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Advances, Challenges, and Future Perspectives in Algae Aquaculture: A Global Review of Cultivation Technologies, Sustainability, and Industrial Applications

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Abstract

Seaweed aquaculture has emerged as one of the fastest-growing sectors of global aquaculture, driven by increasing demand for sustainable food, feed, bioactive compounds, biostimulants, pharmaceuticals, and bioenergy resources. Algae contribute significantly to nutrient cycling, carbon sequestration, and ecosystem restoration while requiring no freshwater, arable land, or synthetic fertilizers. This review provides a comprehensive assessment of current seaweed cultivation practices, production trends, environmental benefits, economic opportunities, and technological innovations. Major cultivated genera, including *Saccharina, Undaria, Pyropia, Kappaphycus, Eucheuma, Gracilaria*, and *Ulva*, are discussed with respect to life cycles, farming methods, and commercial applications. Particular attention is given to Integrated Multi-Trophic Aquaculture (IMTA), offshore farming systems, selective breeding programs, and digital technologies for precision aquaculture. Challenges related to climate change, disease outbreaks, biofouling, genetic erosion, and regulatory barriers are examined. Future development of seaweed aquaculture will depend on technological innovation, sustainable management practices, and expanded value-chain diversification. The review highlights the essential role of seaweed aquaculture in supporting the transition toward a resilient and sustainable blue economy.

Keywords: Seaweed Farming; Algae; Aquaculture; Blue Economy; IMTA; Sustainability; Offshore Cultivation; Seaweed Biotechnology

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Introduction

The global demand for sustainable aquatic resources continues to increase due to population growth, food security concerns, and environmental degradation associated with conventional agriculture [1]. Seaweed aquaculture has gained considerable attention as an environmentally friendly production system capable of providing food, feed ingredients, hydrocolloids, nutraceuticals, pharmaceuticals, cosmetics, and renewable biomass [2].

Unlike terrestrial crops, marine algae do not require fertile land, irrigation, or extensive chemical inputs. As photosynthetic marine organisms, they efficiently capture dissolved nutrients and carbon dioxide while contributing to ecosystem services, including habitat provision, eutrophication mitigation, and coastal protection [3]. Over the last decades, seaweed cultivation has expanded dramatically, particularly in Asian countries such as China, Indonesia, South Korea, Japan, and the Philippines. More recently, Europe, North America, South America, and Africa have increased investments in commercial seaweed farming due to growing interest in sustainable aquaculture and blue biotechnology [4].

This review aims to synthesize current knowledge on seaweed aquaculture and critically evaluate its role as a sustainable component of the global aquaculture sector. Particular emphasis is placed on worldwide production trends, economic relevance, and the increasing diversification of seaweed-derived products [5]. The review discusses the biology and reproductive strategies of the principal cultivated macroalgae, providing the biological framework necessary for understanding commercial production systems.

Current cultivation technologies, ranging from traditional nearshore farms to emerging offshore and integrated multi-trophic aquaculture systems, are comprehensively examined. In

addition, the environmental and socio-economic benefits associated with seaweed farming are assessed, including nutrient remediation, carbon sequestration potential, biodiversity support, food security, and employment generation [6]. Major constraints affecting the industry, such as environmental variability, disease occurrence, genetic limitations, technological bottlenecks, and regulatory challenges, are also analyzed. Finally, the review explores emerging innovations in breeding, biotechnology, precision aquaculture, and circular bioeconomy applications, offering perspectives on how seaweed aquaculture can contribute to sustainable food systems, climate resilience, and the future growth of the blue economy [7].

Global Status of Seaweed Aquaculture

Historical development

Seaweed cultivation has a documented history spanning several centuries in East Asia, where marine macroalgae were initially harvested from natural stocks before the development of organized farming systems. Among the earliest cultivated species were the red seaweed *Neopyropia yezoensis* (formerly *Porphyra yezoensis*) and *Pyropia tenera*, widely consumed as edible seaweeds in Japan, Korea, and China, as well as the brown kelps *Saccharina japonica* (formerly *Laminaria japonica*) and *Undaria pinnatifida*. These species formed the foundation of traditional seaweed farming and continue to dominate global production of edible macroalgae [8].

The transition from traditional collection methods to modern aquaculture began during the twentieth century, following major advances in the understanding of seaweed reproductive biology and life cycles [9]. Breakthrough studies on the alternation of generations in N. yezoensis and the cultivation biology of *Saccharina japonica* enabled the development of hatchery-based seedling production and controlled cultivation techniques [10]. The introduction of artificial seeding methods, rope-based culture systems, and nursery technologies substantially increased productivity and facilitated the expansion of commercial seaweed farming throughout East Asia [11].

A major milestone in the global development of seaweed aquaculture occurred during the 1970s and 1980s with the successful cultivation of tropical carrageenophyte species, particularly *Kappaphycus alvarezii* and *Eucheuma denticulatum*. These species became highly valued as sources of carrageenan, a commercially important hydrocolloid extensively used in the food, pharmaceutical, cosmetic, and biotechnology industries. Their cultivation rapidly expanded throughout Southeast Asia, especially in the Philippines, Indonesia, Malaysia, and Tanzania, transforming seaweed farming into a major source of income for coastal communities [13].

Simultaneously, cultivation techniques for agar-producing red algae such as *Gracilaria vermiculophylla*, *Gracilaria chilensis*, *Gracilaria edulis*, and *Gelidium amansii* were developed and refined in several regions. These species became important raw materials for agar extraction, supporting the growing demands of the food, microbiological, and biotechnology sectors [14]. In addition, green seaweeds such as *Ulva lactuca*, *Ulva rigida*, and *Caulerpa lentillifera* began attracting commercial interest due to their nutritional value and potential applications in aquafeeds, functional foods, and environmental remediation [15].

During the last three decades, seaweed aquaculture has expanded well beyond its traditional Asian centers [16]. Commercial cultivation activities have been established in Europe, North America, South America, Africa, and Oceania, targeting native and introduced species including *Saccharina latissima*, *Alaria esculenta* (Phaeophyceae), *Palmaria palmata*, *Gracilaria* spp. (Rhodophyta), and *Ulva* spp. (Chlorophyta). This expansion has been driven by increasing demand for sustainable food production, hydrocolloids, aquaculture feeds, biostimulants, nutraceuticals, pharmaceuticals, and renewable biomass [17].

Today, seaweed aquaculture represents one of the fastest-growing sectors of marine aquaculture, encompassing a diverse range of cultivated species and production systems. Ongoing advances in selective breeding, genomics, hatchery technologies, offshore cultivation systems, and Integrated Multi-Trophic Aquaculture (IMTA) are further strengthening the industry's capacity to support global food security, climate resilience, and the sustainable development of the blue economy [18].

Current production trends

Seaweed aquaculture has become one of the largest and fastest-growing sectors of global mariculture, accounting for a substantial proportion of total aquaculture biomass produced worldwide [19]. Over the past few decades, cultivated seaweeds have transitioned from traditional food resources to strategic raw materials supporting multiple industries, including food and feed production, hydrocolloid extraction, nutraceuticals, pharmaceuticals, cosmetics, biofertilizers, biostimulants, biomaterials, and bioenergy. This diversification has significantly increased the economic importance of seaweed farming and stimulated continuous expansion of cultivation activities across both established and emerging aquaculture regions [20].

Despite increasing interest in seaweed farming in Europe, North America, South America, Africa, and Oceania, global production remains overwhelmingly concentrated in Asia, which contributes more than 95% of worldwide cultivated biomass. This dominance reflects the region's long history of seaweed cultivation, advanced hatchery technologies, extensive farming infrastructure, and well-established processing industries [21]. China is currently the world's leading producer, followed by Indonesia, South Korea, and the Philippines, collectively accounting for the majority of global seaweed production [22].

Commercial cultivation focuses on a relatively small number of species that combine rapid growth, high biomass yields, and valuable biochemical properties (Table 1). Brown seaweeds are dominated by the kelps *Saccharina japonica* and *Undaria pinnatifida*, which are extensively cultivated for human consumption, animal feed ingredients, and the extraction of alginates. Additional species such as *Sargassum fusiforme* and *Cladosiphon okamuranus* are also cultivated in certain regions for food and functional ingredients [23].

Red seaweeds constitute another major component of global production and include economically important species such as *Neopyropia yezoensis*, *Pyropia tenera*, *Kappaphycus alvarezii*, *Eucheuma denticulatum*, *Gracilaria chilensis*, *G. vermiculophylla*, and *G. edulis*. These species are primarily cultivated for direct human consumption and for the industrial production of agar and carrageenan, two hydrocolloids widely used in food, pharmaceutical, and cosmetic formulations [24].

Green seaweed currently represents a smaller but rapidly expanding segment of industry. Species such as *Ulva lactuca*, *U. rigida*, *U. prolifera*, and *Caulerpa lentillifera* are increasingly cultivated due to their high nutritional value, rapid growth rates, and potential applications in aquafeeds, functional foods, biostimulants,

Table 1: Major cultivated seaweed species and their principal applications [26-28].

Group	Major Species	Main Applications
Brown algae (Phaeophyceae)	*Saccharina japonica*, *Undaria pinnatifida*, *Sargassum fusiforme*, *Cladosiphon okamuranus*	Human food, alginate extraction, feed ingredients, nutraceuticals
Red algae (Rhodophyta)	*Neopyropia yezoensis*, *Pyropia tenera*, *Kappaphycus alvarezii*, *Eucheuma denticulatum*, *Gracilaria chilensis*, *G. vermiculophylla*	Human food, agar, carrageenan, pharmaceuticals, biotechnology
Green algae (Chlorophyta)	*Ulva lactuca*, *Ulva rigida*, *Ulva prolifera*, *Caulerpa lentillifera*	Functional foods, aquafeeds, biostimulants, bioremediation

and environmental remediation programs [25].

Recent market trends indicate increasing investments in high-value seaweed products rather than solely bulk biomass production. Consequently, commercial interest has shifted toward species rich in bioactive compounds such as fucoidans, phlorotannins, laminarin, ulvans, and sulfated polysaccharides. These compounds are being explored for applications in human health, animal nutrition, cosmetics, and biotechnology, creating new opportunities for value-chain diversification and enhancing the profitability of seaweed aquaculture [29].

Furthermore, the growing recognition of seaweeds as tools for carbon mitigation, nutrient bio-extraction, and ecosystem restoration has stimulated the development of Integrated Multi-Trophic Aquaculture (IMTA) systems and offshore cultivation projects. These emerging production models are expected to play a central role in the future expansion of the sector and strengthen the contribution of seaweed aquaculture to sustainable food systems and the global blue economy [30].

Biology of Cultivated Seaweeds

Classification

Seaweeds comprise a highly diverse group of multicellular marine macroalgae that play fundamental ecological and economic roles in coastal ecosystems worldwide. Although commonly referred to collectively as "seaweeds," these organisms belong to distinct evolutionary lineages and are traditionally classified into three major groups: brown algae (Phaeophyceae), red algae (Rhodophyta), and green algae (Chlorophyta) [31]. Their classification is based on differences in pigment composition, storage compounds, cellular structure, reproductive strategies, and phylogenetic relationships. These biological characteristics not only determine their ecological distribution and environmental adaptations but also influence their suitability for cultivation and industrial applications [32].

Brown algae (Phaeophyceae) are among the most extensively cultivated seaweeds, particularly in temperate and cold-water regions. Their characteristic brown coloration results from the predominance of the accessory pigment fucoxanthin, which masks the green pigments chlorophyll a and c [33]. Many brown algae develop large and structurally complex thalli, enabling high biomass production and making them ideal candidates for commercial cultivation. These species synthesize valuable metabolites, including alginates, fucoidans, laminarin, and phlorotannins, compounds that have attracted considerable interest due to their technological and biological properties [34]. The most important cultivated species include *Saccharina japonica*, the dominant farmed kelp globally, *Undaria pinnatifida*, widely consumed as wakame, *Sargassum fusiforme*, *Cladosiphon okamuranus*, and *Alaria esculenta*. Brown seaweeds are primarily cultivated for food, animal nutrition, hydrocolloid production, and the extraction of bioactive compounds used in nutraceutical and pharmaceutical products [35].

Red algae (Rhodophyta) constitute another major component of global seaweed aquaculture. Their red coloration originates from the abundance of phycobiliproteins, particularly phycoerythrin and phycocyanin, which enable efficient photosynthesis under low-light conditions. Red seaweeds exhibit remarkable taxonomic diversity and often possess complex life cycles involving multiple reproductive stages and alternation of generations [36]. From a commercial perspective, this group is of particular importance because it includes the primary sources of agar and carrageenan, hydrocolloids extensively utilized by the food, pharmaceutical, cosmetic, and biotechnology industries [37]. Among the most economically relevant cultivated species are *Neopyropia yezoensis* and *Pyropia tenera*, which form the basis of the global nori industry, *Kappaphycus alvarezii* and *Eucheuma denticulatum*, cultivated for carrageenan extraction, and several species of *Gracilaria*, such as *Gracilaria* chilensis, *Gracilaria vermiculophylla*, and *Gracilaria edulis*, widely used for agar production [38]. Beyond their industrial value, many red algae contain sulfated polysaccharides and other bioactive compounds with demonstrated antioxidant, antiviral, anti-inflammatory, and immunomodulatory activities [39].

Green algae are characterized by the predominance of chlorophylls a and b, giving them a bright green appearance and making them physiologically similar to terrestrial plants. Compared with brown and red seaweeds, green macroalgae generally exhibit simpler morphologies, rapid growth rates, and exceptional nutrient assimilation capacities. These characteristics make them highly attractive for aquaculture systems designed for biomass production, nutrient remediation, and Integrated Multi-Trophic Aquaculture (IMTA) [40]. The most relevant cultivated species include *Ulva lactuca*, *Ulva rigida*, *Ulva prolifera*, *Ulva compressa*, *Caulerpa lentillifera*, and *Caulerpa racemosa*. In recent years, these species have attracted increasing interest due to their high protein content, balanced amino acid profiles, valuable polysaccharides such as ulvans, and potential applications in functional foods, aquafeeds, biostimulants, and bioremediation programs [41]. In particular, *Caulerpa lentillifera*, commonly marketed as "sea grapes" or "green caviar", has become an increasingly valuable aquaculture commodity in Asian markets [42].

The biological diversity represented by these three macroalgal groups provides the foundation for the remarkable versatility of seaweed aquaculture (Table 2 and 3). Differences in morphology, physiology, biochemical composition, and environmental tolerances allow the cultivation of species adapted to a wide range of climatic conditions and commercial objectives, supporting the continued expansion and diversification of the global seaweed industry [43].

Life cycles

The life cycles of seaweeds are among the most important biological features influencing their cultivation, productivity, and commercial exploitation. Unlike terrestrial crops, many macroalgae exhibit complex reproductive patterns involving the alternation

Table 2: Comparative characteristics of the principal groups of cultivated seaweeds [43].

Characteristic	Brown Algae (Phaeophyceae)	Red Algae (Rhodophyta)	Green Algae (Chlorophyta)
Dominant pigments	Fucoxanthin, chlorophyll *a* and *c*	Phycoerythrin, phycocyanin, chlorophyll *a*	Chlorophyll *a* and *b*
Typical coloration	Brown to olive green	Red, purple, pink to dark brown-red	Bright green
Main storage compounds	Laminarin, mannitol	Floridean starch	Starch
Major commercial polysaccharides	Alginates, fucoidans, laminarin	Agar, carrageenan, sulfated galactans	Ulvans
Morphological complexity	High, often forming large kelps and canopy-forming species	Moderate to high, with diverse morphologies	Generally simple, sheet-like or filamentous forms
Predominant cultivation environments	Temperate and cold waters	Tropical, subtropical, and temperate waters	Wide environmental tolerance from tropical to temperate waters
Growth rate	Moderate to high	Moderate	High to very high
Nutrient uptake efficiency	High	Moderate to high	Very high
Carbon sequestration potential	High	Moderate	Moderate to high
Suitability for IMTA systems	Excellent	Good	Excellent
Major cultivated species	*Saccharina japonica*, *Undaria pinnatifida*, *Alaria esculenta*, *Sargassum fusiforme*, *Cladosiphon okamuranus*	*Pyropia yezoensis*, *Pyropia tenera*, *Kappaphycus alvarezii*, *Eucheuma denticulatum*, *Gracilaria chilensis*, *G. vermiculophylla*	*Ulva lactuca*, *Ulva rigida*, *Ulva prolifera*, *Ulva compressa*, *Caulerpa lentillifera*, *C. racemosa*
Principal commercial products	Food, alginates, feed ingredients, nutraceuticals, pharmaceuticals, cosmetics	Food, agar, carrageenan, pharmaceuticals, biotechnology products	Functional foods, aquafeeds, biofertilizers, biostimulants, biomaterials
Representative bioactive compounds	Fucoidan, phlorotannins, laminarin, fucoxanthin	Carrageenans, agarans, mycosporine-like amino acids, phycoerythrin	Ulvans, chlorophylls, carotenoids, polyphenols, proteins
Main industrial sectors	Food, hydrocolloids, pharmaceuticals, cosmetics, aquaculture	Food, hydrocolloids, pharmaceuticals, biotechnology	Functional foods, agriculture, aquaculture, environmental biotechnology

Table 3: Major cultivated seaweed species and their primary commercial applications [6, 8, 11].

Species	Common Product Name	Main Producing Countries	Main Commercial Uses
Saccharina japonica	Kombu/Kelp	China, South Korea	Food, alginates, feed, nutraceuticals
Undaria pinnatifida	Wakame	China, Japan, South Korea	Food, nutraceuticals, functional ingredients
Pyropia yezoensis	Nori	China, Japan, South Korea	Human food, protein-rich products
Pyropia tenera	Nori	Japan, South Korea	Food and processed products
Kappaphycus alvarezii	Cottonii	Indonesia, Philippines, Tanzania	Carrageenan extraction
Eucheuma denticulatum	Spinosum	Indonesia, Philippines	Carrageenan production
Gracilaria chilensis	Gracilaria	Chile	Agar extraction, food industry
Gracilaria vermiculophylla	Gracilaria	China, Vietnam	Agar and feed applications
Ulva lactuca	Sea lettuce	Europe, Asia	Functional foods, feed, bioremediation
Ulva rigida	Sea lettuce	Mediterranean region	Biofertilizers, feed, IMTA systems
Caulerpa lentillifera	Sea grapes/Green caviar	Philippines, Vietnam, Japan	Fresh consumption, nutraceuticals
Caulerpa racemosa	Sea grapes	Southeast Asia	Food products and functional ingredients
Alaria esculenta	Atlantic wakame	Europe, North America	Premium food products and nutraceuticals
Sargassum fusiforme	Hijiki	China, Japan	Food, traditional medicines, bioactive extracts

of different multicellular generations. These life-history strategies determine how propagules are produced, how seedstock is generated, and how cultivation systems are designed. Consequently, a detailed understanding of seaweed reproductive biology is essential for successful aquaculture operations, selective breeding programs, and long-term industry sustainability [44].

Most cultivated seaweeds display an alternation of generations, in which haploid (gametophytic) and diploid (sporophytic) phases occur during the life cycle. However, the complexity of this alternation varies considerably among taxonomic groups [45]. Green seaweed often exhibits relatively simple life cycles, with isomorphic alternation of generations, whereas many commercially important red and brown algae possess heteromorphic life cycles in which the sporophyte and gametophyte differ markedly in morphology, physiology, and ecological requirements. These differences have important implications for cultivation because specific life stages may be more suitable for propagation, transplantation, or biomass production [46].

Brown seaweeds (Phaeophyceae), including species such as *Saccharina japonica*, *Saccharina latissima*, *Undaria pinnatifida*, and *Alaria esculenta*, typically exhibit heteromorphic alternation of generations. In these species, the large and conspicuous kelp thallus represents the diploid sporophyte, which produces meiotic spores within specialized reproductive structures known as sori. The released

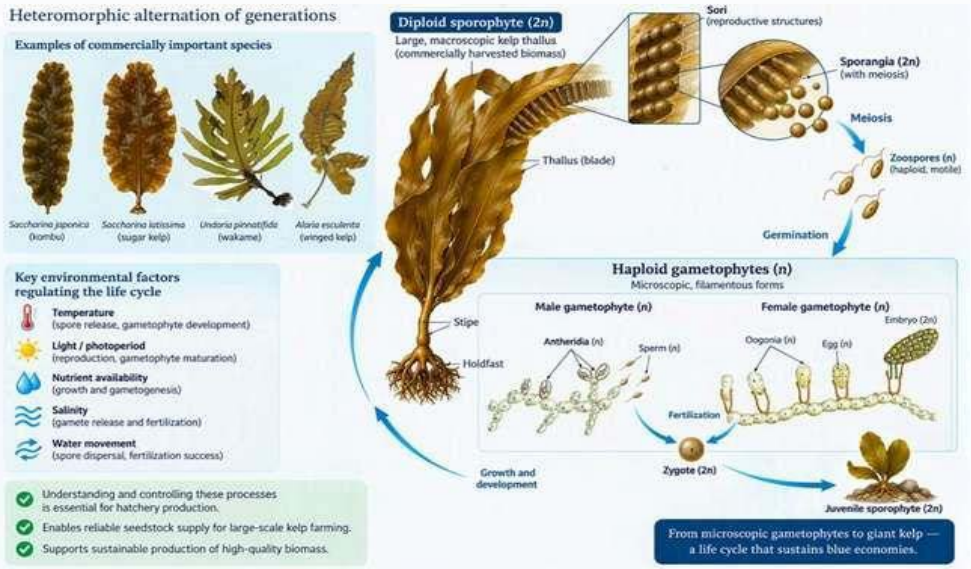


Figure 1: Life cycle of brown seaweeds (Phaeophyceae).

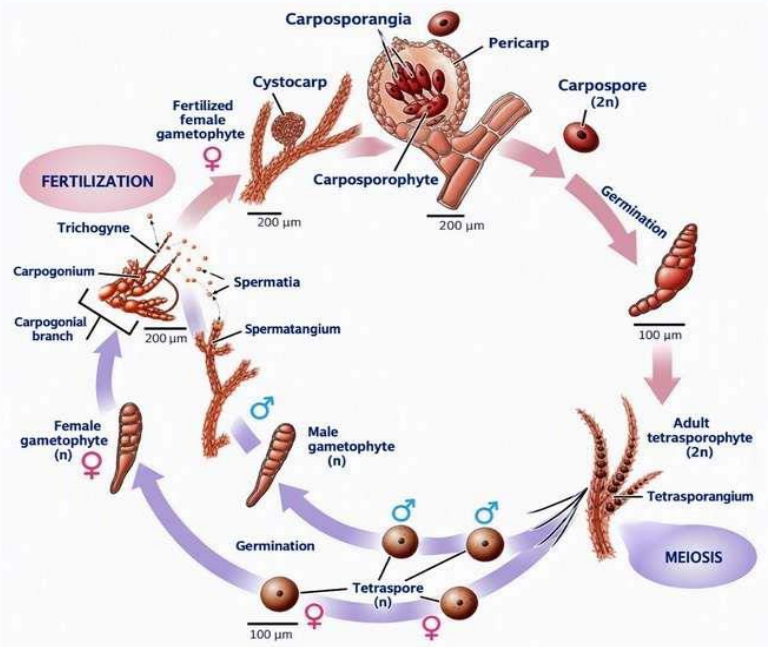


Figure 2: Triphasic cycle of a red alga (*Polysiphonia* type).

spores germinate into microscopic male and female gametophytes that produce gametes. Following fertilization, the resulting zygote develops into a new sporophyte (Figure 1), which ultimately forms the commercially harvested biomass [47]. Knowledge of the environmental factors regulating spore release, gametophyte maturation, and fertilization is critical for hatchery production and large-scale kelp farming.

Red seaweeds (Rhodophyta) often exhibit more complex triphasic life cycles involving gametophyte, carposporophyte, and tetrasporophyte stages [48] (Figure 2). Species such as *Kappaphycus alvarezii*, *Eucheuma denticulatum*, and *Gracilaria chilensis* are cultivated worldwide for food, hydrocolloid production, and biotechnology applications [8].

In *Porphyra*/*Pyropia*/*Neopyropia* species, the life cycle alternates between a leafy gametophytic stage and a filamentous sporophytic stage known as the Conchocelis phase (Figure 3). The discovery and manipulation of the Conchocelis stage revolutionized nori cultivation, enabling controlled hatchery production and industrial-scale farming [49]. Similarly, understanding the reproductive biology of carrageenan-producing species has facilitated the development of more efficient propagation techniques and strain-selection programs [50].

Green seaweeds (Chlorophyta), including species such as *Ulva lactuca*, *U. rigida*, *U. ohnoi* and *Ulva prolifera*, generally display isomorphic or only slightly heteromorphic alternation of generations (Figure 4). In these species, sporophytic and gametophytic stages

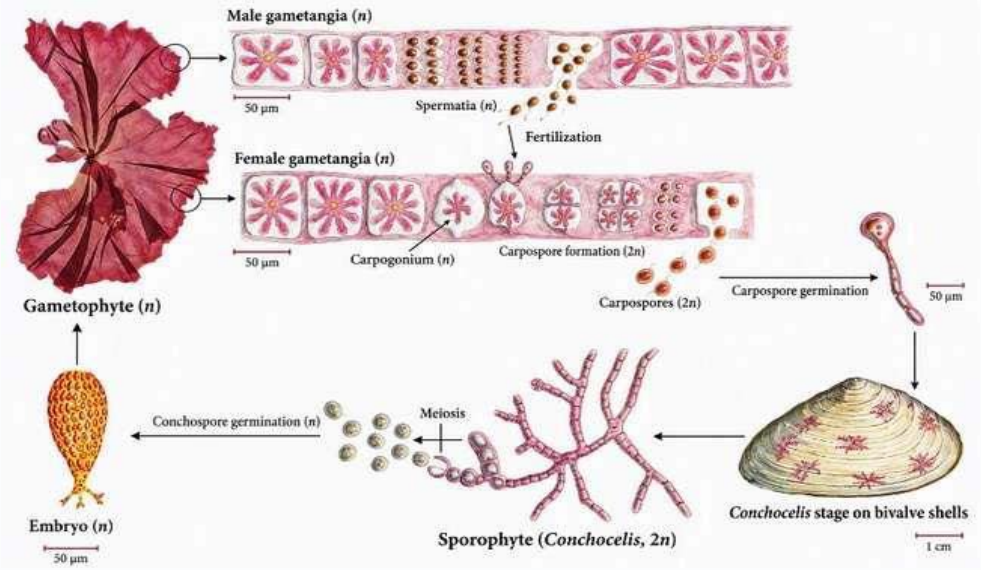


Figure 3: *Porphyra* life cycle.

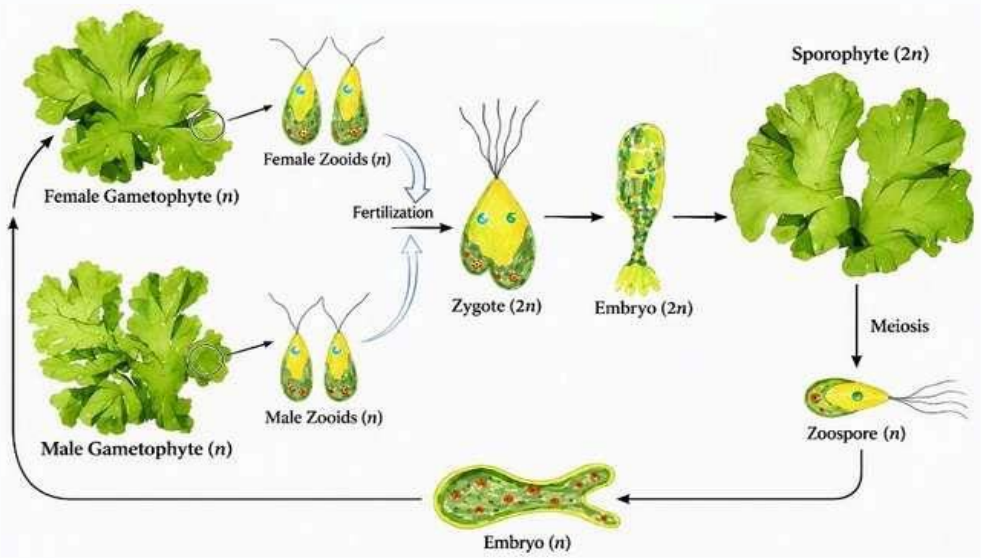


Figure 4: *Ulva* life Cycle.

often appear morphologically similar, making life-cycle identification more challenging [51]. Nevertheless, control of reproductive events remains important because excessive sporulation can reduce biomass yield and affect product quality. Advances in the understanding of reproductive induction mechanisms have improved cultivation strategies for *Ulva* species, particularly in Integrated Multi-Trophic Aquaculture (IMTA) systems [52].

The practical importance of life-cycle management in seaweed aquaculture cannot be overstated. Modern hatchery operations rely on precise control of environmental parameters such as temperature, photoperiod, nutrient availability, salinity, and irradiance to induce reproduction and optimize seedstock production. Successful management of these factors enables the year-round production of juvenile sporophytes or thalli, ensuring a consistent supply of high-quality cultivation material [53]. Hatchery-produced seedlings generally exhibit improved uniformity, enhanced growth performance, and reduced vulnerability to environmental fluctuations compared with naturally collected propagules [54].

A comprehensive understanding of reproductive biology is also fundamental for selective breeding and genetic improvement programs. Controlled crosses between genetically distinct individuals allow the development of strains with desirable traits, including faster growth, enhanced nutritional value, increased hydrocolloid yield, improved resistance to diseases and epiphytes, and greater tolerance to temperature fluctuations and other environmental stressors. The ability to manipulate reproductive stages has therefore become a cornerstone of modern seaweed biotechnology and aquaculture innovation [55]. Furthermore, life-cycle knowledge contributes to the conservation of genetic diversity and the sustainable management of cultivated stocks. Excessive reliance on vegetative propagation or limited genetic resources can increase the risk of genetic erosion and reduce the adaptability of cultivated populations. Maintaining diverse

breeding populations and understanding reproductive dynamics are essential for preserving resilience against climate change, emerging diseases, and other environmental challenges that may affect future seaweed production [56].

Overall, the study of seaweed life cycles provides the biological foundation for hatchery development, seedstock production, genetic improvement, and sustainable aquaculture management. As global demand for seaweed-derived food, feed, pharmaceuticals, biomaterials, and bioactive compounds continues to grow, advances in reproductive biology will remain critical for improving productivity, ensuring genetic resilience, and supporting the continued expansion of the seaweed farming industry [57].

Seaweed Cultivation Systems

Seaweed cultivation systems have been developed to maximize biomass production while adapting to different environmental and economic conditions. The choice of cultivation method depends on factors such as species biology, water depth, hydrodynamic conditions, nutrient availability, and farm management objectives. Among the available approaches, nearshore farming and longline cultivation are the most widely adopted systems for commercial seaweed production worldwide [3].

Nearshore farming

Nearshore farming is practiced in sheltered coastal waters, including bays, lagoons, estuaries, and protected shorelines. This cultivation method is the most common worldwide because of its simplicity, relatively low investment requirements, and ease of management. Species frequently cultivated in nearshore environments include *K. alvarezii*, *E. denticulatum*, *G. chilensis*, *U. lactuca*, and *S. fusiforme*. The proximity of these farms to the coast facilitates routine operations such as seeding, monitoring, maintenance, and harvesting, while also reducing transportation and logistical costs [58]. Nearshore cultivation benefits from natural nutrient inputs and moderate water movement, which support seaweed growth. In many developing coastal regions, these systems provide important socioeconomic opportunities by generating employment and supporting small-scale aquaculture enterprises. However, increasing competition for coastal resources and growing environmental pressures have highlighted some limitations associated with this cultivation approach [59].

The principal advantages of nearshore farming include relatively low infrastructure costs, simple farm management, easy access for maintenance and harvesting, and suitability for community-based production systems. Nevertheless, nearshore farms can be affected by coastal pollution, eutrophication, biofouling, and grazing by herbivorous organisms. In addition, competition with tourism, fisheries, maritime transportation, and coastal conservation activities may restrict the availability of suitable farming areas. Extreme weather events such as storms and strong wave action also pose significant risks to farm infrastructure and crop survival [60].

Longline systems

Longline cultivation is one of the most successful and widely used technologies for commercial seaweed farming. The system consists of horizontal ropes suspended between flotation devices and secured by anchors or mooring structures. Seeded cultivation lines are attached to these ropes, allowing seaweeds to grow within the water column where they can efficiently access sunlight and dissolved nutrients [61]. Longline systems are particularly suitable for large brown seaweeds such as *Saccharina japonica*, *S. latissima*, *Undaria pinnatifida*, *Alaria esculenta*, and *Macrocystis pyrifera*, although they are also extensively used for the farming of commercially valuable red algae [62].

The cultivation process typically begins with the collection of reproductive material from selected broodstock. Seedlings or propagules are produced under controlled hatchery conditions and subsequently attached to cultivation ropes. These seeded lines are then deployed at sea, where the developing thalli remain suspended in nutrient-rich waters throughout the grow-out phase. Regular monitoring is required to evaluate growth performance, manage biofouling, inspect infrastructure integrity, and determine the optimal harvest time [63].

Longline systems offer several advantages over traditional nearshore methods. By utilizing the vertical dimension of the water column, they can achieve high biomass yields while requiring relatively little seabed area [64]. Their scalability makes them suitable for both small commercial farms and large industrial operations, and they can be incorporated into integrated multi-trophic aquaculture systems alongside fish and shellfish production. Furthermore, longline cultivation generally has a lower environmental footprint than many fed aquaculture systems because seaweeds require no external feed inputs [65].

Despite these advantages, longline systems require greater technical expertise and higher initial investment than simpler farming methods. Infrastructure components such as anchors, moorings, ropes, and flotation devices must withstand constant exposure to waves, currents, and storms. Damage to equipment can result in crop losses and increased maintenance costs [66]. In offshore environments, operational complexity and harvesting logistics may also become significant challenges. Nevertheless, the high productivity and adaptability of longline cultivation have established it as a cornerstone technology in modern seaweed aquaculture, and continued technological improvements are expected to further expand its application in offshore farming systems [64].

Raft cultivation

Raft cultivation is a floating farming technique widely used for the commercial production of seaweeds such as *Porphyra*/*Pyropia* spp. (Nori) [67, 68], and *Gracilariopsis longissima* [69]. In this system, cultivation nets or ropes are suspended from floating rafts constructed from bamboo, wood, plastic, or other buoyant materials. The rafts are anchored in coastal waters, allowing the cultivated seaweeds to remain within the optimal zone for light penetration and nutrient uptake throughout the production cycle [68, 69]. This cultivation method is particularly popular in East and Southeast Asia, where it supports large-scale production of edible seaweeds for food and industrial applications. By maintaining the crop close to the water surface, raft systems maximize access to sunlight, thereby enhancing photosynthetic efficiency and promoting rapid biomass accumulation. The continuous movement of water around the suspended thalli also improves nutrient exchange and reduces the accumulation of sediments and epiphytes on the algal surface [70]. Raft cultivation offers several advantages, including efficient light exposure, enhanced water circulation, and high productivity compared with bottom-based cultivation methods. The system also facilitates routine farm management activities such as inspection, cleaning, and harvesting. Furthermore, raft structures can be adapted to different environmental conditions and species requirements, making them highly versatile and suitable for both small-scale and

commercial operations [71].

Despite these benefits, raft cultivation is not without challenges. The structures may be vulnerable to strong winds, storms, and high wave energy, which can damage infrastructure and result in biomass losses [4]. In densely utilized coastal areas, raft farms may also compete with fisheries, navigation routes, and tourism activities. Additionally, regular maintenance is required to prevent fouling, ensure structural stability, and maintain optimal production performance. Nevertheless, due to their simplicity, effectiveness, and relatively high yields, raft systems remain among the most important cultivation technologies used in modern seaweed aquaculture [72].

Bottom culture

Bottom culture is one of the simplest and most traditional methods of seaweed farming, involving the direct cultivation of seaweeds on natural sediments in shallow coastal areas, lagoons, estuaries, and intertidal flats [73]. This technique is particularly suitable for species that can tolerate partial burial, variable salinity, and periodic exposure during low tides. Among commercially cultivated seaweeds, *Gracilaria* spp. are the most commonly grown using bottom-culture systems due to their ability to thrive on soft, muddy or sandy substrates [74]. In bottom culture operations, seaweed fragments or propagules are either scattered directly onto prepared cultivation grounds or secured using stakes, nets, or simple anchoring structures. Growth occurs under natural environmental conditions, with nutrients supplied by surrounding waters and sediments. The method requires minimal infrastructure and is therefore especially attractive in regions where financial resources and technological capacity are limited [75].

The primary advantages of bottom culture include low establishment and maintenance costs, reduced requirements for specialized equipment, and ease of implementation over large cultivation areas. Because the crop grows directly on natural substrates, operational activities are relatively simple, and harvesting can often be carried out manually. Bottom culture also provides opportunities for small-scale and community-based aquaculture development, contributing to rural livelihoods and local economies [76]. However, productivity is generally lower than in suspended cultivation systems because the seaweeds may experience reduced light availability, sediment accumulation, and limited water movement. Crops are also more susceptible to grazing by herbivorous organisms, competition with other benthic species, and environmental fluctuations such as changes in salinity and temperature. Furthermore, excessive sedimentation and poor water quality can negatively affect growth and biomass quality [77]. Despite these limitations, bottom culture remains an important cultivation strategy for *Gracilaria* and other sediment-tolerant species, particularly in tropical and subtropical regions where suitable shallow-water habitats are abundant. Its low-cost nature and operational simplicity continue to make it an attractive option for sustainable seaweed production, especially in areas with limited access to advanced farming technologies [78].

Offshore seaweed farming

Offshore seaweed farming has emerged as one of the most promising directions for the future expansion of global seaweed aquaculture. As coastal zones become increasingly crowded due to competition from fisheries, tourism, shipping, urban development, and marine conservation activities, the availability of suitable nearshore farming sites has become a significant constraint. Consequently, attention has shifted toward offshore environments located further from the coastline, where extensive areas remain available for cultivation [79].

Offshore farms are typically deployed in deeper waters and are designed to withstand stronger waves, currents, and wind exposure to conventional nearshore systems. These operations often utilize reinforced longlines, submerged cultivation structures, advanced mooring systems, and automated monitoring technologies. Species commonly considered for offshore cultivation include large brown seaweeds such as *Saccharina latissima*, *Saccharina japonica*, *Macrocystis pyrifera*, *Alaria esculenta*, and *Undaria pinnatifida*, which exhibit rapid growth and high biomass productivity under nutrient-rich marine conditions [80].

One of the principal advantages of offshore farming is the reduction of spatial conflicts with other coastal users. By relocating cultivation activities away from densely utilized nearshore areas, offshore farms can minimize competition for marine space while enabling substantial expansion of production capacity. Offshore environments also generally provide better water exchange, lower exposure to land-based pollution, and more stable environmental conditions, which can contribute to improved crop quality and reduced biofouling. Furthermore, the vast area available in offshore waters offers significant opportunities for large-scale biomass production, supporting the growing demand for food, feed, biofuels, pharmaceuticals, nutraceuticals, and biobased materials [81].

Despite its considerable potential, offshore cultivation presents important technical and economic challenges. Infrastructure must be capable of withstanding severe environmental conditions, including strong currents, large waves, storms, and occasional extreme weather events. Consequently, the development and installation of offshore farming systems require substantial engineering expertise and high capital investment. Routine operations such as deployment, monitoring, maintenance, and harvesting are also more complex and costly than in nearshore farms, often requiring specialized vessels and equipment [82].

Additional challenges include ensuring structural durability, minimizing biomass losses during adverse weather conditions, and developing economically viable harvesting technologies for large offshore installations [83]. Regulatory frameworks and marine spatial planning policies may also influence the expansion of offshore aquaculture in many regions [84]. Nevertheless, continuing advances in engineering design, remote sensing technologies, automation, and integrated offshore aquaculture systems are expected to enhance the feasibility and profitability of offshore seaweed farming (Figure 5). As global demand for sustainable marine biomass continues to increase, offshore cultivation is likely to become an increasingly important component of the future blue economy [72].

Hatchery Technologies and Seed Production

A reliable and consistent supply of high-quality seedstock is fundamental to the success of commercial seaweed aquaculture. Hatcheries play a critical role in producing healthy seedlings, ensuring genetic quality, reducing crop losses, and enabling year-round cultivation. Modern hatchery technologies allow producers to control environmental conditions during the early developmental stages of seaweeds, thereby improving seedling survival, growth rates, and overall farm productivity [19].

The hatchery process generally begins with the selection of healthy reproductive material from broodstock populations. Spores,



Figure 5: Major seaweed cultivation systems and their main characteristics. Schematic comparison of coastal cultivation, longline systems, floating rafts, bottom culture, and offshore farming, highlighting typical locations, infrastructure, environmental conditions, advantages, and operational constraints. The suitability of each system depends on the cultivated species, local hydrodynamic conditions, water depth, and farm design. Depth ranges and production scales are indicative and may vary among sites and cultivation practices.

gametes, or vegetative propagules are collected and cultured under carefully controlled laboratory conditions before being transferred to nursery systems and, subsequently, to grow-out farms. Successful hatchery management requires precise regulation of environmental parameters that influence growth, reproduction, and morphogenesis [85].

Modern hatcheries commonly utilize controlled photoperiods to regulate reproductive cycles and optimize seedling development. Temperature regulation is equally important, as different species exhibit specific thermal requirements for spore release, germination, and juvenile growth. Nutrient optimization through the use of enriched culture media helps maximize growth performance and improve seedling quality, while sterile culture techniques reduce contamination by bacteria, fungi, epiphytes, and competing microalgae. Together, these practices contribute to higher survival rates and more predictable production outcomes [86].

Recent technological advances have significantly expanded the capabilities of seaweed hatcheries. Tissue culture techniques enable the propagation of elite germplasm and facilitate the rapid multiplication of desirable strains. Clonal propagation methods are increasingly employed to maintain genetically uniform stocks with advantageous characteristics such as rapid growth, environmental tolerance, and enhanced biochemical composition [75]. Cryopreservation technologies provide long-term storage of genetic resources, supporting breeding programs, biodiversity conservation, and germplasm banking. In parallel, molecular-assisted breeding approaches are accelerating the development of improved cultivars through the identification and selection of desirable genetic traits [87]. The application of molecular tools, including DNA markers, genomic sequencing, and molecular diagnostics, is transforming seaweed breeding programs by enabling more precise selection of strains with superior productivity, disease resistance, and environmental adaptability [88]. These innovations are particularly important as industry seeks to develop cultivars capable of thriving under changing climatic conditions and expanding into new cultivation regions [89].

Despite major advances, hatchery operations continue to face challenges related to contamination control, maintenance of genetic diversity, scaling-up production, and the economic costs associated with highly controlled culture facilities. Nevertheless, ongoing improvements in biotechnology, automation, and breeding methodologies are expected to enhance seed production efficiency and provide the genetic foundation necessary for the continued growth and sustainability of the global seaweed aquaculture industry [90].

Integrated Multi-Trophic Aquaculture (IMTA)

Integrated Multi-Trophic Aquaculture (IMTA) is an increasingly important approach in sustainable aquaculture that combines the cultivation of organisms from different trophic levels within the same production system. The concept is based on ecological principles, whereby the waste products generated by one cultured species serve as resources for another, creating a more balanced and resource-efficient farming environment. In seaweed aquaculture, IMTA commonly integrates finfish, shellfish, and macroalgae within a single production unit [91].

In typical IMTA systems, finfish such as salmon, sea bass, or sea bream are cultivated as the primary fed component. Fish farming activities release dissolved nutrients, particularly nitrogen and phosphorus compounds, into the surrounding water through uneaten feed and metabolic excretions. Seaweeds cultivated adjacent to fish cages absorb these nutrients for growth, thereby acting as natural biofilters that help improve water quality and mitigate the environmental impacts associated with intensive aquaculture. Shellfish such as mussels, oysters, and scallops may also be incorporated into the system, where they remove particulate organic matter from the water column through filter-feeding activities [92]. The integration of seaweeds into aquaculture operations provides multiple environmental benefits. Through nutrient uptake, seaweeds contribute to nutrient bio-extraction, reducing the risk of eutrophication and improving ecosystem health in areas surrounding

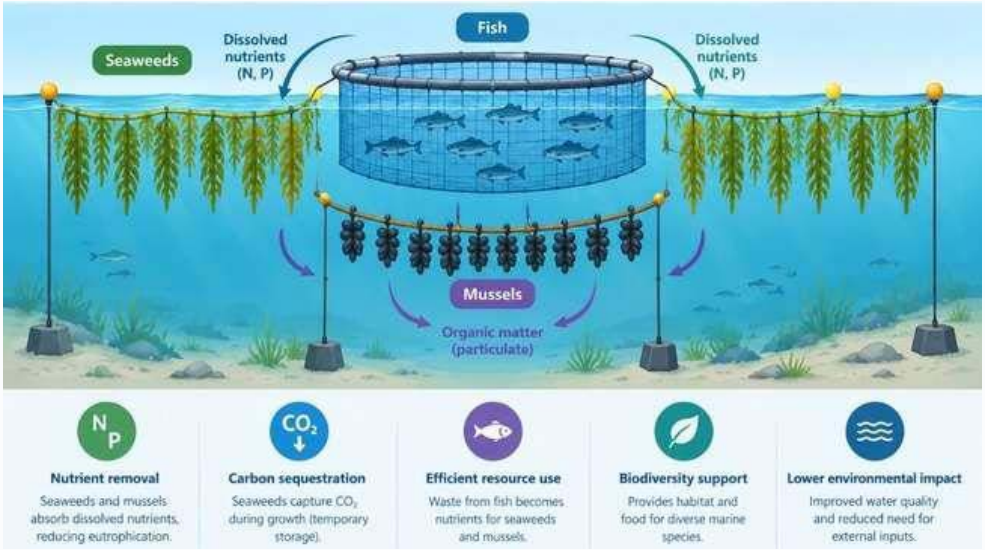


Figure 6: Integrated Multi-Trophic Aquaculture (IMTA) System. Fish, seaweed, and mussels are cultivated in an integrated system in which dissolved nutrients and particulate organic matter can be recovered by complementary organisms. Potential benefits include improved nutrient cycling, more efficient resource use, and reduced environmental impacts.

fish farms. In addition, seaweed photosynthesis can increase dissolved oxygen levels and contribute to local carbon sequestration, further enhancing environmental sustainability (Figure 6) [93].

From an economic perspective, IMTA offers opportunities for product diversification and additional revenue generation. Farmers can simultaneously produce fish, shellfish, and seaweed biomass for food, feed additives, nutraceuticals, pharmaceuticals, cosmetics, biofertilizers, and bioproducts. This diversification can improve farm profitability while reducing economic risks associated with dependence on a single cultured species [94]. Another important advantage of IMTA is the enhancement of ecosystem resilience. By mimicking natural ecological interactions and promoting nutrient recycling, integrated systems are often more environmentally stable than conventional monoculture operations. The presence of multiple cultured species can improve resource utilization efficiency and contribute to a more circular and sustainable aquaculture model [95].

Despite its considerable potential, successful implementation of IMTA requires careful species selection, optimization of stocking densities, appropriate farm design, and continuous environmental monitoring. Regulatory frameworks, market development, and technical expertise also remain important factors influencing large-scale adoption. Nevertheless, growing interest in sustainable aquaculture and ecosystem-based management is driving increased investment in IMTA research and commercial applications worldwide [94].

Overall, IMTA represents one of the most promising strategies for enhancing the environmental sustainability, economic viability, and social acceptance of modern aquaculture. As global demand for seafood and marine biomass continues to increase, integrated production systems are expected to play a central role in the future development of the blue economy.

Environmental Benefits of Seaweed Aquaculture

Seaweed aquaculture is increasingly recognized as one of the most environmentally sustainable forms of food production. Unlike many conventional aquaculture systems, seaweed does not require freshwater irrigation, arable land, fertilizers, or external feed inputs. Through their natural metabolic activities, cultivated seaweed provides a range of ecosystem services, including nutrient removal, carbon sequestration, habitat provision, and water quality improvement. These environmental benefits have positioned seaweed farming as an important component of sustainable coastal management and the emerging blue economy [3].

Nutrient removal

One of the most significant environmental functions of cultivated seaweeds is their ability to absorb excess nutrients from aquatic environments. Seaweeds require substantial amounts of nitrogen and phosphorus to support growth and biomass production. These nutrients are assimilated directly from seawater, primarily in the form of ammonium, nitrate, and phosphate [96].

In coastal regions affected by agricultural runoff, urban wastewater discharge, and intensive aquaculture activities, elevated nutrient concentrations can stimulate excessive phytoplankton growth, resulting in eutrophication, harmful algal blooms, oxygen depletion, and ecosystem degradation. Seaweed cultivation can help mitigate these impacts by removing dissolved nutrients from the water column and incorporating them into harvestable biomass [97]. The effectiveness of nutrient removal varies according to species, cultivation density, environmental conditions, and seasonal productivity. Fast-growing species such as *Ulva* spp., *Saccharina latissima*, *Saccharina japonica*, *Gracilaria* spp., and *Pyropia* spp. are particularly efficient at nutrient uptake and have been widely investigated for nutrient bio-extraction applications [98].

Seaweed farms located near fish cages and other aquaculture facilities can function as biological filters, capturing nutrients that would otherwise accumulate in surrounding waters. This capacity has made seaweeds an essential component of Integrated Multi-Trophic Aquaculture (IMTA) systems, where they contribute to nutrient recycling and environmental remediation [30]. Beyond improving

water quality, nutrient removal through seaweed cultivation can also generate valuable biomass that may be utilized for food, feed, biofertilizers, pharmaceuticals, nutraceuticals, and bioenergy applications. Consequently, seaweed farming provides a unique opportunity to simultaneously address environmental challenges while supporting economically productive activities [99].

Overall, the nutrient assimilation capacity of seaweeds contributes significantly to reducing eutrophication risks, enhancing ecosystem health, and promoting more sustainable management of coastal and marine resources. As pressures on coastal ecosystems continue to increase worldwide, the role of seaweed aquaculture in nutrient mitigation and ecological restoration is expected to become increasingly important [76].

Carbon sequestration

Seaweed cultivation has attracted significant attention as a potential nature-based solution for climate change mitigation due to its capacity to absorb carbon dioxide during photosynthesis and convert it into biomass. Through rapid growth and high primary productivity, seaweeds can remove substantial quantities of carbon from marine environments, contributing to the regulation of global carbon cycles [100]. During growth, seaweeds capture dissolved inorganic carbon from seawater and incorporate it into their tissues. This process not only supports biomass accumulation but can also influence local carbonate chemistry and potentially alleviate some effects of ocean acidification [101]. Large-scale cultivation of highly productive species such as *Saccharina latissima*, *Saccharina japonica*, *Macrocystis pyrifera*, and *Undaria pinnatifida* has therefore been proposed as a strategy to enhance biological carbon capture in coastal and offshore ecosystems [102].

The climate benefits of seaweed farming extend beyond direct carbon uptake. Harvested biomass can be utilized to produce biofuels, bioplastics, biochar, and other biobased products that may partially replace fossil fuel-derived materials. In addition, the incorporation of seaweed-derived products into agricultural systems can contribute to carbon storage in soils and reduce greenhouse gas emissions associated with conventional fertilizers and industrial processes [103]. Seaweeds contribute to carbon storage through several pathways. A portion of naturally detached biomass may be transported to deep ocean environments, where carbon can remain isolated from the atmosphere for extended periods. Some organic matter may also become buried in coastal sediments, creating longer-term carbon reservoirs. However, the extent to which cultivated seaweeds contribute to permanent carbon sequestration remains an active area of scientific research [104]. Although there is broad agreement regarding the substantial carbon capture capacity of seaweeds, uncertainties remain concerning the magnitude, permanence, and verification of long-term carbon storage. Factors such as species composition, cultivation practices, environmental conditions, biomass fate, and ecosystem interactions can influence the overall sequestration potential. Consequently, robust monitoring and standardized carbon accounting methodologies are required before large-scale carbon sequestration credits can be reliably attributed to seaweed farming operations [105].

Nevertheless, seaweed aquaculture is widely regarded as a promising component of future climate mitigation strategies. In combination with its additional environmental benefits, including nutrient removal, habitat enhancement, and sustainable biomass production, seaweed cultivation has considerable potential to support global efforts toward carbon neutrality and the development of resilient blue-economy initiatives [4].

Biodiversity enhancement

In addition to their role in nutrient cycling and carbon capture, seaweed farms can provide valuable ecological functions by enhancing marine biodiversity. The three-dimensional structure created by cultivated seaweed beds increases habitat complexity, offering shelter, feeding grounds, and nursery areas for a wide range of marine organisms. As a result, seaweed farms often function as artificial habitats that support diverse biological communities and contribute to the ecological productivity of coastal ecosystems [106].

Numerous studies have shown that seaweed cultivation areas can attract and sustain fish populations, including both juvenile and adult stages of commercially and ecologically important species. The physical structure of the algal canopy provides protection from predators, while the associated microbial and invertebrate communities serve as a food resource. Consequently, seaweed farms may act as localized biodiversity hotspots within otherwise less structured marine environments [107]. Crustaceans, including shrimps, crabs, amphipods, and copepods, are frequently found among cultivated seaweeds. These organisms utilize the dense thalli as refuge from predation and as a substrate for feeding and reproduction. Similarly, numerous mollusks, such as snails, bivalves, and juvenile shellfish, are commonly associated with seaweed farming structures and benefit from the increased availability of habitat and food resources [108].

Seaweed farms also support diverse epiphytic and epifaunal communities. Epiphytic algae, bacteria, fungi, and microorganisms colonize the surfaces of cultivated seaweeds, creating complex microhabitats that contribute to ecological interactions and nutrient cycling. These communities form the foundation of local food webs and play important roles in maintaining ecosystem functioning and biological productivity [109]. The biodiversity benefits of seaweed aquaculture can extend beyond the immediate cultivation area. By increasing habitat availability and structural complexity, seaweed farms may contribute to the recovery of degraded coastal environments, enhance local fisheries production, and improve ecosystem resilience in the face of environmental disturbances. However, the magnitude of these benefits depends on factors such as cultivation scale, species composition, farm design, and local environmental conditions [110].

Although careful management is necessary to prevent negative ecological impacts, such as the introduction of non-native species or excessive habitat modification, well-designed seaweed farms are generally considered compatible with biodiversity conservation objectives. Consequently, seaweed aquaculture is increasingly recognized not only as a sustainable food production system but also as a valuable tool for supporting marine ecosystem health and promoting nature-positive coastal development [111].

Reduced resource demand

One of the most important sustainability advantages of seaweed aquaculture is its exceptionally low demand for natural resources compared with conventional terrestrial agriculture. As global concerns regarding freshwater scarcity, land degradation, and agricultural intensification continue to grow, seaweed cultivation has emerged as an attractive alternative for producing food, feed, and biomass without placing additional pressure on limited terrestrial

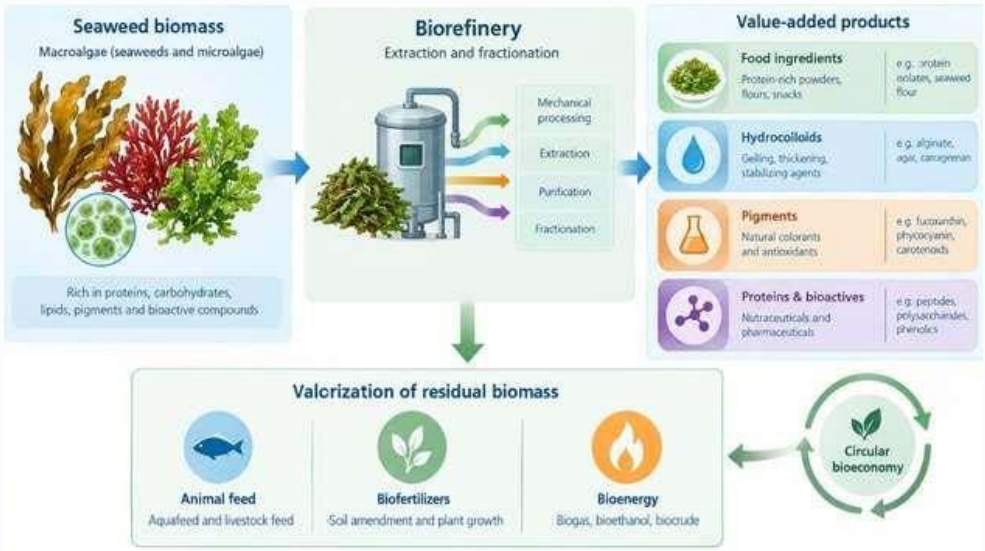


Figure 7: Seaweed biorefinery and biomass valorization pathways. Conceptual overview of the processing of seaweed biomass into food ingredients, hydrocolloids, pigments, proteins, and bioactive compounds, alongside potential applications of residual biomass in animal feed, biofertilizers, and bioenergy. Product yields and valorization routes depend on the seaweed species, biomass composition, and processing technologies employed.

resources [72].

Unlike most agricultural crops, seaweeds do not require freshwater irrigation. Growth occurs entirely in marine or brackish environments, eliminating competition with human consumption, industrial use, and conventional agriculture for freshwater resources. This characteristic is particularly relevant in regions facing increasing water stress and climate-related droughts [112]. Seaweed farming also eliminates the need for arable land. Cultivation takes place in coastal and marine environments, allowing biomass production without converting forests, grasslands, or agricultural areas. Consequently, seaweed aquaculture avoids many of the environmental impacts associated with land-use change, including habitat destruction, soil erosion, biodiversity loss, and greenhouse gas emissions resulting from deforestation and agricultural expansion [113]. Another significant advantage is the minimal requirement for fertilizer inputs. Most cultivated seaweeds obtain essential nutrients directly from surrounding waters through natural biological processes. Nitrogen, phosphorus, potassium, and micronutrients are absorbed from seawater, reducing dependence on synthetic fertilizers whose production and application can contribute to environmental pollution and greenhouse gas emissions. In some cases, seaweed farms can even remove excess nutrients from eutrophic waters, transforming environmental pollutants into valuable biomass [114].

The efficient use of resources makes seaweed cultivation one of the most sustainable biomass production systems currently available. Life-cycle assessments have consistently shown that seaweed farming generally exhibits lower freshwater consumption, reduced land-use requirements, and smaller environmental footprints compared with many terrestrial crops and livestock production systems [115]. These characteristics position seaweed aquaculture as a promising component of future sustainable food systems and bioeconomy strategies. By producing large quantities of biomass while requiring no freshwater, no agricultural land, and minimal external nutrient inputs, seaweed farming offers a pathway toward increasing global food and bioproduct production without exacerbating existing pressures on terrestrial ecosystems. As demand for sustainable resources continues to increase, the resource efficiency of seaweed cultivation is expected to become an increasingly important factor supporting its global expansion [60].

Industrial Applications

The remarkable biochemical diversity of seaweeds has led to their utilization across numerous industrial sectors, including food production, pharmaceuticals, nutraceuticals, cosmetics, agriculture, animal feed, and bioenergy. Seaweeds are rich sources of proteins, polysaccharides, minerals, vitamins, pigments, and bioactive compounds, making them valuable renewable resources for the development of sustainable products (Figure 7). As consumer demand for natural, functional, and environmentally friendly ingredients continues to increase, the commercial importance of seaweed-derived products is expanding worldwide [116].

Food and functional foods

Seaweeds have been consumed for centuries, particularly in Asian countries such as China, Japan, and Korea, where they constitute an important component of traditional diets. In recent decades, interest in seaweed as a food resource has expanded globally due to growing awareness of its nutritional value and potential health benefits. Numerous species, including *Pyropia* spp., *Saccharina japonica*, *Undaria pinnatifida*, *Ulva* spp., and *Palmaria palmata*, are commercially harvested or cultivated for direct human consumption [117]. Seaweeds possess a highly favorable nutritional profile and provide a diverse range of essential nutrients. They are rich in proteins, particularly certain red and green algae that contain significant quantities of essential amino acids. Seaweeds are also important sources of dietary fiber, including soluble polysaccharides such as alginate, agar, and carrageenan, which contribute to digestive health and may help regulate blood glucose and cholesterol levels [118]. In addition to macronutrients, seaweeds provide a wide range of vitamins, including vitamins A, C, E, and several B-complex vitamins. They are also recognized as valuable sources of essential minerals such as iodine, calcium, magnesium, potassium, iron, zinc, and selenium. The high mineral content of many species has attracted

considerable attention for addressing micronutrient deficiencies and supporting balanced nutrition [119]. Seaweeds further contain numerous bioactive compounds, including polyphenols, carotenoids, phycobiliproteins, sulfated polysaccharides, and other secondary metabolites with antioxidant, anti-inflammatory, antimicrobial, and potential health-promoting properties. These compounds have stimulated growing interest in the development of functional foods designed to provide benefits beyond basic nutrition [120].

The incorporation of seaweed ingredients into food systems is increasing worldwide. Seaweed-derived products are now used in snacks, salads, soups, noodles, bakery products, dairy alternatives, meat analogues, beverages, and nutritional supplements. Hydrocolloids extracted from seaweeds, particularly agar, carrageenan, and alginate, are extensively employed as gelling, thickening, stabilizing, and emulsifying agents in the food industry [2]. Recent consumer trends favoring plant-based diets, sustainable food production, and functional ingredients have further accelerated the integration of seaweeds into modern food formulations. Consequently, seaweed-based foods are increasingly viewed as important contributors to future sustainable food systems capable of supporting both human health and environmental sustainability [121].

The extraction and commercialization of hydrocolloids represent one of the oldest and most economically important applications of seaweeds. Hydrocolloids are water-soluble polysaccharides characterized by their ability to form gels, increase viscosity, stabilize emulsions, and modify texture. The global hydrocolloid industry relies heavily on cultivated seaweeds as renewable raw materials for the production of alginate, agar, and carrageenan. These compounds are widely utilized in the food, pharmaceutical, biomedical, cosmetic, and biotechnology sectors due to their unique physicochemical properties and biocompatibility [122].

Alginate

Alginate is a naturally occurring polysaccharide extracted primarily from brown seaweeds such as *Saccharina japonica*, *Macrocystis pyrifera*, *Ascophyllum nodosum*, and *Laminaria digitata*. Chemically, alginate consists of linear chains of mannuronic and guluronic acid residues, which confer excellent gelling, thickening, and stabilizing properties [123].

The food industry is the largest consumer of alginates, where they are employed as thickening agents, stabilizers, emulsifiers, and moisture-retention additives in products such as ice cream, sauces, beverages, and processed foods. In pharmaceutical applications, alginates are incorporated into drug delivery systems, wound dressings, and antacid formulations due to their biocompatibility and ability to form hydrogels [124]. Furthermore, alginate-based biomaterials have gained considerable attention in biomedical engineering, tissue regeneration, cell encapsulation, and regenerative medicine, making alginate one of the most versatile seaweed-derived polymers [125].

Agar

Agar is extracted primarily from red algae belonging to the genera *Gracilaria*, *Gelidium*, and *Pterocladia*. This hydrocolloid consists mainly of agarose and agaropectin, which provide exceptional gel-forming capacity and thermal stability. Agar is particularly valued because it forms strong gels at relatively low concentrations and remains stable over a wide range of temperatures [126]. One of the most well-known applications of agar is in microbiology, where it serves as the standard solidifying agent for microbial culture media. Its resistance to microbial degradation and favorable gel properties have made it indispensable in biological and medical laboratories worldwide [127]. In the food industry, agar is widely used in confectionery products, desserts, jellies, bakery items, and vegetarian food formulations as a gelling and stabilizing agent. In biotechnology, agar supports numerous applications including plant tissue culture, molecular biology, and microbial research, reinforcing its importance as a strategic biomaterial for scientific and industrial purposes [128].

Carrageenan

Carrageenan is a sulfated polysaccharide obtained primarily from red seaweeds such as *Kappaphycus alvarezii*, *Eucheuma denticulatum*, *Chondrus crispus*, and *Gigartina* spp. Depending on its chemical structure, carrageenan is classified into several types, including kappa (κ), iota (ι), and lambda (λ), each possessing distinct gelling and thickening characteristics [129]. The dairy industry represents one of the largest markets for carrageenan. It is extensively used to improve texture, stability, and mouthfeel in products such as chocolate milk, yogurt, cream, ice cream, and plant-based dairy alternatives [130]. In cosmetic formulations, carrageenan serves as a thickener, stabilizer, and moisture-retaining ingredient in lotions, shampoos, creams, and personal care products. Pharmaceutical applications include tablet formulations, controlled drug-release systems, wound-healing materials, and other biomedical products owing to its biocompatibility and functional versatility [131].

Economic importance of hydrocolloids

The commercial success of alginate, agar, and carrageenan has been a major driver of global seaweed cultivation. Many of the world's largest seaweed farming industries were originally developed to supply raw material for hydrocolloid extraction. Species such as *Kappaphycus alvarezii*, *Eucheuma denticulatum*, and *Gracilaria* spp. are now cultivated extensively across Asia, Africa, and Latin America to meet growing industrial demand [132]. As consumer preferences increasingly shift toward natural ingredients and sustainable materials, hydrocolloids derived from seaweeds are expected to remain essential components of numerous industrial processes. Ongoing research aimed at improving extraction technologies, enhancing product functionality, and developing novel biomedical applications is likely to further increase the economic importance of seaweed-derived hydrocolloids in the coming decades [133].

Animal feed

The use of seaweeds as ingredients in animal nutrition has expanded considerably in recent years, driven by the growing demand for sustainable feed resources and natural alternatives to conventional feed additives. Seaweeds are rich in proteins, minerals, vitamins, dietary fibers, essential fatty acids, and bioactive compounds that can contribute to improved animal health and performance. Consequently, numerous species are being incorporated into feeds for aquaculture, poultry, ruminants, and other livestock production systems [134].

In aquaculture, seaweed-derived ingredients are increasingly used in feeds for fish, shrimp, and mollusks. Species such as *Ulva*, *Gracilaria*, *Saccharina*, and *Porphyra*/*Pyropia* provide valuable nutrients and bioactive compounds that can enhance growth performance, strengthen immune responses, improve feed utilization efficiency, and increase resistance to environmental stress and disease. Seaweed supplementation can also improve the nutritional quality of

aquaculture products by enriching them with minerals, antioxidants, and beneficial fatty acids [135].

The poultry industry has similarly shown growing interest in seaweed-based feed additives. Inclusion of seaweed biomass or extracts in poultry diets has been associated with improved gut health, enhanced immune function, better nutrient digestion, and improved egg and meat quality. The natural antioxidant and antimicrobial properties of certain seaweed compounds may further contribute to animal health while reducing dependence on synthetic growth promoters [136]. In livestock production, seaweeds are increasingly utilized as feed supplements for cattle, sheep, goats, and pigs. Beyond their nutritional value, seaweeds contain bioactive metabolites that can positively influence digestive processes and overall animal productivity. Several studies have demonstrated improvements in feed efficiency, weight gain, milk production, and animal health following dietary supplementation with selected seaweed species [137].

A particularly important area of current research concerns the ability of certain seaweeds to reduce enteric methane emissions from ruminants. Methane produced during digestion represents a significant source of greenhouse gas emissions from livestock agriculture. Species such as *Asparagopsis taxiformis* have demonstrated considerable potential to reduce methane production by inhibiting specific microbial pathways in the rumen. This discovery has generated substantial interest in seaweed-based feed additives as tools for improving the environmental sustainability of livestock production [138].

The growing application of seaweeds in animal feed reflects their dual value as both nutritional resources and functional ingredients. As research continues to optimize inclusion rates, processing methods, and species selection, seaweed-derived feed products are expected to play an increasingly important role in sustainable animal agriculture, supporting improved animal health, enhanced productivity, and reduced environmental impacts [139].

Nutraceuticals and pharmaceuticals

Seaweeds have emerged as valuable sources of nutraceutical and pharmaceutical compounds owing to their remarkable diversity of bioactive metabolites. Interest in marine-derived products has expanded significantly over the past decade as researchers seek natural compounds capable of supporting disease prevention and promoting human health. Brown, red, and green seaweeds synthesize a wide array of polysaccharides, polyphenols, pigments, peptides, and other secondary metabolites that exhibit important biological activities and show considerable potential for application in functional foods, dietary supplements, and therapeutic products [140].

Among the most extensively studied seaweed-derived compounds is fucoidan, a sulfated polysaccharide found primarily in brown algae such as *Fucus vesiculosus*, *Undaria pinnatifida*, *Saccharina japonica*, and *Sargassum* species. Fucoidan has attracted considerable scientific interest due to its antioxidant, anti-inflammatory, anticoagulant, antiviral, immunomodulatory, and potential anticancer properties. Numerous experimental studies suggest that fucoidan may influence cell signaling pathways associated with inflammation, oxidative stress, and tumor progression, making it a promising candidate for future pharmaceutical applications [141]. Another important bioactive polysaccharide is laminarin, a storage glucan predominantly found in brown seaweeds including *Laminaria* and *Saccharina* species. Laminarin exhibits antioxidant, immunostimulatory, antimicrobial, and anti-inflammatory activities. It has been investigated for its potential role in enhancing immune responses, promoting gut health, and supporting the development of functional foods and nutraceutical formulations [142].

Phlorotannins are unique polyphenolic compounds synthesized exclusively by brown algae. Species such as *Ecklonia cava*, *Ascophyllum nodosum*, and various *Sargassum* species are particularly rich sources of these molecules. Phlorotannins possess strong antioxidant activity and have demonstrated anti-inflammatory, antimicrobial, antidiabetic, neuroprotective, and cardioprotective properties in numerous experimental models. Their ability to neutralize reactive oxygen species and modulate key biochemical pathways has generated considerable interest for applications in nutraceuticals, pharmaceuticals, and cosmeceuticals [143].

Red seaweeds provide carrageenans, sulfated galactans widely known for their hydrocolloid properties. In addition to their industrial importance as gelling and stabilizing agents, carrageenans have been investigated for biological activities including antiviral, immunomodulatory, antioxidant, and anti-inflammatory effects. Their biocompatibility has also encouraged the development of carrageenan-based drug delivery systems, tissue engineering scaffolds, and biomedical materials [144].

Green seaweeds such as *Ulva* species produce ulvans, complex sulfated polysaccharides that have demonstrated antioxidant, immunomodulatory, antimicrobial, anticoagulant, and anti-inflammatory activities. Ongoing research suggests that ulvans may have potential applications in functional foods, pharmaceutical formulations, biodegradable biomaterials, and regenerative medicine [145].

Collectively, these seaweed-derived compounds exhibit a broad spectrum of biological activities, including antioxidant activity, anti-inflammatory properties, antimicrobial potential, antiviral effects, immunomodulatory functions, and anticancer activity. Many of these effects are associated with the capacity of seaweed metabolites to regulate oxidative stress, inflammatory pathways, cellular signaling mechanisms, and microbial growth [2].

The growing demand for natural health-promoting products has stimulated substantial investment in marine biotechnology and seaweed bioprospecting. Advances in extraction technologies, purification methods, metabolomics, and molecular biology are facilitating the discovery of new bioactive compounds and improving their commercial development. As a result, seaweeds are increasingly recognized as strategic resources for the nutraceutical and pharmaceutical industries, with significant potential to contribute to future innovations in preventive healthcare and therapeutic interventions [146].

Bioenergy

The growing demand for renewable and sustainable energy sources has stimulated significant interest in the use of seaweed biomass as a feedstock for bioenergy production. Unlike terrestrial energy crops, seaweeds can be cultivated without requiring arable land, freshwater irrigation, or large quantities of fertilizers, making them attractive candidates for the development of low-impact bioenergy systems. Their rapid growth rates, high productivity, and ability to accumulate carbohydrates further enhance their potential as renewable energy resources within the emerging blue bioeconomy

[147].

Seaweed biomass has been investigated for the production of several forms of bioenergy, including bioethanol, biogas, biohydrogen, and sustainable aviation fuels. The suitability of seaweeds for these applications largely derives from their high carbohydrate content and relatively low lignin concentrations compared with terrestrial plants, which can facilitate biomass conversion processes [148].

Bioethanol production has received considerable attention, particularly from brown and red seaweeds rich in fermentable carbohydrates such as laminarin, mannitol, agar, and carrageenan. Through hydrolysis and microbial fermentation processes, these carbohydrates can be converted into ethanol, offering a renewable alternative to fossil-derived transportation fuels. Species such as *Saccharina japonica*, *Saccharina latissima* (Phaeophyceae), and *Gracilaria* spp. (Rhodophyta) have been widely explored as potential feedstocks for bioethanol production [149, 150].

Biogas can be generated through the anaerobic digestion of seaweed biomass by microbial communities under oxygen-free conditions. This process produces methane-rich gas that can be utilized for heating, electricity generation, or upgraded biomethane applications. Anaerobic digestion also generates nutrient-rich digestates that may be used as agricultural fertilizers, supporting circular bioeconomy strategies [151].

Seaweeds have also been investigated as substrates for biohydrogen production through dark fermentation, photo-fermentation, and other biological conversion technologies [152]. Hydrogen is considered one of the most promising future energy carriers because its combustion produces water as the primary by-product. Although commercial-scale seaweed-based hydrogen production remains at an early stage of development, ongoing research continues to improve production efficiencies and technological feasibility [153].

More recently, seaweed biomass has attracted interest as a raw material for the production of Sustainable Aviation Fuels (SAFs) [154]. Advanced thermochemical and biochemical conversion technologies, including hydrothermal liquefaction, pyrolysis, gasification, and catalytic upgrading, have demonstrated the potential to convert seaweed-derived biomass into liquid fuels suitable for aviation applications. These approaches could contribute to reducing the carbon footprint of the aviation sector while avoiding competition with food crops and agricultural land [155]. Despite these promising opportunities, the economic viability of seaweed-based bioenergy remains a significant challenge. Large-scale cultivation, harvesting, transportation, biomass processing, and conversion technologies often involve substantial costs that currently limit commercial competitiveness relative to conventional fossil fuels and some terrestrial bioenergy feedstocks [156]. Additional challenges include seasonal variations in biomass composition, logistics associated with offshore production systems, and the need for improved processing efficiencies [157].

Nevertheless, continued advances in cultivation technologies, biorefinery concepts, strain improvement, and biomass conversion processes are expected to enhance the feasibility of seaweed-derived biofuels. Increasing integration of bioenergy production with the extraction of high-value compounds may further improve economic performance by maximizing biomass utilization. Consequently, seaweed-based bioenergy is increasingly viewed as a promising component of future renewable energy portfolios and sustainable blue-economy strategies aimed at reducing dependence on fossil resources and mitigating climate change [158].

Challenges Facing Seaweed Aquaculture

Despite its rapid growth and substantial contribution to global food systems and the blue economy, seaweed aquaculture faces numerous biological, environmental, technological, and socioeconomic challenges. These constraints can influence productivity, profitability, environmental sustainability, and the long-term resilience of farming operations. Among the most significant challenges, climate change has emerged as a major threat to both wild and cultivated seaweed resources worldwide [8].

Climate change

Climate change is increasingly affecting marine ecosystems and is expected to have profound implications for seaweed aquaculture. Rising greenhouse gas concentrations are altering oceanographic conditions, creating environmental stressors that can negatively impact seaweed growth, reproduction, physiological performance, and survival. The effects of climate change vary among species and regions, but many commercially important seaweeds are already experiencing increased environmental pressure [159, 160]. One of the most important challenges is ocean warming. Seaweeds possess species-specific temperature ranges for optimal growth, and prolonged exposure to elevated temperatures can reduce photosynthetic efficiency, impair reproductive success, and increase susceptibility to disease. Several commercially cultivated species, particularly temperate kelps such as *Saccharina latissima*, *Saccharina japonica*, and *Macrocystis pyrifera*, are considered especially vulnerable to rising seawater temperatures [161].

The increasing frequency and intensity of marine heatwaves represent an additional threat. These extreme temperature events can cause rapid declines in seaweed biomass, trigger large-scale mortality events, and disrupt cultivation cycles. Marine heatwaves have been associated with significant losses of natural kelp forests and cultivated seaweed stocks in several regions, highlighting their potential economic consequences for aquaculture producers [162]. Ocean acidification, resulting from the absorption of atmospheric carbon dioxide by seawater, can also influence seaweed cultivation. Although some seaweed species may benefit from increased carbon availability for photosynthesis, acidification can alter nutrient dynamics, species interactions, and ecosystem processes [163]. Furthermore, changes in seawater chemistry may indirectly affect seaweed production by impacting associated organisms, including shellfish and other species commonly cultivated in integrated aquaculture systems [164].

Another major concern is the increasing occurrence of extreme weather events, including storms, cyclones, flooding, and unusually strong wave conditions. Such events can damage cultivation infrastructure, dislodge seaweed biomass, interfere with harvesting schedules, and increase operational costs. Offshore and nearshore farms are particularly vulnerable to physical damage resulting from severe weather, which may lead to substantial crop losses and economic uncertainty [165]. Climate-related environmental changes may also facilitate the spread of pests, pathogens, and invasive species [166]. Shifts in temperature and ocean circulation patterns can alter species distributions, potentially increasing disease outbreaks and creating new management challenges for the aquaculture industry. In addition, fluctuations in nutrient availability and water quality may further affect seaweed productivity and biomass composition [167].

To address these challenges, researchers and industry stakeholders are increasingly focusing on the development of climate-resilient cultivation strategies. These include selective breeding programs for stress-tolerant strains, diversification of cultivated species, improved farm design, offshore expansion, and the application of advanced monitoring technologies [72]. Continued investment in research, adaptation measures, and sustainable management practices will be essential to maintain productivity and support the long-term resilience of global seaweed aquaculture under changing climatic conditions [168].

Diseases and biofouling

Diseases and biofouling represent some of the most significant biological constraints affecting seaweed aquaculture worldwide. These factors can reduce growth rates, compromise biomass quality, increase production costs, and lead to substantial economic losses. The prevalence and severity of disease outbreaks and fouling organisms are often influenced by environmental conditions, cultivation density, water quality, and climate-related stressors. As the global seaweed industry continues to expand, effective management of these challenges has become increasingly important for maintaining production efficiency and sustainability [169].

One of the most common problems encountered in seaweed farms is epiphyte proliferation. Epiphytes, which include filamentous algae, microalgae, and sessile invertebrates growing on seaweed surfaces, compete with cultivated seaweeds for light, nutrients, and space. Excessive epiphytic growth can reduce photosynthetic efficiency, impair nutrient uptake, decrease biomass quality, and complicate harvesting and processing operations. The problem is particularly severe in nutrient-rich waters and during periods of elevated temperatures [170].

Pathogenic bacteria can also significantly affect seaweed health and productivity. Bacterial infections may cause tissue degradation, discoloration, reduced growth, and deterioration of commercial quality [171]. Environmental stressors such as high temperatures, salinity fluctuations, and poor water quality often increase the susceptibility of seaweeds to bacterial diseases. Understanding host-microbe interactions and maintaining favorable cultivation conditions are therefore critical components of disease management [172].

Another important challenge arises from grazing organisms, including herbivorous fish, sea urchins, gastropods, amphipods, and other marine invertebrates that consume cultivated seaweeds. Grazing pressure can substantially reduce biomass yields and, in severe cases, cause complete crop loss. The impact of grazers varies among cultivation systems and geographic regions, often requiring the implementation of protective measures such as netting, strategic farm placement, or integrated management approaches [173].

Among the most economically important seaweed diseases is ice-ice disease, which primarily affects carrageenophytes such as *Kappaphycus alvarezii* and *Eucheuma denticulatum*. This disease is characterized by whitening and necrosis of thallus tissues, followed by branch breakage and biomass loss. Ice-ice disease is generally associated with environmental stress, including elevated temperatures, salinity fluctuations, excessive irradiance, and nutrient imbalances, which weaken the algae and increase susceptibility to opportunistic bacterial colonization. The disease has caused significant production losses in major carrageenan-producing regions and remains a major concern for the global carrageenophyte industry [174]. Management strategies for diseases and biofouling include the selection of resistant strains, optimization of cultivation density, maintenance of good water circulation, regular cleaning of cultivation structures, implementation of biosecurity measures, and continuous monitoring of environmental conditions. Advances in molecular diagnostics, microbiome research, and selective breeding programs are also contributing to the development of more resilient seaweed cultivars capable of withstanding biological and environmental stressors [175].

As seaweed aquaculture continues to intensify and expand into new regions, effective disease prevention and biofouling management will be essential for ensuring stable production, maintaining product quality, and supporting the long-term sustainability of the industry [19].

Genetic erosion

Genetic diversity is a fundamental factor determining the resilience, adaptability, and long-term sustainability of cultivated seaweed populations. However, the increasing reliance on a limited number of high-performing strains and the widespread use of vegetative propagation techniques have raised concerns regarding genetic erosion within commercial seaweed farming systems. Genetic erosion refers to the progressive loss of genetic variability within cultivated populations, potentially reducing their capacity to adapt to changing environmental conditions and biological threats [176].

Many commercially important seaweeds, including *K. alvarezii*, *E. denticulatum*, and several *Gracilaria* species, are propagated through clonal methods in which fragments of selected individuals are repeatedly used to establish new cultivation cycles. While this approach offers advantages such as uniform growth, predictable biomass quality, and rapid multiplication of desirable strains, long-term dependence on genetically similar material can significantly reduce overall genetic diversity [177].

Reduced genetic variability can increase vulnerability to disease outbreaks, pest infestations, and environmental stressors. Cultivated populations with narrow genetic bases often possess limited adaptive capacity, making them more susceptible to emerging pathogens, temperature fluctuations, salinity changes, marine heatwaves, and other climate-related disturbances. Historical experiences in both terrestrial agriculture and aquaculture have demonstrated that genetically uniform production systems are generally more vulnerable to large-scale seaweeds crop failures [72]. Genetic erosion may also reduce productivity over time by limiting opportunities for natural adaptation and selective improvement. As environmental conditions continue to change, the availability of diverse genetic resources becomes increasingly important for breeding programs aimed at developing cultivars with enhanced growth performance, disease resistance, stress tolerance, and improved biochemical composition [178]. To address this challenge, researchers and industry stakeholders are implementing various strategies to conserve and enhance genetic diversity in cultivated seaweed stocks. These include the establishment of germplasm banks, cryopreservation of reproductive material, periodic introduction of genetically diverse wild populations into breeding programs, and the development of molecular tools for genetic monitoring. Selective breeding programs that incorporate multiple parental lines can further help maintain diversity while improving commercially desirable traits [179].

Advances in genomics, molecular markers, and population

genetics are providing new opportunities to assess genetic variation and guide sustainable breeding practices. These technologies enable the identification of valuable genetic resources and support the development of improved cultivars without excessively narrowing the genetic base of production systems [180]. Maintaining genetic diversity is essential for ensuring the long-term resilience and sustainability of the seaweed aquaculture industry. As cultivation continues to expand globally and environmental pressures intensify, effective genetic resource management will become increasingly important for safeguarding productivity, supporting industry growth, and enhancing the adaptive capacity of cultured seaweed populations [181].

Regulatory constraints

Regulatory and governance challenges represent significant barriers to the sustainable expansion of seaweed aquaculture in many regions of the world. While industry has experienced rapid growth in several countries, regulatory frameworks have often failed to keep pace with technological advances and increasing commercial interest. As a result, producers frequently encounter administrative, legal, and policy-related obstacles that can delay farm development, increase operational costs, and discourage investment [182].

One of the most common challenges is the absence of clear licensing and permitting procedures for seaweed farming. In many jurisdictions, aquaculture regulations were originally designed for finfish or shellfish production and may not adequately address the specific requirements of macroalgal cultivation. Complex approval processes involving multiple governmental agencies can create uncertainty for investors and hinder the establishment of new farming operations [183].

Another important limitation is the lack of comprehensive environmental guidelines tailored specifically to seaweed aquaculture. Although seaweed farming is generally regarded as environmentally sustainable, appropriate environmental assessments are often required to evaluate potential impacts on biodiversity, water quality, navigation, fisheries, and coastal ecosystems. In many countries, insufficient regulatory guidance can lead to inconsistent decision-making and delays in project implementation [184].

The absence of dedicated seaweed-specific management policies further complicates industry development. Effective governance requires clear regulations concerning farm siting, biosecurity, the introduction of non-native species, genetic resource management, product certification, harvesting practices, and ecosystem protection. Without well-defined policies, there is an increased risk of conflicts among stakeholders, environmental concerns, and uncertainty regarding long-term industry development [1]. Marine spatial planning also presents a major challenge. Competition for coastal and offshore areas among aquaculture, fisheries, tourism, shipping, renewable energy installations, and conservation programs can restrict access to suitable cultivation sites. The lack of coordinated planning frameworks may create conflicts among users and limit opportunities for industry expansion [185].

International trade regulations and quality standards represent additional considerations for seaweed producers. Access to global markets often requires compliance with food safety regulations, traceability systems, sustainability certifications, and export requirements that can vary considerably among countries. For small-scale producers, meeting these regulatory obligations may be technically and financially challenging [186]. To support sustainable growth, governments and regulatory agencies are increasingly recognizing the need for dedicated seaweed aquaculture policies. Improved licensing procedures, science-based environmental regulations, standardized monitoring protocols, and integrated marine spatial planning frameworks can facilitate responsible industry development while ensuring environmental protection. International collaboration and harmonization of regulatory standards may further promote market expansion and encourage investment in the sector [187].

As global demand for seaweed-derived products continues to rise, the establishment of clear, transparent, and adaptive regulatory frameworks will be essential for supporting innovation, ensuring environmental sustainability, and fostering the long-term development of the seaweed aquaculture industry [168].

Economic limitations

Despite the rapid expansion of the seaweed industry and its considerable potential to contribute to sustainable food production, environmental management, and bioeconomy, several economic challenges continue to constrain sector development. These limitations affect both emerging and established producers and can influence the profitability, competitiveness, and long-term viability of seaweed aquaculture operations [188].

One of the most significant economic concerns is market instability. Prices for seaweed biomass and processed products can fluctuate substantially in response to changes in global demand, supply dynamics, product quality, and international trade conditions [189]. Industries dependent on hydrocolloid production, such as carrageenan and agar manufacturing, are particularly sensitive to fluctuations in raw material availability and market prices. Such volatility can create financial uncertainty for producers and discourage investment in farm expansion [190]. Infrastructure costs represent another major challenge, especially for large-scale and offshore cultivation systems. Significant capital investment may be required for hatcheries, cultivation structures, mooring systems, vessels, harvesting equipment, storage facilities, and processing plants. In many developing regions, limited access to financial resources and investment capital can restrict the adoption of modern technologies and impede industry growth [191].

The seaweed industry also remains highly dependent on labor-intensive operations. Activities such as seed production, farm installation, maintenance, monitoring, harvesting, cleaning, and post-harvest handling often require substantial manual labor. Labor costs can therefore represent a significant portion of production expenses, particularly in regions experiencing rising wages or labor shortages. The seasonal nature of production in some areas may further complicate workforce management and operational planning [192]. Another important limitation is insufficient processing capacity. While global seaweed production continues to increase, processing infrastructure has not always expanded at the same pace. Inadequate facilities for drying, storage, extraction, refinement, and product manufacturing can reduce product quality, increase post-harvest losses, and limit opportunities for value addition. As a result, many producers remain dependent on the sale of low-value raw biomass rather than higher-value processed products [193]. Logistical and supply-chain challenges may further affect profitability, especially in remote coastal and island regions where transportation costs are high and access to markets is limited. The lack of cold-chain infrastructure,

efficient distribution networks, and reliable processing facilities can reduce competitiveness and constrain market development [194].

To overcome these economic barriers, greater investment is needed in processing technologies, mechanization, infrastructure development, and product diversification. The adoption of integrated biorefinery approaches, in which multiple high-value products are extracted from the same biomass stream, may improve economic performance and enhance resource efficiency. Government support programs, public-private partnerships, and improved access to financing can also facilitate industry expansion and technological innovation [195].

As demand for sustainable marine resources continues to grow, addressing these economic limitations will be essential for unlocking the full potential of seaweed aquaculture. Improvements in processing capacity, market development, technological efficiency, and value-added product generation are likely to play a critical role in ensuring the long-term economic sustainability and global competitiveness of the seaweed industry [196].

Emerging Technologies and Future Perspectives

The future of seaweed aquaculture will be strongly influenced by advances in biotechnology, engineering, digital technologies, and sustainable production systems. As global demand for seaweed-derived products continues to increase, the industry must improve productivity, resilience, resource efficiency, and environmental sustainability. Emerging technologies are expected to play a central role in overcoming current limitations while supporting the expansion of seaweed cultivation into new geographic regions and markets [197].

Selective breeding

Selective breeding programs are becoming increasingly important for the improvement of commercially cultivated seaweeds. Historically, many seaweed farming operations relied on wild-collected propagules or vegetative propagation from locally available stocks. While these approaches have supported industry growth, they often provide limited opportunities for genetic improvement [15].

Modern breeding programs seek to develop superior cultivars with characteristics that enhance both productivity and crop resilience. Key breeding objectives include faster growth rates, increased biomass yields, improved tolerance to environmental stressors, enhanced resistance to diseases and biofouling, and optimized biochemical composition for specific industrial applications. For example, breeding efforts are increasingly targeting higher concentrations of proteins, hydrocolloids, bioactive compounds, and other valuable metabolites [198].

As climate change continues to affect marine environments, selective breeding will become increasingly important for generating strains capable of maintaining productivity under elevated temperatures, variable salinity conditions, and other environmental challenges [199].

Genomics and precision aquaculture

Recent advances in genomics, precision aquaculture, offshore automation, and circular bioeconomy approaches are reshaping the seaweed sector. High-throughput sequencing, molecular markers, and bioinformatics tools are accelerating breeding programs through marker-assisted selection, while supporting genetic conservation and sustainable resource management. At the same time, precision aquaculture technologies, including artificial intelligence, remote sensing, drones, and Internet of Things (IoT) systems, enable real-time environmental monitoring, predictive analytics, and optimized farm management. As cultivation expands into offshore environments, automated monitoring platforms, robotic systems, Autonomous Underwater Vehicles (AUVs), and Remotely Operated Vehicles (ROVs) are improving operational efficiency, safety, and the economic feasibility of large-scale farms. In parallel, seaweed biorefineries are promoting a circular bioeconomy by maximizing biomass utilization through the sequential extraction of high-value compounds and the conversion of residual biomass into biofertilizers, feed, and bioenergy products. Together, these innovations are expected to enhance productivity, resilience, and sustainability, reinforcing the role of seaweed aquaculture as a key contributor to food security, human health, renewable materials, and the emerging blue bioeconomy [200].

Conclusions

Seaweed aquaculture has emerged as one of the fastest-growing and most promising sectors of global aquaculture, playing an increasingly important role in sustainable food production, environmental management, and the development of the blue economy. The cultivation of marine macroalgae offers a unique combination of economic, environmental, and social benefits, distinguishing it from many other forms of agriculture and aquaculture. Seaweeds provide a renewable source of food, feed ingredients, hydrocolloids, pharmaceuticals, nutraceuticals, biomaterials, and bioenergy feedstocks, while simultaneously delivering valuable ecosystem services such as nutrient removal, carbon uptake, habitat provision, and biodiversity enhancement.

The rapid expansion of seaweed farming has been driven by advances in cultivation technologies, hatchery development, selective breeding, and processing systems. Modern production methods, including longline, raft, bottom, nearshore, and offshore cultivation systems, have enabled substantial increases in biomass production across diverse geographic regions. Furthermore, the integration of seaweeds into multi-trophic aquaculture systems has demonstrated significant potential for improving resource efficiency and reducing the environmental impacts of intensive aquaculture.

Despite these achievements, several challenges continue to constrain the sustainable growth of the industry. Climate change, disease outbreaks, biofouling, genetic erosion, regulatory limitations, and economic barriers remain important concerns that require continued scientific attention and adaptive management. Addressing these challenges will require coordinated efforts among researchers, industry stakeholders, governments, and international organizations to promote innovation, strengthen governance frameworks, and improve production resilience.

Future progress in seaweed aquaculture will depend on the successful application of emerging technologies, including genomics, molecular breeding, artificial intelligence, remote sensing, automation, and precision aquaculture. These innovations have the potential to improve productivity, enhance crop resilience, optimize farm management, and support the development of climate-adaptive cultivation strategies. Simultaneously, advances in seaweed biorefinery technologies will facilitate the complete utilization of

biomass, enabling the production of multiple high-value products within circular bioeconomy frameworks.

The growing recognition of seaweeds as strategic marine resources positions the industry at the intersection of food security, environmental sustainability, renewable materials, and climate action. As global populations continue to increase and pressure on terrestrial resources intensifies, seaweed cultivation offers a viable pathway for expanding biomass production without increasing demands on freshwater resources or arable land. Moreover, its contribution to ecosystem restoration and sustainable coastal development aligns closely with international sustainability goals and blue-economy initiatives.

Ultimately, the future of seaweed aquaculture will depend on continued interdisciplinary research, technological innovation, effective policy development, and international collaboration. With appropriate investment and sustainable management, seaweed farming has the potential to become a cornerstone of future marine-based economies, contributing to resilient food systems, renewable bioproduct industries, and healthier coastal ecosystems in an increasingly resource-constrained world.

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Conflicts of Interest

The authors declare no conflicts of interest.

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