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Riti Thapar Kapoor *Editors*

Multidisciplinary Applications of Marine Resources

A Step towards Green and Sustainable Future

Springer

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Foreword

Ocean plays a significant role in energy production, human health and economic prosperity. Blue economy has been widely advocated to safeguard oceans and water resources through sustainable application of marine organisms/biomass for societal benefit all over the globe. Sea or oceans represent safe sources of food, energy and minerals, and they also provide the transport of more than 90% of traded goods worldwide. Seas cover more than 70% of the Earth's surface and contain more than 97% of the Earth's water as well as minerals. The marine environment is a source of a plethora of beneficial organisms which are rich in functional/bioactive compounds and exhibit their remarkable potential for medical, industrial and biotechnological applications. Marine organisms such as micro- and macroalgae, sponges, crustaceans, microbes and fishes are valuable source of functional ingredients such as polysaccharides, vitamins, minerals, pigments, enzymes, proteins and peptides, lipids, polyunsaturated fatty acids, phenolics and other secondary metabolites. Due to the presence of bioactive compounds, marine biomass can be incorporated in the food industry as colorants, natural preservatives, stabilizers, gelling agents and also in nutraceutical and pharmaceutical industries due to their anti-inflammatory, antihypertensive, antioxidant, anti-coagulant, anti-diabetic and cardiovascular protective activities.

However, current biorefinery technologies mainly rely on edible crops and freshwater resources. With an ever-growing population, there are concerns for excessive exploitation of the world's limited freshwater and food crop resources for nonnutritional activities. In this context, marine-based biorefinery represents as a promising approach, where seawater, seaweed, kelp, microalgae, yeast and bacteria act as renewable and alternative feedstock due to their tremendous potential for the production of biofuel and high-value products. Marine biomass can be used in bioconversion/fermentation processes for the production of food, feed, biofuel, biogas and high-value chemicals. Due to the fast growth rate of marine biomass, ease of availability and harvesting, low production cost make them suitable candidate for trapping of the solar energy, utilize CO_2 from atmosphere and can be used in marine biorefinery. As compared to terrestrial biomass, seaweed grows much faster up to 50 times and highly efficient in CO_2 fixation. Seaweed can form sea forest and can be used in the production of food, cosmetics, fertilizers, extraction of industrial gums and other chemicals, etc. Biofuels and bio-based products are among the best alternatives to fossil-based fuels and synthetic chemicals due to their capacity for net-negative carbon emissions, which is a vital contribution to the global ambition of a net-zero economy. Marine biorefinery may enhance the overall energy output and economic feasibility as compared to conventional fossil fuels. Therefore, the development of integrated marine biorefinery system with marine resources can be a promising approach in mitigation of climate change as well as addressing the shortage of water, food and energy at global level. This book provides wide information to readers on state-of-the-art of application of marine biomass, diatom and their integrative applications for the development of marine biorefinery, wastewater/industrial effluent treatment, exploitation of marine organisms/biomass in food, pharmaceutical industries and other value-added products.

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Preface

Oceans cover 70% of the planet's surface and besides being an immense reservoir of biological life they serve as an important source for transport, commerce, and human sustenance. However, 80% of the oceans remain unexplored. Energy is an essential infrastructure for economic growth and social advancement due to the rapid expansion of global population and industrialization. Using fossil fuels as a primary energy source has resulted in a slew of negative consequences, including climate change, adverse impact on environment and human health. Therefore, in order to address the energy crisis, it is crucial to rely on a sustainable and promising energy source alternative. There is a high demand for alternative fuels because of rising environmental issues and depletion of fossil fuels. Renewable energy and sustainable technologies offer a promising avenue for mitigating environmental impacts while reducing dependence on fossil fuels. Amid the global energy crisis and environmental concerns, marine biomass in its diverse forms has emerged as a promising, green, and cost-effective alternative which has potential for conversion into sustainable energy in alignment with the United Nations sustainable development goals. Marine biomass is a globally abundant renewable resource that has gained significant attention for its potential for the development of wide portfolio of bioproducts such as biofuel, bioethanol, value-added products, and chemicals that are traditionally derived from non-renewable resources. Marine biomass has excellent biological activity, unique chemical texture, and good biocompatibility that can be used for various purposes. Bioactive compounds derived from marine biomass are considered as vital sources of functional ingredients with favorable functions for human health and disease risk reduction. Hence, there has been a growing interest in researching and developing marine-derived functional food ingredients, nutraceuticals, pharmaceuticals, cosmetics, and dietary supplements. The utilization of renewable marine resources to produce carbon materials, such as biofertilizers, biochar, and low-emission fuels, plays an important role in gradually replacing conventional fossil fuel. Application of marine biomass offers ecological viability, low-cost production, and green credentials. After careful evaluation of every aspect of marine resources, it represents a cornerstone of our future global sustainability.

Sankha Chakrabortty and their research team members from multiple institutions such as Kalinga Institute of Industrial Technology, Bhubaneswar and Bankura Christian College, Bankura, West Bengal, India, present a comprehensive review on the production of biofertilizer from marine biomass. Vivekananda Saha and Goutam

Biswas from Panchanan Barma University, Cooch Behar, India highlight the formulation of marine-derived natural cosmetics. John Tsado Mathew et al., an interdisciplinary group of authors from multiple institutions of Nigeria, focus on applications of diatoms in the treatment of industrial effluent which acts as a sustainable tool for food production. Krishna Neeti et al. from the National Institute of Technology Patna, Bihar, India highlight the utilization of diatoms in the development of value-added products. A study by a research group of W.V.Celcia Gnana Rathinam et al. from Annamalai University, Tamil Nadu, India highlights the application of marine resources as a promising source for cosmetic industries. Immanuel Suresh. J and Divyeswari S from the American College, Madurai, Tamil Nadu, India describe the application of seaweeds in the production of bioethanol. Deepshikha Datta and their research group from Brainware University, Kolkata, West Bengal and the National Institute of Technology, Durgapur, India describe valorization of marine waste towards the production of value-added industrial products like bioplastics. They also highlight the application of marine biomass, regulations, and policy framework for carbon neutrality, sustainable environment, and bioeconomy. Anwesha Patel and their research team members from Dayananda Sagar University, Bengaluru, India highlight the potential of marine microalgae in food and feed industry. Asmita Saha et al. from Dayananda Sagar University, Bengaluru focus on seaweed-derived bioactive compounds for pharmaceutical applications. Rekha Rani et al., a group of authors from multiple institutions such as the College of Dairy and Food Technology, Agriculture University, Jodhpur and Dayalbagh Educational Institute, Agra, India and Food Science and Nutrition Department, University of Minnesota, Minnesota, USA, highlight the potential of seaweeds as antioxidants and marine-based food as a drug to fight against infectious diseases. Mardiana Idayu Ahmad and their research team from the School of Industrial Technology, Universiti Sains Malaysia, Penang, Malaysia and Hail University, Saudi Arabia describe extraction and development procedure of biodiesel from marine macroalgae-seaweed as a renewable feedstock. Mohammad Aliff Shakir et al. from the School of Industrial Technology, Universiti Sains Malaysia, Penang, Malaysia focus on the development of bioplastics from marine green algae. Hamza Mohamed Flafel et al., a group of authors from multiple institutions such as the School of Industrial Technology, Universiti Sains Malaysia, Penang, Malaysia, Wadi Al-Shatti University, Brack Al-Shatti, Libya, Amity University Uttar Pradesh, India and King Saud University, Riyadh, Saudi Arabia, highlight the production of biochar from marine algae and its use in the treatment of industrial effluent. C. Madhuri et al. from Yogi Vemana University, Kadapa, Andhra Pradesh, India explain the production of biofuel from macroalgae/seaweed. Indahayu Ab. Rahman et al. from the School of Industrial Technology and Centre for Marine and Coastal Studies, Universiti Sains Malaysia, Penang, Malaysia focus on biomonitoring of mangroves which acts as an indicator of sustainable coastal environment. Harinisri Ram K and Thamarai Selvi B from Sri Ramakrishna College of Arts and Science for Women, Coimbatore, India explore inventive applications of marine resources in the production of cosmetics.

This book presents a snapshot of research covering transformation of marine biomass into valuable products. The intended readers of this book include environmentalists, engineers, scientists, industrial personnel, and policy makers who wish to specialize in utilization of marine biomass-based renewable resources for the production of biofuel and in the development of value-added products such as biofertilizers, biochar, cosmetics, pharmaceuticals, and nutraceuticals. We are very thankful to the authors for contributing chapters and to the numerous learned reviewers who carefully read and gave valuable suggestions on the chapters of this book to improve the quality. We would also like to gratefully acknowledge Springer Editorial Office, especially Dr. Sanchi Bhimrajka and Dr. Naren Aggarwal for bringing us this opportunity and guiding us throughout the publication process. Our sincere thanks go to Ms Muthuneela Muthukumar for her wonderful help and continuous support.

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About the Editors

Mohd Rafatullah I am presently working as an Associate Professor of Environmental Technology in the School of Industrial Technology, Universiti Sains Malaysia (USM), Malaysia. I joined this School in the year 2008 as a Post-Doctoral Fellow. I have completed my education; Ph.D. in Environmental Chemistry, Master of Science in Analytical Chemistry, and Bachelor of Science in Chemistry from Aligarh Muslim University (AMU), India. My research interest is in the areas of environmental water pollutants and their safe removal; preparation of various nanomaterials to protect the environment; water and wastewater treatment; adsorption and ion exchange; microbial fuel cells; advance oxidation process; activated carbons and their electrochemical properties. My contribution was recognized by Guest Editors and Member of Editorial Board of various scientific journals. I am listed in World's Top 2% Scientist by Stanford University and also listed in Top 1% peer reviewer, in Chemistry, Environmental Science, and cross-field on Publons global reviewer, Web of Science. I am life-time Fellow Member of the International Society of Sustainable Developments and member of various professional international societies. I have published several review articles and regular research papers in the journals of international repute and presented my research work in various national and international conferences. I have also attended many workshops and seminars of environmental chemistry. Based on my performance and contribution in research, total citations: >11500 and h index: 47 reported in Scopus database.

Masoom Raza Siddiqui is currently working as professor of Chemistry at King Saud University, Riyadh, Saudi Arabia. Prof. Siddiqui received his bachelor's, master's, and Ph.D. degrees from Aligarh Muslim University, Aligarh, Uttar Pradesh, India. Prof. Siddiqui has 2.5 years of experience in the pharmaceutical R&D in addition to 12 years of academic experience. His research experience includes analytical method development of pharmaceutical, environmental, and food additive and contaminants, bioremediation, and water treatment. Prof. Siddiqui has more than 120 papers to his credit. He also contributed to book chapters and patents. Prof. Siddiqui also served as guest editor in two special issues of sustainability journal, published by MDPI. He also successfully guided master's and Ph.D. students.

Moonis Ali Khan is a full professor working in Chemistry Department, College of Science, King Saud University, Riyadh, Saudi Arabia. He is an interfacial chemist with research focused on the development of advanced materials for energy, environmental, and biomedical applications. His research is also focused on waste conversion to valuables for both energy and environmental applications. Dr. Khan had guided three students for their respective Ph.D. research work. Till date, he has authored more than 195 research/review articles and have three US patents to his name. He had edited one and authored chapters in two books. His current H-index is 47 (on Google Scholar). He is also serving as an editor, guest editor, and editorial board member for many journals. For the last three consecutive years (2021, 2022, and 2023), he has been listed among the World's Top 2% Scientists, a list released by Stanford University.

Riti Thapar Kapoor is Associate Professor in Amity Institute of Biotechnology, Amity University Uttar Pradesh, Noida, India. Dr. Kapoor received her Ph.D. from the University of Allahabad and worked as post-doctoral fellow at Banaras Hindu University, Varanasi, India. Dr. Kapoor has 15 years of teaching and research experience and her area of specialization is environmental biotechnology, bioremediation, wastewater treatment, and abiotic stresses. Dr. Kapoor has published 8 books and over 105 research papers in various journals of national and international repute. Dr. Kapoor has visited 8 countries for participation in different academic programs. Dr. Kapoor has received prestigious travel award from Bill & Melinda Gates Research Foundation under CGIAR project for participation in international training program held at the International Rice Research Institute (IRRI), Manila, Philippines in 2010. She is also recipient of DST travel grant for participation in International Conference held at Sri Lanka in 2013. Dr. Kapoor has been awarded with Teacher's Research Fellowship from the Indian Academy of Sciences, Bengaluru in 2019. She has supervised and mentored a number of research projects sanctioned by different government funding agencies such as DAE, DST, and UPCST. She has successfully supervised three research students for Ph.D. degree besides several (more than 70) master's and graduate students for their dissertation thesis.

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Bio-Fertilizer Synthesis from Marine Biomass: An Eco-Friendly Approach to Sustainable Agriculture

1

Sankha Chakrabortty, Satyabrata Si, Jyotisikha Mohapatra, and Prithviraj Karak

Abstract

Meeting the rising demand for food while reducing the negative effects on the environment caused by traditional farming methods is a major challenge for the agricultural sector worldwide. In addition to contributing to soil and water pollution, the widespread use of synthetic chemical fertilizers in agriculture also significantly depletes nonrenewable resources. Bio-fertilizers are a promising new option in the search for environmentally friendly substitutes. Marine biomass is an alternative and largely untapped source for bio-fertilizer production that has enormous potential for eco-friendly, nutrient-rich formulations. This abstract explores the process, benefits, challenges, and potential future applications of bio-fertilizer synthesis from marine biomass. Macroalgae (seaweeds) and microalgae are two types of marine biomass that together make up a wide range of species with a high nutrient density. These marine organisms are a rich source of nutrients because they absorb them from their environment. Many urgent agricultural and environmental problems could be alleviated if these nutrients could be extracted and processed into bio-fertilizers. Harvesting, pretreatment, extraction, and formulation are just some of the steps involved in making bio-fertilizers from marine biomass. Ecological damage can be avoided during the harvesting phase by collecting macroalgae and microalgae in a sustainable manner. The next step is pretreatment, which involves getting rid of things like salts and

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organic matter that are not wanted. Macro and micronutrients like nitrogen, phosphorus, potassium, and trace elements are extracted using methods like enzymatic hydrolysis and bio-refinery processes. Careful formulation of these extracted nutrients into bio-fertilizers makes them compatible with widespread agricultural practices. Bio-fertilizers made from marine biomass have numerous advantages. First, they are a greener option than chemical fertilizers and help cut down on pollution and climate change byproducts. These bio-fertilizers improve crop yields and quality by boosting soil structure, nutrient retention, and microbial activity. Additionally, a blue bio-economy can flourish, providing advantages to coastal communities and encouraging ocean conservation, thanks to the sustainable harvesting of marine biomass. However, there are still barriers to the widespread use of bio-fertilizers made from marine biomass. Extraction and formulation methods must be fine tuned through research and development to achieve maximum efficiency and scalability. Standardizing production processes and guaranteeing the safety and quality of bio-fertilizers call for the establishment of regulatory frameworks. Successful adoption also requires greater publicity and understanding among farmers and other relevant parties. Bio-fertilizers made from marine biomass have bright future prospects. The use of marine biomass for bio-fertilizer production is in line with international targets for environmentally responsible and economically viable food production, as sustainability becomes imperative in agriculture. More study and development in this area could have far-reaching effects on marine ecosystem preservation and the agricultural industry. The synthesis of bio-fertilizer from marine biomass represents a novel and environmentally sound strategy for meeting the challenges of contemporary agriculture. This area has a lot of potentials to improve farming in the future because of its environmental benefits, the chance to increase crop yields, and the backing of a growing blue bio-economy. To overcome obstacles and reach its full potential, however, researchers, policymakers, and stakeholders must work together.

Keywords

Agriculture · Biofertilizer · Environment · Marine biomass · Sustainable

1.1 Introduction

The specter of a burgeoning global population casts a long shadow over the agricultural sector, posing an unprecedented challenge: how to nourish billions while safeguarding the very environment that sustains us. Conventional farming practices, while undeniably productive, have left deep scars on the Earth. The widespread reliance on synthetic fertilizers, for instance, has become a double-edged sword, boosting yields but exacting a heavy toll on soil and water quality, jeopardizing long-term sustainability [1]. In the face of this mounting pressure, the agricultural community urgently seeks solutions that can reconcile productivity with environmental responsibility. Bio-fertilizers, formulated from organic matter and teeming with beneficial microbes, offer a beacon of hope in this quest for sustainable agriculture [2]. Among the diverse candidates for bio-fertilizer production, marine biomass shines brightly as a largely untapped treasure trove. Encompassing a breathtaking array of macroalgae (seaweeds) and microalgae, this marine bounty boasts remarkable nutrient density. These organisms, through their inherent ability to absorb nutrients from their environment, serve as natural storehouses of vital elements like nitrogen, phosphorus, and potassium [3]. Harnessing this inherent richness to create bio-fertilizers presents a potent opportunity to address crucial agricultural and environmental concerns.

Transforming this marine bounty into potent bio-fertilizers involves a meticulous dance of science and sustainability. The journey begins with sustainable harvesting practices, ensuring minimal ecological impact during the collection of macroalgae and microalgae [4]. This is followed by a meticulous pretreatment phase, aimed at removing unwanted elements such as salts and organic matter that could hinder the extraction process. The heart of the process lies in the extraction stage, where various techniques, including enzymatic hydrolysis and bio-refinery processes, are employed to liberate macro and micronutrients. Finally, careful formulation ensures the extracted nutrients are transformed into bio-fertilizers compatible with existing agricultural practices, maximizing their accessibility and impact. The advantages of bio-fertilizers derived from marine biomass extend far beyond their impressive nutrient content. They offer a greener alternative to conventional fertilizers, reducing pollution and mitigating the harmful byproducts associated with climate change. By improving soil structure, nutrient retention, and microbial activity, these bio-fertilizers contribute to enhanced crop yields and quality, creating a virtuous cycle of abundance and environmental well-being. Furthermore, the sustainable harvesting of marine biomass can stimulate the development of a thriving blue bio-economy, generating economic benefits for coastal communities while incentivizing ocean conservation efforts [5]. Imagine vibrant coastal communities bustling with activity, fueled by the responsible harvesting and processing of marine biomass, while pristine ocean ecosystems flourish alongside thriving agricultural landscapes—a powerful testament to the harmonious relationship between humanity and nature. However, the path to widespread adoption of marine-based bio-fertilizers is not without its challenges. Research and development efforts are crucial to optimize extraction and formulation methods, ensuring maximum efficiency and scalability. Robust regulatory frameworks are needed to standardize production processes and guarantee the safety and quality of these bio-fertilizers, fostering trust and confidence among farmers and policymakers [4]. Moreover, increasing awareness and education among farmers and stakeholders is vital for successful adoption. Overcoming these hurdles requires a collaborative effort, bringing together researchers, policymakers, farmers, and consumers in a shared commitment to sustainable agriculture.

Despite these challenges, the future of bio-fertilizers derived from marine biomass is brimming with promise. This approach aligns seamlessly with international aspirations for environmentally responsible and economically viable food production. Continued research and development hold immense potential to transform the agricultural landscape, safeguarding marine ecosystems while bolstering agricultural productivity. This novel and environmentally sound strategy represents a significant step toward overcoming the challenges of contemporary agriculture, paving the way for a more sustainable and prosperous future. As we embark on this exciting journey, let us remember that the vast potential of marine biomass lies not just in its ability to nourish our crops, but also in its power to forge a new paradigm of agriculture—one that is in harmony with nature, ensures food security for all, and paves the way for a thriving blue future.

1.2 Marine Biomass as a Source for Bio-fertilizers

1.2.1 Natural Marine Biomass Used as a Source for Bio-fertilizers

The complex and widely distributed group of photosynthetic organisms known as seaweed is essential to aquatic environments [6]. The aquatic plant kingdom Thallophyta includes seaweeds, commonly referred to as macroalgae, which are regarded as a vital component of marine ecology and lives in coastal waters [7]. There are thought to be 9000 species of macroalgae. Based on the existence of photosynthetic pigment, storage capacity, and other factors, macroalgae can be divided into three primary groups based on components of food products' cell walls and include Rhodophyta (red), Phaeophyta (brown), and Chlorophyta (green) [8]. Seaweeds are typically found clinging to the bottom of rather shallow coastal waters. A new generation of natural organic fertilizers called seaweed extract contains an effective nutrient source that encourages faster seed germination, increased crop yield, and increased crop resistance [9]. Seaweed extracts enhance the biological characteristics of the soil and raise output under biotic and abiotic stress. Brown macroalgae, such as *Ascophyllum nodosum* (L.), are most frequently utilized in agriculture. In addition to *Ascophyllum nodosum*, other brown algae such as *Ecklonia maxima* (Osbeck) Papenfuss, Fucus spp., Laminaria spp., Sargassum spp., and Turbinaria spp. serve as biofertilizers. Mediterranean red algae like Corralina, Green algae, *Pterocladia pinnata* (Hudson) Papenfuss, and *Jania rubens* (L.) J.V. such as *Enteromorpha intestinalis* (L.) Nees, *Cladophora dalmatica* Kützing, and *Ulva lactuca* L. are also employed as a biostimulant for plant growth [5]. Algal extracts and inorganic fertilizers can be combined, which might promote sustainable agricultural productivity [10]. They can be used in various ways, including foliar sprays, soil additives, and on seeds. Demonstrating a broad range of applications, many beneficial effects are found, such as improved germination, radicular system development, better fruit quality, increased leaf area and chlorophyll content, improved crop output, vitality, strong resilience to biotic and abiotic stress, and extended postharvest shelf-life products. Macroalgae have the ability to increase crop yield, improve seed germination, improve soil characteristics, increase growth and quality of crops, and improve abiotic stress tolerance.

Some marine macroalgae are used as biofertilizers by mixing their pulverized form with the soil. They contain unexplored reservoirs of naturally occurring physiologically active chemicals [7]. They serve as abundant sustainable botanical bioresources. Due to their high quantities of organic matter, which enriches soil with nutrients, marine macroalgae are effective biofertilizers. Additionally, when applied in sufficient amounts, they were superior and a more acceptable alternative to chemical and mineral fertilizers [11]. Marine macroalgae have numerous uses as eco-friendly fertilizers in contemporary agriculture and horticulture crop enhancement (in finely powdered form) [12]. The application of seaweed as a soil amendment was effective in enhancing plant growth. Many parts of the world employ seaweed manure to improve agricultural soil [13].

While other marine macroalgae are used as liquid biofertilizers and are sprayed over the soil and plants. Due to their high levels of organic matter, micro and macro elements, vitamins, and other nutrients, liquid fertilizers made from natural sources, such as seaweed, are effective fertilizer alternatives for agricultural crops. Fatty acids and growth regulators are abundant. In agriculture and horticulture, bioactive compounds derived from marine algae are used, and numerous positive results in terms of improvement in productivity and quality have been observed. Seaweed extracts have the potential to replace chemical fertilizers with environmentally friendly liquid biofertilizers, which is essential for organic agricultural techniques leading to sustainable agriculture. A variety of liquid fertilizers from seaweed are applied as a foliar spray.

1.2.2 Waste Marine Biomass, a Source for Bio-fertilizers

Marine trash is typically utilized as a fertilizer in sea areas due to the fact that it includes a significant number of nutrients (nitrogen and phosphorus). Biotransformation is the process by which organic materials can be transformed into complex materials by the activity of bacteria or fungi [14]. Composting is classified as a biotransformation operation. There are four stages that are involved in the process of composting. These stages are as follows: (1) the decomposition phase, (2) the thermophilic phase, (3) the second thermophilic phase, and (4) the maturation phase. The final product that is utilized for the purpose of enhancing the fertility and texture of soil results in an increase in the ability to store carbon, a reduction in the utilization of synthetic fertilizers, and ultimately a reduction in the emission of greenhouse gases. On one side, the chemical in question has a significant potential for use in agricultural settings, and on the other hand, it is recommended that it be stabilized in order to prevent the problems that are associated with the appearance of phytotoxic components [15].

1.2.3 Nutrient Content in Marine Biomass

Marine biomass, a vast and diverse collection of living organisms inhabiting the world's oceans, is an essential component of Earth's biosphere. From microscopic phytoplankton to majestic whales, marine biomass encompasses a wide range of species that play crucial roles in marine ecosystems and global nutrient cycles. Understanding the nutrient content within marine biomass is fundamental to comprehending its ecological significance, its potential for human utilization, and its role in sustaining life on our planet. Research into the nutrient content of marine biomass has revealed the abundance and diversity of essential elements within these organisms. Nitrogen, phosphorus, potassium, calcium, magnesium, and various trace minerals are among the key nutrients found in marine biomass [16, 17]. These nutrients are essential for the growth, development, and reproduction of marine organisms, as well as for the functioning of marine ecosystems as a whole (Fig. 1.1). One of the most abundant and widely studied components of marine biomass is seaweed, also known as marine algae. Seaweeds are renowned for their high nutrient content, particularly in nitrogen and phosphorus. Studies have shown that the nitrogen content of seaweeds can range from 1% to 4% of dry weight, making them a significant source of this essential nutrient [19]. Additionally, seaweeds are rich in other nutrients such as potassium, calcium, and magnesium, which are vital for plant and animal nutrition. Fish and shellfish are another important component of marine biomass, providing valuable nutrients for human consumption. These organisms are rich sources of protein, omega-3 fatty acids, vitamins, and minerals, including calcium and phosphorus. Consuming fish and shellfish as part of a balanced diet

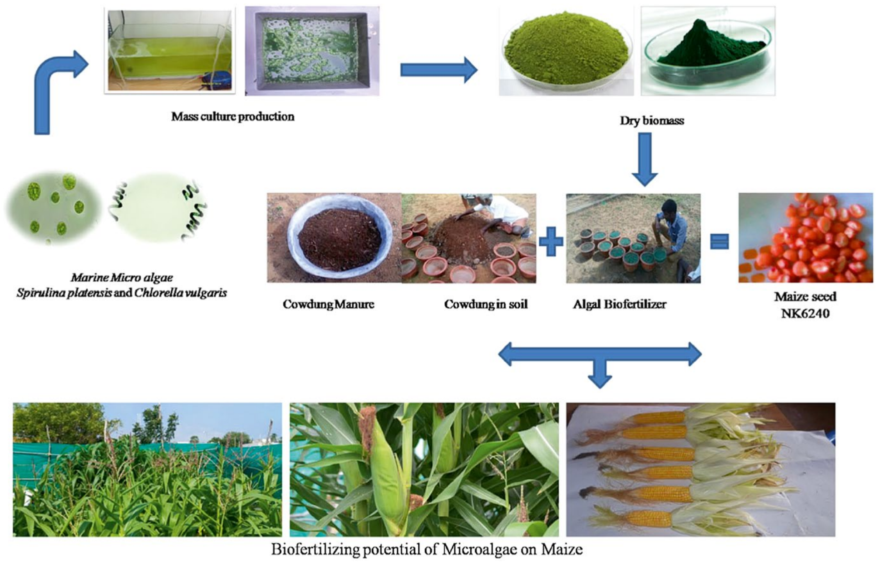

Fig. 1.1 Effect of marine microalgal fertilizer on the growth and yield of maize [18]

can provide numerous health benefits, including cardiovascular health and cognitive function [20]. In addition to macroscopic organisms like seaweeds, marine microorganisms also play critical roles in nutrient cycling and ecosystem functioning. Phytoplankton, for example, are microscopic algae that form the base of the marine food web. These tiny organisms are prolific producers of organic matter and are responsible for a significant portion of the Earth's oxygen production through photosynthesis. Phytoplankton also play a crucial role in the global nitrogen cycle by fixing atmospheric nitrogen into organic compounds, making this essential nutrient available to other marine organisms [21]. Understanding the nutrient content of marine biomass has important implications for various human activities, including fisheries, aquaculture, and marine conservation efforts. Sustainable management of marine resources requires knowledge of nutrient availability and distribution within marine ecosystems. By understanding which nutrients are present in marine biomass and how they are utilized by different organisms, scientists and resource managers can develop strategies to promote ecosystem health and resilience. Furthermore, the nutrient content of marine biomass has implications for human nutrition and food security. Incorporating marine-derived nutrients into the human diet can provide essential vitamins, minerals, and omega-3 fatty acids that are beneficial for health. Additionally, exploring alternative sources of marine biomass for food and feed production, such as seaweeds and marine microorganisms, has the potential to alleviate pressure on traditional fisheries and contribute to sustainable food systems. Marine biomass is a rich and diverse source of essential nutrients that play critical roles in marine ecosystems and global nutrient cycles. Understanding the nutrient content of marine biomass is essential for comprehending its ecological significance, its potential for human utilization, and its role in sustaining life on our planet. Further research into marine biomass nutrition holds promise for addressing challenges related to food security, human health, and environmental sustainability in the future.

1.2.4 Sustainability Considerations in Marine Biomass Harvesting

Sustainability considerations in marine biomass harvesting are paramount due to the delicate balance of marine ecosystems and the potential impact of human activities. Harvesting marine biomass, whether for food, pharmaceuticals, or other purposes, must be conducted in a manner that ensures the long-term health and productivity of oceanic ecosystems. Factors such as overfishing, habitat destruction, bycatch, and pollution can all pose significant threats to the sustainability of marine biomass harvesting practices. Overfishing, in particular, can deplete fish stocks to unsustainable levels, disrupting marine food webs and endangering species. Bycatch, the unintentional capture of nontarget species, can also have detrimental effects on marine biodiversity and ecosystem health. To address these sustainability challenges, various management measures and regulations have been implemented at local, regional, and international levels. These may include fishing quotas, gear restrictions, marine protected areas, and certification schemes such as the Marine Stewardship Council (MSC) for sustainable seafood. Furthermore, advancements in technology and innovation are enabling more sustainable practices in marine biomass harvesting. This includes the development of selective fishing gear to reduce bycatch, the implementation of ecosystem-based management approaches, and the promotion of sustainable aquaculture practices as alternatives to wild harvesting. However, achieving true sustainability in marine biomass harvesting requires a holistic approach that considers ecological, social, and economic factors [22]. Collaboration among governments, industry stakeholders, scientists, and local communities is essential to develop and implement effective management strategies that balance conservation objectives with socio-economic needs. Overall, sustainability considerations in marine biomass harvesting are critical for safeguarding the health and resilience of marine ecosystems, preserving biodiversity, and ensuring the long-term viability of marine resources for future generations.

1.3 Benefits of Bio-fertilizers from Marine Biomass

Since synthetic fertilizers originate from chemicals, their over-application causes eutrophication, which is harmful to both soil and plants [23]. These fertilizers seep into adjacent streams and rivers, contaminating water and harming fish and other aquatic animals. Conversely, plants gradually and safely deliver nutrients to the soil. Many plants used for soil fertilization are initially planted as cover crops to mitigate soil erosion from wind and rain [24, 25]. The enhancement of soil fertility necessitates the maintenance of a healthy topsoil layer. Hence, scientists are currently exploring new technologies to produce eco-friendly fertilizers from living organisms, particularly microbes, which can biodegrade without leaving any residues and are known as biofertilizers [26]. Thus, biofertilizers are natural or organic substances containing living microorganisms, primarily bacteria, fungi, or algae, which enhance soil fertility and promote plant growth by fixing atmospheric nitrogen, solubilizing phosphorus, or producing plant growth-promoting substances. Figure 1.2 shows the pictorial representation of the benefits of bio-fertilizers for soil fertility and crop productivity. Unlike chemical fertilizers, which provide nutrients directly to plants, biofertilizers work symbiotically with plants and soil microorganisms to improve soil health and nutrient availability. There are several types of biofertilizers, each with specific modes of action and benefits. Bio-fertilizers derived from marine biomass offer multiple benefits for sustainable agriculture, including nutrient enrichment, soil health improvement, environmental conservation, and cost effectiveness [27–29]. Their widespread adoption has the potential to contribute to more resilient and environmentally friendly agricultural practices while enhancing food security and livelihoods worldwide [30].

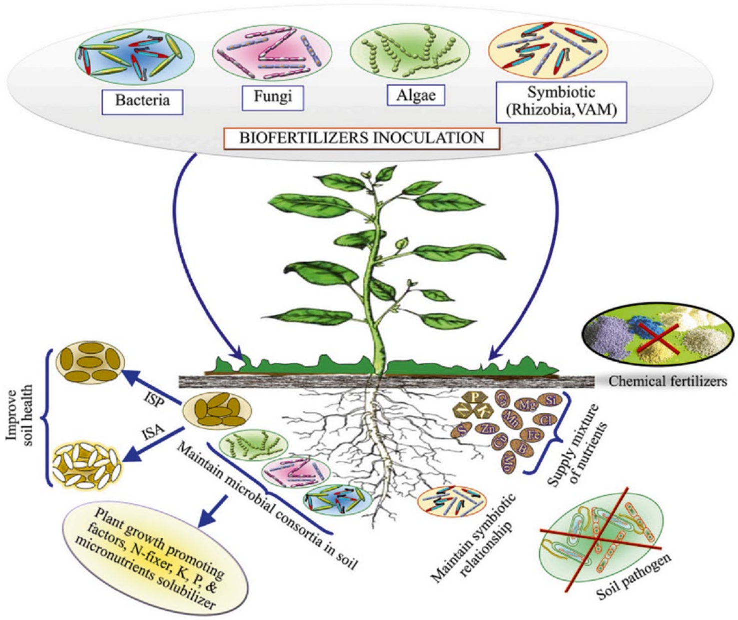

Fig. 1.2 The benefit of biofertilizers toward soil fertility and crop productivity [27]

1.4 Environmental Benefits

Marine-based bio-fertilizers contribute to environmental sustainability and resilience in the face of climate change [23]. Bio-fertilizers derived from marine biomass offer significant environmental benefits, including reduced dependence on chemical fertilizers, decreased soil and water pollution, improved soil health, conservation of marine resources, and carbon sequestration, which are described below.

Marine-based bio-fertilizers provide a natural and sustainable alternative to synthetic chemical fertilizers [31]. By reducing the dependence on chemical inputs, particularly N- and P-based fertilizers derived from fossil fuels, the environmental burden associated with their production, transportation, and application is mitigated [32]. This helps to minimize the release of greenhouse gases, such as CO_2 and N_2O, during fertilizer manufacturing and application, thus contributing to climate change mitigation efforts.

Unlike chemical fertilizers, which can leach into groundwater and surface water bodies, marine-based bio-fertilizers have minimal environmental impact and do not contribute to soil and water pollution [33, 34]. They are biodegradable and non-toxic, posing no risk of contaminating water sources or harming aquatic ecosystems. By promoting nutrient cycling and reducing nutrient runoff, bio-fertilizers help to maintain water quality and protect biodiversity in freshwater and marine environments.

Marine-based bio-fertilizers enhance soil health and fertility by replenishing essential nutrients, improving soil structure, and stimulating microbial activity. They promote the growth of beneficial soil microorganisms, such as nitrogen-fixing bacteria and mycorrhizal fungi, which play key roles in nutrient cycling, organic matter decomposition, and soil structure formation [35]. By enhancing soil organic carbon content and water retention capacity, bio-fertilizers contribute to soil erosion prevention and drought resilience, thereby supporting ecosystem stability and biodiversity conservation.

Utilizing marine biomass for bio-fertilizer production helps to conserve marine ecosystems and biodiversity [34]. Instead of relying on unsustainable practices such as overfishing or destructive harvesting methods, marine-based bio-fertilizers utilize renewable resources, such as seaweed and algae, which can be sustainably harvested or cultivated without causing significant environmental harm. By promoting responsible resource management and ecosystem stewardship, bio-fertilizers contribute to the conservation of marine biodiversity and the preservation of coastal ecosystems.

Marine-based bio-fertilizers have the potential to sequester carbon dioxide from the atmosphere and mitigate climate change [36]. Seaweed cultivation, for example, can act as a carbon sink, absorbing CO_2 during photosynthesis and storing carbon in biomass and ocean sediments [37]. By incorporating seaweed-derived organic matter into agricultural soils, bio-fertilizers enhance soil carbon sequestration and contribute to climate change mitigation efforts. Additionally, the cultivation of marine biomass for bio-fertilizer production can help to reduce greenhouse gas emissions associated with conventional agricultural practices, such as fertilizer production and land-use change.

1.5 Agricultural Benefits

Bio-fertilizers derived from marine biomass offer significant agricultural benefits, including nutrient enrichment, soil conditioning, sustainable nutrient management, improved crop quality, reduced environmental footprint, adaptability to organic farming practices, and cost-effectiveness [37]. By harnessing the natural potential of marine resources, bio-fertilizers contribute to sustainable agriculture, food security, and environmental conservation.

Marine-based bio-fertilizers are rich sources of essential nutrients, including nitrogen, phosphorus, potassium, calcium, magnesium, and micronutrients [34, 37]. These nutrients are readily available in forms easily assimilated by plants, promoting healthy growth, flowering and fruiting. By replenishing soil fertility and correcting nutrient deficiencies, bio-fertilizers support optimal crop development and yield potential [38].

Marine-based bio-fertilizers improve soil structure, texture, and fertility, improving soil tilth and fostering aeration, water retention and root penetration [39, 40]. They contribute organic matter to the soil, increasing microbial activity and nutrient cycling, and reducing soil compaction and erosion. This leads to healthier, more resilient soils that are better able to support vigorous plant growth and withstand environmental stresses.

Utilizing marine-based bio-fertilizers enables farmers to adopt sustainable nutrient management practices, reducing reliance on synthetic chemical fertilizers and minimizing the risk of nutrient leaching, runoff, and pollution [41, 42]. By promoting nutrient cycling and soil organic matter accumulation, bio-fertilizers support long-term soil health and productivity, contributing to sustainable agricultural systems and ecosystem resilience.

The application of marine-based bio-fertilizers can lead to improvements in crop quality, including increased nutrient content, enhanced flavor, color, and aroma and extended shelf life [43, 44]. By providing balanced nutrition and promoting plant vigor and stress resistance, bio-fertilizers help to optimize crop yield and quality, ensuring high marketability and consumer satisfaction.

Marine-based bio-fertilizers have lower environmental impacts compared to synthetic chemical fertilizers [23, 26]. They are biodegradable, nontoxic, and environmentally friendly, posing minimal risks to soil, water, and air quality. By reducing greenhouse gas emissions, nutrient runoff, and chemical residues in the environment, bio-fertilizers contribute to environmental conservation and mitigate climate change.

Marine-based bio-fertilizers are compatible with organic and sustainable farming practices, supporting certification requirements and principles of ecological stewardship [45]. They can be used in organic farming systems as alternatives to synthetic inputs, helping farmers meet organic certification standards and fulfill consumer demand for sustainably produced food.

While initial investment and production costs may vary, marine-based bio-fertilizers offer long-term cost savings for farmers by reducing the need for expensive synthetic fertilizers and agrochemical inputs. By improving soil fertility and crop productivity, bio-fertilizers contribute to sustainable productivity gains and economic viability in agriculture, enhancing farm profitability and livelihoods.

1.6 Challenges in Adoption

The rising adoption of biofertilizers represents a recent effort to enhance crop yields and soil fertility by harnessing their ability to fix atmospheric nitrogen, solubilize insoluble phosphate in the soil biologically, and produce growth hormones and vitamins [28]. Additionally, biofertilizers aid in improving soil structure, texture, and water-holding capacity within the agricultural sector [41]. A key and beneficial aspect of biofertilizers is their significant role in reducing environmental pollution and promoting agroecological sustainability [28]. Biofertilizers are economically advantageous for farmers due to their affordability and their critical role in supplying essential nutrients like nitrogen and phosphorus to crop plants. But there still remain many challenges that need to be addressed for their ease of adoption to the mass community.