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Exploring Seaweed Cultivation in the Marine Environment and Its Interaction with Microplastic

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Abstract

Background: Seaweed cultivation in marine environments offers ecological and economic benefits, but the increasing presence of microplastics poses risks. This review explores cultivation techniques and the impact of microplastic pollution on seaweed growth, nutrient absorption, and health. **Methods:** Literature was sourced from Google Scholar and academic databases using keywords related to seaweed cultivation and microplastic pollution, focusing on peer-reviewed articles, books, and credible reports from the past decade. Studies were selected based on methodological rigor, relevance, and source credibility. The literature was synthesized to highlight key patterns, trends, and knowledge gaps on the impact of microplastic pollution on seaweed farming. **Results:** Seaweed aquaculture provides food, biofuel, pharmaceuticals, and environmental benefits, varying cultivation methods by species, environment, and product. Despite growing demand, microplastic pollution threatens seaweed farming and marine ecosystems. This study explores seaweed's role in microplastic retention, its potential as a bioindicator, and its broader impact on marine health. Urgent action is needed to address plastic and microplastic emissions and mitigate long-term environmental and health risks. **Conclusions:** Seaweed aquaculture provides food, biofuel, and ecological benefits. However, microplastic pollution threatens its sustainability. Immediate action is required to address plastic pollution, as it poses long-term risks to marine ecosystems and human health. Governments are increasingly focusing on mitigation measures to address these pressing issues.

Keywords: Aquaculture: Benefit; Marine environment; Microplastic; Seaweed

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Introduction

Seaweed is recognized as an up-and-coming resource due to its adaptability, rapid growth cycle, and sustainability (Critchley et al., 2020). It offers a significant solution to potential future resource challenges. In recent years, algae resources have experienced substantial growth, driven by the rising global demand and production of seaweed. Over the past two decades, various aspects of seaweed cultivation, production, and processing have been studied extensively, including current practices and advancements in farming techniques (Garcia-Poza et al., 2020).

Seaweed has long been valued as a significant nutritional resource, especially in Asian countries, and has recently gained prominence in Europe, South America, North America, and Australia. Edible seaweeds are rich in proteins, lipids, and dietary fibers. Globally, seaweed is utilized in the production of food and fertilizers. Additionally, seaweed contains abundant bioactive compounds with applications in the nutraceutical, pharmaceutical, and cosmetic industries, making it a valuable resource for various industrial sectors (Garcia-Poza et al., 2020).

Ahmed et al. (2022) highlight that seaweed farming provides financial opportunities and a vital source of income for marginalized coastal communities. Recognizing this potential, international development organizations promote seaweed farming among coastal rural populations as a strategy for poverty alleviation.

Seaweeds, also called macroalgae, differ from microalgae (Cyanophyceae), microscopic, predominantly unicellular organisms, often recognized as blue-green algae responsible for blooms in rivers and streams. Seaweeds are broadly categorized into three groups based on pigmentation: brown (Phaeophyceae), red (Rhodophyceae), and green (Chlorophyceae) (Pinak, 2022).

The global seaweed industry is experiencing rapid growth due to its high economic value. As of recent estimates, global seaweed production has surpassed 32.4 million tonnes, marking a threefold increase compared to production levels in 2000 (Cai et al., 2021).

Integrated multi-trophic aquaculture (IMTA) systems can be tailored to various regions' specific physical, chemical, environmental, biological, social, and economic conditions. IMTA promotes sustainable aquaculture, offering environmental, financial, and societal benefits (Khan et al., 2023).

There are different methods of seaweed farming, with the specific technique employed by each farmer contingent upon the type of seaweed, its taxonomy, and unique characteristics. About seven established seaweed farming techniques are practiced by farmers in different parts of the world. These methods include floating rafts, tube nets, off-bottom monoclines, PVC pipe rafts, cage systems, multiple raft long lines, and spider web systems (Behera et al., 2022).

The cultivation of seaweed has been a challenging factor for many farmers in Asian countries, as well as in Europe and America. Microplastic invasion is one of the factors that affect seaweed cultivation. Microplastics are found throughout the world's oceans, from tropical estuaries to Polar Regions, spanning surface waters to deep-sea habitats. They pose risks to organisms through both physical and toxic effects (Li et al., 2023).

Thus, it is imperative to formulate comprehensive policies and regulations to tackle the serious issues of microplastic pollution in the marine ecosystem. To avoid future threats to our marine ecosystem, we must discourage plastic production and promote environmentally friendly alternatives that support seaweed aquaculture (Chatterjee & Sharma, 2019).

Challenges in seaweed farming and processing have been analyzed, and countermeasures have been proposed to improve practices (Zhang et al., 2022). Preventive strategies, including quarantine measures and enhanced aquaculture practices, are recommended as effective solutions (Campbell et al., 2019).

Seaweed naturally interacts with its surrounding environment, including microplastics, which can impact its growth and biochemical composition. While seaweed produces biochemical compounds to defend against epiphytism, its role in microplastic retention and potential bioaccumulation remains a growing concern. Understanding the biotic and abiotic factors influencing seaweed cultivation is essential for assessing the extent of microplastic contamination and its ecological consequences. This review explores the interactions between seaweed cultivation and microplastic pollution, highlighting the mechanisms of microplastic adherence, potential pathways into the marine food web, and sustainable strategies to mitigate contamination in aquaculture systems.

Methods

Asia has become the leading continent in the world, predominantly known for seaweed farming. People on this continent see seaweed as a source of food, employment, biomedical income, etc. Most families in rural communities depend on seaweed farming for sustainable living conditions. In response to the positive outcomes witnessed in Asian countries, several European and American nations have ventured into seaweed cultivation. The profound impacts of seaweed cultivation date back two decades and have created many opportunities for the farmers involved. Nonetheless, the practice of seaweed cultivation came with some significant constraints, such as the prevalence of microplastic, which occurs due to plastic accumulation in the sea around the seaweed farms.

This study endeavors to provide insights into various pivotal research questions. These include an examination of why Asia has assumed a leading role in seaweed farming in recent years, the repercussions of seaweed aquaculture on the marine ecosystem, the challenges faced in seaweed farming and their implications for the marine environment, the advantages reaped by farmers engaged in this practice, the influence of seaweed farming on biodiversity and the overall health of the aquatic ecosystem, the essential factors and design considerations for sustainable seaweed farming, and an exploration of the potential impacts of microplastics on seaweed farming, along with the requisite measures to ensure its sustainability within the marine ecosystem.

Various articles were identified using the search engines Google and Google Scholar. Keywords used in searching for references include seaweed farming, seaweed aquaculture, sea cultivation, marine ecosystem, and marine microplastic.

Result

Seaweed Aquaculture in Marine Ecosystem

Seaweeds have long been a dietary staple in coastal regions, especially in East Asia. They have been increasingly utilized beyond direct consumption, notably in industries, for unique polysaccharides. The rising demand for seaweed and its derivatives, such as sugar, alginate, and carrageenan, has driven advancements in production technologies.

Seaweeds are diverse, and there is no universal approach to their claims. Different seaweeds and their extracts possess unique properties, leading to specific applications. As such, not all seaweeds can deliver the same benefits or fulfill all claimed uses. The natural products are those in which the seaweed is used as the end product. These may be whole, ground, or dried. Such products are mainly used for human food, animal feed, and fertilizers. The derived products are those manufactured from seaweeds by chemical process. Historically, these products have included various materials such as iodine, acetone, and decolonization carbon (Hurtado et al., 2020).

Types of Seaweed Cultivated in Marine Ecosystem

Marine algae, commonly known as seaweeds, are classified based on their distinctive pigment colors. These classifications encompass green algae (Chlorophyceae), blue-green algae (Cyanophyceae), brown algae (Phaeophyceae), and red algae (Rhodophyceae) (Pinak et al., 2022).

The green seaweed, Chlorophyceae, is found in fresh and salt water. Some varieties grown on trees, and others grow on terrestrial locations. Marine marine forms are better developed than freshwater ones (Darmawan et al., 2022).

The brown seaweed (Phaeophyceae), which is part of most of this group of seaweeds, is either unicellular or multicellular. The size may vary from microscopic filament with branches to microscopic thallic. Brown seaweeds are best grown in the colder waters of the ocean. Some larger forms are called rockweed because they cover rocks between the low and high tides. On the other hand, the most significant form is called kelps. This alga grows best below or at the low tide; sometimes, they combine to form a sea bed. This algae can overcome the battering of heavy surfs because of its firm texture and strong holdfast. The smaller forms are generally grown in quiet waters and are membranous or cordlike (Remya et al., 2022).

Red seaweed (Rhodophyceae) generally flourishes in water, unlike brown seaweed. They are usually found in deeper waters, and some of their other forms grow to 200 feet or more. The depth depends on the cleanliness of the water in which the seaweed is grown. Since most red seaweeds prefer shaded locations, their characteristic color is probably associated with their habit of growing where the light is subdued (Ondarza, 2022).

Techniques in Seaweed Cultivation

Seaweed cultivation is an emerging food production sector that can help meet the growing global food demand. Asia plays a key role, with seven of the top ten seaweed-producing nations contributing 99.1% of all seaweed cultivated for food. There are different methods that farmers use during seaweed farming. These methods are influenced by factors such as location, the variety of the seaweed, taxonomy, depth of the sea, etc. According to Jaikumar et al. (2022) and (Behera et al., 2022), some methods used in seaweed cultivation are discussed below.

Floating Raft: The floating raft (**Figure 1**) method provides favorable environmental conditions during seaweed farming, enhancing economic, eco-friendly, and user-friendly activities. The disadvantages of this method can be considered to be sensitivity to weather changes, more ecological risks such as microplastic invasion, pests, disease, and lack of uniform growth.

Figure 1. Floating raft method
source: https://www.researchgate.net/profile/Kaladharan-P?

Tube Net: The Tube net method of seaweed farming (**Figure 2**) is practiced by farmers due to low-risk weather conditions, uniform growth rate, and suitability for deep waters with minimal infrastructure requirements. There are limitations to this seaweed farming technique because it involves using more seedlings, it's not user friendly, not eco-friendly, and has poor economic benefits.

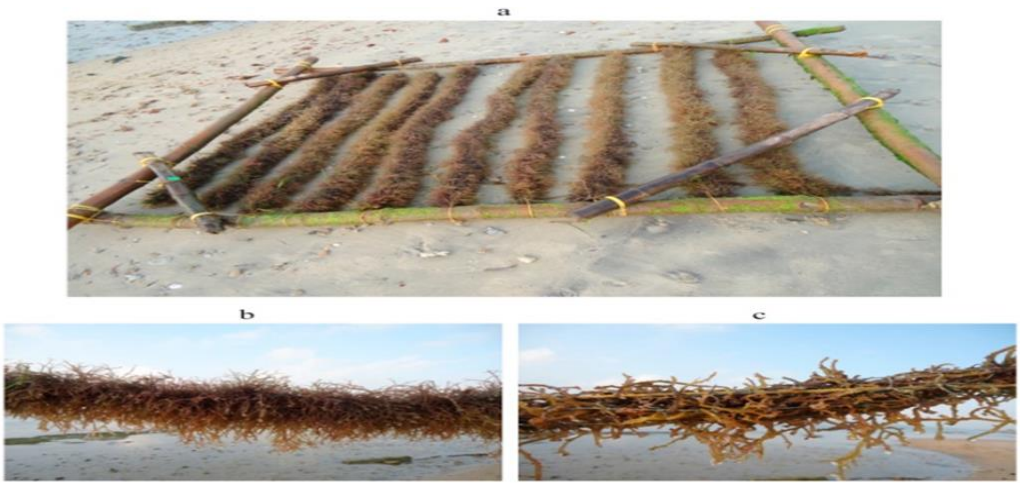

Figure 2. Floating raft method
source: https://www.researchgate.net/profile/Kaladharan-P?

Off-bottom monoline: This method of seaweed farming is easy to handle, particularly during low tides. Commercial or large-scale farmers commonly use this method. The farm is cheap to maintain and easy to install (**Figure 3**). It has low capital investment during its implementation. The disadvantage of the off-bottom monoline is that the system leads to the loss of many seedlings. This seaweed farming is vulnerable to various factors such as wind, tides, and storms. Controlling epiphytes (growing on other plants) is challenging, and their removal becomes difficult during adverse weather conditions.

Figure 3. Off bottom monoline
source: Jaikumar et al., 2022

Cage System: The cage system (Figure 4) is a technological design used for seaweed cultivation. It helps protect seaweed from pests and minimizes the risk of disease infection. In this method of seaweed farming, mechanisms are also developed to control epiphytes. The cage system is sustainable and reliable in case of bad weather conditions (Kasim et al., 2020).

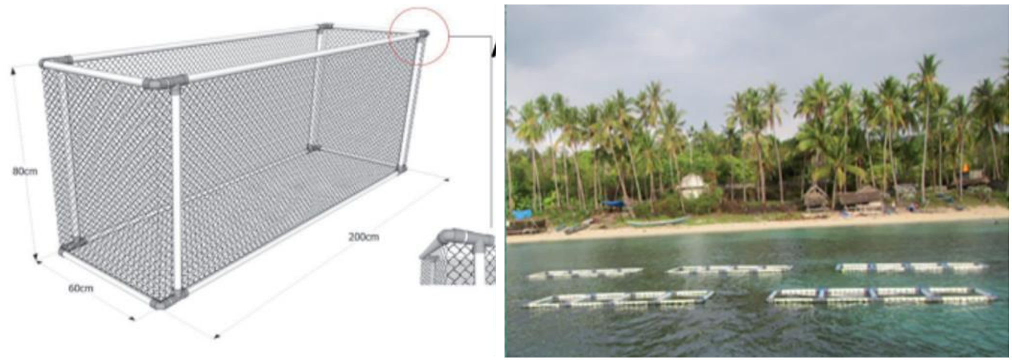

Figure 4. Cage system
source: Kasim et al., 2020

PVC Pipe Raft: This method of seaweed farming closely resembles the tube net method, as it floats effortlessly and is simple to handle. However, its main drawbacks are high implementation and maintenance costs, along with being less eco-friendly.

Multiple Rafts: This seaweed farming method is well-suited for commercial and large-scale operations. However, it has drawbacks, including potential ecological concerns such as shading effects and increased proliferation of epifaunal or epiphytic organisms. Additionally, it carries a high risk of loss during adverse weather conditions.

Spider Web Method: The spider web method (Figure 5) effectively maximizes production in limited areas, while the floating method offers more significant ecological advantages, particularly when integrated with polyculture systems. The spider web method is also used in open water bodies with depths of 10 to

20meters. In this system, there is a high risk of epiphytes and it is sensitive to weather changes. The spider web method is labor intensive.

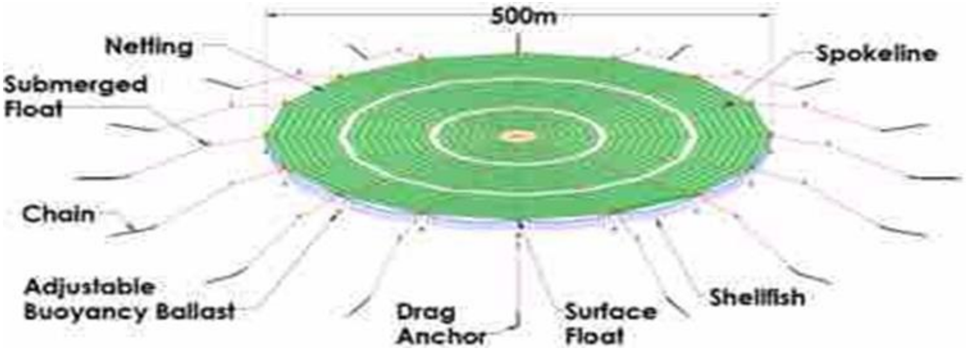

Figure 5. Spider web method
Source: Capron et al., 2018

Seaweed Farming Methods

To address the increasing demand for high-quality seaweed, driven by population growth and commercial and small-scale farming, while preserving marine ecosystems from over-exploitation, developing and sustaining an efficient and sustainable seaweed cultivation system is essential. Seaweed farming can be divided into three main techniques.

Open sea cultivation (offshore and near shore): This technique involves cultivating seaweed at a specified minimum distance from the coastline. Offshore or open sea cultivation supports commercial production, as seaweed grown in such systems is typically reserved for high-value products. However, due to inadequate coastal space availability, environmental impacts, and seaweed species, the best and most profitable technique is land-based/offshore production. Ultimately, the expansion towards large-scale seaweed cultivation is likely to be more feasible offshore rather than in coastal waters. This is due to more stable temperatures, excellent water mixing, and higher availability of light and nutrients. The advantages of open cultivation are that it has a low installation and maintenance cost and seaweed seedlings. The technique has disadvantages such as susceptibility to adverse environmental conditions (tides, waves, and wind) and infection by microscopic organisms (epiphytes), which cause biomass loss, and year-round cultivation is impossible. The technique must be extensively developed and implemented across various geographical locations To reduce environmental risks and ensure economic viability (Wilding et al., 2021).

Land-based (onshore) cultivation: This widely recognized and commonly employed technique is typically established in estuaries and nearshore areas, where access to clean water, along with precise control of temperature, lighting, and nutrient availability, ensures optimal growth conditions. The technique can be installed in any geographical area and closed systems such as ponds, tanks, and raceways near the coast where seawater availability and other climatic conditions support the growth of seaweed (Echeverri et al., 2022).

The land-based technique offers advantages like cultivating multiple seaweed species in the same area. It is cost-effective, requires minimal labor, and supports bioremediation of basins polluted with nutrients, primarily from agricultural activities. This system has some disadvantages, such as the high cost of building infrastructure, the inability to maintain optimal growing conditions, and the scarcity of land.

Integrated Multi-trophic Aquaculture (IMTA): This system achieves bio-mitigation and increased biomass production by integrating various commercially valuable aquatic species with different feeding habits. Integrated Multi-Trophic Aquaculture (IMTA) provides farmers with environmental and economic benefits. Rather than focusing on a single species, IMTA combines multiple organisms from different food chain levels, utilizing uneaten feed, waste, nutrients, and by-products from one species to fertilize, feed, and support the growth of others. Integrated multi-trophic aquaculture can be viewed as an experimental approach that targets developing and establishing an aquatic food production system with different variations that can be tailored to various regions. (IMTA) can be adapted to land-based and offshore aquaculture systems in salt and freshwater ecology (Johnson et al., 2020).

Importance of Seaweed Aquaculture

Seaweed cultivation is easy, eco-friendly, and does not harm water quality or other marine organisms, as it involves non-invasive species. It improves the livelihoods of both small and large-scale farmers, offering additional income for sustainable growth. Seaweed farming provides job opportunities for coastal communities, ensures a steady supply of high-quality raw materials for the seaweed industry, and helps conserve wild seaweed populations (Jaikumar et al., 2022).

Economic Benefits of Seaweed Cultivation

Seaweed species are considered healthy, low-calorie foods, especially for those on low-carbohydrate or plant-based diets, which are non-toxic and edible. Both dried and fresh seaweeds provide essential vitamins and minerals. They are rich in micronutrients, fiber, and bioactive compounds, offering promising health benefits (Shannon & Abu Ghannam, 2019; Balboa et al., 2022; Bhatt et al., 2022; Cotas et al., 2022; Debbarma et al., 2022; Malyarenko et al., 2022). While seaweed's nutritional and sensory benefits as whole or functional foods are acknowledged, they vary across species and environments. Small-scale farmers can benefit from food and nutrition security through household consumption and dietary improvements (Rimmer et al., 2021).

When dried or milled into powder, seaweeds can be used as animal feed. Seaweeds are considered a valuable feed for both ruminant and non-ruminant livestock, enhancing animal rations with their rich protein, fiber, and phytochemicals, which improve nutritional quality (Morais et al., 2020). They are also an excellent source of organic fertilizer for local and commercial farming communities. Seaweeds such as brown seaweed contain a good amount of nitrogen and potassium and less phosphorus when compared to animal manure and chemical fertilizer (N, P, K). Green seaweed, when decomposed, can be used as compost manure, which is a nutrient provider in the marine ecosystem. As an organic fertilizer, seaweed helps address nutrient deficiencies in plants, such as nitrogen, phosphorus, and potassium and shows great potential for commercialization. Researchers worldwide recognize its importance, and its use provides a promising alternative to the harmful effects of chemical fertilizers (Raghunandan et al., 2019).

Seaweed cultivation has generated employment for thousands of people within the local and commercialized coastal farming communities. In Asia and Africa, where seaweed aquaculture has gained prominence, approximately 80% of local communities participate in cultivating seaweed as a primary livelihood. Seaweed farming is a rapidly growing sector within aquaculture and is regarded as a more sustainable farming method. Moreover, the prospective development of a new supply chain based on cultivated seaweed could strengthen the path towards a circular clue bio-economy and promote revenue sources and employment opportunities to the marine communities (Cerca et al., 2022).

Environmental Benefits of Seaweed Cultivation

Abrasion control: Environmental denudations such as abrasion are a significant factor affecting most coastal settlements, thereby leading to soil depletion, loss of topsoil, loss of organic manure, destruction of soil structure, soil texture, soil living micro-living organisms, etc. (Farghali et al. 2022). Seaweed in seaweed farming acts as a buffer in controlling soil abrasion. It helps stabilize sediments to reduce wave impacts and protect the shoreline from damages caused by abrasion.

Coastal resource protection through climate change mitigation and carbon sequestration: Seaweeds such as green seaweed contain chloroplast, a green pigment used in photosynthesis. Carbon dioxide (CO2) is used by seaweed during photosynthesis as an energy source, reducing carbon footprints and greenhouse gas emissions. Coastal land resources are increasingly overburdened, particularly in economically developed and densely populated areas, making them highly valuable. As a result, seaweed cultivation offers a sustainable solution by conserving significant amounts of land, which can help protect the environment and better use resources in coastal provinces (Zheng et al., 2019).

Improving biodiversity living conditions: Seaweeds contribute to the marine ecosystem by enhancing good health conditions and resilience by providing habitat and shelter to aquatic organisms such as fish and other microorganisms. Most globally farmed seaweed is processed for direct human consumption or into hydrocolloids, which are used as stabilizers, thickeners, suspending agents, and gelling agents in food products. Due to the high demand for seaweed production in Asia, America, Europe, and Africa, seaweeds are harvested many times in a single growing season. This renewable nature makes seaweed a sustainable source of biomass for various applications such as food, feed, biofuel, and bio-plastics (Feehan, 2023).

Challenges Faced in Seaweed Aquaculture Farming

The challenges farmers face in seaweed production include crop production fluctuation after harvesting, contributing to farmers' low-income generation from the seaweed. This issue results from inadequate knowledge and capital in seaweed cultivation. The low production of seaweeds has caused farmers to have limited production factors such as seeds, labor availability, land area, and insufficient capital. Due to low seaweed production, most small-scale farmers receive low income after tedious farm work (Marhawati et al., 2020).

Seaweed Disease Infection: Due to the flourishing and increasing demand in seaweed and seaweed industry on different continents, there is an increase in disease prevalence and aquaculture pests. In some tropical regions, seaweeds are prone to various diseases, with seaweed farming being particularly vulnerable to environmentally driven diseases like ice-ice and other infectious pests. These challenges pose a long-term risk to communities that rely heavily on seaweed farming as they become increasingly susceptible to climate-induced disease burdens (Spillias et al., 2023).

Harvesting and Handling: Seaweed harvesting and handling are technical processes requiring careful treatment. Reckless and mismanaged handling and harvesting can reduce seaweed quality, quantity, and market value (Sugumaran et al., 2022).

Microplastics in the Marine Ecosystem and Seaweed Aquaculture

These are small pieces of plastic particles less than 5mm in length that move in the marine ecosystem due to plastic pollution. Plastic pollution has become a challenging environmental effect worldwide (Tan et al., 2022). Microplastics are carbon and hydrogen atoms chemically bonded together in long polymer chains. Many of the chemical additives found in plastic leach to the environment, causing damage to marine organisms (Rogers, 2023).

Microplastics are distributed throughout the ocean and other water bodies, occurring on shorelines, surface water, and seabed sediments. Microplastics are discarded particles entering the sea through land and sea-based activities. Yet, there are no reliable estimates of the quantities involved at regional or global scales (Proskurowski, 2023).

Plastic pollution is undoubtedly an emerging issue that requires worldwide cooperation with immediate mitigation strategies. Its consequences affect the entire planet and its biodiversity. Microplastic pollution and its effects threaten ocean health, the health of marine species, marine life contamination (seaweeds and other aquatic organisms), human health, and coastal tourism and contribute to climate change impacts (Chatterjee & Sharma, 2019). Reducing the presence of plastics in our marine ecosystem will not only assist us in protecting marine species and the ecosystem and improve our health and the environment in general.

Today, plastic production and its uses are still at their highest, but there is a low percentage of about 10% of the produced plastics that have been recycled, which is not promising at all. The rest is either incinerated, causing air pollution, or it ends up in the oceans and marine ecosystem, causing negative impacts on the aquatic biodiversity through microplastic contamination (Fava, 2022).

Sources of Microplastics

According to National Geography (2022), different sources of microplastic affect the marine ecosystem, leading to a significant loss in quality, quantity, and economic value. These sources are categorized into two: primary and secondary microplastic sources. Primary microplastic sources are tiny particles such as cosmetics products and microfiber obtained from clothing, textiles, fishing nets, personal care products, and plastic pellets obtained from the environment to cause pollution in the marine ecosystem. Primary microplastics enter the aquatic ecosystem through human interference (waste dumping), transportation, and other anthropogenic activities. Secondary microplastic sources are microplastic sources that occur due to the breaking down of large plastic items such as water bottles, plastic buckets, etc. This breakdown is caused by exposure to environmental factors, mainly sun radiation and ocean waves (Yan et al., 2021).

As a result of inadequate waste disposal, solid materials such as plastics, glasses, metals, paper, rubber, textiles, processed timber, cigarettes, cups, and beverage bottles are usually discharged into the marine ecosystem due to the increase in human population. Removing plastic waste from the ecosystem is a vast socioeconomic cost, and financial constraints are estimates of economic losses of marine ecosystems (Onyena et al., 2022).

Microplastic breaking down into tiny particles to form dust particles called nanoplastics is challenging to measure as it's impossible to be separated from the environment. This microplastic is very toxic to seaweed and other marine life (Begum, 2020).

Impacts of Microplastics in the Marine Ecosystem

Microplastics are transported in the aquatic ecosystem through surface water runoff, blowing wind, anthropogenic activities, etc. Plastics are composed of polymers that are overall buoyant materials accumulated in water bodies in the marine ecosystem. When plastic pollution is fragmented, these tiny particles are easily transported through the aquatic environment. The impacts of microplastic in the marine ecosystem include the following (Sangiolo, 2022).

Microplastics can adversely affect plants by hindering or slowing seed germination, suppressing growth, modifying root structures, diminishing biomass, and disrupting photosynthesis. Microplastics are particles that can accumulate in seaweed tissues, resulting in direct exposure to farm-raised organisms and subsequent ingestion by higher trophic levels. This accumulation can reduce seaweed quality, quantity, and economic value (Bosker et al., 2019).

Marine microplastics have significantly impacted various seaweeds and aquatic organisms, reducing food intake, stunted growth, oxidative stress, and abnormal behaviors. Due to their small particle size, microplastics are pervasive in marine ecosystems. They are readily ingested by aquatic organisms, causing a range of harmful effects such as impaired growth and development, altered feeding patterns, behavioral disruptions, reproductive and immune system toxicity, and genetic damage. These contaminants are among the most detrimental pollutants, adversely affecting seaweed cultivation's growth and overall health. The accumulation of microplastic particles in the marine ecosystem has resulted in seaweeds' inhibition and uptake of harmful nutrients, leading to stunted growth and reduced biomass content (Li et al., 2021).

The consequences of microplastic pollution in the marine ecosystem are an issue of concern nowadays due to its harmful effects on the aquatic biota. Harmful contaminants attached to microplastic serve as a vector to the marine environment, causing physiological effects such as poor health, poor economic service, reduction in seaweed quality, exposure to toxic chemicals, boss of biomass content, etc. The absorption of these microplastics by seaweeds has contributed to the health of seaweed consumers due to the high toxicity content of microplastics in seaweeds (Chatterjee & Sharma, 2019).

A range of ecological factors, in addition to geographic considerations, influence the presence of microplastics in marine ecosystems. Due to their small size, shape, and both physical and toxic properties, microplastics are easily ingested by marine organisms such as zooplankton, mollusks, and fish. Seaweeds can trap microplastics by reducing water flow velocity or through direct contact. Microplastics can become incorporated into the food web when organisms consume seaweed at various trophic levels. As a result, there is a significant risk of microplastics entering the human body through the food chain, potentially leading to adverse health effects (Cham & Yasman, 2024). There have been a lot of changes in the nutritional composition of seaweed cultivation due to microplastic contamination. Microplastics absorbed by seaweeds in the marine ecology can transfer harmful chemicals and additives to their tissues, leading to the potential contamination of the food chain. The changes and contaminations in the nutritional value of cultivated seaweed have critical implications on human consumption and raise concerns regarding food safety (Chen et al., 2023).

Measures to Mitigate Microplastic Contamination in the Marine Ecosystem

Several initiatives should be implemented, including implementing waste management strategies, wastewater treatment systems, innovative designs, development regulations, and laws that ban plastics from contributing to microplastic contamination. These measures are essential for ensuring the protection and sustainability of marine ecosystems to address the growing issue of plastic pollution (Roy et al., 2022).

Educational Inclusiveness: One of the first steps in microplastic mitigation is making it part of the school curriculum from primary to elementary school, senior high school, college, and university. The school system covers significant areas such as the origin, types, effects, and other relevant aspects of teaching and learning. Plastics and their pollution agents have caused much destruction to the marine environment and the general ecosystem. This pollution has led to the loss of many marine lives, including the seaweed aquaculture, which affects the entire human population. With the early introduction of this topic to the students at the earliest stage, they can become familiar with the general knowledge of microplastics and their environmental effects. Students should be provided with opportunities, support, and guidance to engage in scientific research and project reports that will help build a strong foundation and generate practical solutions for addressing environmental microplastic issues (Osman et al., 2023).

Awareness and Capacity Building Campaigns: Attitudinal change on the side of the population will contribute immensely towards plastic pollution in our environment. Shifting attitudes toward the conservation and sustainable management of the environment is crucial for improving the quality of marine and coastal ecosystems. Promoting public awareness about plastic waste—such as littering, waste disposal, and the dumping of trash into coastal waters, as well as the impacts of microplastic pollution on marine and coastal environments—can help foster new mindsets among local communities, particularly those in coastal areas (Onyena et al., 2022).

Coastal Marine Area Cleansing: Cleanup initiatives represent another critical mitigation strategy, but they should not be considered the only solution, given the vastness of the oceans and the challenges involved in collecting plastic waste. People living around the coastal areas dump waste along the banks of the rivers and lakes, contributing to plastic waste generation moving into the water bodies. Through coastal community mobilization, communal groups and community development associations organize monthly cleansing exercises around the coastal areas to prevent waste from entering the marine environment (OECD, 2021). However, continued efforts to remove larger plastic debris, which can degrade into microplastics, are crucial. Community involvement is key in driving the behavioral changes needed to reduce plastic waste. These initiatives can help encourage responsible consumption habits and proper waste disposal practices (Yu & Singh, 2023).

Conclusions

Seaweed aquaculture, cultivated for food, biofuel, pharmaceuticals, and environmental benefits, is gaining importance for addressing global challenges like food security, climate change, and sustainable resource use. Cultivation methods vary based on species, environment, and desired product, including open sea, land-based, and integrated multi-trophic methods. However, the rising demand for seaweed is threatened by microplastic pollution, which harms both seaweed farming and marine ecosystems. Immediate action is needed to address microplastic pollution to sustain seaweed aquaculture's growth and protect aquatic life. Increasing plastic in marine ecosystems damages habitats threatens coastal communities' livelihoods, and disrupts natural disaster protection. As plastic pollution continues to rise, its long-term environmental and health risks necessitate mitigation efforts, with governments focusing on reducing microplastic emissions.

Declaration statement

The authors reported no potential conflict of interest.

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