging molecules such as pharmaceuticals. Studies have observed that pharmaceuticals' biodegradation ranges from 22% to 99%, while conventional sludge results in just 7% of sorption (Tiwari et al., 2017).

Microbial biodegradation

Microbial biodegradation is one of the most effective and natural methods for dealing with pharmaceutical pollution in aquatic environments.

Microbial communities degrade pharmaceutical compounds through transformation, detoxification, and, in some cases, complete mineralization of the parent molecules (Suleiman et al., 2023). Although many pharmaceuticals are structurally resilient to breakdown due to their design for biological stability, microbial populations can adapt and evolve specific enzymatic pathways to utilize these compounds as energy or carbon sources (Taoufik et al., 2021). *Actinobacteria, Firmicutes*, and *Bacteroidetes* have emerged as key players in the biodegradation of pharmaceuticals, particularly in systems like Integrated fixed-film activated sludge (IFAS), which supports microbial colonization through media that prevent washout (Kumar et al., 2021). Additionally, anaerobic bio-entrapped membrane bioreactors provide enhanced degradation using microbes such as *Elusimicrobia* and *Methanimicrococcus* (Méheust et al., 2020). Microbial species capable of degrading common environmental pharmaceuticals under various environmental and engineered conditions are summarized in Table 1.

Table 1. Microbial remediation of common environmental pharmaceuticals

Pharmaceutical	Microorganism(s)	Conditions	References
Acetaminophen	*P. extremaustralis*, *S. stutzeri*	10–40 °C, pH 5–9, 500 mg/L	(Vargas-Ordóñez et al., 2023)
	Pseudomonas, *Bacillus* spp.	Upflow fixed-bed bioreactor + H_2O_2 stimulation	(Baratpour and Moussavi, 2018)
Diclofenac	*Klebsiella* sp.	30 °C, 120 rpm	(Kandhasamy et al., 2022)

Membrane bioreactors (MBRs)

This is a hybrid technology that involves the combination of conventional activated sludge (CAS) processes with membrane filtration technologies like microfiltration or ultrafiltration. What sets MBRs apart is their ability to physically separate treated water from microbial biomass using a membrane barrier, rather than relying on sedimentation. This results in a much cleaner effluent, low in suspended solids, pathogens, and nutrients, making it highly suitable for reuse, especially in water-scarce regions.

A major advantage of MBRs is their remarkable efficiency in removing pharmaceuticals and endocrine-disrupting compounds that often slip through traditional wastewater treatments (Melvin and Leusch, 2016). This is largely due to their longer solids retention time and hydraulic retention time which allow microorganisms more time to break down even the most persistent contaminants. Studies have shown that MBRs can remove over 99% of some drugs like acetaminophen, diclofenac, sulfamethoxazole, and even synthetic hormones such as 17α-ethinylestradiol (Radjenović et al., 2009).Research has highlighted how MBRs consistently outperform CAS systems, especially when treating complex effluents like hospital wastewater (Snyder et al., 2007). Recently innovated advanced configurations such as Powdered Activated Carbon Membrane Bioreactor, Granular Activated Carbon Membrane Bioreactor, further improve removal efficiency by incorporating activated carbon or mobile carriers that support biofilm growth (de Cazes et al., 2014). However, membrane fouling remains a challenge, requiring aeration, backwashing, or chemical cleaning. In summary, MBRs are a powerful tool in removing pharmaceutical pollutants in aquatic environments. Their ability to consistently produce high-quality effluents while removing a wide range of pharmaceutical contaminants makes them an essential part of modern wastewater treatment, particularly in hospitals, cities, and areas where water recycling is a priority.

Phytoremediation

Phytoremediation utilizes green plants and their associated microbial communities to remove, degrade, or stabilize environmental contaminants. Despite their simple body plans, microalgae can actively take up and break down contaminants through complex biological processes. For example, *Chlorella pyrenoidosa*, a green microalga commonly found in freshwater, has been shown to remove up to 50% of triclosan from water at high concentrations (800 µg/L) within one hour (Wang et al., 2022). Microalgae secrete extracellular enzymes that can transform toxic pharmaceuticals into less harmful or non-toxic intermediates. These by-products are then absorbed into the algal cells, where another round of enzymatic breakdown occurs. However, the effectiveness of the process varies depending on the strain used and the environmental conditions. For instance, during the removal of the antibiotic 7-amino-cephalosporanic acid (7-ACA), *Chlorella* sp. exhibited the highest adsorption capacity, followed by *Chlamydomonas* sp. and *Mychonastes* sp. In high-rate algal ponds where *Coelastrum* sp. is often the dominant species, removal efficiencies for a broad spectrum of pharmaceuticals were up to 50% greater than those achieved by conventional activated sludge systems (Villar-Navarro et al., 2018).

The low cost, versatility, adaptability, and biological eco-friendliness make microalgae and plants ideal candidates for integration into next-generation wastewater treatment strategies, especially in regions where low-cost, nature-based solutions are most needed.

Enzymatic degradation of pharmaceuticals

Enzymatic degradation is gaining momentum as a smart, eco-friendly solution because enzymes are less likely to be affected by the toxicity or complexity of pollutants. The main enzyme types used for this purpose include oxidoreductases, hydrolases, and lyases (Zhao et al., 2012). Among oxidoreductases, laccases, mainly sourced from fungi, perform oxidation using oxygen and are effective against estrogens, antibiotics, and phenols. Peroxidases, derived from plants, catalyze oxidation using hydrogen peroxide (H_2O_2) and can degrade triclosan, diclofenac, and tetracyclines. The range of compounds the enzymes target, and the reaction speed, can often be enhanced by small helper molecules called redox mediators (like ABTS or vanillin); in some cases, up to 80 times boosted reaction speeds have been observed (de Boer et al., 2023). In large-scale industries, instead of free enzyme immobilization strategies (adsorption, covalent bonding, entrapment, and encapsulation), cross-linked enzyme aggregates (CLEAs) are used to improve stability, reusability, and cost effectiveness (Naghdi et al., 2018). Enzyme-based systems show great promise for sustainable wastewater treatment, but further research is needed to enhance their cost-effectiveness, pollutant specificity, and environmental safety, especially considering the potential risks and high costs of some enzymatic chemicals.

Constructed wetlands (CWs)

Constructed wetlands, resembling natural wetland ecosystems, utilize gravel beds and vegetation such as reeds or cattails to filter and degrade harmful substances through multiple complementary mechanisms. As water passes through the system, pollutants are removed via microbial degradation, plant uptake, sunlight-induced breakdown, and physical trapping within the soil matrix. These processes collectively achieve significant reductions in pharmaceutical contaminants. For example, Ávila et al., (2010) reported that a hybrid constructed wetland achieved removal rates of 85–99% for compounds such as naproxen, ibuprofen, and bisphenol A. Similarly, removal efficiencies exceeding 90% for acetaminophen, with performance varying according to plant species, have been observed (Ranieri et al., 2011). Although space requirements and the potential for clogging remain constraints, targeted design improvements can substantially enhance the feasibility and long-term effectiveness of such systems.

Real-World applications and case studies

Sustainable, nature-based solutions for pharmaceutical pollution are gaining global momentum. Countries are increasingly turning to biological methods for cost-effective and eco-friendly wastewater treatment. Real-world applications of biological remediation include a vertical-flow constructed wetland with recirculation for the removal of erythromycin, diclofenac, and carbamazepine in Brazil, a vertical-flow constructed wetland planted with *Scirpus* spp. in Vietnam, and an aerated subsurface-flow hybrid constructed wetland in Europe (Vo et al., 2019).

Sri Lanka's efforts and emerging opportunities

Sri Lanka is in the early stages of addressing pharmaceutical pollution directly; however, several initiatives indicate growing national capacity in this area. A notable example is the Colombo Wetland Park, developed under the Metro Colombo Urban Development Project. While not specifically targeted at pharmaceutical contaminants, this wetland restoration initiative demonstrates the potential of nature-based infrastructure to enhance urban water quality. In parallel, research groups at some state universities are conducting laboratory-scale studies employing locally sourced microbial consortia and algal species for the treatment of pharmaceutical-contaminated water. These approaches could offer promising, low-cost remediation strategies adapted suitable for tropical environmental conditions and could serve as a foundation for future large-scale applications.

Future directions and research needs

Biological methods for cleaning up pharmaceutical pollution are promising, but there's still much to explore and improve in several fields. An important approach involves using omics techniques, such as metagenomics and transcriptomics, to gain a clearer understanding of microbial communities and their roles in pollutant degradation. This approach will ultimately facilitate the identification of microbial strains specifically adapted for the degradation of pharmaceutical compounds. To further improve the performance of such biological strategies, it is essential to employ integrated treatment frameworks. Combining biological methods with advanced technologies such as advanced oxidation processes or membrane filtration can offset the relatively slower degradation rates of certain microbial processes, thereby achieving higher overall removal efficiencies. Long-term success will also depend on fostering collaboration among researchers, industry stakeholders, and local communities, coupled with the establishment and maintenance of rigorous operational standards. Such coordinated efforts can enhance both the sustainability and the practical applicability of these treatment solutions.

Conclusion

Pharmaceutical compounds have become emerging contaminants in urban aquatic ecosystems, affecting ecosystem and human health. Traditional treatment methods have been unsuccessful in removing these pollutants completely in an eco-friendly manner. Biological approaches have emerged as sustainable and eco-friendly alternatives. Successful implementation of these methods around the globe, such as in Vietnam and France, shows that biological approaches are not just theoretical. However, these emerging solutions require continuation in research, more investment, and the development of clear policies. In conclusion, biological remediation has the potential to address pharmaceutical pollution while supporting biodiversity and ecosystem health. With continued innovation, collaboration, and public involvement, we can build a more sustainable future.

References

Agarwal N (2022). Paracetamol - A Contaminant of High Concern: Existence in Environment and Adverse Effect. *Pharmaceutical Drug Regulatory Affairs Journal*, 5 (1).

Ahmed Z, Asghar MM, Malik MN & Nawaz K (2020). Moving towards a sustainable environment: The dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China. *Resources Policy*, vol. 67, p. 101677.

Ávila C, Pedescoll A, Matamoros V, Bayon, JM & García J (2010). Capacity of a horizontal subsurface flow constructed wetland system for the removal of emerging pollutants: an injection experiment. *Chemosphere*, vol. 81, no. 9, pp. 1137–1142, doi:10.1016/j.chemosphere.2010.08.006

Baratpour P & Moussavi G (2018). The accelerated biodegradation and mineralization of acetaminophen in the H_2O_2-stimulated upflow fixed-bed bioreactor (UFBR). *Chemosphere*, vol. 210, pp. 1115–1123.

David A & Pancharatna K (2009). Effects of acetaminophen (paracetamol) in the embryonic development of zebrafish, Danio rerio. *Journal of Applied Toxicology*, 29 (7), pp. 597–602.

de Boer SR, Schäffer A & Moreira MT (2023). Towards oxidoreductase-based processes for the removal of antibiotics from wastewater. *Reviews in Environmental Science and Biotechnology*, 22, pp. 899–932.

De Cazes M, Abejón R, Belleville MP & Sanchez-Marcano J (2014). Membrane bioprocesses for pharmaceutical micropollutant removal from waters. *Membranes*, 4, pp. 692–729.

De Oliveira LLD, Antunes SC, Gonçalves F, Rocha O & Nunes B (2016). Acute and chronic ecotoxicological effects of four pharmaceuticals drugs on cladoceran Daphnia magna. *Drug and Chemical Toxicology*, 39 (1), pp. 13–21.

Jelic A, Gros M, Ginebreda A, Cespedes-Sánchez R, Ventura F, Petrovic M & Barcelo D (2011). Occurrence, partition and removal of pharmaceuticals in sewage water and sludge during wastewater treatment. *Water Research*, 45(3), pp. 1165–1176.

Kandhasamy S, Balraj S, Kanagaraj S & Sundaravadivelu S (2022). *Microbial Degradation of Pharmaceuticals*.

Karungamye PN (2020). *Methods used for removal of pharmaceuticals from wastewater: A review*, */ Applied Journal of Environmental Engineering Science.*

Kumar M, Yadav AN, Saxena R, Paul D & Tomar RS (2021). Biodiversity of pesticides degrading microbial communities and their environmental impact. *Biocatalysis and Agricultural Biotechnology*, Elsevier Ltd.

Luo Y, Guo W, Ngo HH, Nghiem LD, Hai FI, Zhang J, Liang S & Wang XC (2014). A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment. *Science of the Total Environment*, Elsevier, pp. 619–641.

Méheust R, Castelle CJ, Matheus Carnevali PB, Farag IF, He C, Chen LX, Amano Y, Hug LA & Banfield JF (2020). Groundwater Elusimicrobia are metabolically diverse compared to gut microbiome Elusimicrobia and some have a novel nitrogenase paralog. *ISME Journal*, 14, (12) pp. 2907–22.

Melvin SD & Leusch FDL (2016). Removal of trace organic contaminants from domestic wastewater: A meta-analysis comparison of sewage treatment technologies', *Environment International*. Elsevier, pp. 183–188.

Michael I, Rizzo L, McArdell CS, Manaia CM, Merlin C, Schwartz T, Dagot C & Fatta-Kassinos D (2013). Urban wastewater treatment plants as hotspots for the release of antibiotics in the environment: A review. 47(3), pp. 957–95.

Naghdi M, Taheran M, Brar SK, Kermanshahi-pour A, Verma M & Surampalli RY (2018). Removal of pharmaceutical compounds in water and wastewater using fungal oxidoreductase enzymes. *Environmental Pollution*, 234, pp. 190–213.

Radjenović J, Petrović M & Barceló D (2009). Fate and distribution of pharmaceuticals in wastewater and sewage sludge of the conventional activated sludge (CAS) and advanced membrane bioreactor (MBR) treatment. *Water Research*, 43 (3), pp. 831–841.

Ranieri E, Verlicchi P & Young TM (2011). Paracetamol removal in subsurface flow constructed wetlands. *Journal of Hydrology*, 404(3–4), pp. 130–135.

Rivera-Utrilla J, Sánchez-Polo M, Ferro-García MÁ, Prados-Joya G & Ocampo-Pérez R (2013). Pharmaceuticals as emerging contaminants and their removal from water. A review. *Chemosphere*, 93(7), pp. 1268–87.

Snyder SA, Adham S, Redding AM, Cannon FS, DeCarolis J, Oppenheimer J, Wert EC & Yoon Y (2007). Role of membranes and activated carbon in the removal of endocrine disruptors and pharmaceuticals. *Desalination*, 202(1-3), pp. 156–181.

Suleiman M, Demaria F, Zimmardi C, Kolvenbach BA & Corvini PFX (2023). Analyzing microbial communities and their biodegradation of multiple pharmaceuticals in membrane bioreactors. *Applied Microbiology and Biotechnology*, 107(17), pp. 5545–5554.

Taoufik N, Boumya W, Achak M, Sillanpää M & Barka N (2021). Comparative overview of advanced oxidation processes and biological approaches for the removal pharmaceuticals. *Journal of Environmental Management*, Academic Press.

Tiwari B, Sellamuthu B, Ouarda Y, Drogui P, Tyagi RD & Buelna G (2017). Review on fate and mechanism of removal of pharmaceutical pollutants from wastewater using biological approach. *Bioresource Technology*, 224, pp. 1–12.

Vargas-Ordóñez A, Aguilar-Romero I, Villaverde J, Madrid F & Morillo E (2023). Isolation of Novel Bacterial Strains Pseudomonas extremaustralis CSW01 and Stutzerimonas stutzeri CSW02 from Sewage Sludge for Paracetamol Biodegradation. *Microorganisms*, 11(1).

Verlicchi, P, Al Aukidy, M & Zambello, E (2012). Occurrence of pharmaceutical compounds in urban wastewater: Removal, mass load and environmental risk after a secondary treatment—a review. *Science of the Total Environment*, 429, pp. 123–155, doi:10.1016/j.scitotenv.2012.04.028

Villar-Navarro E, Baena-Nogueras RM, Paniw M, Perales JA & Lara-Martín PA (2018). Removal of pharmaceuticals in urban wastewater: High rate algae pond (HRAP) based technologies as an alternative to activated sludge based processes. *Water Research*, 139 pp. 19–29.

Vo HNP, Koottatep T, Chapagain SK, Panuvatvanich A, Polprasert C, Nguyen TMH, Chaiwong C & Nguyen NL (2019). Removal and monitoring acetaminophen-contaminated hospital wastewater by vertical flow constructed wetland and peroxidase enzymes. *Journal of Environmental Management*, 250.

Wang G, Ren Y, Bai X, Su Y & Han J (2022). Contributions of Beneficial Microorganisms in Soil Remediation and Quality Improvement of Medicinal Plants. *Plants*, 11(19), p. 2601

Wilkinson, JL, Boxall, ABA, Kolpin, DW, Leung, KMY, Lai, RWS, Galban-Malagon, C, Adell, AD, Mondon, J, Metian, M, Marchant, RA et al. (2022). 'Pharmaceutical pollution of the world's rivers', *Proceedings of the National Academy of Sciences*, 119, no. 8, e2113947119, doi:10.1073/pnas.2113947119

Zhao GH, Li J, Blair D, Li XY, Elsheikha HM, Lin RQ, Zou FC & Zhu XQ (2012). Biotechnological advances in the diagnosis, species differentiation and phylogenetic analysis of Schistosoma spp. *Biotechnology Advances*, pp. 1381–1389.

CHAPTER 12

Biodegradable Plastics in Sri Lanka: A Review of Current Status, Challenges and Opportunities

K.A.S.H. Wijayasenarathne, R.T. K. Ariyawansha* and R.M.A. Dilini

Department of Environmental Technology, Faculty of Technology, Sri Lanka Technology Campus, Padukka 10500, Sri Lanka.

renukaa@sltc.ac.lk

Abstract

The global challenge of plastic pollution has led to increasing interest in biodegradable plastics as an environmentally friendly alternative. This chapter examines the current status of biodegradable plastics in Sri Lanka, focusing on their adoption, challenges, government policies, industry initiatives, and consumer perceptions. Sri Lanka imports over 500,000 metric tonnes of virgin plastic annually, with a significant portion contributing to environmental pollution. Recent government regulations on the manufacturing and use of conventional plastic products have encouraged the production of biodegradable plastics in the country. These biodegradable plastics are primarily derived from starch, polylactic acid (PLA), and polyhydroxyalkanoates (PHA), with applications in packaging, agriculture, and the medical industry. However, concerns persist regarding their degradation efficiency under diverse environmental conditions. This review highlights the environmental trade-offs of biodegradable plastics, including microplastic formation and greenhouse gas emissions. Despite their potential benefits, widespread adoption is hindered by high production costs, inadequate infrastructure, limited public awareness, weak enforcement of regulations, and greenwashing practices, leading to market inconsistencies. Improvements in regulatory frameworks, waste management infrastructure, and public awareness are essential to enhancing the availability of biodegradable plastics in Sri Lanka. Encouraging research on locally available raw materials and developing industrial composting facilities will further support their availability. A holistic approach involving policymakers, industry stakeholders, researchers, and consumers is necessary to maximize environmental benefits while mitigating potential drawbacks.

Keywords: Biodegradable plastics, Environmental impact, Policy, Sri Lanka, Waste management

Introduction

Plastics are one of the most widely used materials in the global economy. The unique features and low cost of plastics facilitate their fast expansion in both production and use and enable to replacement of conventional materials (such as concrete, glass, metals, wood, natural fibers, and paper) in numerous applications (OECD, 2018). According to estimates, 26 billion tonnes of post-consumer plastic waste will be produced by 2050, with half of it being dumped in the environment, creating a recurring issue with waste management (Moshood et al., 2023). However, the plastics industry will be responsible for 20% of world oil use by 2050 if current plastic usage growth continues at its current rate (Moshood et al., 2023). Over 500,000 metric tonnes of virgin plastic are being imported to Sri Lanka each year, placing a burden on the country's waste disposal facilities (Kahawita et al., 2016). The total estimated municipal plastic waste generation in Sri Lanka is approximately 250,000 tonnes annually. The majority of this is generated in rural areas. Approximately 181,000 tonnes per year (73%) of plastic waste is collected by a combination of formal and informal collection systems. In Sri Lanka, while 97,000 tonnes of plastic waste are sent to designated disposal sites annually, an estimated 27% remains uncollected and 41% leaks from the waste management system, with most waste ultimately ending up in uncontrolled dumpsites (Ministry of Envionment, 2024).

Biodegradable plastics (BP) have been recognized as the most viable alternative to conventional plastics (Rujnić-Sokele et al., 2016). Biobased plastics are not a new development, some have been around since the beginning of civilization (Havstad, 2020). BP was first developed in the 1850s by a British scientist using cellulose, a byproduct of wood pulp (Havstad, 2020). Henry Ford experimented with using soy-based polymers as a substitute for fossil fuels for various automobiles later in the early 20th century (Havstad, 2020). Since then, interest in biodegradable polymers has increased, especially during the 1970s oil crisis (Arasaretnam, 2020). Biodegradable plastics can be completely or partially transformed into CO_2 and H_2O by microbes with minimal negative environmental effects (Rujnić-Sokele et al., 2016; Ribba et al., 2022). If the biodegradation process occurs under anaerobic environments such as seas, rivers, lakes, ponds, marshes, and brackish waters, methane is also emitted from BP (Ghosh and Jones, 2021). The prevalence of BP in Sri Lanka has increased notably since the early 2000s, following the implementation of regulatory measures aimed at restricting the use of conventional fossil fuel-derived plastic products. Despite this policy-driven shift, there remains a significant lack of comprehensive and systematically documented information regarding the production, market presence, and environmental performance of biodegradable plastics in the Sri Lankan context. Accordingly, the objective of this review is to synthesize the existing literature and available data to present a consolidated overview of the current status of BP in Sri Lanka. This includes an examination of their production, market adoption, and potential environmental impacts, as well as a critical evaluation of relevant polices and institutional framework. The review further aims to identify key challenges and opportunities associated with the integration of BP into Sri Lanka's waste management and sustainability strategies.

A literature review was conducted using the two keywords "Biodegradable plastics" and "Sri Lanka" while limiting the period to 2010 onwards in Google Scholar. Ongoing research and preliminary studies were found using Sri Lankan University databases, and Research Gate while government, recognized NGO websites, the websites of biodegradable plastics manufacturers, and gazette notifications were used to gather information.

Current Status of Biodegradable Plastics (BP) in Sri Lanka

Types of BP

BP can be divided into two groups based on the source of origin (Ribba et al., 2022) (Table 1).

1. BP from biobased resources: plastics that are manufactured from biomass feedstock and with the ability to biodegradation. They can be divided into two categories: (i) Natural polymers including starch, cellulose, and lignin; (ii) Polymers made from biomass (Ghosh and Jones, 2021).

2. BP from fossil resources: biodegradable plastics made from fossil fuels. This is a comparatively small category of plastics that is combined with starch-based biodegradable polymers (Havstad, 2020).

Table 01. Applications of biodegradable plastics from different types and sources with due constraints

Category	Type	Sources	Advantages	Drawbacks	Applications	Ref
Biobased	Strach	Corn, potato, wheat, rice, barley	Wide availability, low cost,& full compostable	Poor mechanical and thermal properties	Packaging agriculture, & hygiene products	Ribba et al., 2022
	Polylactic acid (PLAs)	Fermented glucose from sugar crops (cane sugar, corn, potatoes, & tapioca).	Good mechanical properties, similar to polyethylene terephthalate (PET)	Brittle, low degradation rate, and hygroscopic	Packaging, textiles, biomedical materials	Rujnić-Sokele et al., 2016; Ribba et al., 2022
	Polyhydroxyalkanoates (PHAs)	Fermentation of sugar and lipids	Biocompatibility & degradability	High production cost, brittle, and low thermal stability	Packaging, agricultural mulch, fertilizers, cosmetics	Rujnić-Sokele et al., 2016; Ribba et al., 2022
	Cellulose-based plastics	Wood and cotton	High tensile strength, and biodegradable	Poor microbial resistance, and moisture absorption	Packaging, medical devices, personal care, construction	Ribba et al., 2022
	Protein-based plastics	Corn zein, wheat gluten, soya protein, and peanut protein	Good oxygen and UV barrier	High cost, brittle, and poor mechanical Properties	Packaging materials & foil in agriculture	Ribba et al., 2022
Fossil fuel based	Polybutylene succinate (PBS)	polycondensation of butanediol and succinic acid	Good low-temperature processability, thermal stability, chemical resistance	Low molar mass, and high crystallinity limits the degradation enzymes	Packaging agriculture, & hygiene products	Rujnić-Sokele et al., 2016; Ribba et al., 2022
	Polybutylene adipate terephthalate (PBAT)	Adipic acid, terephthalic acid, and butanediol	PBAT possesses excellent toughness, biodegradability, & processability	Low stiffness and poor barrier properties	Organic waste bags, agricultural mulch films, disposable tableware	Rujnić-Sokele et al., 2016; Ribba et al., 2022
	Polycaprolactone (PCL)	Polyester derived from caprolactone by ring-opening polymerization.	Compatible, slow degradation, low melting point	Low biodegradability, & High production cost	Medical applications, such as sutures, & drug delivery,	Ribba et al., 2022
	Polyvinyl alcohol	Hydrolyzed polyvinyl acetate	Biocompatibility, self-cross-linking	High water absorption, moderate strength	Medical, water-soluble films, detergents	Ribba et al., 2022

BP makes up only 0.33% of the approximately 368 million tons of plastic generated each year (Ghosh and Jones, 2021). Polybutylene adipate terephthalate (PBAT), polylactic acid (PLA), and starch-based plastics are popular BP types that make up around 71.1% of the market for BP globally (Rujnić-Sokele et al., 2016). BP have been widely used for disposable packaging, crockery, cutlery, food service containers, and even surgical sutures (Rujnić-Sokele et al., 2016). Packaging contributes to more than 50% of global BP consumption while waste/carrier bags, flexible/rigid packaging, and disposable crockery are the best-selling items (Folino et al., 2020). The two stages of biodegradation are fragmentation, which is the shortening and weakening of polymer chains due to heat, moisture, sunlight, and/or enzymes, resulting in the fragmentation of the plastic material, and mineralization, which is the complete assimilation of plastic fragments by the microbial population in the disposal environment (Rujnić-Sokele et al., 2016; Ghosh and Jones, 2021). Plastic products must undergo complete biodegradation (both fragmentation and mineralization) in order to be deemed biodegradable (Ribba et al., 2022). Otherwise, fragments of plastic that are not fully assimilated by the microbial populations present in the disposal system within a shorter period of time can pose risks to the environment (Ribba et al., 2022).

BP in Sri Lanka

As shown in Table 02, most packaging manufacturing companies in Sri Lanka, as well as supermarket chains, have initiated the introduction of biodegradable packaging materials, grocery bags, and garbage bags.

Table 02. Summary of the biodegradable plastics products available in the Sri Lankan market

Products	**No of Manufacturers**			
	CEA-Registered	**Unregistered**	**Main constituent**	**Sources of raw material**
Lunch sheets	2	-	Strach	No data available
Shopping bags	5	2	Strach, PLA, PBAT	Corn
Mulch films	1	-	No data available	No data available
Food grade packaging	1	-	No data available	No data available
Garbage bags	1	1	No data available	No data available
Bin liners	1	1	No data available	No data available
Grow bags	1	-	Strach	Corn
Textile packaging	-	1	No data available	No data available
Carrier bag	2	1	No data available	No data available

As the Table 02 shows, most of the research also focused on the production of BP materials for packaging applications. Furthermore, manufacturing industries have transitioned towards the production of biodegradable packaging items, including biodegradable tea bags and materials for chicken packaging. Some companies are involved in manufacturing BP products without registering with the Central Environmental Authority (CEA). Although a few of these companies claim to have certifications on their websites, only a small number actually possess these certifications.

According to the Sri Lanka Standards Institution, guidelines for producing biodegradable and compostable polythene have already been established. Consequently, the Institution allows the CEA to evaluate both the manufacturing quality and the quality of imported raw materials. Despite governmental support, industrialists lack the motivation to produce biodegradable polythene. As of May 2018, the Sri Lanka Standards Institute had granted authorization to 16 individuals to import biodegradable polythene products. Moreover, only six to seven manufacturers have applied to obtain the manufacturing standards for biodegradable polythene.

These certified products are primarily tested for biodegradability in composting environments. However, due to inadequate waste collection and handling practices in Sri Lanka, BP products can still find their way into the environment, potentially ending up in marine ecosystems. Notably, durable biodegradables like Polylactic Acid (PLA) persist in marine environments, ultimately breaking down into microplastics that pose a threat to marine life. Consequently, there is a critical need to develop BP products capable of breaking down in various environmental conditions. Some companies market oxo-biodegradable plastic products, which do not meet the criteria for true biodegradability. This practice accounts for greenwashing, as it involves the promotion of environmentally unfriendly materials in the market. Additionally, many companies do not disclose the raw materials and constituents used in their products. Research-based on BP production in Sri Lanka is given in Table 03.

Table 03. Summary of research on the development of biodegradable plastics in Sri Lanka

Type	Feedstock	Applications	Mechanical properties	Challenges and Opportunities	Reference
Starch-Based Polymers	Cassava, sweet potato, banana pseudostems, corn starch, jackfruit seeds, mango seeds, kitul flour, sawdust.	Packaging, medical products, food wrapping	Improved with acid hydrolysis; elongation decreases; tensile strength varies with additives.	Eco-friendly, cost-effective, & biodegradable; water absorption limits certain applications.	Amaraweera et al., 2021; Amaraweera et al., 2022; Senevirathna et al., 2022
PLA & scratch composites (Polylactic Acid)	Cassava starch,	Packaging, orthopedic implants	Slight reduction in tensile strength and elongation with higher starch content.	Promotes biodegradability; low-cost solutions for packaging and medical implants.	Kaushalya et al., 2019;
Cellulose-Based Polymers	Banana peels, cassava starch, & banana stem fiber	Packaging, engineering, water purification	Tensile strength increases with the increase of banana stem fiber content, increase of cassava starch content increases the moisture content	Abundant feedstock; potential for pollution reduction & biodegradable composites.	Ishara et al.,2015
Pectin & Protein Polymers	Passion fruit, ginger root, fish and prawn shell wastes with polyvinyl alcohol (PVA) and chitosan.	Food packaging, biodegradable films	Tensile strength & elongation decrease with additives.	Enhances biodegradability; improved barrier properties for food packaging.	Arasaretnam et al., 2020
Starch-Based Polymers (PBA, WF, & PBAT (Polybutylene Adipate Terephthalate)	Wheat flour (WF) (10–40% composition ratios)	Food wrapping, shopping bags	Mechanical properties decrease with higher WF content, but are sufficient for food wrapping at lower ratios	Wheat flour lowers production cost. 20% WF is ideal for aqueous food wrap; 30% WF is suitable for other packaging uses.	Perera, et al., 2023
Screw-pine Leaf Natural Rubber Composite	Natural rubber latex blended with Screw-pine leaf particles (0.5–60% w/w)	Gloves	Tensile & tear strength decrease with higher filler; biodegradability increases	Addresses waste disposal issues from NR gloves by enhancing biodegradability. 0.5% filler gives the highest biodegradability with acceptable mechanical properties.	Jayatunga, 2014
Peanut Shell-Based Biopolymer Film	Peanut shell powder (1–2%), cellulose powder (1–2%), microcrystalline powder (1–2%); agar & glycerine as control	Packaging material for guava fruits	No data available	Shows potential for developing biodegradable packaging for guava fruits with minimal changes in postharvest storage — promising for sustainable fruit preservation.	Husna & Vasantharuba, 2022

Most studies concentrate on developing biodegradable polymers such as starch as cellulose-hemicellulose, from highly abundant and low-cost raw materials. The primary application of these polymers is in packaging materials. Findings indicate that while increasing starch content improves biodegradability, it also reduces the strength of the polymers, which impacts their market usability. Therefore, it is essential to determine the optimal blending ratios of the constituents to balance biodegradability with functional performance. To enhance the strength of biodegradable polymers, researchers add natural fibers (e.g., jute, hemp), nanomaterials (e.g., nanocellulose, nanoclay), plasticizers (e.g., glycerol, sorbitol), crosslinking agents (e.g., citric acid, glutaraldehyde), synthetic biodegradable polymers (e.g., PLA, PCL, PBS), and compatibilizers (e.g., maleic anhydride) to balance biodegradability with mechanical and functional performance. Biodegradable products available in the current market, as well as the biodegradable polymers developed by the majority of the researchers, have tested biodegradability as weight loss. However, measurement of secondary parameters such as weight loss, decrease in molecular weight, and deterioration of mechanical characteristics cannot provide definite proof of the complete BP. Thus, it is crucial to use primary parameters such as carbon-to-carbon dioxide conversion (and methane in case of anaerobic conditions) to evaluate the biodegradation of plastics more accurately (Reddy et al., 2013).

Legal framework for biodegradable plastic management in Sri Lanka

In response to the growing environmental concerns associated with plastic pollution, the Government of Sri Lanka has enacted several regulatory measures over the past two decades. These are largely implemented under the guidance of the CEA. The core legal instrument governing these regulations is the National Environmental Act No. 47 of 1980. Sri Lanka’s first significant regulatory action on polythene was introduced in 2007, which banned the use of polythene bags and lunch sheets made of polyethylene that were less than 20 microns in thickness. However, due to weak enforcement and lack of public awareness, this ban had minimal impact. In 2017, the government reinforced its stance through a Cabinet-approved ban on several single-use plastic items under the Gazette Extraordinary No. 2034/34 dated September 1, 2017. This regulation banned such as the manufacture, import, sale, and use of polythene lunch sheets, polythene bags less than 20 microns thick, decorative polythene for festival purposes, and the open burning of plastic and polythene. Further reinforcement came in 2021, when the government, under

Gazette No. 2211/51, extended the ban to include additional plastic items such as: plastic sachets of <20 ml or 20 g capacity (except for medicinal uses), plastic cutlery (spoons, forks, knives, stirrers), plastic straws (except those attached to tetra packs) and plastic garlands used in religious and cultural activities. These bans were introduced with the dual objective of reducing the volume of plastic waste entering the environment and promoting the adoption of environmentally friendly alternatives such as biodegradable plastics.

The implementation of these bans is primarily overseen by the CEA in collaboration with provincial councils and local government bodies. Environmental unit of police, Public Health Inspectors (PHIs), and municipal officers play a key role in monitoring compliance at retail and manufacturing levels. Despite the clear regulatory framework, enforcement has faced significant challenges. These includes inadequate manpower for field inspections, limited resources for monitoring rural and informal sectors, insufficient awareness campaigns among consumers and retailers, resistance from industries due to the economic implications of switching to alternatives. To ensure compliance, the CEA has initiated regular inspections, awareness programs, and raids on non-compliant manufacturers and retailers. In some regions, especially urban centers, enforcement has shown moderate success, but rural penetration remains weak violations of the polythene ban are punishable under the National Environmental Act. The CEA has reported several successful interventions, such as the seizure of polythene stocks from major supermarkets and plastic importers. However, systemic issues such as loopholes in supply chains, limited legal follow-through, and lack of centralized data on violators hinder the long-term effectiveness of punitive measures.

Cultural practices, such as the use of plastic garlands in religious events, also hinder compliance, despite being included in the 2021 ban. Moreover, limited impact of fines is a considerable challenge. Fines imposed are often not a significant deterrent, especially for medium to large-scale vendors. The lack of a centralized digital offender tracking system also allows repeat offenders to escape stricter penalties. Furthermore, most critical challenge is that weak public awareness campaigns. While some efforts have been made (e.g., radio ads and school campaigns), there is no sustained national-level media strategy to reinforce behavioral change. As a result, public understanding of what is banned remains poor, especially outside major cities.

Legislation enforcing nonbiodegradable plastics acts as the major driver for the production of BP (Ghosh and Jones, 2021). The ban enforced on non-biodegradable products encouraged the production of grocery bags, lunch sheets, food wrappers, food containers, plates, cups, spoons, and items used for special events and occasions. However, gazette notifications have been also formulated to ban BP. For instance, gazette notification No.2211/51 banned the manufacturing, and trade of products such as sachets, inflatable toys, and cotton buds made of biodegradable plastics. Moreover, recent gazette notification No. 2341/30 banned the manufacturing, importation for local use, sale, offering for sale, displaying for sale, offering free of charge, or exhibiting within the country of single-use plastic items. However, Sri Lanka lacks regulations governing the production, utilization, and disposal of BP currently prevalent in the market, including items such as packaging materials, shopping bags, and food wrappers. The 2020 national solid waste management policy did not include provisions for the management of BP waste. Further, the policy neglects end-of-life management of biodegradable plastic products.

Challenges of biodegradable plastics

BP offers a promising alternative to conventional petroleum-based plastics, but their performance and environmental impact are influenced by a complex interplay of raw material composition, chemical structure, additives, and environmental conditions (Ribba et al., 2022). For BP to achieve effective degradation, not only must the primary polymer material biodegradable, but all supporting elements such as fillers, pigments, and stabilizers should also degrade under natural conditions (Ribba et al., 2022). However, the degradation efficiency of BP is sensitive to both their molecular design and environmental factors (Rujnić-Sokele et al., 2016). Many BP struggle to meet the same mechanical and design standards as their conventional counterparts, particularly in applications such as packaging (Reddy et al., 2013). Modifications such as polymer blending, copolymerization, and chain restructuring are often used to overcome these limitations (Reddy et al., 2013). Also, marine degradation is hindered by the smooth surface of polymer films (Ghosh and Jones, 2021). Adding hydrophilic fillers can enhance seawater penetration and microbial attachment, thereby accelerating degradation (Ghosh, and Jones, 2021). Thin films degrade more readily than thicker counterparts; for instance, polyhydroxyalanoates (PHA) films under 0.2 mm degrade in months, whereas thicker variants can persist for years (Ghosh and Jones, 2021). Feedstock choice also presents economic and ethical challenges. Many BP, such as polylactic acid (PLA), are produced from edible crops like corn, wheat, and cassava, raising concerns about food security and resource allocation (Thuppahige et al., 2022). Agro-waste materials, including cassava peels, fruit residues, and low-value biomass from forestry and agriculture, offer more sustainable raw material alternatives for BP production (Thuppahige et al., 2022). Advanced carbon capture utilization (CCU) technologies and the valorization of waste cellulose from sources like water hyacinth and waste papers also hold promise for more sustainable production pathways (Folino et al., 2020; Anantachaisilp et al., 2021; Mori, 2023). Biodegradation rates are strongly dependent on environmental variables such as microbial diversity, oxygen levels, pH, temperature, and light exposure (example, the degradation of PLA in soil environments is minimal at temperatures below 30oC, while industrial composting systems offer ideal conditions for rapid decomposition (Havstad, 2020).

Biodegradable polymers like PLA often require additives to improve their mechanical properties, since pure PLA can be brittle and have low impact strength (Jamshidian et al., 2010). Common additives include plasticizers, nucleating agents, and natural fibers, which help increase flexibility, tensile strength, and thermal resistance (Faruk et al., 2012). However, studies show that some pigments and fillers may introduce trace heavy metals such as lead or cadmium, which could pose risks if not properly regulated, especially for food-contact packaging (Liu et al., 2021). The development of composite bioplastics — such as PLA or PHA reinforced with natural fibers or agro-waste — shows promise for producing stronger biodegradable products that can compete with conventional plastics while supporting sustainability goals (Ramesh et al., 2025). Composite bioplastics combine the benefits of both bioplastics and composites, often enhancing properties like strength, durability, and biodegradability. Common examples include wood-plastic composites (WPCs) used for decking, and bio-composites made from natural fibers (like wood, hemp, or flax) combined with starch or other biopolymers. Other examples include alginate-based bioplastics reinforced with starch and other additives, and composites made from rice starch and organic clay.

In Sri Lanka, the transition toward biodegradable plastic is hindered by weak enforcement of plastics bans, price competition from low-cost high-density polyethylene

(HDPE) products, and a lack of testing infrastructure to verify product claims (Fernando et al., 2020). Local manufacturers report challenges including high machine costs, limited tax incentives, and inadequate government support for biodegradable raw material imports (Fernando et al., 2020). Furthermore, several market-available BP are found to engage in greenwashing, as laboratory tests reveal only partial degradation with minimal structural breakdown (Jayaweera et al., 2023).

Another concern is the environmental impact of oxo-biodegradable plastics. These products, often labelled as biodegradable, fragment into microplastics rather than fully decomposing, contributing to persistent plastic pollution (Goel et al., 2021, Kim et al., 2023). Proactive regulatory frameworks are needed to ban oxo-degradable plastics and to certify authentic biodegradable products through standardized testing, including field-based validation (Ghosh and Jones, 2021). In terms of environmental performance, life cycle assessment (LCAs) of bioplastics such as PLA reveals a mixed picture. Although PLA outperforms HDPE in categories like terrestrial acidification and marine ecotoxicity, its production often results in higher greenhouse gas emissions, eutrophication, and particulate matter formation (Jayasekara et al., 2020). The use of alternative feedstocks like sugarcane molasses in Sri Lanka offers energy-efficient pathways with significantly lower climate impact than imported corn-based PLA (Jayasekara et al., 2022). Laboratory simulations of marine degradation and field studies confirm that biodegradation profiles vary depending on environmental conditions, material formulations, and microbial communities (Jayasooriya et al., 2022). Partial degradation in real-world conditions can lead to the generation of microplastics, which have been found to act as carriers for pollutants and pathogens, even if their toxicological impact is generally lower than that of conventional plastics (Rujnić-Sokele et al., 2016).

Recommendations

The use of edible materials in biodegradable plastic production has raised concerns about food security. As a sustainable alternative, incorporating waste materials can help reduce pressure on food resources while contributing to waste management. To ensure environmental performance, raw materials must enable effective biodegradation under varying local conditions. Bioplastics derived from organic waste may contain heavy metals such as lead, cadmium, and mercury, whose migration under conditions like heat or moisture can pose significant safety and environmental concerns, making it important to evaluate their levels and behavior for sustainable use. Further research is essential to identify and develop sustainable alternatives to heavy metals in bioplastic production, aiming to enhance environmental safety and material performance. Sri Lanka should develop a comprehensive regulatory framework that includes biodegradability standards, certification processes, and product labeling. Public education campaigns targeting consumers, businesses, and policymakers are important to promote awareness and responsible use. Investment in research and development of cost-effective, high-quality biodegradable materials suited to local climates should be encouraged. Collaboration among government agencies, industries, and research institutions will be key to advancing innovation and production. Financial incentives such as subsidies or tax benefits can support market expansion. Strengthening waste collection, composting, and recycling infrastructure is vital for proper disposal. Adoption of green procurement policies in both public and private sectors will further support the transition. Finally, ongoing monitoring and environmental impact assessments are needed to inform regulatory improvements and ensure safe, long-term use of biodegradable plastics.

Conclusion

This chapter highlights the increasing interest in biodegradable plastics in Sri Lanka as a response to the pressing issue of plastic pollution. With growing environmental consciousness, legislative efforts, and changing consumer preferences, biodegradable plastics are emerging as a potential solution. However, their successful adoption hinges on technical advancements, careful consideration of environmental impacts, and the continuous refinement of regulatory frameworks. Collaborative efforts among stakeholders are essential for a successful transition. As Sri Lanka endeavors to address its plastic waste challenges, this research provides valuable insights and underscores the importance of holistic approaches to sustainable plastic management in the country.

References

Amaraweera SM, Gunathilake C, Gunawardene OHP, Fernando NML, Wanninayaka DB, Manamperi A, Dassanayake RS, Rajapaksha SM, Gangoda M, Kulathunge A, Manipura A (2021). Tuning the chemical and thermo-mechanical properties of cassava starch thin films to produce biodegradable packaging materials. doi:10.21203/rs.3.rs-375688/v1.

Amaraweera SM, Gunathilake C, Gunawardene OHP, Dassanayake RS, Fernando NML, Wanninayaka DB, Rajapaksha SM, Manamperi A, Gangoda M, Manchanda A, Fernando CAN, Kulatunga AK & Manipura A (2022). Preparation and Characterization of Dual-Modified Cassava Starch-Based Biodegradable Foams for Sustainable Packaging Applications. *ACS Omega*, 7(23):19579-19590.

Anantachaisilp S, Siripromsombut S, Ruansoong T & Kwamman T (2021). An eco-friendly bioplastic film obtained from water hyacinth. Journal of Physics: Conference Series, 1719(1), p.012110.

Arasaretnam S (2020). Preparation of biobased plastic from banana peel and application in industrial wastewater purification. In Conference Proceedings of the 2nd Asia International Conference on Multidisciplinary

Fernando SP, De Silva PCJ, Kuruppu IV, Aiome GVN, Dembatapitiya DRP, Nilusha GKC (2020). Study on potential alternatives for the banned polythene bags and lunch sheets (PBLS) and exploring the nature of PBLS prevailing in the market in Sri Lanka. Sri Lanka Journal of Economic Research, 7(2), pp. 25–45. doi:10.4038/sljer.v7i2.113.

Faruk, O, Bledzki AK, Fink HP & Sain M (2012). Biocomposites reinforced with natural fibers: 2000–2010. *Progress in Polymer Science*, 37(11), 1552–1596. https://doi.org/10.1016/j.progpolymsci.2012.04.003.

Folino A, Karageorgiou A, Calabrò PS & Komilis D (2020). Biodegradation of Wasted Bioplastics in Natural and Industrial Environments: A Review. *Sustainability*. 12(15)

Ghosh K & Jones BH (2021). Roadmap to biodegradable plastics—current state and research needs. *ACS Sustainable Chemistry & Engineering*, 9(18), pp. 6170–6187. doi:10.1021/acssuschemeng.1c00801.

Goel V, Luthra P, Kapur GS & Ramakumar SSV (2021). Biodegradable/bio-plastics: myths and realities. *Journal of Polymers and the Environment*, 29, pp.3079-3104. https://doi.org/10.1007/s10924-021-02099-1

Haider TP, Völker C, Kramm J, Landfester K & Wurm FR (2019). Plastics of the future? The impact of biodegradable polymers on the environment and on society. *Angewandte Chemie International Edition*, 58(1), 50-62.

Havstad MR (2020). Biodegradable plastics. *Plastic Waste and Recycling*, pp. 97–129. doi:10.1016/b978-0-12-817880-5.00005-0.

Husna MFF & Vasantharuba S (2022). Effect of packaging material extracted from peanut shell on post-harvest storage parameters of guava fruits. http://repo.lib.jfn.ac.lk/xmlui/handle/123456789/8775

Ishara GKK, Koliyabandara PA & Samarakoon G (2024). Eco-friendly bio-composite sheets: a study on the utilization of banana peels, cassava starch, and banana stem fibers. *Frontiers in Sustainability*, 5. https://doi.org/10.3389/frsus.2024.1410986.

Jamshidian M, Tehrany EA, Imran M, Jacquot M & Desobry S (2010). Poly-Lactic Acid: Production, Applications, Nanocomposites, and Release Studies. *Comprehensive Reviews in Food Science and Food Safety*, 9(5), 552–571. https://doi.org/10.1111/j.1541-4337.2010.00126.x

Jayasekara JHAT, Surendra YW, Rathnayake M (2020). Life cycle assessment of single-use biodegradable bags produced from corn-derived biopolymer.

Jayasekara T, Wickrama Surendra Y & Rathnayake M (2022). Polylactic Acid Pellets Production from Corn and Sugarcane Molasses: Process Simulation for Scaled-Up Processing and Comparative Life Cycle Analysis. *Journal of Polymers and the Environment*, 30(11), pp.4590–4604. doi:https://doi.org/10.1007/s10924-022-02535-w.

Jayasooriya JKBP, Jayaweera CD & Gamage NS (2022). Biodegradability Assessment of Bio-based Film Products (Lunch Sheets) in the Marine Environment. *Proceedings of International Forestry and Environment Symposium*, doi:https://doi.org/10.31357/fesympo.v26.5763.

Jayatunga, HGTH (2014). Development of biodegradable polymer composite for glove material based on natural rubber and screw-pine leave particles. Peradeniya University International Research Sessions, 18.

Jayaweera CD, Senadheera SKMS & Gamage NS (2024). Testing the Biodegradability and Biodegradation Rate of Bio-based Film Products in Composting Environment. Proceedings of International Forestry and Environment Symposium, doi:https://doi.org/10.31357/fesympo.v27.6569.

Kahawita KD & Samarasekara AMPB (2016). Extraction and characterization of cellulosic fibers from sawmill waste. *Moratuwa Engineering Research Conference (MERCon*), pp. 343–348. doi:10.1109/mercon.2016.7480165.

Kaushalya R.ANC, Dhanushka MKDT, Samarasekara AMPB & Weragoda VSC (2019). Development of Biodegradable Packaging Materials Using Polylactic Acid (PLA) and Locally Extracted Starch. *Moratuwa Engineering Research Conference*. https://doi.org/10.1109/MERCON.2019.8818917

Kim MS, Chang H, Zheng L, Yan Q, Pfleger BF, Klier J, Nelson K, Majumder EL & Huber GW (2023). A Review of Biodegradable Plastics: Chemistry, Applications, Properties, and Future Research Needs. *Chem Rev*. 123(16):9915-9939.

Liu G, Dave PH, Kwong RW, Wu M & Zhong H (2021). Influence of microplastics on the mobility, bioavailability, and toxicity of heavy metals: a review. *Bulletin of Environmental Contamination and Toxicology,* 107(4), 710-721.

Ministry of Environment (2024). National Plastic Waste Inventory for Sri Lanka: A Material Flow Approach, "Sobadam Piyasa", Robert Gunawardana Mawatha, Battaramulla, Sri Lanka.

Mori R (2023). Replacing All Petroleum-Based Chemical Products with Natural Biomass-Based Chemical Products: A Tutorial Review. *RSC Sustainability*. doi:https://doi.org/10.1039/d2su00014h.

Moshood TD, Nawanir G, Mahmud F, Mohamad F, Ahmad MH & Ghani AA (2022). Biodegradable plastic applications towards sustainability: A recent innovation in the green product. Cleaner Engineering and Technology, 6,100404,

OECD, Organisation for Economic Co-operation and Development (2018). Improving Plastics Management: Trends, Policy responses, and the Role of International co-operation and trade. Available at:
ttps://www.oecd.org/content/dam/oecd/en/publications/reports/2018/09/improving-plastics-management_af0b327f/c5f7c448-en.pdf.

Perera KAIS, Milani MDY, Nayanajith LDC, Arachchige RCW & Ratnaweera CN (2023). Development of polybutyrate (PBAT) based biodegradable film with wheat flour as a filler Material. RISTCON 2023, University of Ruhuna, Sri Lanka.

Ramesh M, Rajeshkumar, Sanjay MR & Siengchin S (2025). Sustainable biocomposites based on polylactic acid and agro waste biofillers for lightweight applications: Fabrication and properties. *Journal of Thermoplastic Composite Materials*, 08927057251322165.

Reddy RL, Gupta GAG & Reddy VS (2022). Bio-based and biodegradable plastics. *Sustainable Plastics*, pp. 75–93. doi:10.1002/9781119882091.ch4.

Ribba L, Loprettin M, de Oca-Vásquez GM, Batista D, Goyanes S & Vega-Baudrit JR (2022). Biodegradable plastics in aquatic ecosystems: Latest findings, research gaps, and recommendations. *Environmental Research Letters*, 17(3), p. 033003. doi:10.1088/1748-9326/ac548d.

Rujnić-Sokele M & Pilipović A (2017). Challenges and opportunities of biodegradable plastics: A mini review. Waste Management Research: *The Journal for a Sustainable Circular Economy,* 35(2), pp. 132–140. doi:10.1177/0734242x16683272.

Senevirathna MASR, Swarnamali VMR, Naseef MNA, Amaraweera THNG & Premathilake MMSN (2022). Development of antibacterial polymer composite films from cassava starch and silver vein graphite composite. *Ceylon Journal of Science*, 51(3), p. 277. doi:10.4038/cjs.v51i3.8035.

Thuppahige VW & Karim M. (2022). A comprehensive review on the properties and functionalities of biodegradable and semibiodegradable food packaging materials. *Comprehensive Reviews in Food Science and Food Safety*, 21(1), 689-718. doi: 10.1111/1541-4337.12873.

CHAPTER 13

Bio-Inspired Solutions for Water Conservation and Purification

P.D.I. Imalka and R. Wimalasekera*

Department of Botany, Faculty of Applied Sciences,
University of Sri Jayewardenepura, Gangodawila, Nugegoda, Sri Lanka.
**rinukshi@sci.sjp.ac.lk*

Abstract

Water is an absolute necessity to sustain life and preserve the health of humans. However, access to fresh water is not uniform worldwide due to global pollution, climatic changes, and the rising global population. To meet growing demand, in addition to the existing conventional techniques, technologies inspired by the structures, processes, and functions of natural systems are used to develop advanced solutions for water conservation and purification. This chapter explores the biomimetic approaches for fog water harvest, water purification through biomimetic membranes incorporated with aquaporins and analogous molecules, microbial and algal systems for wastewater treatment, and phytoremediation using plants. These approaches demonstrate a significant potential for improving efficiency, reducing environmental impact and enhancing the adaptability of water treatment systems. Current limitations, such as scalability, cost, and regulatory challenges, are also addressed in this chapter while highlighting the future directions involving synthetic biology and function-integrated smart systems. Technological innovations aligned with ecological principles present a promising network for achieving sustainable water security.

Keywords: Aquaporins, Bio-inspired, Fog harvest, Sustainability, Water conservation

Introduction

Although 71% of the Earth's surface is covered by water, only 3% of that includes fresh water. About 69% of the total available fresh water is locked away in glaciers and polar ice caps, and another 30% as groundwater. Only 1% of that is readily available for human consumption (World Economic Forum, 2025). The agricultural sector claims 72% of the total global fresh water usage, 15% for industrial usage, while the household, municipal systems, and small and medium industry usage occupy another 13% (UNWWDR, 2024).

Water is vital to sustain life. While safe, clean, and accessible water remains a human right, over 791 million people are impacted by the global water stress by 2021, which is a 2.8% increment since 2015. Around 10% of the global population lives in countries with high and critical water stress levels, in the regions of Northern Africa, Western, Southern, and Central Asia (FAO & UN-Water, 2024). The global urban population facing water scarcity is estimated to double in number from 930 million people in 2016 to 1.7-2.4 billion by 2050 (UNESCO, 2023).

With the non-uniform global distribution of fresh water, ever-increasing global population, reduced rainfall with lengthy and intense droughts, and pollution of available fresh water sources, water scarcity has become a global issue that threatens access to safe drinking water and basic hygiene (UNICEF, 2025). Limited irrigation and agricultural productivity due to high water stress conditions have enhanced the vulnerability of the agrifood systems, which can pose a threat to global food security. The job market can also be affected as 78% of the jobs of the international labour pool rely on water (Gonzalez-Perez and Persson, 2016; FAO and UN-Water, 2024) thereby raising the demand for clean, safe water and the need for novel, highly advanced and efficient purification and recovery technologies.

Conventional methods of water conservation and purification are becoming less feasible due to their limitations in removing emerging pollutants such as microplastics, pharmaceutical residue, and endocrine disruptors, and they also form harmful byproducts such as disinfection byproducts. Most conventional methods have a high environmental impact in terms of sludge disposal and carbon emissions. Also, methods like desalination are energy-intensive and require high maintenance (Brown and Bhushan., 2016).

In this context, bio-inspired methods are crucial in developing highly efficient and environmentally sustainable solutions. Designing and producing materials, structures, and systems inspired by biological systems or processes is termed bio-inspired (IUCN, 2020).

Bio-inspired technologies (Figure 01) examine biomimetic approaches in collection, filtration, desalination, and wastewater treatment processes, highlighting innovations such as fog water collectors, bio-engineered membranes for water purification, microbial biofilters for water treatment, algae-based removal of pollutants in wastewater treatment systems, and phytoremediation or plant-based water treatment/ purification approaches that explore the pollutant absorbent properties of plants. This chapter also discusses the practical applications, challenges, limitations, and future directions in sustainable water management (Ede et al., 2024).

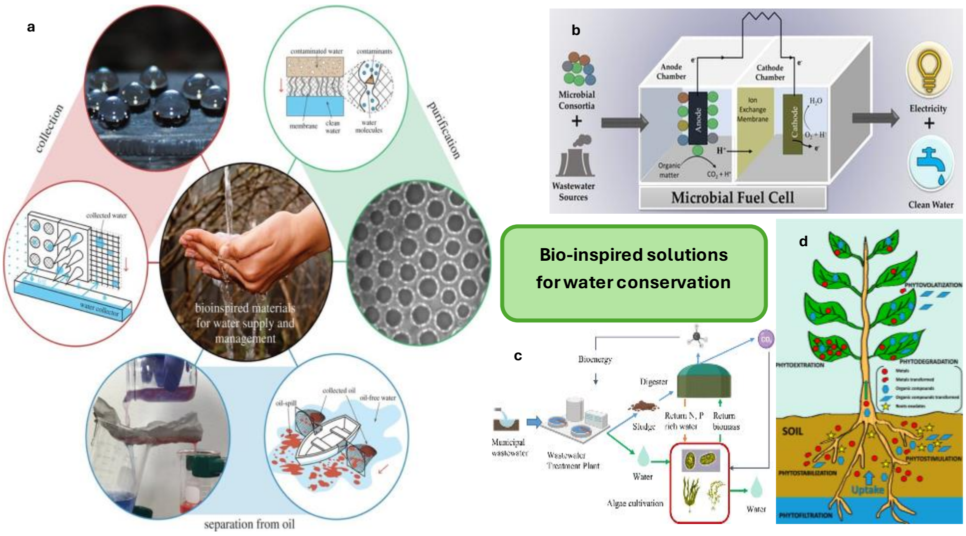


Figure 01. Bio-inspired solutions for water conservation **a)** Biomimetic surfaces or membranes for fog harvesting, oil-water separation, and purification, **b)** Microbial fuel cell, **c)** Algae-based water purification, and **d)** Phytoremediation (Sources: Brown and Bhushan, 2016; Nguyen et al., 2022; Malik et al., 2023; Bellomi et al., 2024)

Bio-inspired fog water harvest

Fog is a visible, dense collection of small water droplets (sized 10-50 µm) suspended in the air near the surface of land or water. Arid and semi-arid regions face a broad range of temperature fluctuations where the ambient temperature can be lower than the dew point during the nighttime, leading to the condensation of atmospheric water, which leads to fog formation (Bhushan, 2019). Depending on the geographical location of the arid or semi-arid region and the time of the year, the amount of fog formed can differ (Fessehaye et al., 2014).

In the arid regions, most fauna and flora species survive due to the fog. These species are capable of collecting water from fog and directly transporting it to be consumed or stored before being evaporated; with the help of their distinctive structures and chemistry, on or within their bodies (Brown and Bushan, 2016).

Fog harvest/collection mechanisms of nature

Beetles

Back of the beetles, E.g., *Stenocara gracilipes, Onymacris unguicularis,* contain hydrophilic bumps (0.5 mm diameter) arranged in a random array. The bumps are surrounded by microstructured wax, creating a hydrophobic surface. Fog condenses on the hydrophilic bumps, forming water droplets which trickle down along the beetles' inclined back into their mouth.

Lizards

Thin water films form on their hydrophilic skin surface, which get transported to the lizards' mouth via capillary action through asymmetric channels. E.g.: *Moloch horridus* (lizard species native to Western and Southern Australia), *Phrynocephalus helioscopus* (lizard species native to Asia), *Phrynosoma cornutum* (Texas horned lizard).

Spider webs

Spider silk contains hygroscopic proteins that absorb water droplets, resulting in swelling of the silk thread. Due to Rayleigh instability, the fluid cylinder breaks into smaller water droplets along the thread. More condensed water will accumulate on the already formed droplets, as a result of the Laplace pressure gradient and surface tension gradient. Such collected droplets will enhance the adhesive nature and assist in capturing prey, and also provide the spider with a source of water.

Cactus

Cactus species endemic to Mexico, *Opuntia microdasys* contains conical spines bearing small barbs at the top. Water droplets form at the tip of the barbs and move along the spine to the base of the cactus, where they are absorbed.

Desert grass and bushes

Leaves of the *Stipagrotis sabulicola,* Namib desert grass, contain ridges which guide the water droplets collected on the leaves to their base. *Setaria viridis* grass is discovered to collect water from fog, similar to *Opuntia microdasys.* Fine hairs on the leaves of native South African bush, *Cotula fallax* collect water droplets which trickle down to the root due to gravity (Brown and Bushan, 2016; Bhushan, 2019).

Translation of bio-inspired surfaces for fog water harvest.

Inspired by the natural surfaces that collect water from the fog, several experiments have been conducted to produce a surface that efficiently collects water from the fog.

Flat surfaces with homogeneous or heterogeneous wettability inspired by beetle

Several experiments have been conducted to test the fog water collection efficiency with flat surfaces with homogeneous wettability (i.e., super hydrophobic, hydrophobic, super hydrophilic, and hydrophilic surfaces) and beetle-inspired surfaces with heterogeneous wettability (containing both super hydrophobic and super hydrophilic) and varying roughness. It was discovered that the beetle-inspired surfaces were more efficient in water collection compared to the surfaces with homogeneous wettability (Garrod et al., 2007; Gurera and Bhushan, 2019a). Another study incorporated techniques of both beetle and spider silk to produce a star shaped super hydrophilic pattern on a super hydrophobic surface, that collected water more efficiently (Bai et al., 2014).

Grass and cactus-inspired surfaces

Arrays of cylindrical and conical water collectors resembling the dimensions of the water collecting structures of cactus and grass were produced using 3D printing technology. Structures were also categorized by their grooved and ungrooved nature, homogeneous or heterogeneous wettability, and inclination of the structure arrays. It was observed that the conical structures as an array, with a higher inclination angle had the highest water collection (Gurera and Bhushan, 2019a).

Beetle, grass, and cactus-inspired surfaces

The results of the above experiment were optimized by incorporating the techniques of the beetle as well. It was observed that an array of cones with grooves, heterogeneous wettability, and a higher inclination angle had the highest water collection rate from fog (Gurera and Bhushan, 2019b).

Fungi-inspired surfaces

Inspired by observations of fungi that naturally accumulate water droplets on their surfaces, researchers analysed their morphology and identified a structure combining fibres of different diameters and amphiphilic properties. Mimicking this, they developed a composite material consisting of a hydrophobic polyurethane (PU) nanofiber membrane with a hierarchical structure, layered over hydrophilic filter paper and bonded with polyacrylamide (PAM). In this design, the hydrophilic paper captures airborne droplets, while the convex PU membrane promotes droplet coalescence and directional transport. The coexistence of thick and thin fibres enhances collection efficiency, enabling the fungi-inspired material to achieve high water-harvesting rates (Zhang et al., 2022).

Fog nets are the most common commercial method that is used to harvest water from the fog (E.g.: FogQuest and Warka water). But mostly, material that has not been optimized for water collection is used to manufacture the nets. These nets can be scaled up by incorporating the bio-inspired surfaces at the net junctions, which can lead to a higher water harvest. For beetle-inspired configurations, super hydrophilic spots may be applied at the junctions, in beetle-, grass-, and cactus- inspired designs, the junctions can feature conical structures and heterogeneous wettability (i.e., with a hydrophobic tip and a super hydrophobic base) and groves oriented at 45^{o} angles (Bhushan, 2019; Gurera and Bhushan, 2019b).

Bioinspired fog-harvesting surfaces show strong potential but face challenges with scalability, durability, and efficiency under realistic conditions. Current designs are costly to fabricate and degrade under UV, dust, or salt, while fog variability and slow droplet transport limit yields. Future progress lies in scalable, low-cost production, hybrid and self-cleaning materials, and integration into smart, multifunctional systems, making them adaptable for agriculture, reforestation, and sustainable water supply (Brown and Bushan., 2016; Bhushan, 2019; Gurera and Bhushan, 2019a; Gurera and Bhushan, 2019b).

Biomimetic membranes for water purification

Water purification using membranes can take place via two mechanisms. In the first mechanism, water molecules dissolve into, from one side, diffuse through, and desorb from the other side of the membrane, whereas in the second mechanism, the water moves through pores that are smaller than the removed contaminants. Membranes are currently used in techniques such as microfiltration, ultrafiltration, nano filtration, and reverse osmosis (RO) (Aydin et al., 2024). Usually, membranes composed of ceramic and other polymers such as graphene and etched silicone are used for the above purposes (Goel et al., 2021). But most of these techniques require pre-treatment of water, and they consume higher energy and cost of operation. Sometimes small nonpolar solutes will not be rejected due to the high selectivity of the RO technique (Shenvi et al., 2015).

Traditional methods for membrane production typically follow a hierarchical design strategy, which can lead to challenges in achieving precise molecular selectivity. This issue arises mainly due to inconsistencies in pore size, which influence how effectively the membrane can differentiate and transport specific molecules. In response, researchers have begun to explore bottom-up approaches that focus on molecular-level architecture. These methods, inspired by natural systems, form the foundation of biomimetic membranes (Tang et al., 2015).

Membranes that are produced with natural or nature-mimicking materials, using strategies such as bio-mineralization, bio-adhesion, or self-assembly, are known as biomimetic and bio-inspired membranes. These membranes are produced to impart significant target functions such as structural architecture, hierarchical organization, selective permeability, or foul resistance (Abdelrasoul et al., 2017). These membranes are categorized according to their pore sizes as macroporous (>50 nm), mesoporous (2-50 nm) and microporous (0.2-2 nm) (Brown and Bhushan, 2016). Biomimetic membranes can be inspired and fabricated using several natural components.

Multicellular components

Biomimetic membranes are mainly fabricated using biomimetic molecules. Ordered silica microstructures (0.5 µm diameter), fabricated by coating colloidal silica nanoparticles on

Bacillus subtilis bacterial threads, were one of the early attempts to produce microporous biomimetic membranes. Another membrane was produced by re-mineralizing the decalcified internal shell of *Sepia officinalis* (cuttlefish) with sodium silicate. The chitin in the shell acts as the template and was removed by calcining. Similarly, by using the same technique, a thin film of silicate nanoparticles having a hierarchical porosity (0.5-50 µm pore size) was produced by using potato starch gels as templates. Egg shells having interwoven fibres forming a microporous network were also used as templates to produce titanium dioxide membranes of pore size 5 µm. Hierarchically ordered porous silicate membranes have been created by using porous cellular structures of wood immersed in a silicate and surfactant solution. These membranes contain nanoporous (0.5-3 nm pore size) channels. The pore diameter, surface area, and volume could be varied depending on the tree/wood sample (Brown and Bhushan, 2016).

Surface layer (S-layer) proteins of unicellular organisms

The surface of unicellular organisms contains a layer of crystalline protein subunits, which form highly uniform pores of 2-8 nm in size. This is called the S-layer. Membranes that incorporate S-layer fragments have been fabricated by depositing them on polymer substrates. Such membranes have achieved complete filtration of large proteins like ferritin (12 nm). These membranes provide chemically modifiable sites within the pores, enhancing the selectivity and antifouling properties. But they are unstable, which limit their large-scale production. However, their assembly principles have inspired the development of other biomimetic membranes (Weigert and Sára, 1995).

Aquaporins

Aquaporins are membrane proteins that allow rapid and selective transport of water across living cells. Functions of the aquaporins may differ. Ones with a smaller pore size (<0.3 nm) restrict the movement of ions and small molecules, while some may allow the transport of small solutes and cations. The opening and closing of certain aquaporins are controlled through external stimuli. Therefore, aquaporins can be used to fabricate membranes that allow higher selectivity and permeability. Compared to the conventional membranes, biomimetic membranes based on aquaporins allow efficient flux of water and solute filtration (Verkman et al., 2014).

Mimicking aquaporins

Larger-scale production of aquaporin proteins under laboratory settings can be hard. Instead of aquaporins, some other molecules that can mimic the aquaporins can be used, such as cyclic peptides, dendritic (branched) dipeptides, crown ethers, calixarenes (cycling macromolecules with aromatic groups). These molecules are capable of self-assembly through intermolecular H-bonds to form long tubules with smaller pore sizes (Brown and Bhushan, 2016).

Carbon nanotubes (CNT) can be used in place of aquaporins. CNTs are naturally hydrophobic and have atomically flat walls. Therefore, when water passes through them, the formation of H-bonds happens between adjacent water molecules. It has been discovered that the rate of movement of water through CNT incorporated membranes is very high compared to conventional membranes and costs less (Corry, 2008). But CNTs should be modified to reduce the diameter or to enhance the selectivity, for them to be used for purification purposes. Also, aligning CNTs in membranes can be extremely expensive (Elimelech and Phillip, 2011).

Self-assembled block copolymers can also be used instead of aquaporins. Compared to CNTs, they can be easily incorporated into membranes and are also suitable for scale-ups. These can produce pores sized 8-30 nm.

Biomimetic surfaces for water purification show enormous promise, but their use is limited by cost, scalability, durability, and fouling under real-world conditions. The future lies in scalable manufacturing, multifunctional and self-healing designs, sustainable materials, and smart integration—paving the way toward robust, eco-friendly purification systems that can operate effectively across diverse environments (Brown and Bhushan, 2016).

Bio-inspired substrates to remove oil from water

The upper surface of the lotus leaf shows the super-hydrophobicity owing to its hierarchical structure of micropapillae and nanotubules made of wax. Super hydrophilic and super oleophobic surface has been developed by Brown and Bhushan, (2016) by joining the hierarchical roughness of the lotus leaf surface with the oleophobic and hydrophilic nature of fluorosurfactants, which allows the separation of mixtures of oil and water.

Oil repellent and water-attracting surfaces have reduced fouling tendency and are compatible with gravity-driven separation processes when water is the dominant phase. Incorporating nanoparticles enhances the membrane properties and surface durability. These surfaces enable immediate phase separation without additional processing steps. Such systems can be effectively used upstream of conventional purification membranes to pre-remove bulk contaminants, thereby improving the overall efficiency and longevity of downstream selective filtration systems.

Microbial fuel cells

Microbial fuel cells (MFC) are a bio-electrochemical system that generate electrical energy through microorganism-catalyzed reactions under anaerobic conditions. They are inspired by the natural ability of certain microorganisms (exoelectrogens) to transfer electrons to external electron acceptors via membrane or conductive pili, during the breakdown of organic matter. Due to being fuelled with wastewater, MFCs provide benefits such as energy recovery, waste remediation, low energy input, reduced sludge production, and removal of contaminants (organic matter, nitrogen, and heavy metals) from wastewater. MFCs also face challenges such as low power output, high material cost, and difficulties in scaling up for industrial applications. So far, advancements in electrostatic materials, integration of systems, and engineering of the microbial community are suggested to overcome these challenges (He et al., 2017).

Algae-based water treatment

Algal-based technologies are emerging as versatile and sustainable solutions for treating nutrient-rich wastewater. Both macroalgae and microalgae, including cyanobacterial species, are used to treat wastewater under controlled conditions.

Algae remove the nutrients in the water, which is a critical aspect in wastewater treatment. They can assimilate nitrogen in the form of ammonium and nitrate ions and phosphorus as phosphate ions as nutrients for their growth. Algae are also capable of sequestering heavy metals such as lead, cadmium, arsenic, and mercury on or within their cells via biosorption, bioaccumulation, and complexation. Some algal species can also break down contaminants such as pharmaceuticals and dyes through enzyme-catalysed reactions or through bacterial symbiosis.

Table 01. Several algal species and their roles in heavy metal and wastewater treatment. (Li et al., 2022)

Algal Species	Treatment Context	Role / Target Pollutants
Planktochlorella nurekis	Industrial wastewater (e.g. pulp and paper)	Removal of nitrate, phosphate, chemical oxygen demand, and heavy metals (Cr, Co, Ni, Cu, Zn, Cd).
Chlamydomonas reinhardtii	Industrial wastewater (pulp and paper effluent)	
Chlorella vulgaris	Petrochemical & industrial wastewater	Removal of hydrocarbons and phenols in petrochemical effluent; significant pollutant degradation in an industrial stream.
Scenedesmus sp. *(e.g. Scenedesmus quadricauda)*	Acid mine drainage and industrial effluent	Removal of heavy metals from acid mine drainage and nutrient-rich industrial discharge; removal of total nitrogen and total phosphorus in brewery wastewater.
Spirulina, Anabaena, Oscillatoria (cyanobacteria)	Acid mine drainage wastewater	Employed for high-efficiency uptake of heavy metals (e.g., from coal mine, acid mine drainage streams) via biosorption and alkalinity-mediated precipitation.

During photosynthesis, algae release oxygen, thereby enhancing the aerobic degradation of organic matter. The rising pH due to algal photosynthesis can precipitate certain metals and reduce pathogen viability. These processes make algae effective in both passive and active water treatment systems. The nutrient concentration of wastewater, light conditions, temperature, and pH level may affect the efficiency of nutrient removal and algal biomass production.

Utilizing algae in water treatment systems offers advantages such as low operational cost, energy efficiency, low carbon emission, and support for sustainable wastewater treatment aims. This process has a strong potential in creating a circular loop where treated water and algal biomass are reused. Algal-based water treatment also facilitates the removal of diverse pollutants across nutrient, heavy metal, and organic categories. Algal-based water treatment has been implemented in countries such as the USA, New Zealand, Chile, Spain, Australia, Europe, and India.

Despite the environmental and functional promise of algae-based water treatment, its widespread adoption faces challenges. Large-scale cultivation is hindered by economic constraints, especially in maintaining optimal growth conditions and harvesting biomass efficiently. Open systems are vulnerable to environmental changes and contamination, while closed systems are costly. Integration with existing infrastructure is also limited due to technical incompatibility and a lack of regulatory guidance. Moreover, gaps remain in strain development, low-energy harvesting, and hybrid system design. Advancements in life-cycle analysis, real-time monitoring, and policy support are needed to overcome these barriers and ensure the viability and scalability of algal technologies in wastewater management (Li et al., 2022; Ugwuany et al., 2024).

Phytoremediation of contaminated water

Phytoremediation is the use of plants to reduce or neutralize the concentrations or toxic effects of environmental contaminants. Mainly organic and inorganic pollutants like heavy metals can be effectively removed by this method. This is done by several mechanisms.

***Phytoextraction* -** Uptake and accumulation of contaminants in plant tissues. Such accumulated contaminants are detoxified at the cellular level within the plant. Mostly, the uptake is made efficient by increasing the bioavailability of contaminants through rhizosphere microorganisms and root exudates.

***Phytostabilization* -** Immobilization of contaminants in the soil through plant roots. This method sequesters pollutants within the rhizosphere without harvesting them from the source location.

***Phytodegradation* -** Breakdown of pollutants into less toxic components via plant metabolic processes, mainly enzymes. The end products are sequestered by the vacuoles or are bound to the cell wall. This process is made efficient through plant-microbe interactions. Mostly used to degrade organic pollutants like tebuconazole.

***Rhizofiltration* -** Absorption or adsorption of pollutants by plant roots from aqueous solutions. Then they are chelated by metal-binding ligands, phytochelatins, and metalloteines. Sequestration happens in the cell vacuoles and apoplast or is bound to the cell wall.

***Phytovaltilation* -** Uptake of pollutants by plants, their conversion into volatile forms, and release into the air. Selenium and volatile organic compounds are removed through this method, while it has limited effectiveness with other pollutants.

In aquatic phytoremediation, plant-microbe interactions significantly increase the pollutant uptake and detoxification. For example, *Pseudomonas spp.* and *Bacillus spp.* improve the pollutant solubility, reduce oxidative stress, and support root growth, thereby increasing the phytoremediation efficiency. Though similar to soil systems, these interactions in aquatic environments require further research.

It has been discovered that around 40 species of plants are capable of phytoremediation in water. Salviniaceae, Araceae, Cyperaceae, Haloragaceae, and Poaceae are the most represented plant families among them.

Factors such as the pollutant characteristics and nutrient uptake, biomass production, and the concentration of the chlorophyll of the plant should be considered when selecting a species for phytoremediation. Usually, a species with a significant pollutant tolerance, higher accumulation capacity, higher yield, and greater pollutant uptake should be selected. Environmental factors such as temperature, salinity, pH, bioavailability of nutrients, and pollutant availability also affect aquatic phytoremediation.

Phytoremediation of water is being applied in many countries worldwide by integrating it with constructed wetlands and hydroponic systems. As of 2025, around 12 patents have been approved globally in the field of water phytoremediation, with leading contri butions from the United States, China, Japan, and the European Union. These patents cover a variety of water treatment systems, including containerized hydroponic units, hybrid groundwater-vegetation systems, and modular purification setups. Commonly used plant species include *Eichhornia crassipes* (water hyacinth), *Lemna minor* (duckweed), *Azolla* *filiculoides, Phragmites australis* (reed), *Typha latifolia* (cattail), *Populus* (poplar), *Salix* (willow), and *Brassica spp. (*mustard).

This strategy provides low cost and requirements, multiple removal mechanisms, while supporting biodiversity. Despite all the novel discoveries, aquatic phytoremediation remains largely experimental, facing limitations in species scope, consistency of meth ods, and field validation. However, expanding biodiversity in studies, standardizing protocols, and conducting practical implementations will help to understand the mechanisms and improve system reliability (Delgado-González et al., 2021).

Conclusion

Bio-inspired technologies cause a profound impact in advancing sustainable water conservation and purification strategies by mimicking and utilizing the natural mechanisms, ranging from fog water collection to the absorptive capabilities of plants and the metabolic functions of microorganisms. Integration of bio-inspired approaches into existing methods of water treatment enhances the performance and also ensures ecological sustainability. However, material scalability, economic feasibility, and regulatory acceptance remain as challenges. Future advancements in fields such as synthetic biology, nanotechnology, and systems engineering are expected to optimize these solutions.

References

Abdelrasoul A, Doan H & Lohi A (2017). Fabrication of biomimetic and bioinspired membranes. Biomimetic and bioinspired membranes for new frontiers in sustainable water treatment technology, DOI:10.5772/intechopen.71718.

Aydin D, Gübbük İH & Ersöz M (2024). Recent advances and applications of nanostructured membranes in water purification. *Turkish Journal of Chemistry*, 48(1), pp.1-20.

Bai H, Wang L, Ju J, Sun R, Zheng Y & Jiang L (2014). Efficient water collection on integrative bioinspired surfaces with star-shaped wettability patterns. *Adv. Mater,* 26(29), pp.5025-5030.

Bellomi S, Motta D, Stucchi M, Prati L, Dimitratos N & Villa A (2024). Hydrogen production from hydrous hydrazine decomposition using Ir catalysts: Effect of the preparation method and the support. *Catalysts*, 14(2), p.119.

Bhushan B (2019). Bioinspired water collection methods to supplement the water supply. *Philosophical Transactions of the Royal Society A*, 377(2150), p.20190119.

Brown PS & Bhushan B (2016). Bioinspired materials for water supply and management: water collection, water purification and separation of water from oil. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 374(2073), p.20160135.

Corry B (2008). Designing carbon nanotube membranes for efficient water desalination. *The Journal of Physical Chemistry B*, 112(5), pp.1427-1434.

Delgado-González CR, Madariaga-Navarrete A, Fernández-Cortés JM, Islas-Pelcastre M, Oz G, Iqbal HM & Sharma A (2021). Advances and applications of water phytoremediation: A potential biotechnological approach for the treatment of heavy metals from contaminated water. *International Journal of Environmental Research and Public Health*, 18(10), p.5215.

Ede SR, Yu H, Sung C & Kisailus D (2024). Bio-inspired functional materials for environmental applications. *Small Methods*, 8(4), p.2301227.

Elimelech M & Phillip WA (2011). The future of seawater desalination: energy, technology, and the environment. *Science*, 333(6043), pp.712-717.

FAO & UN-Water (2024). Progress on the level of water stress – Mid-term status of SDG Indicator 6.4.2 and acceleration needs, with special focus on food security. Rome, FAO, viewed 29 April 2025, <https://doi.org/10.4060/cd2179en>.

Fessehaye M, Abdul-Wahab SA, Savage MJ, Kohler T, Gherezghiher T & Hurni H (2014). Fog-water collection for community use. *Renewable and Sustainable Energy Reviews*, 29, pp.52-62.

Garrod RP, Harris LG, Schofield WCE, McGettrick J, Ward LJ, Teare DOH & Badyal JPS (2007). Mimicking a *Stenocara* Beetle's back for microcondensation using plasmachemical patterned superhydrophobic– super hydrophilic surfaces. *Langmuir*, 23(2), pp.689-693.

Goel G, Hélix-Nielsen C, Upadhyaya HM & Goel S (2021). A bibliometric study on biomimetic and bioinspired membranes for water filtration. *NPJ Clean Water*, 4(1), p.41.

Gonzalez-Perez A & Persson KM (2016). Bioinspired materials for water purification. *Materials*, 9(6), p.447.

Gurera D & Bhushan B (2019a). Designing bioinspired surfaces for water collection from fog. *Philosophical Transactions of the Royal Society A*, 377(2138), p.20180269.

Gurera D & Bhushan B (2019b). Optimization of bioinspired conical surfaces for water collection from fog. *Journal of colloid and interface science*, 551, pp.26-38.

He L, Du P, Chen Y, Lu H, Cheng X, Chang B & Wang Z (2017). Advances in microbial fuel cells for wastewater treatment. *Renewable and Sustainable Energy Reviews*, 71, pp.388-403.

IUCN 2020. Guidance for using the IUCN global standard for nature-based solutions. 1. Gland, Switzerland: IUCN. IUCN, International Union for Conservation of Nature. DOI:10.2305/IUCN.CH.2020.09. en

Li M, Zamyadi A, Zhang W, Dumée LF & Gao L (2022). Algae-based water treatment: A promising and sustainable approach. *Journal of Water Process Engineering*, 46, p.102630.

Malik S, Kishore S, Dhasmana A, Kumari P, Mitra T, Chaudhary V, Kumari R, Bora J, Ranjan A, Minkina T & Rajput VD (2023). A perspective review on microbial fuel cells in treatment and product recovery from wastewater. *Water*, 15(2), p.316.

Nguyen LN, Adity L, Vu HP, Johir AH, Bennar L, Ralph P, Hoang NB, Zdarta J & Nghiem LD (2022). Nutrient removal by algae-based wastewater treatment. *Current Pollution Reports*, 8(4), pp.369-383.

Shenvi SS, Isloor AM & Ismail AF (2015). A review on RO membrane technology: Developments and challenges. *Desalination*, 368, pp.10-26.

Tang C, Wang Z, Petrinić I, Fane AG & Hélix-Nielsen C (2015). Biomimetic aquaporin membranes coming of age. *Desalination*, 368, pp.89-105.

Ugwuanyi ED, Nwokediegwu ZQS, Dada MA, Majemite MT & Obaigbena A (2024). The role of algae-based wastewater treatment systems: A comprehensive review. *World Journal of Advanced Research and Reviews*, 21(02), pp.937-949.

UNESCO 2023. The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water. Paris: UNESCO, viewed 29 April 2025, <https://unesdoc.unesco.org/ark:/48223/pf0000384655>.

UNICEF 2025, viewed 29 April 2025, <https://www.unicef.org/wash/water-scarcity>.

UNWWDR 2024. The United Nations World Water Development Report 2024: Water for Prosperity and Peace. UNESCO, viewed 29 April 2025, <https://www.unwater.org/publications/un-world-water-development-report-2024>.

Verkman AS, Anderson MO & Papadopoulos MC (2014). Aquaporins: important but elusive drug targets. *Nature reviews Drug discovery*, 13(4), pp.259-277.

Weigert S & Sára M (1995). Surface modification of an ultrafiltration membrane with crystalline structure and studies on interactions with selected protein molecules. *Journal of membrane science*, 106(1-2), pp.147-159.

World economic forum 2025, viewed 29 April 2025, <https://www.weforum.org/stories/2023/07/global-distribution-fresh-water-withdrawals/>.

Zhang Y, Zhu C, Shi J, Yamanaka S & Morikawa H (2022). Bioinspired composite materials used for efficient fog harvesting with structures that consist of fungi-mycelia networks. *ACS Sustainable Chemistry & Engineering*, 10(38), pp.12529-12539.

CHAPTER 14

Biological Approaches in the Sustainability of Medicinal Plant Production: Improving Resilience and Reducing Environmental Footprint

D. D. N. Dissanayaka[1] and R. M. S. M. B. Rathnayaka[2*]

[1]College of Horticulture, Sichuan Agricultural University, Chengdu City, China.
[2]Faculty of Technology, Sri Lanka Technology Campus, Padukka, Sri Lanka.
*sangeethr@sltc.ac.lk

Abstract

The sustainable production of medicinal plants is crucial to fulfill the global demand for natural health products while maintaining ecological integrity. This chapter discusses the biological approaches that help to enhance the sustainability, resilience, and environmental conservation approaches for medicinal plant cultivation. The main objectives of this review are to explore the main challengers for sustainable medicinal plant production, including overharvesting, and climate vulnerability; assess biological approaches to increase productivity and ecological adaptability, including microbes assisted cultivation and using stress resistant cultivars; focus about conservation methods like in-situ conservation, and organic farming to reduce environmental impact and provide some suggestions, future directions for integration of biotechnology and policy frameworks to support sustainable cultivation. furthermore, this chapter outlines strategies for reducing ecological stress while maintaining the quality and yield of medicinal plants. The integration of traditional knowledge with modern biotechnological innovations offers a viable approach for sustainable medicinal plant production, by ensuring long-term availability while protecting biodiversity. This review provides a basis for researchers and policymakers to promote sustainable medicinal plant cultivation.

Keywords: Biotechnology, Conservation, Medicinal Plants, Sustainability

Introduction

For thousands of years, medicinal plants have contributed to human health and traditional medicine systems by providing bioactive compounds necessary for medicines, nutraceuticals, and functional foods. However, the worldwide growing demand, along with threats like destroying natural habitats, over-harvesting of plants, and climate change, put the future of medicinal plant production at risk (Huang, 2024). The conventional farming practices often depend on chemicals, monocultivation, and intensive land usage, which can harm biodiversity, degrade soil quality, and increase carbon emissions. To address these challenges, more sustainable approaches like agroecology, microbiome management, natural growth stimulants, and conservation efforts are gaining attention. These strategies help make cultivation more resilient, stabilize yields, and reduce the environmental impact of growing medicinal plants.

Sustainable medicinal plants production means shifting away from resource-intensive farming while creating a balanced ecosystem that protects biodiversity, soil health, and supports the natural ecosystem. (David, 2023). Biological techniques support natural mechanisms like increasing plant growth through friendly soil microbes and fungi, increasing the tolerance, and producing secondary metabolites while reducing the use of synthetic fertilizers and pesticides. For example, introducing plant growth-promoting rhizobacteria (PGPR), which act as an alternative to chemical pesticides, promotes plant growth, controls pests' damage, and induces resistance along with various abiotic stresses, while bioremediation of contaminated soil (Saeed et al., 2021). Agroforestry and mixed cropping systems encourage beneficial relationships that enhance crop yields and support ecological health. These methods help to grow valuable medicinal plants sustainably while playing a part in carbon sequestration and water conservation.

Implementing *in situ* and *ex situ* techniques for the conservation of genetic diversity and resource management is another important concern of sustainable medicinal plants production (Chen et al., 2016). Due to overexploitation and habitat fragmentation, most of the wild populations of medicinal plants are in danger. Modern biotechniques like tissue culture, freezing genetic material using plant parts, and molecular breeding are important for conserving these genetic resources while creating climate-resilient cultivars (Salgotra and Chauhan, 2023). Combining traditional knowledge about local ecosystems with scientific methods can optimize the cultivation practices by ensuring environmental sustainability. Adapt comprehensive and biologically driven approaches from farmers to legislators can reduce the environmental effects while ensuring the long-term availability of the medicinal plants.

Moving towards sustainable ways of growing medicinal plants is ecologically appropriate, while socially and economically required. As people become more aware of the environmental and health impacts, the demand for organically grown, ethically sourced medicinal plants is rising. Using biological methods offers a smart way to meet this demand while tackling key challenges, including climate change, loss of soil fertility, and declining biodiversity. In this chapter, we explore the progressive biological techniques to increase the sustainability of medicinal plant production. It helps to increase the climatic resilience, reducing the environmental impacts while conserving these valuable resources for the next generation.

Challenges in sustainable medicinal plant production

Medicinal plants are playing a very important role in traditional and modern medicine, and the health industry all over the world. Demand for natural raw materials is increasing day by day, with the increasing herbal companies and also with the increasing population that prefers herbal products over artificial synthetic medicines. Because of this, it became a burning issue to ensure the sustainable harvesting of medicinal plants from their natural habitats. In Sri Lanka, the sustainable production of medicinal plants is significant in ecological, socio-economic, and agronomically. These considerable challenges pose a threat to the long-term availability of key medicinal plants such as Kothala himbitu (*Slalacia reticulata*), Weniwal (*Coscinium fenestratum*).

Overharvesting from the wild

Around 80% of the medicinal plants used in traditional medicine are collected from the wild. These collectors are harvesting medicinal plants without any proper sustainable harvesting methods or any proper regulations, and collectors are practicing over-harvesting of plant roots, bark, and stem parts, are leads to exploitation of their natural habitat/depletion of the wild population, and finally, this is causing plant mortality. Also, uncontrolled root, bark, and stem harvesting for *Salacia reticulata* in Sri Lanka caused to depletion of the plant from its natural habitat (Rathnayaka and Subasinghe, 2011). Also, most of the collectors are uprooting whole plants for medicinal purposes and which causes their natural regeneration and affects their genetic diversity of the species.

Poor natural regeneration and propagation difficulties

Mainly, farmers are not focusing on cultivating medicinal plants for commercial cultivation. Most of them are planting a countable number of plants in their home gardens for their home consumption. Not only that, these plants have having very slow growth rate and need to use efficient propagation technologies when used for cultivation (Sonali et al., 2024).

Lack of domesticated cultivars and agronomic research

Because of the lack of growing global demand for medicinal plants, conservation practices and sustainable use of herbs are hampered severely due to the lack of domestications and limited agronomic research. Considering other crop varieties, there is a lack of improved high-yielding cultivars because medicinal plants have not been subjected to breeding or domestication programs (Sonali et al., 2023). There are no developed, proper agronomic packages and best practices for medicinal plant cultivations. Domestication and developing proper agrotechnological packages need to align with the medicinal plant conservation and commercialization.

Inadequate cultivation knowledge and support services

Because of the very low popularity, herbal cultivations are lacking in knowledge and technical guidance for soil management, crop management, and sustainable harvesting methods. This will lead to low yield and plant mortality. Also, in Sri Lanka, there is no proper extension service to promote medicinal plant cultivation.

Market uncertainty and poor incentives

Even though there is a very high demand for the traditional medicinal plant industry, the market for the raw materials is not well-organized and secure. It is always fluctuating, and cultivators are worried about investing in cultivation due to the uncertainty.

Policy and regulatory gaps

Still, there are no properly developed policies for unsustainable medicinal plant harvesting and cultivation. Not only that, but plant conservation rules and regulations need to be reorganized, and the current system is also discouraging local growers, even though they have their own cultivations.

Biological approaches for sustainable medicinal plant cultivation

Biological approaches are the foundation of sustainable medicinal plant cultivation, which maximizes the yield while reducing environmental impacts. Mycorrhizal fungi and Rhizobacteria association are one of the important methods for enhancing the resilience and the health of the plant. As a natural plant symbiont, Arbuscular mycorrhizal fungi (AMF) offer resilience to stress conditions, providing essential inorganic fertilizers to boost the growth and yield (Begum et al., 2019). Similarly, plant growth-promoting rhizobacteria (PGPR) encourage plant growth by fixing nitrogen, producing natural hormones, Phosphate solubilization, and biocontrol of pathogens (Shrivastava et al., 2014). Using these friendly microbes reduces the need for chemical fertilizers and pesticides, which helps keep the soil healthy, higher bioactivate components of medicinal plants, and supports long-term agricultural sustainability while maintaining ecological balance.

Organic and ecological farming

It is important for sustainable medicinal plant cultivation by increasing soil health, focusing on biodiversity, while reducing chemical applications. Crop rotation, intercropping, and adding organic materials help keep the soil fertile and encourage helpful microbes. Agroforestry produces microclimatic conditions that act as a buffer for extreme weather. Compared with conventional monocultivation, this would reduce greenhouse gas emissions and water pollution while producing high-quality medicinal plants with a lower environmental footprint.

In vitro propagation and genetic conservation

It is important to conserve the threatened medicinal plant while facilitating a continuous supply. Tissue culture, cryopreservation, seed banking, molecular breeding, and CRISPR-based genome editing facilitate to production of climate resilience varieties with enriched medicinal properties.

Enhancing resilience to climate and ecological stress in medicinal plant production

Climate change and ecological degradation pose serious challenges to medicinal plants production by reducing yield, changing the helpful bioactive compounds, and making plants more vulnerable to pests and diseases. The application of bio-stimulants such as seaweed extract, humic substances, and protein hydrolysates leads to an increase in the physiological resilience of medicinal plants. These substance helps to increase photosynthesis, antioxidant activity, and osmotic regulation while mitigating osmotic stress, which is caused by extreme environmental conditions. Using biochar and carbon-rich amendments also helps by improving soil structure, water retention, microbial activities, and enhancing resilience to stress. Combination with organic farming practices creates a stable agroecosystem that protects medicinal plants from climate change while keeping the soil healthy and diverse.

Genetic and biotech methods are important for developing medicinal plants that are adapted to climate change. Stress-tolerance varieties can be produced by in vitro selection and somaclonal variation, while molecular breeding and CRISPR gene editing techniques are used to produce improved varieties with good immunity and resistance. Protecting wild varieties by ecological restoration and habitat preservation ensures the genetic diversity needed for future breeding efforts. As a combination of traditional knowledge with modern science, farmers and researchers can grow medicinal plants with high resilience to climatic changes and a sustainable environmental footprint. All these biological strategies together help create a stronger, more adaptable system for producing medicinal plants.

Reducing environmental footprint

To ensure the long-term ecological balance and sustainability, it is need to reduce the environmental footprint. There are a lot of biological and ecological practices needed to reduce water wastage, minimize synthetic inputs (eg., can use neem oil as chemical fertilizer), enhance soil health, and carbon sequestration. Not only will this promote on-farm biodiversity via biological control methods.

Low-impact harvesting techniques.

Design corrects harvesting methods, with continuous viability of plant populations. Practice selective harvesting (mature plants), minimize soil disturbance while avoiding uprooting whole plants.

Waste reduction, recycling, and biological practices

Using agricultural waste in the composting system and practicing biopesticides and biocontrol agents, such as natural pest control methods, to lower the health risk and minimize environmental contamination.

Agroforestry and ecological buffering

It can be integrated with medicinal plants into the agroforestry systems, which work as an *in-situ* or *ex-situ* conservation method, and the system will help to establish the plants by enhancing biodiversity and improving microclimates.

Conservation-oriented cultivation practices

Biological approaches to medicinal plant cultivation with conservation-oriented practices are needed. These approaches should address sustainable yield while conserving ecological integrity, genetic diversity, and traditional knowledge. Conservation can be divided into two main parts*: In situ* conservation and *Ex situ* conservation.

In situ conservation

In situ conservation means protecting and maintaining medicinal plants in their natural habitats. This will help ensure the preservation of plant species in their native environment, which involves a complex interplay of interactions between plants, soil microbes, insects, and the natural environment. This will help ecosystem services and ensure the long-term availability of genetic resources.

Ex situ conservation

This involves protecting plant species outside their natural habitats. This is necessary for endangered, rare, and slow-growing species, which are at risk of immediate habitat loss due to over-harvesting. In general, this practice is carried out by Seed gene banks, which store seeds in cold conditions; field gene banks, which collect and manage plants in live conditions; and botanical gardens, which propagate and maintain plants in selected gardens. Because of this, cultivators can collect planting materials without disturbing their natural habitats, which will facilitate research by reducing pressure on wildlife populations.

Constraints and research gaps

To achieve sustainable medicinal plant production, it needs to address several challenges, including technical, institutional, policy, and market dimensions. It needs to address these to achieve success in a broad field-level impact. Based on those, we can identify several constraints as below in the medicinal plant industry.

i. Lack of awareness and technical capacity among rural farmers (IPM, microbial inoculation, *in vitro* propagation)

ii. Policy barriers to the approval and use of biocontrol agents (Harmonization between agriculture, environment, and Health regulations)

iii. Insufficient research related to plants and microbial associations

iv. Limited market for certified productions (Organic, fair trade, biodiversity-friendly labels)

v. Fragmentation of traditional and scientific knowledge

Future directions

It needs to coordinate a multi-level approach to address the above gaps. by conducting advanced studies based on species-level related plant stress physiology, phytochemical responses, and plant-microbe interactions. Also, it needs to do field trials to find out cost-effective cultivating techniques with introducing all agroecological zones (Sonali et al., 2023). Also, by integrating traditional knowledge with new innovative scientific solutions and by supporting and making policies to develop the infrastructures, knowledge, and providing incentives to give green certification schemes.

References

Begum N, Qin C, Ahanger MA, Raza S, Khan MI, Ashraf M, Ahmed N & Zhang L (2019). Role of Arbuscular Mycorrhizal Fungi in Plant Growth Regulation: Implications in Abiotic Stress Tolerance. *Frontiers in Plant Science*, 10(1068). doi:https://doi.org/10.3389/fpls.2019.01068.

Chen S., Yu H, Luo H-M, Wu Q, Li C-F & Steinmetz A (2016). Conservation and sustainable use of medicinal plants: problems, progress, and prospects. *Chinese Medicine*, [online] 11(1). doi:https://doi.org/10.1186/s13020-016-0108-7

David H (2023). Medicinal Plants for a Sustainable Future: Conservation and Ethical Harvesting. *J Tradit Med Clin Natur*, 12: 400.

Huang JA (2024). Sustainable Harvesting and Conservation of Medicinal Plants: A Pharmacognostic Perspective. *J Pharmacogn Nat Prod* 10 (2024), p.318.

Saeed Q, Xiukang W, Haider FU, Kučerik J, Mumtaz MZ, Holatko J, Naseem M, Kintl A, Ejaz M, Naveed M, Brtnicky M & Mustafa A (2021). Rhizosphere Bacteria in Plant Growth Promotion, Biocontrol, and Bioremediation of Contaminated Sites: A Comprehensive Review of Effects and Mechanisms. *International Journal of Molecular Sciences*, 22(19), p.10529. doi:https://doi.org/10.3390/ijms221910529.

Salgotra RK & Chauhan BS (2023). Genetic Diversity, Conservation, and Utilization of Plant Genetic Resources. *Genes* 14(1), p.174.

Shrivastava S, Egamberdieva D & Varma A (2014). Plant Growth-Promoting Rhizobacteria (PGPR) and Medicinal Plants: The State of the Art. *Soil Biology*, pp.1–16. doi:https://doi.org/10.1007/978-3-319-13401-7_1.

Sonali PAY, Alahakoon MRCSB, Thathsara DKP, Herath HMUKB, Jayaweera WMG, Udakotuwage GS, Vibodhani DDN, Rajapaksha RMPI, Rathnayaka RMSMB (2023). Developing a fertilizer recommendation for gurmar (Gymnema sylvestre). *Proceedings of the International Research Conference of the SLTC Research University*, 3, 59-62.

Sonali PAY, Alahakoon MRCSB, Thathsara DKP, Herath HMUKB, Jayaweera WMG, Udakotuwage GS, Vibodhani DDN, Rajapaksha RMPI & Rathnayaka RMSMB (2024). Developing an effective vegetative propagation method for commercial cultivation in Gurma plant (Gymnema sylvestre). *Proceedings of the International Research Conference of the SLTC Research University*, 4, 226-229.

Rathnayaka RMSMB & Subasinghe S (2011). Development of busy type Kothala Himbutu (*Salacia reticulata* white) plantation for sustainable leaf/stem harvesting' 08th Academic Session, 45.

ISBN: 978-624-5998-06-7

The Institute of Biology Sri Lanka