Promoting APEC Cooperation for Seaweed-based Sustainable Bioenergy Production

APEC Energy Working Group

April 2025

Asia-Pacific Economic Cooperation

Promoting APEC Cooperation for Seaweed-based Sustainable Bioenergy Production

APEC Energy Working Group

April 2025

APEC Project: EWG_201_2023

Produced by
Prof. Gyoo Yeol Jung, Pohang University of Science and Technology
Prof. Sang Woo Seo, Seoul National University
Prof. Sung In Lim, Pukyong National University
Prof. Hyun Gyu Lim, Inha University
Prof. Sungho Jang, Incheon National University
Prof. Jina Yang, Jeju National University
Dr. Giyoung Shin, Korea Research Institute of Chemical Technology
Dr. Myung Hyun Noh, Korea Research Institute of Chemical Technology

For
Asia-Pacific Economic Cooperation Secretariat
35 Heng Mui Keng Terrace
Singapore 119616
Tel: (65) 68919 600
Fax: (65) 68919 690
Email: info@apec.org
Website: www.apec.org

APEC#225-RE-01.4

Contents

I. Seaweed as a renewable feedstock for bioenergy and biorefinery

Historically, industries have evolved around the crude oil value chain, refining crude oil to produce a variety of energy materials and petroleum-based chemicals. This structure has facilitated rapid industrial growth, but it has also led to significant challenges, such as the depletion of crude oil reserves and the acceleration of climate change due to excessive carbon dioxide emissions. To address these issues, the concept of biorefineries has emerged, focusing on utilizing various biomass sources, such as microorganisms and plants, as renewable feedstocks for producing sustainable fuels and chemicals.

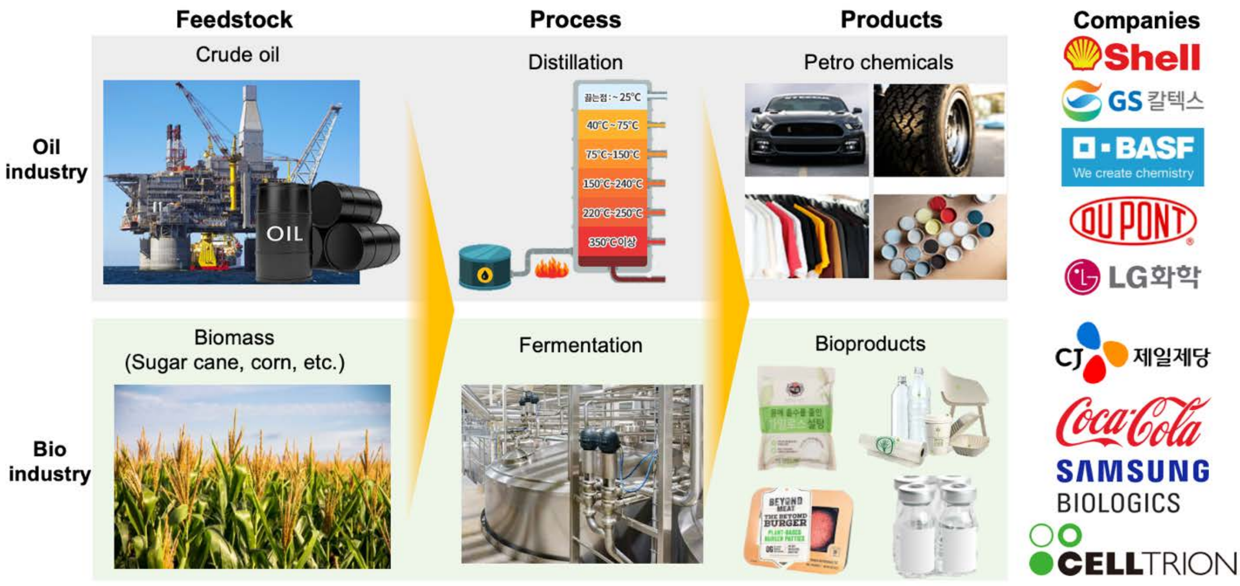

Figure 1. Comparison of Oil Refinery and Biorefinery

Ongoing research is exploring the potential of using readily available crops and non-edible terrestrial plants as raw materials for biorefineries, aiming to reduce reliance on crude oil and mitigate carbon emissions. However, many crops are in high demand for food, making them costly as biomass sources. This demand is expected to increase with the projected global population reaching 8.5 billion by 2030 and 10.4 billion by 2100 (United Nations, 2023). Additionally, non-edible terrestrial plants present challenges due to the presence of lignin, which is difficult to decompose and can cause microbial toxicity, requiring significant preprocessing. As a result, achieving cost competitiveness with fossil fuel-based production remains difficult. Moreover, large-scale terrestrial plant cultivation requires nitrogen fertilizers, which contribute to greenhouse gas emissions and environmental pollution.

In contrast, seaweed is emerging as an ideal feedstock for biorefineries due to its high photosynthetic efficiency, rapid growth, and carbohydrate content. Unlike terrestrial plants, seaweed does not require arable land, freshwater, or fertilizers for cultivation, making it suitable for regions with limited land and water resources. Seaweed's ability to absorb significant amounts of carbon dioxide during growth also aids in carbon sequestration and climate change mitigation, a feature known as "blue carbon." This characteristic is particularly valuable for industries aiming to reduce emissions and earn carbon credits.

Additionally, seaweed lacks lignin, which simplifies the conversion process. Simple saccharification can produce fermentable sugars, making it easier to convert seaweed into valuable bioenergy sources and chemicals using well-established biomass conversion methods. However, despite these advantages, the seaweed cultivation industry is still in its early stages globally, and the current production scale is insufficient to meet the growing demand for biorefinery feedstocks.

Establishing a robust seaweed value chain is more complex than the straightforward petroleum value chain. To secure the economic viability of seaweed-based biorefineries, significant efforts are needed in areas such as ensuring a stable raw material supply, improving conversion technologies, optimizing facilities, and maintaining economies of scale. The development of a sustainable seaweed value chain is crucial for realizing its full potential as a renewable feedstock for future energy and chemical industries.

In addition to its applications in food, chemicals, and materials, seaweed biomass is not only a sustainable resource but also holds considerable potential for bioenergy production. The technology for producing bioethanol from seaweed follows a process similar to that of crops like corn or sugarcane. The biomass is first broken down into fermentable sugars, which are then fermented to produce ethanol. This process requires a variety of technologies, including efficient strain selection, large-scale cultivation techniques, and advanced fermentation systems. As the seaweed bioenergy sector develops, technologies for seaweed large-scale cultivation, pretreatment, and fermentation will play a crucial role in ensuring a stable biomass supply and optimizing production efficiency. Despite its promising potential, the industrialization of seaweed-based bioenergy is still in its early stages, with challenges remaining in scaling up production and improving process efficiencies.

II. Advancements in seaweed production and bioenergy technologies

1. Seaweed biomass production and carbon sequestration

1.1. Background

The cultivation of seaweed, also known as marine macroalgae, has emerged as one of the most promising solutions for addressing multiple global challenges in sustainable resource production and environmental conservation. Over the past several decades, seaweed cultivation has evolved from traditional small-scale farming practices into a sophisticated industry that encompasses various technological innovations and scientific advancements. A comprehensive analysis of global seaweed farming potential has demonstrated that this form of aquaculture presents unique advantages over conventional biomass production methods, particularly because it requires no arable land, freshwater resources, or additional fertilizer inputs (Duarte et al. 2017).

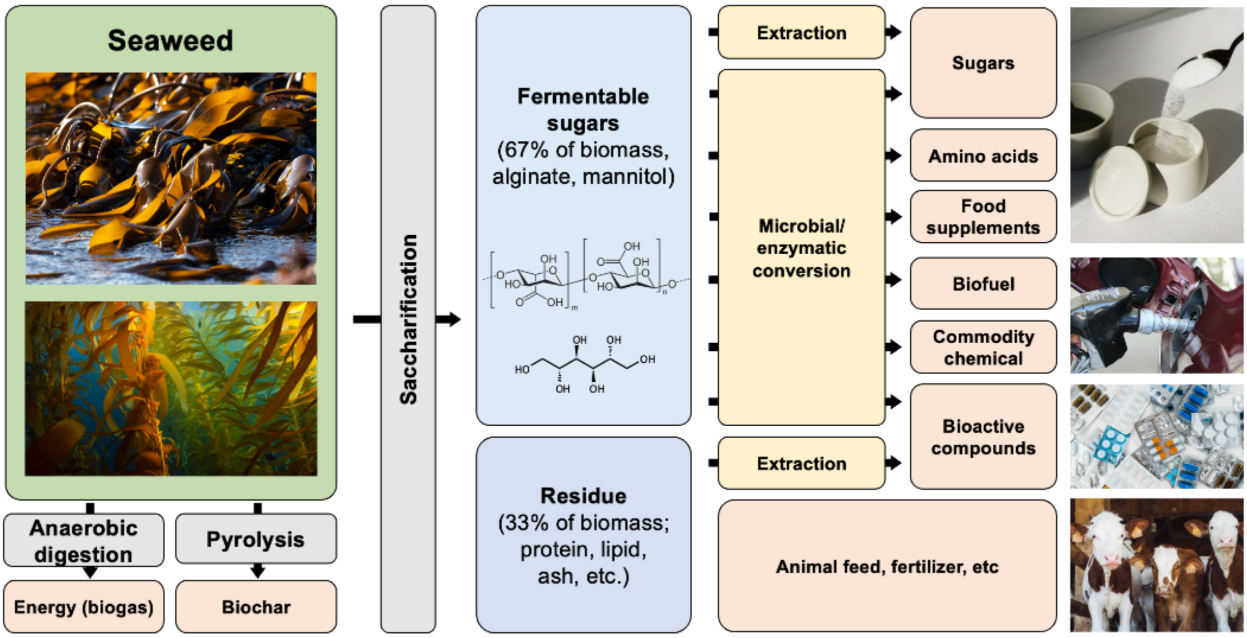

Figure 2. Versatility of seaweed as a renewable resource for value-added products

Seaweed's remarkable versatility as a renewable resource has garnered increasing attention from both the scientific community and industry stakeholders. Recent studies have demonstrated that seaweed cultivation can address multiple sustainability challenges, including food security, renewable energy production, and climate change mitigation (Froehlich et al. 2019). Seaweeds' ability to rapidly accumulate biomass while absorbing carbon dioxide from seawater makes them highly valuable for mitigating climate change. Figure 2 illustrates the seaweed value chain, where seaweed is processed into fermentable sugars through saccharification, and then converted into valuable products such as amino acids, food supplements, biofuels, commodity chemicals, and bioactive compounds via microbial or enzymatic conversion. Additionally, the residual biomass, which includes proteins, lipids, and ash, can be processed into animal feed, fertilizers, and other byproducts. Seaweed can also undergo anaerobic digestion to produce biogas for energy or pyrolysis to generate biogas and biochar. These processes highlight the diverse range of products that seaweed can produce, supporting sustainable solutions across energy, nutrition, and agriculture sectors.

The global seaweed industry has experienced remarkable growth and transformation in recent years, driven by technological innovations and increasing market demand across various sectors. A systematic analysis of worldwide seaweed production and utilization patterns has revealed significant expansion in both cultivation methods and applications. This growth has been particularly notable in the development of large-scale cultivation systems, which have evolved to incorporate advanced technologies for improved efficiency and productivity. Furthermore, extensive research into the carbon sequestration potential of seaweed cultivation has highlighted its significant role in marine carbon capture and storage strategies (Buschmann et al. 2017).

1.2. Current state of large-scale seaweed cultivation

1.2.1. Global production overview

The contemporary landscape of seaweed cultivation represents a remarkable convergence of traditional farming practices and modern technological innovations, resulting in a rapidly expanding global industry. An extensive analysis of worldwide production patterns has revealed that seaweed aquaculture has become one of the fastest-growing sectors within the broader field of marine biotechnology. The geographical distribution of production facilities demonstrates a particularly strong concentration in Asian regions, where decades of cultivation experience have led to the development of highly efficient farming systems and well-established market channels.

The evolution of seaweed cultivation, from traditional near-shore farming to large-scale, sophisticated operations, has been driven by several interconnected factors. A comprehensive analysis of industry development has shown that advancements in cultivation technologies, rising global demand for seaweed products, and supportive government policies have all played crucial roles in this transformation. Additionally, extensive research indicates that large-scale seaweed farming offers significant environmental benefits, such as enhancing coastal ecosystems and restoring marine habitats, beyond its direct economic returns (van der Molen et al. 2018).

1.2.2. Production systems

The development of efficient and reliable production systems represents one of the most significant achievements in modern seaweed cultivation (**Figure 3**). These systems have evolved through extensive experimentation and technological innovation, resulting in diverse approaches adapted to different environmental conditions and species requirements. A detailed technical assessment has identified and characterized several distinct categories of production systems, each offering specific advantages for large-scale cultivation operations.

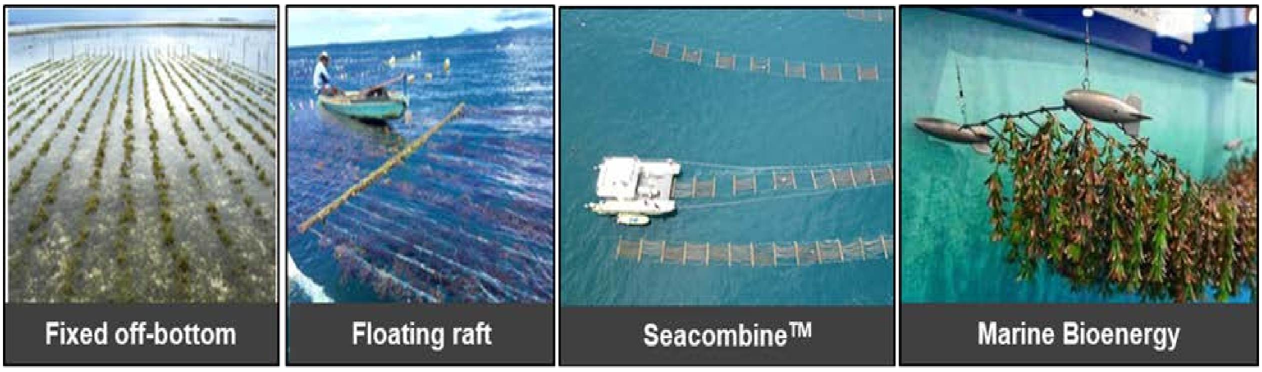

Figure 3. Conventional vs. Innovative technologies for seaweed cultivation

The images were obtained from seafdec.org, sea6energy.com, and marinebiomass.com

1.2.2.1. Longline systems

Longline cultivation systems have become the cornerstone of modern large-scale seaweed production, blending traditional farming knowledge with contemporary engineering principles. Over several decades, these systems have been continuously refined and optimized. They consist of intricate arrangements of horizontal and vertical lines designed to maximize growing surface area while maintaining structural integrity under various oceanographic conditions. A comprehensive evaluation of offshore cultivation techniques shows that longline systems offer exceptional versatility across diverse geographical locations and environmental conditions, making them especially well-suited for large-scale commercial operations (Peteiro, Sánchez, and Martínez 2016).

The evolution of longline system design has been marked by significant advancements in materials science and structural engineering. Modern installations now incorporate sophisticated mooring configurations and specialized synthetic materials, which enhance durability and stability in exposed marine environments. Recent innovations in mooring system design have further improved the resilience of these installations, enabling them to be deployed in increasingly challenging offshore conditions (Walls et al. 2017). These advancements have been particularly crucial in expanding the potential cultivation area for seaweed production, allowing farmers to access previously unreachable offshore locations.

1.2.2.2. Floating raft systems

Floating raft systems represent another significant advancement in seaweed cultivation technology, particularly well-suited for sheltered coastal areas and semi-exposed marine environments. These systems have evolved to incorporate innovative design elements that address specific challenges associated with shallow water cultivation. The development of floating raft technologies has been characterized by continuous improvements in structural design and materials selection, resulting in systems that offer remarkable stability and operational efficiency. Recent engineering studies have led to the creation of enhanced raft designs that demonstrate superior wave resistance characteristics and significantly reduced maintenance requirements compared to earlier iterations.

1.2.2.3. Integrated Multi-trophic Aquaculture (IMTA)

Integrated Multi-trophic Aquaculture (IMTA) represents one of the most sophisticated and ecologically sound approaches to modern aquacultivation, embodying the principles of circular economy and sustainable resource utilization in marine environments (**Figure 4**). These systems have been developed through extensive research and practical experimentation, incorporating complex interactions between different trophic levels to create highly efficient and environmentally beneficial production systems. A comprehensive analysis of IMTA performance has demonstrated that seaweeds cultivated within these integrated systems can achieve substantially higher growth rates compared to traditional monoculture approaches, primarily due to the optimized nutrient cycling and synergistic relationships between different species.

The implementation of IMTA systems requires careful consideration of multiple factors, including species selection, spatial arrangement, and environmental conditions. Extensive research has shown that successful IMTA operations depend on achieving the right balance between fed species, such as fish, and extractive species, including seaweeds and filter-feeding organisms. The economic viability of these systems has been thoroughly evaluated through detailed cost-benefit analyses, which have consistently demonstrated that IMTA can significantly enhance overall farm profitability through product diversification and improved resource utilization efficiency. However, current techniques used for sheltered coastal areas will require adaptation for offshore operations to withstand the powerful forces of currents, waves, and swells prevalent in open environments.

Figure 4. IMTA naval technologies

The images were obtained from IntraFish.com and DNV.com.

1.3. Advanced technologies in seaweed cultivation

1.3.1. Offshore cultivation systems

The development of offshore cultivation technologies represents one of the most significant technological advances in modern seaweed aquaculture, opening up vast new areas for potential production while addressing many of the spatial constraints associated with coastal farming. These systems have evolved through extensive research and development efforts, incorporating sophisticated engineering solutions to overcome the considerable challenges presented by exposed ocean environments. A comprehensive evaluation of offshore cultivation technologies has revealed several groundbreaking innovations that have fundamentally transformed the possibilities for large-scale seaweed production (Bak, Gregersen, and Infante 2020).

Modern offshore cultivation systems incorporate several revolutionary technological elements that distinguish them from traditional nearshore installations. The development of advanced mooring systems represents a particularly significant advancement, enabling cultivation structures to maintain stability under high-energy ocean conditions while minimizing environmental impact on the seafloor. These mooring systems utilize sophisticated dynamic tension mechanisms and advanced materials that can withstand the considerable forces generated by ocean currents and wave action. Furthermore, the implementation of submersible cultivation structures has provided an innovative solution to the challenges posed by surface storms and extreme weather events, allowing farming operations to continue even under adverse conditions.

The automation and monitoring capabilities integrated into contemporary offshore systems represent another crucial advancement in seaweed cultivation technology. These systems incorporate state-of-the-art sensor networks and remote monitoring equipment that enable continuous surveillance of cultivation conditions and crop status. Recent field trials of these advanced offshore systems have demonstrated that they can achieve production efficiencies comparable to, or even exceeding, those of traditional nearshore installations, while simultaneously reducing conflicts with other maritime activities and minimizing environmental impacts.

1.3.2. Automation and mechanization

The integration of automated systems and mechanized operations into seaweed cultivation represents a transformative development in the industry, fundamentally changing how large-scale farming operations are conducted. These technological innovations encompass a wide range of specialized equipment and systems designed to optimize various aspects of the cultivation process, from initial seeding through to final harvest. The implementation of automation technologies has led to substantial improvements in operational efficiency and consistency, while simultaneously reducing the physical demands on farm workers and minimizing the potential for human error in critical processes.

Automated seeding systems, in particular, have revolutionized one of the most labor-intensive aspects of seaweed cultivation. These sophisticated systems utilize precision mechanisms and advanced control systems to achieve uniform distribution of seaweed spores or juvenile plants along cultivation lines. Extended studies comparing manual seeding operations with automated alternatives have revealed substantial improvements not only in operational efficiency but also in the consistency and reliability of seeding outcomes. The implementation of automated seeding technology has demonstrated remarkable potential for reducing labor requirements while simultaneously improving cultivation success rates through more precise and controlled deployment of seeding materials (Forbord et al. 2021).

1.3.3. Artificial intelligence and IoT Integration

The incorporation of artificial intelligence and Internet of Things (IoT) technologies into seaweed cultivation systems represents one of the most advanced developments in modern aquaculture management. These sophisticated technological solutions encompass a comprehensive array of sensors, data processing systems, and automated response mechanisms that work in concert to optimize growing conditions and maximize production efficiency. The implementation of AI-driven monitoring systems has transformed the ability of farm operators to predict and respond to changing environmental conditions, enabling proactive management strategies that significantly enhance cultivation outcomes.

Modern IoT systems deployed in seaweed farming operations utilize an extensive network of sophisticated sensors capable of continuously monitoring a wide range of environmental parameters. These advanced monitoring systems provide farm operators with unprecedented insight into cultivation conditions, enabling real-time adjustments to management strategies based on current environmental conditions and crop status. The integration of these technologies has led to significant improvements in farm productivity through the optimization of growing conditions and early detection of potential problems.

1.4. Processing and storage technologies

1.4.1. Drying technologies

The development and refinement of seaweed drying technologies represents a critical advancement in post-harvest processing capabilities, fundamentally impacting the quality and commercial value of seaweed products. Contemporary drying systems encompass a diverse range of technological approaches, each designed to address specific challenges associated with moisture removal while preserving the valuable biochemical components of seaweed biomass. The evolution of these technologies has been driven by the need to optimize energy efficiency while maintaining product quality, leading to significant innovations in equipment design and process control mechanisms.

Heat pump drying technology has emerged as a particularly promising advancement in seaweed processing, offering substantial improvements in energy efficiency compared to conventional drying methods. These sophisticated systems utilize carefully controlled temperature and humidity parameters to achieve optimal drying conditions while minimizing energy consumption. The implementation of heat pump technology in seaweed processing operations has demonstrated remarkable potential for reducing operational costs while maintaining, or even enhancing, the quality characteristics of dried seaweed products (Schiener et al. 2015).

1.4.2. Preservation methods

The advancement of preservation technologies for harvested seaweed represents another crucial area of technological development in the seaweed industry. Modern preservation methods incorporate sophisticated approaches to maintaining product quality during storage and transportation, utilizing carefully controlled environmental conditions and specialized packaging materials. The development of modified atmosphere packaging technologies, in particular, has revolutionized the ability to maintain seaweed quality during extended storage periods, significantly expanding the potential market reach for seaweed products.

Contemporary preservation systems often integrate multiple technological approaches to achieve optimal results. The implementation of controlled temperature storage facilities, combined with advanced packaging technologies, has created unprecedented opportunities for extending product shelf life while maintaining nutritional value and organoleptic properties. Furthermore, the development of natural preservation methods has provided innovative solutions for maintaining product quality without relying on synthetic preservatives, meeting increasing consumer demand for natural and minimally processed products.

1.5. Monitoring and management systems

1.5.1. Environmental monitoring

The implementation of sophisticated environmental monitoring systems represents a fundamental advancement in modern seaweed cultivation practices, enabling unprecedented levels of control and optimization in farming operations. These advanced monitoring systems incorporate multiple layers of sensor technologies and data analysis capabilities, providing comprehensive insight into the complex environmental parameters that influence seaweed growth and development. The integration of real-time monitoring capabilities has transformed the ability of farm operators to respond to changing environmental conditions, leading to significant improvements in cultivation outcomes and operational efficiency.

Modern environmental monitoring systems utilize an extensive array of sophisticated sensors capable of continuously measuring critical parameters such as water temperature, salinity, nutrient levels, and light penetration. These advanced monitoring capabilities are further enhanced by the implementation of data analytics platforms that can process and interpret complex environmental data streams in real-time. The development of these integrated monitoring solutions has significantly improved the ability of farm operators to maintain optimal growing conditions, leading to substantial increases in biomass production and product quality.

1.5.2. Growth assessment technologies

The evolution of growth assessment technologies has revolutionized the ability to monitor and optimize seaweed cultivation processes with unprecedented precision and reliability. Modern assessment systems incorporate sophisticated underwater imaging technologies, automated measurement systems, and advanced data analysis capabilities that enable detailed monitoring of biomass development throughout the cultivation cycle. These innovative technologies have transformed traditional growth monitoring approaches, providing farm operators with comprehensive insights into marine crop development patterns and potential issues that may affect production outcomes.

Underwater imaging systems, in particular, have emerged as a crucial tool in modern seaweed cultivation management. These advanced systems utilize high-resolution cameras and sophisticated image processing algorithms to provide detailed visual documentation of crop development. The integration of machine learning capabilities has further enhanced the utility of these systems, enabling automated analysis of growth patterns and early detection of potential problems such as disease outbreaks or nutrient deficiencies. Furthermore, the development of predictive modeling capabilities based on accumulated growth data has significantly improved the ability of farm operators to optimize harvest timing and maximize product quality.

1.6. Carbon sequestration technologies and measurement

1.6.1. Carbon capture mechanisms

The investigation and optimization of carbon sequestration mechanisms in seaweed cultivation systems represents one of the most significant areas of contemporary research in marine biotechnology. Modern understanding of these processes has revealed multiple pathways through which seaweed cultivation contributes to carbon dioxide removal from marine environments. These mechanisms include not only direct biomass accumulation but also the export of dissolved organic carbon to deeper water layers and the enhancement of ocean alkalinity (Krause-Jensen and Duarte 2016).

Recent advancements in understanding carbon sequestration mechanisms have led to the development of sophisticated cultivation strategies specifically designed to maximize carbon capture potential. These approaches integrate knowledge of seaweed physiology, oceanographic processes, and environmental interactions to optimize carbon dioxide removal from marine environments. Mathematical modeling efforts have provided valuable insights into the potential scale of carbon sequestration achievable through large-scale seaweed cultivation, highlighting the significant role these systems could play in global climate change mitigation strategies (Wu et al. 2020).

1.6.2. Measurement and verification technologies

The development of accurate and reliable methods for measuring carbon sequestration in seaweed cultivation systems represents a critical advancement in validating their potential contribution to climate change mitigation. Modern measurement approaches incorporate a diverse array of sophisticated technologies and analytical methods, enabling comprehensive assessment of carbon flows through seaweed cultivation systems. The implementation of stable isotope analysis techniques has provided particularly valuable insights into carbon movement patterns within these systems, enabling detailed tracking of carbon transfer between different ecosystem components.

The establishment of standardized protocols for quantifying carbon sequestration represents another crucial development in this field. These protocols incorporate comprehensive guidelines for measurement procedures, data collection methodologies, and verification processes, ensuring consistency and reliability in carbon sequestration assessments. Furthermore, the integration of advanced monitoring technologies with standardized measurement protocols has significantly improved the ability to accurately quantify the climate mitigation potential of seaweed cultivation operations (Macreadie et al. 2019).

1.7. Conclusions

The advancement of large-scale seaweed cultivation technologies and carbon sequestration capabilities represents a significant milestone in the development of sustainable marine biotechnology. Through comprehensive examination of current technological developments, this review has highlighted the remarkable progress achieved in multiple aspects of seaweed cultivation and carbon sequestration measurement. The evolution of cultivation systems, from traditional nearshore operations to sophisticated offshore installations, demonstrates the industry's capacity for technological innovation and adaptation to emerging challenges.

Integration of advanced technologies, including artificial intelligence, IoT technologies, and automated systems, has fundamentally transformed the operational capabilities of modern seaweed cultivation facilities. These technological advancements have not only improved production efficiency and reliability but have also enhanced our ability to monitor and optimize growing conditions while minimizing environmental impacts. Furthermore, the development of sophisticated processing and storage technologies has significantly expanded the commercial potential of seaweed products, creating new opportunities for industry growth and market development.

Particularly noteworthy is the progress made in understanding and quantifying the carbon sequestration potential of seaweed cultivation systems. The development of advanced measurement and verification technologies has provided crucial tools for validating the role of seaweed cultivation in climate change mitigation strategies. These advancements have established a solid foundation for the integration of seaweed cultivation into global carbon management initiatives.

2. Seaweed-based biofuels: technologies and challenges

2.1. Background

Seaweed is increasingly recognized as a promising feedstock for biofuels due to its rapid growth, high carbon capture efficiency, and sustainability. Unlike traditional biofuel crops such as corn and sugarcane, seaweed does not require arable land, freshwater, or fertilizers for cultivation, making it a more environmentally sustainable option. Moreover, its ability to absorb large amounts of carbon dioxide during growth contributes to climate change mitigation through carbon sequestration, known as "blue carbon."

The conversion of seaweed into bioenergy and biochemicals via fermentation processes offers a significant alternative to traditional feedstocks like corn starch and sugarcane. This process could address concerns related to price volatility, ethical issues, and the environmental impacts of land-use, water use, and fertilizer application associated with conventional crops. However, the bioenergy production from seaweed involves several stages, including harvest, pretreatment, saccharification, and fermentation.

Despite its potential, seaweed-based biofuel production faces several challenges. Seaweed's high moisture content (80-90%) increases transportation costs and complicates storage and drying processes, making the overall production less efficient and sustainable. The biomass also contains various compounds such as polysaccharides, proteins, and lipids, which are not easily extracted at an industrial scale. The extraction of valuable components like alginates or biofuels requires complex and costly processes, and the infrastructure for large-scale seaweed production and processing is not yet as developed as that for other crops. Scaling up production will require significant investment in new technologies, as well as the development of suitable microbial strains for fermentation and processing.

In the biofuel sector, bioethanol is primarily derived from food-based crops like corn or sugarcane. This has raised concerns about land-use competition, food security, and sustainability, especially with price fluctuations in feedstocks like corn, which account for up to 85% of ethanol production costs. Additionally, ethanol prices are closely tied to gasoline prices, which creates a dependency on crude oil price fluctuations. This dependency affects both the pricing and demand for ethanol.

Seaweed-based bioethanol production offers a scalable and sustainable alternative, as it does not compete with food production. Advances in seaweed cultivation, biomass processing, and fermentation technologies are unlocking its full potential as a biofuel feedstock. Research has demonstrated that seaweed-based bioethanol can be produced cost-competitively, contributing to reduced greenhouse gas emissions and providing a sustainable alternative to fossil fuels.

However, to make seaweed-based bioethanol economically viable, it is crucial to reduce feedstock costs and improve production methods. Progress in microbial engineering, including the development of yeast strains capable of efficiently fermenting seaweed sugars, is essential to enhance conversion efficiencies. Additionally, the development of efficient extraction and conversion technologies is necessary to make seaweed a viable feedstock for industrial bioethanol production. Governments can further support this by introducing policies and incentives to boost seaweed-based biofuel production and reduce reliance on land-based feedstocks.

In conclusion, seaweed-based bioethanol presents an exciting opportunity to reduce reliance on traditional biofuels and contribute to sustainability goals. Although the seaweed biofuel industry is still in its early stages, it holds immense potential for large-scale, sustainable bioenergy production. Through technological innovation, cost optimization, and supportive policies, seaweed-based bioethanol can play a critical role in creating a more sustainable and eco-friendly energy future.

2.2. Technologies for seaweed sugar extraction

Seaweed has gained increasing attention as a sustainable and renewable source for various industrial applications, particularly in the extraction of sugars. Seaweed contains a rich array of polysaccharides, such as alginate, agar, and carrageenan, which can be broken down into simple sugars like uronic acid, glucose, galactose, and mannose. These sugars hold great potential for use in biofuel production, food additives, bioplastics, and other biochemical industries. Unlike terrestrial crops, seaweed does not require arable land, fresh water, or fertilizers, making it an attractive alternative to traditional feedstocks. However, the extraction of sugars from seaweed presents unique challenges due to its cell wall structure and the presence of high moisture content, which necessitates energy-intensive drying and processing techniques. Moreover, the variability in seaweed composition across species and harvesting conditions adds another layer of complexity to the sugar extraction process. As research advances, developing cost-effective and scalable methods for seaweed sugar extraction will be critical to unlocking its full potential as a resource for sustainable industrial applications.

Exemplary techniques for extracting alginate, the major polymer of brown seaweed, are explained (**Figure 5**).

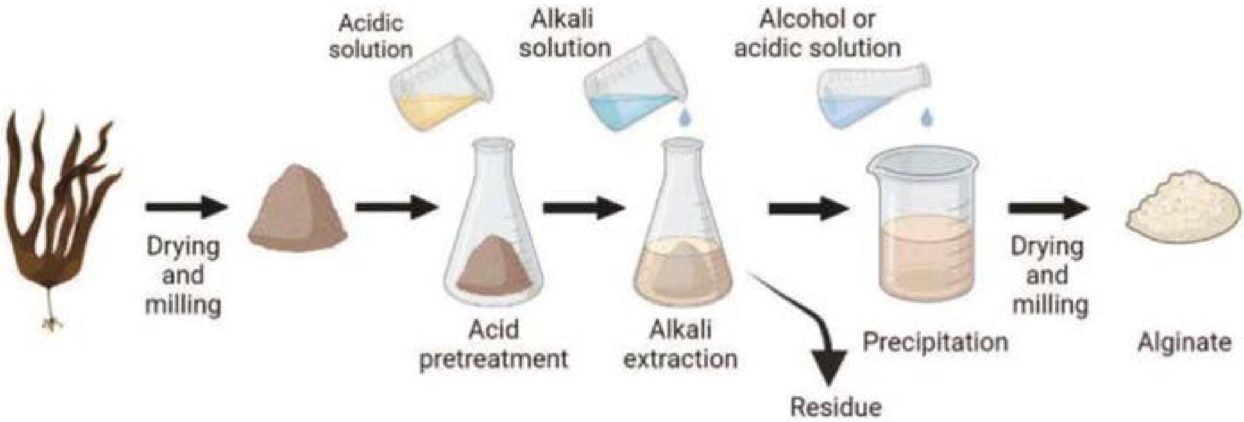

Figure 5. Alginate extraction from seaweed. This image was obtained from Deniz et al., 2022 (Deniz, Imamoglu, and Gundogdu 2022).

Harvest: The timing of seaweed harvest is critical for its various applications, including bioenergy, food, feed, and bioplastics. Harvest timing significantly affects the quality and suitability of seaweed for different uses. For bioenergy production, seaweed needs to be harvested when its carbohydrate content is at its peak. This typically occurs when the seaweed is nutrient-stressed. Early harvesting is essential for food applications to ensure low biofouling and heavy metal content. This helps provide clean material, reduce processing time, and minimize allergenic risks. Protein, lipid, and carbohydrate levels fluctuate over the season.

Maceration: grind or chop the cleaned seaweed biomass into small pieces to increase the surface area. Mechanical maceration can be achieved using grinders, blenders, or milling equipment.

Alginate extraction: extract alginate from the macerated seaweed biomass using hot water or alkaline solutions. The choice of extraction solvent depends on factors such as seaweed species, alginate yield, and desired product properties.

Hot water extraction: immersing the macerated seaweed biomass in hot water (typically around 80-100°C) and stirring to promote the dissolution of alginate into the aqueous solution. The mixture is then filtered to separate the alginate extract from the residual seaweed solids.

Alkaline extraction: treating the macerated seaweed biomass with alkaline solutions, such as sodium carbonate or sodium hydroxide, to break down the cell wall structure and release alginate. The resulting alginate solution is neutralized with acid and filtered to remove impurities.

Precipitation and Filtration: after extraction, alginate is precipitated from the aqueous solution by adding calcium chloride ($CaCl_2$) or other divalent cations. Calcium ions cross-link alginate molecules, causing them to form a gel or precipitate. The alginate precipitate is then separated from the solution by filtration or centrifugation, and the filtrate may be recycled for further extraction or processed for other purposes.

Washing and Drying: wash the alginate precipitate with water to remove excess salts, residual chemicals, and impurities. Washing helps improve the purity and quality of the extracted alginate. Dry the washed alginate either by air drying, spray drying, or freeze drying to obtain a powdered or granular form suitable for storage, transportation, and further processing.

Extraction of mannitol follows similar process to alginate.

Hot water extraction: add hot water (around 80–90°C) to the powdered seaweed. The high temperature helps to solubilize mannitol from the seaweed matrix. Stirring the mixture for several hours (typically 2–4 hours) can ensure complete extraction. Solution can be filtered to remove insoluble materials, such as fibrous residues and non-water-soluble compounds. Filtration techniques like vacuum filtration or centrifugation can be used.

Alcohol Precipitation (Optional for higher purity): to increase the purity of mannitol, ethanol can be added to the aqueous extract. Mannitol is less soluble in ethanol, and this step helps in precipitating mannitol out of the solution. Mannitol can be precipitated by slowly adding ethanol (usually in a 1:1 or 1:2 ratio with the water extract). Allow the solution to sit and cool, facilitating mannitol crystallization.

Purification: evaporate the solvent (water and ethanol) using a rotary evaporator or low heat to concentrate the mannitol solution. Crystallize mannitol by cooling the concentrated solution. Mannitol will form crystals as the solution cools.

Filtration and Drying: Once the mannitol has crystallized, filter out the crystals from the liquid. Use a fine filtration method to collect the mannitol crystals. Dry the mannitol crystals in an oven or air dry at low temperatures.

Final Product: The dried mannitol crystals can now be ground to the desired size and are ready for use in various applications.

Ultrasound-Assisted Extraction (Optional): Some researchers use ultrasound waves to enhance the extraction of mannitol from seaweed, which reduces extraction time and increases efficiency.

Supercritical CO_2 Extraction (Optional): An advanced technique where CO_2 under high pressure is used to extract bioactive compounds, including mannitol, although it's more expensive than traditional methods.

2.3. Technologies for seaweed saccharification

Seaweed saccharification, the process of breaking down complex carbohydrates (polysaccharides) into simple sugars (monosaccharides), involves several advanced techniques to extract fermentable sugars from the cell walls of seaweed efficiently. Seaweeds, especially brown and red varieties, are rich in polysaccharides such as alginate, carrageenan, and laminarin, which can be challenging to degrade due to their complex molecular structure. One of the primary methods used for saccharification is enzymatic hydrolysis, where specific enzymes like alginate lyase or cellulase are employed to break down polysaccharides into simple sugars like glucose and mannose. This method is highly selective and can preserve the integrity of the sugars, but it requires the optimization of enzyme concentrations and reaction conditions for efficiency. Another common approach is acid hydrolysis, which involves treating seaweed biomass with diluted acids at high temperatures to break down the cell walls and release the sugars. While this method is faster and can be applied to large-scale processes, it risks generating by-products that may inhibit downstream fermentation, and it may require additional purification steps. Thermal and mechanical pretreatment techniques, such as steam explosion or milling, are often combined with chemical or enzymatic processes to improve the accessibility of polysaccharides by disrupting the seaweed’s cellular structure. These methods can increase sugar yields, but they also come with higher energy requirements. The choice of saccharification technique depends on the type of seaweed, desired product yields, and the overall efficiency of the biofuel production process, with ongoing research focused on optimizing these methods for industrial-scale applications.

Enzymatic hydrolysis involves using enzymes to catalyze the breakdown of seaweed polysaccharides into monosaccharides (**Figure 6**). Enzymes such as alginate lyases target specific bonds within the seaweed cell wall structure to release sugars (Zhu et al. 2015; Zheng et al. 2022). Enzymatic hydrolysis is relatively mild and selective, offering high conversion efficiency and minimal chemical inputs. However, it can be slow and expensive due to the cost of enzymes.

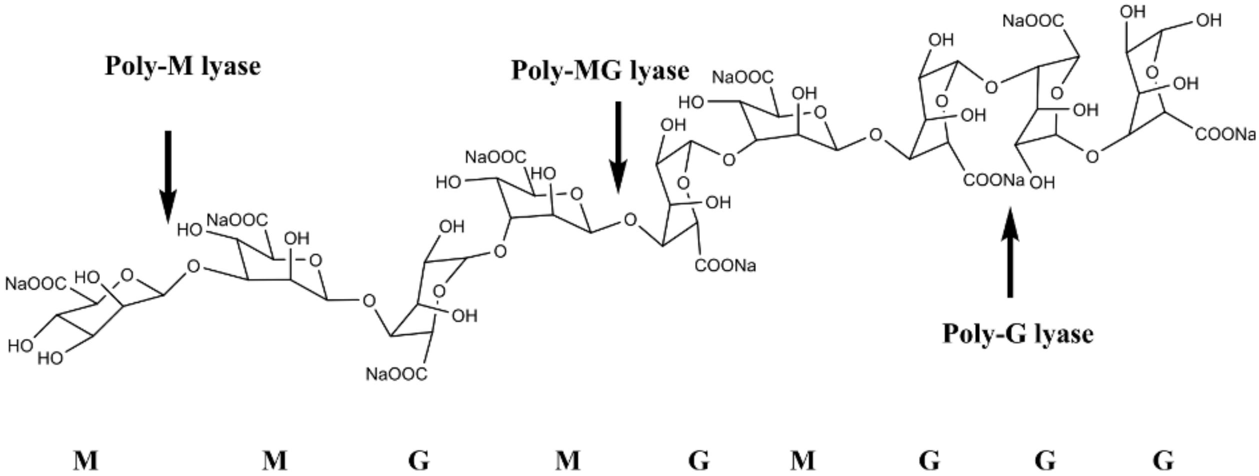

Figure 6. Alginate structure and alginolytic enzymes

This image was obtained from Zheng et al. 2022 (Zheng et al. 2022).

Acid hydrolysis utilizes strong acids, such as sulfuric acid or hydrochloric acid, to cleave the glycosidic bonds in seaweed polysaccharides, resulting in the release of sugars. Acid hydrolysis is faster and more cost-effective than enzymatic hydrolysis but requires careful control of reaction conditions to prevent degradation of sugars and formation of inhibitory by-products. Acid hydrolysis typically requires neutralization and detoxification steps to remove residual acids and inhibitors before downstream processing.

Thermochemical conversion techniques, such as pyrolysis and hydrothermal liquefaction, involve heating seaweed biomass at high temperatures in the absence or presence of water to break down polysaccharides into sugars and other organic compounds. Thermochemical conversion can be highly efficient in converting seaweed biomass into sugars and bio-oil but may require additional purification and upgrading steps to produce high-quality sugars suitable for downstream applications.

Combined approaches leverage the strengths of each method while mitigating their respective limitations, leading to improved overall performance and cost-effectiveness. Seaweed saccharification technologies are still in the early stages of development, and ongoing research efforts focus on optimizing process conditions, enhancing conversion efficiency, reducing costs, and exploring novel approaches to valorize seaweed biomass for sustainable biorefinery applications.

Mechanical disruption techniques are relatively simple and scalable but may require significant energy input and can result in loss of sugar yield due to degradation or recalcitrance of polysaccharides. Mechanical disruption techniques play a crucial role in seaweed saccharification by physically breaking down the seaweed's tough cell walls, making its polysaccharides more accessible for subsequent enzymatic or chemical hydrolysis. These techniques help to increase the surface area of the biomass and reduce the energy required for saccharification. One common mechanical disruption method is milling, where seaweed is ground into smaller particles using specialized equipment, such as ball mills or hammer mills, to reduce particle size and improve the efficiency of downstream processes. Ultrasonication is another widely used technique that employs high-frequency sound waves to generate cavitation bubbles in a liquid medium containing seaweed biomass. The collapse of these bubbles produces intense shear forces that break down the seaweed's cell walls, enhancing the release of intracellular compounds. High-pressure homogenization is a third method, where seaweed slurry is subjected to extremely high pressure, causing cells to rupture as they pass through a narrow valve. This process is particularly effective at disrupting the complex cell wall structure of macroalgae and releasing valuable polysaccharides for saccharification. In some cases, these mechanical methods are combined with thermal or chemical pretreatments to maximize efficiency and improve sugar yields, but they can also be energy-intensive. The selection of an appropriate mechanical disruption technique depends on the specific characteristics of the seaweed species, the desired scale of operation, and the cost-effectiveness of the overall saccharification process.

Integrated saccharification processes often combine multiple techniques, such as enzymatic hydrolysis followed by acid hydrolysis or thermochemical pretreatment, to enhance sugar release and maximize conversion efficiency.

2.4. Technologies for seaweed-based fuel production

Seaweed-based biofuel production has gained significant attention in recent years as a promising alternative to fossil fuels in the quest for cleaner, renewable energy sources. Seaweed offers several advantages over traditional biofuel feedstocks, such as terrestrial crops like corn and sugarcane. Unlike these land-based sources, seaweed does not require arable land, freshwater, or fertilizers for cultivation, making it an environmentally sustainable and resource-efficient option. Additionally, seaweed grows rapidly and can be cultivated in large quantities in ocean-based farms, providing a highly scalable biomass source for biofuel production. The use of seaweed for biofuel also addresses some of the food-versus-fuel debates that arise with other bioenergy crops, as seaweed cultivation does not compete with food production. Furthermore, certain species of seaweed contain high levels of carbohydrates, such as laminarin and mannitol, which can be converted into bioethanol or biobutanol, while other species with high lipid content can be processed into biodiesel. These biofuels have the potential to replace conventional gasoline, diesel, and aviation fuels, contributing to reduced greenhouse gas emissions and a lower carbon footprint.

There is a huge demand for fuel production by biorefineries and the most representative example is bioethnaol production from corn, whose market is estimated to reach USD 124.5 billion in

2030 globally (Awogbemi and Kallon 2024). It is mainly produced in Brazil, the United States, Sweden (Ramsey et al. 2023). By far, its production takes 80% share of the total biochemical production capacity and it is mostly used as an additive in gasoline. Currently, bioethanol is mostly derived from corn or sugarcane. However, it has raised concerns regarding land-use competition, food security, and sustainability (Ramachandra and Hebbale 2020).

In addition, the price of bioethanol is critical and there are various factors affecting it. Corn prices are a primary determinant of ethanol production costs. Corn accounts for approximately 85% of the total variable costs in ethanol production (Bušić et al. 2018). Fluctuations in corn prices impact the profitability of ethanol producers, as higher corn prices squeeze profit margins. In addition, ethanol prices are closely tied to gasoline prices, as ethanol is blended with gasoline. Ethanol prices tend to track gasoline prices due to their substitution relationship in fuel markets. Changes in crude oil prices and fuel demand thus influence the demand and pricing of ethanol.

Government policies significantly shape the economics of corn-based biofuels. Governments encourage to use bioethanol since corn-based ethanol can provide significant greenhouse gas emissions reductions compared to gasoline. For example, the Renewable Fuel Standard (RFS) in the United States mandates the blending of renewable fuels, including ethanol, into transportation fuels. In addition, ethanol producers benefit from government subsidies and incentives provided to support biofuel production (Yacobucci 2013).

In addition to these two major factors, technological innovations and economies of scale play a crucial role in reducing ethanol production costs. Advancements in corn processing technology and larger-scale ethanol plants have contributed to cost reductions in ethanol production (Wang et al. 2019). Furthermore, selling byproducts from an ethanol production process can further reduce the overall cost; for example, the revenue generated from distillers' dried grains with solubles sales can offset feedstock costs and improve the overall economics of ethanol production (Iram, Cekmecelioglu, and Demirci 2020).

Recent research into seaweed biofuel production has highlighted promising alternatives to traditional biofuels, such as the use of Hydrothermal Liquefaction (HTL) and partial anaerobic digestion processes. These two approaches, each with distinct advantages and challenges, have emerged as key technologies in improving the efficiency and sustainability of biofuel production from seaweed. HTL is a thermochemical process that breaks down wet biomass using high temperature (250–400°C) and pressure to produce a liquid biofuel. It offers a high conversion efficiency (~90%) and has the benefit of not requiring dry biomass, which reduces energy costs related to drying. However, HTL requires significant investment due to the high operational costs associated with high temperature and pressure conditions, and it is still in the early stages of technological development.

Partial anaerobic digestion, on the other hand, is a biochemical process where seaweed biomass is decomposed in the absence of oxygen by microorganisms. While this process is more cost-effective and has a higher technological maturity, it has a lower conversion rate (~40%) and is slower compared to HTL. However, its simplicity, low investment cost, and mature technology make it an attractive option for industrial applications.

Combining these two processes with Carbon Capture, Utilization, and Storage (CCUS) technology could potentially reduce carbon emissions and even achieve negative emissions, making it an area of active research.

Seaweed-based bio-ethanol production holds immense potential as a sustainable and scalable solution for renewable energy generation. By leveraging advances in seaweed cultivation, biomass processing, and fermentation technologies, this case study demonstrates the viability of seaweed biofuels as a competitive alternative to traditional fossil fuels. With careful market analysis, economic planning, and environmental stewardship, seaweed-based bio-ethanol production can contribute to a more sustainable energy future.

The microbial platform was engineered to digest and metabolize seaweed biomass and produce valuable chemicals. In a seminal study, a microbial platform was engineered for the direct conversion of brown macroalgae into bioethanol (Wargacki et al. 2012). Through metabolic engineering, *E. coli* was endowed with the ability to metabolize alginate, a major polysaccharide in brown macroalgae, showcasing a viable pathway for biofuel production directly from seaweed biomass.

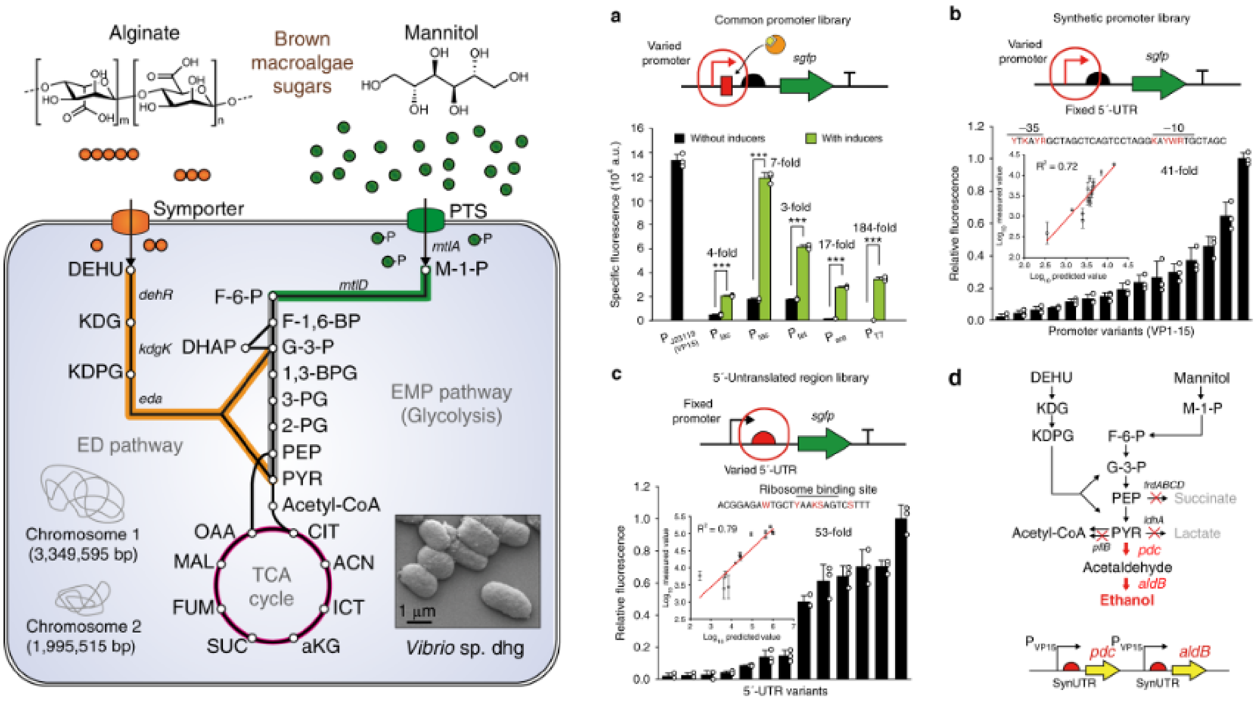

Figure 7. Screening and domestication of seaweed-utilizing microorganism

This figure was obtained from Lim et al., 2019 (H. G. Lim et al. 2019)

Alternative to engineer model microorganisms, natural microbial strains capable of direct utilization of seaweed biomass can be screened and domesticated. Recently, a marine bacteria *Vibrio* sp. dhg was isolated and developed as a platform strain for the chemical production using brown macroalgae (H. G. Lim et al. 2019) (**Figure 7**). This innovative work illustrated the conversion of macroalgae into bioethanol and other valuable chemicals, highlighting the versatility and efficiency of engineered microorganisms in utilizing macroalgal biomass.

Conditions for seaweed pretreatment should be carefully determined. For example, a fermentation study was conducted on *Saccharina latissima*, a species of macroalgae, examining the effects of various pretreatments on bioethanol production (Adams, Gallagher, and Donnison 2009). Their research provides critical insights into optimizing fermentation processes, a key step in the bioconversion of macroalgae into biofuels.

Finally, economic viability and sustainability should be assessed through techno-economic and life cycle assessments. The techno-economic and life cycle assessments of algae-based biofuels have been reviewed recently, shedding light on the potentials and challenges of scaling up biofuel production from macroalgae (Quinn and Davis 2015). This work emphasizes the importance of integrated assessments in understanding the sustainability and economic viability of macroalgae biofuels.

2.5. Bioethanol Production Technologies from Green and Red Seaweed

Green and red seaweeds, particularly species like Gracilaria and Ulva, show high potential for bioethanol production due to their unique biochemical compositions. Gracilaria, a red seaweed, has been a focal point in bioethanol research due to its high carbohydrate content—1.5 to 2 times higher than lignocellulosic feedstocks—and its lack of lignin, which simplifies the conversion process. Research has demonstrated that Gracilaria can yield 20-32% bioethanol through direct or multi-step saccharification, which is considered economically viable compared to the 20-25% yield from lignocellulosic materials.

Seaweed-based bioethanol production aligns with global efforts to reduce dependence on fossil fuels and address climate change, especially with the growing demand for non-food feedstocks like seaweed. Unlike terrestrial crops, seaweed cultivation does not compete with food production, making it an attractive option for biofuel production. However, scaling up production from Gracilaria requires a consistent yield, with industrial processes aiming for over 300 liters of ethanol per ton of biomass.

While bioethanol production from green seaweeds like Ulva has progressed more slowly than from red seaweeds, advancements have been made. Ulva bioethanol production typically involves acid pre-treatment to break down cellulose into fermentable sugars, but this process generates toxic by-products that can inhibit fermentation. Researchers have applied high-pressure liquefaction technology to mitigate this toxicity without chemicals, and developed new yeast strains capable of efficiently fermenting monosaccharides into ethanol.

Both green and red seaweeds are being explored as sustainable feedstocks for bioethanol production. Although progress has been made, further research is needed to optimize efficiency, overcome toxicity issues, and ensure consistent, high yields for large-scale commercialization.

2.6. Regulatory and Policy Support for Seaweed-Based Biofuels

The utilization of seaweed for biofuel production offers a viable alternative to traditional feedstocks, with its abundance and minimal environmental footprint. To accelerate the growth of the seaweed biofuel industry, drawing from the success of bioethanol production, particularly in the United States, could be crucial. The Renewable Fuel Standard (RFS), for instance, has been instrumental in integrating bioethanol into the broader energy market by mandating its inclusion in gasoline blends. This regulatory framework created a stable and predictable demand for bioethanol, which has proven essential for driving market development, technological advancement, and large-scale production.

In the context of seaweed-based biofuels, a similar regulatory approach could play a key role in spurring market adoption and scaling production. By implementing regulations that mandate the inclusion of seaweed-based biofuels in energy mixes, governments can guarantee a market for these fuels, encouraging long-term investments in infrastructure, research, and technology development. This could help overcome the challenges currently limiting the commercialization of seaweed-based biofuels, such as the need for large-scale processing infrastructure and efficient extraction methods.

The success of the bioethanol industry was also fueled by complementary policies such as subsidies and tax incentives, which helped to offset the higher production costs associated with renewable fuels. A similar model could be applied to seaweed-based biofuels, offering financial incentives for the development of seaweed cultivation and processing infrastructure. These incentives would reduce the economic barriers to entry and support early-stage investments in this promising sector.

Furthermore, substantial research and development have been a driving force behind the success of bioethanol, particularly in crop improvement, production efficiencies, and conversion technologies. A similar emphasis on R&D would be crucial for optimizing seaweed cultivation, improving biomass yields, and developing efficient conversion technologies that can make seaweed biofuels commercially competitive. Government support for such R&D, alongside financial incentives, would ensure the continued evolution of the seaweed biofuel industry.

2.7. Conclusions

The development of seaweed-based bioenergy technologies marks a significant step toward sustainable and eco-friendly energy production. This section has covered the key stages in the process, from harvesting and pretreatment to sugar extraction and biofuel conversion. While challenges such as high moisture content, complex biomass composition, and the need for advanced extraction and conversion technologies remain, ongoing research and innovation continue to improve the feasibility of seaweed as a viable biofuel feedstock.

Seaweed’s rapid growth, high carbon capture efficiency, and ability to thrive without arable land or freshwater make it a highly sustainable alternative to traditional biofuel feedstocks like corn and sugarcane. Furthermore, the potential for seaweed-based bioethanol production to reduce greenhouse gas emissions and mitigate climate change is substantial. Research has shown that seaweed can be converted into bioethanol with promising yields, and advancements in microbial engineering, enzyme optimization, and fermentation processes are increasing its commercial viability.

Regulatory frameworks, such as the Renewable Fuel Standard (RFS) for bioethanol, could support the large-scale deployment of seaweed-based biofuels. By implementing mandatory usage regulations, financial incentives, and research funding, APEC members could stimulate the seaweed biofuel industry, making it a competitive alternative to fossil fuels.

While still in its early stages, seaweed-based biofuels hold great promise for a sustainable energy future. Continued advancements in cultivation, processing, and conversion technologies, along with supportive policy frameworks, are key to unlocking the full potential of seaweed as a renewable, eco-friendly biofuel feedstock.

III. Promoting APEC cooperation for seaweed cultivation and its potential use as sustainable bioenergy

1. Promotion of R&D cooperation

1.1. Background

This proposal describes potential collaborative research areas focusing on developing advanced solutions for maximizing carbon sequestration and economic benefits through seaweed. The major research area will be genetic optimization, innovative carbon storage technologies, and advanced biomass conversion systems that complement existing seaweed research programs.

1.2. Objectives

The goal of the collaboration will be to advance seaweed-based carbon reduction technologies through innovative research and development. This collaboration seeks to enhance carbon sequestration capabilities through genetic optimization and developing advanced biomass conversion technologies. Several important future research areas that need concerted efforts from APEC economies are organized.

1.2.1. Advanced seaweed development

The genetic improvement program will focus on developing optimized seaweed strains using advanced gene editing and genome engineering technologies, such as CRISPR, to enhance carbon fixation pathways. This work will include engineering temperature-resilient variants and strains specifically adapted for deep-water environments. Research will prioritize improving photosynthetic efficiency and carbon storage capacity through targeted metabolic engineering, with a particular emphasis on enhancing stress tolerance and growth rates under diverse environmental conditions. Collectively, these efforts aim to boost carbon reduction by facilitating CO_2 capture through seaweed cultivation.

1.2.2. Innovative carbon storage

Research in carbon storage will focus on developing permanent sequestration methods, including seaweed-based carbon mineralization processes and deep-sea storage systems. Advanced preservation techniques for harvested biomass will be developed as well as new methods for chemical stabilization and long-term carbon storage. This work will be complemented by research into enhanced burial methods and carbon-enriched material development.

1.2.3. Conversion of seaweed biomass to valuable products

Research will focus on developing innovative approaches to biomass conversion through biorefinery processes. These efforts will include the creation of chemical, biochemical, and biological conversion methods. Notably, it is essential to emphasize that the scale of conversion must align with the scale of l**arge-scale seaweed cultivation.** The development of cell-free enzymatic conversion systems and artificial enzyme cascades will enable the production of novel biochemicals. These processes will be further optimized through AI-driven manufacturing systems and real-time quality control.

1.3. Conclusion

Through these collaborative research projects, APEC economies can expect significant advances in carbon sequestration efficiency while developing commercially viable products. This collaboration will drive the creation of new technologies in genetic engineering and advanced materials production. The economic benefits include the emergence of new industry opportunities and the enhancement of value chains within the seaweed sector. Furthermore, knowledge development will focus on advancements in biorefinery optimization, product development expertise, and sustainable manufacturing processes.

2. Education and training programs

2.1. Background

Education and training programs are essential for developing a skilled workforce capable of driving innovation and growth in the seaweed-based bioeconomy sector. As the industry evolves, there is an increasing need for professionals with specialized knowledge in seaweed cultivation, processing, and biorefinery technologies. Several APEC economies have begun to incorporate seaweed-related content into their educational curricula and vocational training programs. However, there is still a significant gap between the skills required by the industry and the current educational offerings. Addressing this gap is crucial for the sustainable development of the seaweed bioeconomy in the APEC region.

2.2. Challenges and opportunities

The seaweed education and training sector faces several significant challenges. There is a notable lack of specialized programs focusing on seaweed bioeconomy, resulting in a shortage of specialists in the field. The rapid pace of technological advancements in the seaweed industry makes it challenging for educational institutions to keep their curricula up-to-date. The interdisciplinary nature of the seaweed bioeconomy, spanning multiple fields such as marine biology, biotechnology, and chemical engineering, makes it difficult to design comprehensive educational programs that cover all necessary aspects.

Insufficient integration between academic research programs and industrial applications often leads to a disconnect between academic research and industry needs, resulting in a skills mismatch among graduates. Furthermore, access to quality education and training in seaweed-related fields varies significantly across different APEC economies, creating geographical disparities in workforce development.

Despite these challenges, there are numerous opportunities in seaweed education and training. The growing seaweed industry creates a demand for skilled professionals, providing an incentive for the development of specialized educational programs. Online learning technologies offer the potential to democratize access to seaweed-related education and training across the APEC region. The global nature of the seaweed industry presents opportunities for cross-border educational initiatives and knowledge exchange. Seaweed-related content can be integrated into existing marine science, biotechnology, and environmental studies programs to broaden their scope. The development of seaweed farms and biorefineries provides opportunities for hands-on training and apprenticeship programs, enhancing practical skills development.

2.3. Education and training programs recommendations

To address the challenges and capitalize on the opportunities in seaweed education and training, we propose several key initiatives. First, developing specialized seaweed bioeconomy curricula at various levels of education (vocational, undergraduate, and graduate) is crucial. These comprehensive educational programs should be created in collaboration with industry experts to ensure they meet current and future industry needs. They should incorporate both theoretical knowledge and practical skills in areas such as seaweed cultivation, processing, and biorefinery technologies, with flexible learning pathways to accommodate students with diverse backgrounds and career goals.

Establishing a regional Seaweed Industry Skills Council is another important recommendation. This council would coordinate education and training efforts across APEC economies, ensuring consistency in skills development and facilitating the mobility of skilled professionals. The council should involve representatives from industry, academia, and government, develop occupational standards and competency frameworks for key roles in the seaweed industry, and regularly assess skills needs to update training recommendations.

Promoting industry-academia partnerships is essential for ensuring that educational programs remain relevant to industry needs and provide students with practical experience. This can be achieved by establishing industry advisory boards for seaweed-related academic programs, developing cooperative education programs that alternate academic study with industry placements, and encouraging industry professionals to participate as guest lecturers or adjunct faculty.

Developing an interconnected ecosystem of research and training centers for seaweed research and training across APEC economies would provide access to state-of-the-art equipment and expertise, enhancing the quality of education and research in the field. This network should include pilot-scale seaweed farms and biorefinery facilities for training purposes, encourage resource sharing and student exchanges between centers in different APEC economies, and integrate with local seaweed industries to ensure relevance and provide opportunities for technology transfer.

Developing online learning platforms for seaweed education can provide flexible, accessible education to a wide audience, helping to address geographical disparities in educational access. This initiative should include the development of Massive Open Online Courses (MOOCs) covering various aspects of seaweed bioeconomy, creation of virtual laboratories and simulations for practical training in seaweed cultivation and processing techniques, and establishment of a central repository for educational resources related to seaweed bioeconomy.

2.4. Conclusions

Developing robust education and training programs is crucial for building the human capital necessary to drive the growth of the seaweed-based bioeconomy in the APEC region. By implementing specialized curricula, fostering industry-academia partnerships, and leveraging digital technologies, APEC economies can address the current skills gap and prepare a workforce capable of meeting the future needs of the industry. These efforts will not only support the development of the seaweed sector but also contribute to broader goals of sustainable economic development and environmental stewardship in the region. The proposed recommendations aim to create a comprehensive and accessible educational ecosystem that can nurture talent, drive innovation, and support the long-term sustainability of the seaweed bioeconomy.

3. Policy Support

3.1. Background

While the potential of seaweed biomass is clear, the industry remains underdeveloped, especially in comparison to more established renewable energy sources. A key factor limiting its growth is the absence of comprehensive policies and infrastructure to support large-scale seaweed cultivation, biorefining, and market integration. Different regions of the world have taken early steps to promote seaweed farming and its applications, yet these efforts are often fragmented and insufficient to drive significant advancements in the sector. By examining case studies from APEC that have pioneered seaweed production, we can understand the existing policy frameworks that support the growth of the industry. These case studies will highlight the importance of strategic government interventions, such as subsidies, tax incentives, and public-private partnerships, in accelerating the development of seaweed-based industries. Additionally, this section will propose policy recommendations for the future of the seaweed industry. These suggestions aim to create a more robust, globally integrated framework that addresses key challenges such as scaling infrastructure, attracting investment, and advancing R&D. By adopting these policies, governments and industry stakeholders can unlock the full potential of seaweed as a sustainable resource for mitigating climate change, reducing ocean pollution, and contributing to a circular bioeconomy.

3.2. Key policies, strategies, and programs in progress

Several regions and global initiatives have implemented or are actively promoting policies and strategies to support the use of seaweed or macroalgae for sustainable bioenergy and biochemical production. These efforts focus on innovation, sustainability, and the development of seaweed farming and conversion technologies.

The European Union has been a leader in supporting seaweed cultivation and its use for renewable energy through various research, innovation programs, and policy frameworks. As above mentioned, Horizon 2020 and Horizon Europe, the EU's flagship research programs, have funded projects like MacroFuels, which develops biofuels from macroalgae in line with the Renewable Energy Directive targets (https://www.macrofuels.eu/). Additionally, the European Green Deal, particularly through its Farm to Fork Strategy, prioritizes sustainable aquaculture, including seaweed farming, to reduce environmental impacts and enhance marine ecosystem conservation (https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en). Another initiative, the Blue Economy Strategy, promotes investments in seaweed-based biorefineries for biofuels, biochemicals, and carbon sequestration, integrating seaweed farming into broader marine sustainability efforts.

The United States has similarly embraced macroalgae as a potential renewable resource. The Bioenergy Technologies Office (BETO) in the Department of Energy's (DOE) supports research into using seaweed as a bioenergy feedstock (https://www.energy.gov/eere/bioenergy/bioenergy-technologies-office). The Marine Algae Research Program and projects under the Advanced Algal Systems work to reduce the costs of seaweed-based biofuels and bioproducts by enhancing farming and bioconversion efficiency. The Advanced Research Projects Agency-Energy (ARPA-E) also plays a pivotal role through its MARINER program, which focuses on developing tools for large-scale seaweed cultivation in the open ocean, paving the way for macroalgae to be used in renewable energy and bioproducts (https://arpa-e.energy.gov/).

In Asia, South Korea has enacted policies that focus on expanding seaweed aquaculture as part of its marine economic strategy. The Korean Ministry of Oceans and Fisheries (MOF) is promoting seaweed cultivation not only for food but also for bioenergy and biochemical applications. By offering subsidies and support, the MOF aims to encourage sustainable seaweed farming practices, positioning seaweed as a critical resource in their renewable energy landscape. Japan has integrated seaweed cultivation into its Basic Plan on Ocean Policy as a strategy to support rural coastal revitalization, reduce carbon emissions, and explore renewable energy alternatives. Seaweed farming is a core component of efforts to explore sustainable bioproducts and biofuels, making it a key element in its broader approach to marine conservation and renewable energy production.

On a global scale, initiatives like the Global Seaweed STAR Program, funded by the Global Challenges Research Fund, focus on promoting sustainable seaweed farming in developing economies. This initiative prioritizes the use of seaweed biomass for producing bioproducts and bioenergy, providing crucial support for regions seeking to leverage seaweed for environmental and economic benefits (https://globalseaweed.org/).

3.3. Challenges and opportunities

While these policies are crucial for advancing seaweed biomass as a sustainable resource, several challenges remain (Yong et al. 2024). In some regions, regulatory frameworks for seaweed farming and biomass conversion are underdeveloped, which slows the path to commercialization. Additionally, the economic viability of seaweed-based bioenergy and biochemicals is still hampered by high production costs and the need for further technological innovation. Another key concern is environmental sustainability; policies must ensure that large-scale seaweed farming avoids over-harvesting, habitat destruction, and other negative impacts on marine ecosystems. Governments and international organizations are actively promoting the use of seaweed biomass for sustainable bioenergy and biochemicals through a combination of policy initiatives, research funding, and strategic frameworks. By addressing challenges related to cost, technology, and regulation, these efforts aim to unlock the potential of seaweed as a key resource for the global bioeconomy and the fight against climate change.

3.4. Policy recommendations

Promoting the use of seaweed biomass for sustainable bioenergy and biochemical production requires targeted policies that address existing challenges while creating incentives for investment, innovation, and large-scale adoption. Below are several policy recommendations to advance these goals.

First, a Seaweed Carbon Credit System could be established to recognize the carbon sequestration benefits of seaweed cultivation. This system would allow farmers and companies to earn carbon credits, which could be traded on domestic carbon markets. Financial incentives from this system would encourage seaweed cultivation, supporting both climate goals and the development of bioenergy and biochemical industries (Fujita et al., 2023).

Second, subsidies for seaweed-based bioenergy and biochemical technologies could provide direct financial support to companies developing technologies that convert seaweed biomass into energy or chemical products. Such subsidies would help address high costs and technological barriers that currently limit economic viability. By allocating funds through APEC members' energy or environmental programs, governments could reduce financial risks, foster innovation, and accelerate research and development (R&D) in seaweed biomass technologies. However, a well-structured subsidy program is essential to avoid inefficiencies, as excessively high subsidies could lead to ineffective resource allocation (Kung, Zhang, and Kong, 2016).

Third, the establishment of Seaweed Aquaculture Development Zones (SADZ) could prioritize seaweed farming in designated coastal areas. These zones would offer streamlined permitting processes, tax incentives, and technical support to businesses and individuals engaged in seaweed cultivation. Such an approach would lower barriers to entry for new farmers while ensuring minimal environmental impact (Venier et al., 2021). Governments, in collaboration with marine conservation authorities, would identify suitable zones based on environmental, ecological, and economic factors, particularly in regions with limited commercial fishing or where seaweed farming could enhance marine ecosystems.

Fourth, an International Feedstock Certification and Standards System for seaweed biomass could ensure compliance with sustainability criteria, similar to existing standards for palm oil or forestry products (Carlson et al., 2018). Certification would promote market differentiation for sustainably sourced seaweed, encourage responsible farming practices, and reassure consumers and investors (Scarlat and Dallemand, 2011). Governments and industry stakeholders would collaborate to develop standards focusing on environmental sustainability, labor practices, and ecosystem preservation, with certification bodies overseeing compliance. Certified products could carry an eco-label to highlight their sustainability.

Fifth, governments could offer Tax Credits for Seaweed-Based Bioenergy Consumption to encourage industries and individuals to adopt seaweed-based biofuels, biogas, or electricity. These tax credits would lower consumer costs, making seaweed bioenergy more competitive with fossil fuels and driving demand for seaweed-based energy products (Goldfarb and Kriner, 2021). The incentives could be structured as percentage-based credits or rebates, depending on the volume or value of seaweed-based energy products purchased.

Finally, to scale up seaweed farming to an industrial level, Public-Private Partnerships (PPPs) could play a central role, particularly in advancing open-ocean cultivation or Integrated Multi-Trophic Aquaculture (IMTA) systems. Governments would provide infrastructure support, such as favorable lease terms for ocean farming areas, while private companies would invest in the required technology and operations (Nakhate and van der Meer, 2021). These partnerships would address the significant investment barriers for large-scale operations, accelerating the development of seaweed biomass as a major feedstock for bioenergy and biochemicals.

3.5. Conclusions

These proposed policies aim to foster the growth of the seaweed biomass industry by providing financial incentives, driving technological innovation, ensuring environmental sustainability, and stimulating market demand. By integrating seaweed into broader energy, environmental, and marine strategies, these policies can accelerate the transition to a more sustainable bioeconomy.

4. Infrastructure development

4.1. Background

The development of infrastructure for the mass production, transportation, and treatment of seaweed biomass for bioenergy and biochemical applications is a critical step in scaling its utilization. Several regions and companies have been investing in the necessary facilities and systems to streamline the seaweed supply chain from cultivation to final product. Here’s an overview of key infrastructure developments across production, transportation, and treatment. Additionally, this section will propose recommendations for future developments.

4.2. Key infrastructure developments

The development of key infrastructure is essential for scaling up seaweed farming and its conversion into bioenergy and biochemicals. Open-ocean farms and offshore platforms represent a significant advancement in seaweed farming infrastructure, utilizing floating or submerged systems to maximize production efficiency by cultivating seaweed in vast quantities (Tullberg, Nguyen, and Wang 2022). For instance, projects like Ocean Rainforest in the North Atlantic employ vertical farming systems with ropes or nets to grow seaweed in deep waters (https://www.oceanrainforest.com/projects-overview). These platforms are designed to withstand harsh marine conditions while minimizing environmental impact and maximizing biomass output. In regions such as Norway and Canada, Integrated Multi-Trophic Aquaculture (IMTA) systems integrate seaweed farming with fish or shellfish farming. IMTA promotes a circular and sustainable form of aquaculture, where waste nutrients from fish farms are absorbed by seaweed (Correia et al. 2020).

To support mass seaweed production, harvesting and processing technologies are advancing. Automated harvesting systems, such as mechanized harvesters, are being developed to reduce labor costs and increase efficiency (Khan, Sudhakar, and Mamat 2024). These systems use mechanical arms, conveyor belts, and nets to gather seaweed rapidly with minimal human intervention. The MARINER project in the USA focuses on harvesting technologies tailored for large-scale cultivation. Additionally, pre-treatment facilities play a critical role in preparing seaweed biomass for conversion into bioenergy or biochemicals. Using mechanical, chemical, or enzymatic processes, these facilities break down cell walls, remove water, and extract specific compounds. For example, Seaweed Energy Solutions in Norway has established pre-treatment facilities for processing seaweed into biogas or bioethanol (https://seaweedsolutions.com/).

Biorefineries are central to transforming seaweed biomass into a range of products, including biofuels, bioplastics, fertilizers, and biochemicals (Samoraj et al. 2024). These facilities use advanced chemical, enzymatic, and thermochemical processes to extract valuable compounds, such as alginates and carrageenan. For example, in the European Union, projects like Macro Cascade are developing integrated biorefineries that utilize techniques like hydrothermal liquefaction and anaerobic digestion to produce high-value products (https://www.macrocascade.eu/). Furthermore, bioethanol refineries are advancing the conversion of seaweed polysaccharides into ethanol. The MacroFuels project in Norway and Ireland is working to develop large-scale bioethanol refineries for seaweed-based fuels (https://www.macrofuels.eu/).

The transportation of seaweed biomass is a critical consideration due to its bulky and heavy nature. Efficient logistics systems are required to move seaweed from offshore farms to coastal processing facilities. In Norway and the USA, companies are testing modular shipping containers and large-scale seaweed barges to streamline the transportation process (https://uniteam.com/) (Solvang et al. 2021).

Finally, research and development infrastructure, including testbeds and pilot plants, is crucial for advancing seaweed-related technologies. Pilot plants allow for testing new technologies and processes on a smaller scale before scaling up to full-scale farms and biorefineries. For example, in the European Union, initiatives such as the MacroBioCrude project and other Horizon 2020 programs have established pilot facilities to explore seaweed-to-biofuel conversion technologies using small-scale biorefineries.

4.3. Future directions

The future of seaweed farming and its contribution to sustainable bioenergy and biochemical production lies in advancing integrated farming systems, optimizing species selection, improving biorefineries, and scaling marine infrastructure. One promising area of research involves IMTA) systems, which combine seaweed cultivation with other marine species, such as fish and shellfish (Nissar et al. 2023). IMTA systems are designed to enhance ecosystem productivity by absorbing nutrients that would otherwise contribute to waste and pollution from traditional aquaculture. By integrating seaweed farming with fish farming, these systems can create a more circular and sustainable form of aquaculture, reducing nutrient runoff and maximizing overall biomass production. Scaling these systems will require targeted research funding from governments and universities to model and test these combinations. Collaboration with the aquaculture industry can further accelerate the implementation of these integrated systems by aligning seaweed production with existing marine farming operations.

Another key area for the future of seaweed cultivation is species selection and genetic engineering. Seaweed species vary widely in their capacities to absorb nutrients, store carbon, and yield bioenergy, making it critical to identify the most suitable species for bioenergy production (V et al. 2021). Developing breeding programs and genetic engineering techniques will allow for the enhancement of seaweed productivity, disease resistance, and bioconversion efficiency. Genetic improvements can also lead to strains that are optimized for specific industrial applications, such as biofuel production or bioplastic synthesis. To advance this field, partnerships between biotechnology companies, academic institutions, and public research grants are necessary. Investments in seaweed genomics could lead to breakthroughs that improve yields and make seaweed farming more economically viable, particularly in the context of growing global demand for renewable energy sources.

In addition to improving farming systems and species selection, the development of advanced biorefineries is critical to making seaweed a profitable and sustainable resource (Arias, Feijoo, and Moreira 2023). Traditional biorefineries often focus on producing single products, such as bioethanol, but future research should aim to develop facilities that can extract multiple high-value products from seaweed biomass. By integrating different bioprocessing techniques, such as enzymatic or thermochemical conversion, into a single biorefinery, a wider range of outputs can be generated, including biofuels, bioplastics, fertilizers, and nutraceuticals. This multi-product approach will improve the cost-effectiveness of seaweed biorefining and enhance its market potential. Forming R&D partnerships between universities, biorefineries, and private investors can accelerate the innovation process, with governments providing matching funds for promising projects. These partnerships can help create the next generation of biorefineries that capitalize on versatility of seaweeds as a raw material for various industries.

Scaling up seaweed production will also require significant advancements in marine infrastructure, particularly for offshore seaweed farms (Lian et al. 2024). Offshore farms offer high potential for large-scale cultivation but must contend with harsh marine conditions. As a result, research is needed to develop more resilient and efficient farming platforms that can withstand open-ocean environments. This includes using new materials for floating farms, designing automated harvesting systems, and developing deep-sea cultivation techniques. The focus should be on building more durable platforms that can handle higher yields while minimizing the need for manual labor. Investment in these innovations should come from marine engineering firms, shipping companies, and government agencies, with research grants from the marine and energy sectors supporting technological advancements. With proper investment and research, offshore seaweed farms can become a cornerstone of sustainable bioenergy and biochemical production.

As seaweed farming expands to meet global demands for renewable resources, these integrated advancements in farming systems, species selection, biorefining technologies, and marine infrastructure will play a pivotal role in driving the industry forward. Governments, universities, and private investors must collaborate to create the conditions necessary for these innovations to thrive, ultimately unlocking a full potential of seaweeds as a key contributor to the bioeconomy and environmental sustainability.

4.4. Conclusions

In conclusion, the development of infrastructure for mass seaweed production and processing is critical for expanding its role in bioenergy and biochemical industries. Advances in farming systems, such as offshore platforms and IMTA, along with innovations in biorefineries, will drive the sector forward. Investment in species selection, genetic engineering, and marine infrastructure is essential for optimizing seaweed cultivation and conversion. Collaboration between governments, research institutions, and private companies will be key to realizing the full potential of seaweeds as a sustainable resource, contributing to a more resilient bioeconomy and addressing environmental challenges.

5. Strategic outreach for the seaweed bioeconomy

5.1. Background

The primary objectives are to (i) raise public awareness of the benefits of seaweed-based bioenergy and biochemicals; (ii) highlight the sustainability and economic opportunities provided by seaweed cultivation; (iii) position seaweed as an important feedstock for the bioeconomy in APEC member economies; (iv) foster collaboration between governments, industries, and research institutions to scale up production.

The key audiences for the promotion and marketing efforts include governmental agencies, academic institutions, investors, industry, and local communities. Governmental agencies are politicians making policies. Audiences should include universities and research centers which can develop specialized program for marine biology, bioenergy, and environmental sciences. As industry will be a key driving sector, companies in the energy, chemical, biotechnology, and marine industries. Venture capitalists and impact investors interested in sustainable technologies and renewable energy. Finally, coastal communities involved in or impacted by seaweed farming.

5.2. Key messages

Key messages to be delivered to public is that seaweed can be a sustainable alternative with highlighting that seaweed cultivation does not require land, fresh water, or fertilizers, positioning it as a critical solution to the global challenges of climate change and resource depletion. Furthermore, it can be emphasized that there are many economic opportunities in seaweed business. This new industry has the potential for job creation, new market development, and increased regional cooperation through the development of the seaweed-based value chain. Furthermore, a key message should also include focusing on the role of seaweed in carbon sequestration, reducing greenhouse gases, and fostering marine biodiversity.

5.3. Marketing strategies

Marketing channels to promote seaweed-based bioeconomy include (i) regional and international conferences, (ii) exhibitions, (iii) workshops and seminars, (iv) publications and reports. Firstly, the seaweed bioeconomy initiative can be presented at APEC summits, regional conferences, and international trade shows focused on bioenergy, sustainability, and the marine economy. These platforms can be utilized to engage key stakeholders and form strategic partnerships. Secondly, educational workshops can be held focusing on carbon sequestration, sustainable energy production, and biochemical applications. Lastly, publishing research papers, white papers, and policy briefs in relevant scientific journals and industry publications can be an important channel. These documents should discuss the economic potential, environmental impact, and case studies related to seaweed-based biorefineries.

Additionally, diverse channels such as website and social media can be utilized. A dedicated website and social media channels (LinkedIn, X, Instagram) can be developed to showcase the benefits of seaweed-based products, ongoing projects, and success stories. Regularly post content such as case studies, infographics, and videos explaining the potential of seaweed as a sustainable resource. Additionally, webinars featuring experts from academia, industry, and government can be organized to discuss advancements in seaweed farming and biorefinery technologies.

5.4. Strategic partnerships

Partner with established businesses in the chemical, energy, and marine sectors to co-brand initiatives and launch pilot projects that demonstrate the viability of seaweed-based bioenergy production. Showcase these collaborations in marketing materials to build credibility and drive further investment. In addition, collaboration with marine and renewable energy associations, environmental NGOs, and industry bodies needs to be facilitated to amplify the message and reach a broader audience.

5.5. Promotional tactics

Leverage case studies from the document that demonstrate (i) Smart Farming for Mass Production: Show the cost reduction benefits from automating seaweed farming using technology and precision agriculture; (ii) Biochemical and Biofuel Production: Highlight lessons learned from corn-based ethanol production and the scalable potential of seaweed-based biofuel; (iii) Carbon Sequestration: Promote seaweed's role in capturing carbon and contributing to climate change mitigation. (iv) Develop a certification system for seaweed-based products that meet high sustainability standards. This will help build trust with consumers, businesses, and governments, increasing the market demand for seaweed-derived products.

5.6. Conclusions

This section outlines strategies to promote the seaweed-based bioeconomy, emphasizing its sustainability, economic potential, and environmental benefits. Key objectives include raising awareness of seaweed's advantages as a bioenergy and biochemical source, highlighting its role in carbon sequestration, and fostering partnerships across APEC member economies. Target audiences span government agencies, academic institutions, industries, investors, and local communities. Key marketing messages focus on the sustainability and resource efficiency of seaweed, job creation, and potential for new markets. Strategies for promotion include conferences, publications, social media, and strategic partnerships with established industries. These efforts will significantly broaden public understanding of seaweed-based bioeconomy and facilitate technology developments for accelerating transition to seaweed-based bioeconomy.

IV. Concluding remarks

To conclude, the APEC report on transitioning to a seaweed-based bioeconomy presents a visionary approach to addressing pressing environmental and economic challenges by leveraging sustainable, marine-based resources. The focus on seaweed cultivation enhances resource efficiency while aligning with global climate and sustainability objectives. By offering an alternative to land-intensive crops and reducing reliance on fossil fuels, seaweed cultivation positions itself as a critical solution for a more sustainable future.

The report highlights the immense potential of seaweed across various industries, including bioenergy, biochemicals, bioplastics, and cosmetics, laying a strong foundation for a diversified bioeconomy. To achieve these goals, the report outlines essential infrastructure, policy frameworks, and collaborative efforts required across APEC member economies. Advanced strategies such as the development of offshore platforms and Integrated Multi-Trophic Aquaculture (IMTA) demonstrate how sustainable, large-scale seaweed farming can minimize land use while enhancing marine ecosystems. Investments in automation, environmental monitoring, and carbon sequestration technologies further underscore the sector's commitment to innovation and its potential for significant climate impact mitigation.

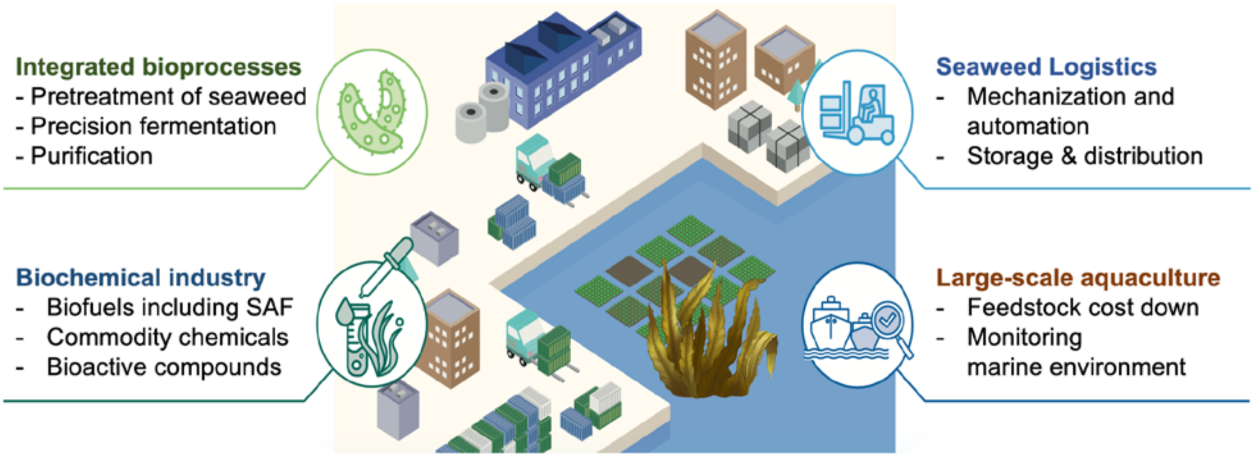

Figure 8. Integrated seaweed biocluster

Strategic policy recommendations—such as the implementation of a seaweed carbon credit system, subsidies for bioenergy technologies, and the establishment of designated seaweed aquaculture zones—are proposed to incentivize industry growth and integrate seaweed into the regional energy mix. These policies, combined with robust funding for research and development, create a strong support system for advancing seaweed technology and production.

The report also emphasizes the critical importance of skill development and education, recognizing that a skilled workforce is vital for sustained growth in the seaweed sector. Initiatives such as regional training programs, specialized curricula, and industry-academia partnerships aim to equip future professionals with the knowledge and expertise needed to drive innovation in the bioeconomy.

In summary, the APEC report provides a forward-looking blueprint for transforming the bioeconomy through seaweed, integrating innovation with environmental consciousness (Figure 11). The proposed strategies promote regional collaboration, resource efficiency, and resilience against environmental challenges, positioning APEC economies as global leaders in sustainable bioeconomic practices. This transition to a seaweed-based bioeconomy offers not only significant environmental benefits but also economic opportunities, including job creation, market expansion, and technological advancements, paving the way for a greener and more sustainable future.

Appendix

Appendix 1. Background paper summary

1. Overall summary

The background paper outlines the potential of a seaweed-centered economy by detailing a comprehensive value chain that includes seaweed cultivation, production, logistics, supply chain management, and bioconversion into high-value chemicals. It critically reviews past efforts in establishing grain biomass-based economies to identify areas of improvement for the seaweed sector. The paper also presents current and emerging technologies relevant to this field, highlighting their importance in improving the scalability and sustainability of seaweed industries.

2. Building seaweed-based biorefineries

Exploring the complex stages of seaweed-based biorefineries, this discussion spans from feedstock supply and preprocessing to the conversion of sugars into biochemicals through microbial fermentation and the chemical separation for creating marketable products. Given the diversity of seaweed species, there is a critical emphasis on developing optimized processes tailored specifically to each species for large-scale aquaculture, saccharification, and cell factory development. These processes are vital for the successful transformation of seaweed into bioenergy and biochemicals, thereby establishing a foundation for a sustainable industry.

Transitioning to a seaweed-centered economy offers significant environmental and sustainability benefits. However, achieving industrial-scale operations requires innovative cultivation and conversion technologies, such as advanced genetic engineering and precision farming, alongside the development of robust industrial infrastructure and regulatory support. Collaboration with local communities is also crucial. The text reviews case studies of previous biorefinery attempts using early-generation feedstocks to extract lessons and devise strategies for overcoming anticipated challenges.

Further discussions focus on reducing costs through automation and smart farming techniques for mass production, employing integrated multi-trophic aquaculture (IMTA) methods for seaweed cultivation, and developing high-yield seaweed varieties and advanced seed technologies. The establishment of a resilient seaweed supply chain is highlighted, complemented by the potential of seaweed farming for carbon sequestration. Additionally, insights from corn-based ethanol production are utilized to enhance efforts in seaweed biofuel production, and the possibilities for producing high-value biochemicals and bioactive compounds from seaweed biomass are explored.

3. Addressing challenges and opportunities in seaweed cultivation

Expected domestic and international challenges for large-scale seaweed cultivation are outlined, highlighting the need for comprehensive regulatory frameworks within the APEC region. Key discussion points include the necessity of environmental impact assessments for large-scale operations, the adoption of regulations for genetically modified seaweed akin to those for terrestrial plants, and the protection of intellectual property for new seaweed varieties. Additionally, the text suggests implementing incentives for seaweed farmers similar to the USDA's Biomass Crop Assistance Program, establishing mandatory usage regulations for seaweed-based biofuels informed by existing bioethanol policies, enacting tax policy reforms to promote seaweed-based chemical products, similar to bioplastic tax exemptions, and introducing price stabilization measures to mitigate the effects of international market fluctuations.

4. Technological developments and insights for seaweed biorefineries

The background paper extensively highlights a range of technologies developed for seaweed biorefineries, including mass production and automation technologies for cultivation, trait improvement in seaweed, and methods for drying and desalinating. It also discusses advanced sugar extraction, saccharification technologies, and the production of seaweed-based products like fuels, bioplastics, bioactive compounds, and cosmetics. Insights from interviews with representatives across government, academia, and industry further enrich the discussion, fostering collaboration and knowledge exchange within the APEC region. Additionally, the paper emphasizes efforts to expand mass production and utilization of seaweed by promoting its carbon reduction benefits, supported by blue carbon certification, thus advocating for the sustainable development of seaweed-related industries.

Appendix 2. Workshop summary

1. Overall summary

- Goal: Promoting cooperation in the field of bioenergy research and development within the APEC regions on the potential for seaweed-based bioenergy production.
- Date: June 25 (Tuesday), 2024
- Venue: Shilla 3F, Seoul Dragon City, Republic of Korea
- Organizer: Ministry of Foreign Affairs (Climate Energy Cooperation Center)
- Sponsor: Asia-Pacific Economic Cooperation (APEC)

- Participants: Over 80 experts from domestic and international industries and research institutions related to seaweed bioenergy, academia, diplomatic corps in Korea, and APEC member economies government officials
- Session 1: Large-scale seaweed biomass production and the potential for carbon sequestration through seaweed cultivation.
- Session 2: Technologies for recovering valuable substances from seaweed and producing bioenergy from seaweed.

Seaweed has the potential to significantly contribute to the mitigation of climate change and the establishment of eco-friendly energy independence in the Asia-Pacific region as a sustainable resource for bioenergy and carbon sequestration. The workshop aimed to strengthen the biomass supply chain and provide support to related industries by facilitating knowledge exchange and research on macroalgae and large-scale cultivation methods through this partnership.

2. Key findings

The transition to clean energy underscores seaweed as a viable biofuel alternative, addressing the constraints of crop-based biofuels. The rapid growth, minimal environmental impact, and exceptional carbon sequestration of seaweed render it an ideal candidate for large-scale cultivations, as it does not compete for land or water resources.

International cooperation, notably among APEC economies, is anticipated to ensure shared progress and benefits as this emerging bioindustry derives innovation in cultivation, supply chains, and marketable products.

Climate change presents challenges to seaweed aquaculture, such as poor growth, reduced sporeling production, and storm vulnerability. These challenges are mitigated through thermotolerant cultivars, advanced cultivation techniques. Efficiency and resilience are enhanced by innovations such as buoyancy systems, autonomous system for offshore monitoring, and mechanized fertilizing and harvesting.

Accurate carbon measurement, international collaboration, habitat preservation, and the development of elite strains to optimize carbon sequestration are the primary objectives of efforts to certify macroalgae as blue carbon sink.

Harvesting timing is vital for optimizing seaweed’s use in bioenergy, food and other valuable applications, while its rapid growth and carbon capture efficiency make it an ideal, sustainable alternative to traditional resources like corn and sugarcane.

Strategic facility positioning in seaweed-rich regions, such as the Asia-Pacific region, in conjunction with international collaboration, enhances scalability and sustainability. It is essential to conduct ongoing research, pilot projects, and implement innovations such as Carbon Capture, Utilization and Storage (CCUS) and Hydrothermal Liquefaction (HTL) in order to fully realize the potential of seaweed for bioenergy and climate change mitigation.

3. Group discussion and feedback

The potential of seaweed-based bioenergy is currently being investigated by China, Viet Nam, the Philippines, and Indonesia as part of their efforts to achieve carbon neutrality.

China is promoting algae-based bioenergy through programs such as the 14th Five-Year Plan and collaboration with APEC economies to develop cost-effective bioenergy solution. Viet Nam is leveraging its coastline and establishing policy frameworks to support bioenergy development as part of its 2050 carbon neutrality goal. Meanwhile Philippines is utilizing the insights shared during the workshop to increase bio ethanol blend rates and investigate seaweed as a feedstock. Indonesia, which has a significant potential for marine energy, recognize the importance of more comprehensive policies and partnerships to encourage the development of seaweed-based bioenergy. Indonesia is employing workshop discussions to illuminate its future initiatives.

There is a distinct expectation that the Workshop will foster valuable exchanges and enhance participant's capabilities in seaweed-based R&D, as 97.5% of participants believe the Workshop can significantly contribute to information sharing and capacity building. This indicates a high degree of assurance in the potential of our endeavor to improve knowledge exchange and collaboration in the field.

4. Conclusion

The APEC Workshop on Seaweed-based Sustainable Bioenergy emphasized the vital role of macroalgae cultivation as a sustainable alternative to petroleum-derived carbon, emphasizing the progress made in breeding technologies, aquaculture methods, and offshore large-scale production. The continuous monitoring of carbon flux and collaboration among APEC members are essential for the evaluation of environmental and economic benefits. Primary objectives include developing the mechanical systems for efficient seeding and harvesting, achieving international certification of algae as blue carbon, conducting precise assess of carbon capture potential, and strengthen international cooperation. Macroalgae are a critical component of sustainability and climate change mitigation strategies due to their rapid growth rate and exceptional carbon absorption efficiency. The maintenance of a consistent biomass supply for applications such as precision fermentation, bioactive substances and bioenergy, as well as the support of biochemical industries and biorefinery systems, is contingent upon innovations in mass production and cultivation. The insights underscore the significance of international cooperation and technological advancements in order to improve the role of macroalgae in sustainable development and carbon neutrality.

Appendix 3. Seaweed-derived materials

1. Technologies for seaweed-based bioplastic production

The increasing environmental concerns surrounding plastic pollution have driven the search for sustainable alternatives, with seaweed emerging as a promising feedstock for producing biodegradable plastics. Seaweed offers a renewable and environmentally friendly source of biomass that can be converted into bioplastics, presenting a potential solution to the growing global plastic waste problem. Unlike traditional petroleum-based plastics, which persist in the environment for hundreds of years, seaweed-based bioplastics are designed to decompose naturally, reducing the environmental footprint of plastic products. Its rapid growth, coupled with its lack of reliance on arable land, freshwater, or fertilizers, makes it a particularly attractive option for sustainable production, especially in contrast to other biomass sources like corn or sugarcane. Rich in polysaccharides such as agar, carrageenan, and alginate, seaweed provides essential building blocks for producing polymers that can be molded into a wide range of plastic products. These polysaccharides can be chemically or enzymatically modified to create materials with properties suitable for applications in packaging, agricultural films, and even medical devices.

Recent research on seaweed-based bioplastic production has shown significant advancements, highlighting its potential as a sustainable alternative to conventional plastics. Scientists are focusing on optimizing the extraction and modification of seaweed polysaccharides such as alginate, carrageenan, and agar, which serve as the primary building blocks for bioplastics. Innovations in chemical and enzymatic modifications have improved the mechanical properties of seaweed-derived polymers, making them more flexible, durable, and suitable for various industrial applications, including packaging and single-use items. One key area of focus has been on improving the biodegradability of these materials, ensuring they decompose more rapidly in natural environments compared to traditional plastics. Recent studies have demonstrated that seaweed bioplastics can break down in a matter of weeks or months, significantly reducing plastic pollution.

Additionally, researchers are exploring blending techniques, combining seaweed polysaccharides with other biopolymers like polylactic acid (PLA) or starch, to enhance performance characteristics like tensile strength and water resistance. Another exciting area of investigation is the use of waste seaweed biomass from aquaculture and other industries, reducing waste while creating valuable new materials. There has also been progress in scaling up seaweed-based bioplastic production, with some startups and companies beginning to commercialize seaweed-derived products, such as compostable food packaging and biodegradable films. While challenges remain—such as cost reduction and ensuring consistent material properties—ongoing research is steadily improving the viability of seaweed as a feedstock for large-scale bioplastic production, potentially transforming the future of sustainable materials.

However, producing biodegradable plastics from seaweed comes with several technical and economic challenges. The composition of seaweed varies significantly between species, growth conditions, and geographic location, leading to variability in the quality and performance of the resulting bioplastics. Additionally, the high moisture content of seaweed biomass presents storage and transportation issues, requiring energy-intensive drying processes before it can be utilized. The extraction of polysaccharides and their conversion into functional plastic materials also require sophisticated technologies that are still being optimized for efficiency and scalability. Despite these challenges, ongoing research is advancing methods to improve the extraction and polymerization processes, making seaweed bioplastics more commercially viable. With the growing global demand for sustainable packaging solutions and increased consumer awareness of the environmental impact of plastic waste, seaweed-based biodegradable plastics represent a significant step toward a more circular economy. They offer the dual benefit of reducing reliance on fossil fuels while also addressing the pressing issue of marine and terrestrial plastic pollution. As the technology matures, seaweed-derived bioplastics could play a critical role in transforming the plastic industry and moving toward a more sustainable future. The metabolic engineering of microorganisms for bioplastic production using macroalgae as substrate requires several technologies that leverage the renewable and abundant nature of macroalgae. These technologies aim to develop sustainable alternatives to conventional plastics by utilizing the complex carbohydrates present in macroalgae to produce biodegradable plastics.

Algal biomass can be directly utilized as raw material for bioplastic production (Sudhakar et al. 2024; C. Lim et al. 2021). In this approach, whole biomass including carbohydrates, lipids, and proteins can be directly blended with petroleum-derived plastics. Alternatively, polysaccharides in algal biomass can be extracted and used for casting bioplastic films.

Development of recombinant microbial strains is required for realization of the potential of seaweed biomass by diversification of bioplastic products (**Figure 9**). The core technology involves genetically modifying bacteria and yeasts to efficiently process macroalgal biomass into bioplastic precursors. Techniques like CRISPR-Cas9 are employed to perform precise genomic modifications, thereby enabling the microorganisms to metabolize macroalgae-derived polysaccharides into monomers suitable for bioplastic synthesis.

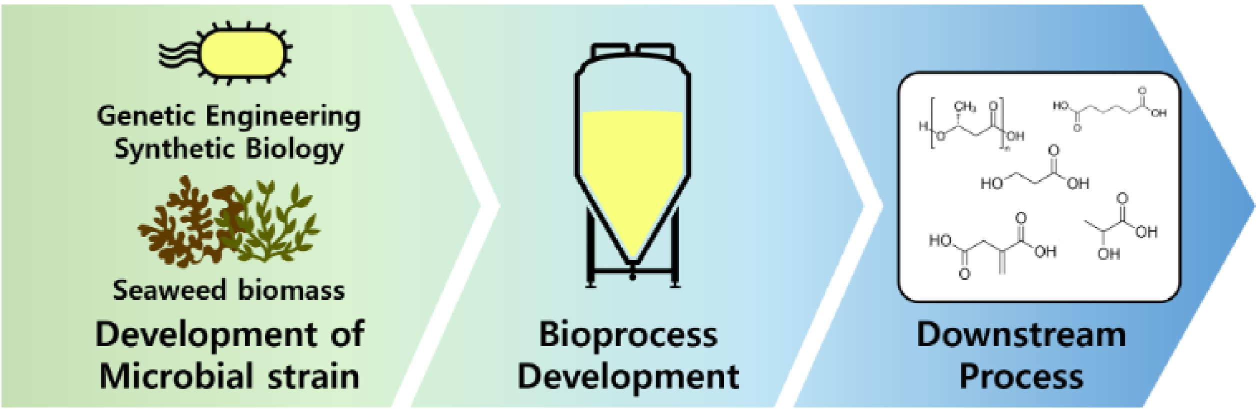

Figure 9. Technologies for seaweed-based bioplastic production

Advancements in synthetic biology have enabled the design of artificial metabolic pathways in microorganisms, significantly enhancing the biosynthesis of bioplastics from macroalgae. These developments focus on optimizing metabolic pathways to boost the yield of bioplastic precursors and creating novel biosynthetic routes to diversify the types of bioplastics produced.

In parallel, advanced fermentation technologies for seaweed-based bioplastic production have evolved, improving the efficiency and yield of bio-based polymers and providing a sustainable alternative to traditional plastics. A key breakthrough in this area is the use of metabolic engineering to optimize microbial strains for efficiently converting seaweed-derived sugars into bioplastic precursors such as lactic acid, polyhydroxyalkanoates (PHAs), and ethanol. Researchers are tailoring the metabolic pathways of bacteria, yeast, and algae to process complex seaweed polysaccharides like alginate, laminarin, and fucoidan. These engineered microbes are designed to withstand the challenging conditions of fermentation while enhancing the overall production of biopolymer precursors.

Consolidated bioprocessing (CBP) has also gained significant attention. This approach employs a single microbial strain or a consortium of microbes capable of both hydrolyzing seaweed biomass and fermenting it into desired bioplastic components in a single, streamlined step, thereby reducing the need for costly pretreatments. Additionally, continuous fermentation systems are being developed to maintain a steady flow of seaweed biomass and microorganisms in bioreactors. These systems optimize production rates and minimize downtime, enabling operations to sustain optimal conditions over longer periods and enhancing overall productivity compared to traditional batch fermentation.

Co-fermentation strategies are another promising innovation. In these systems, multiple microbial species work synergistically to break down different components of seaweed simultaneously, improving the efficiency of sugar conversion into bioplastic monomers. Such strategies further enhance resource utilization and reduce waste, making the process more economically viable and environmentally sustainable.

These advanced fermentation technologies not only improve the feasibility of seaweed-based bioplastic production but also minimize environmental impact by maximizing resource efficiency. As these technologies continue to progress, they hold great promise for making seaweed-based bioplastics a commercially competitive and eco-friendly alternative to conventional plastics.

The optimized cultivation of genetically engineered microorganisms is achieved through advanced fermentation technologies. These technologies are designed to maximize the production efficiency of bioplastic precursors by fine-tuning growth conditions and utilizing specialized bioreactor designs tailored to the needs of engineered strains.

Following fermentation, downstream processing techniques are employed to extract and purify bioplastic materials from the microbial biomass. Methods such as solvent extraction and centrifugation are used to isolate bioplastic polymers, which are then refined through processes like pelletization and extrusion to create commercially viable products.

In the initial fermentation stage, microbes break down seaweed-derived sugars to produce bio-based precursors such as lactic acid, ethanol, or butanol. These intermediates undergo a series of downstream processes to transform them into functional bioplastics. One critical step is polymerization, where monomers like lactic acid are chemically or enzymatically linked to form long-chain polymers, such as polylactic acid (PLA), a widely used bioplastic. This process requires precise control of reaction conditions, including temperature, pH, and catalysts, to ensure the formation of high-quality polymers with the desired mechanical and thermal properties.

Additionally, the fermentation broth must be purified to remove residual biomass, by-products, and unconverted sugars, which could interfere with polymerization or negatively impact the final product’s properties. Advanced separation techniques, such as filtration, distillation, or solvent extraction, are employed to isolate the desired bio-based chemicals.

Once the polymers are synthesized, they are processed and shaped using techniques such as extrusion, injection molding, or film casting to produce the final bioplastic products. Throughout this post-fermentation phase, researchers focus on optimizing each step to improve yield, reduce costs, and enhance the biodegradability and performance of the bioplastics. Ensuring consistency and scalability during this phase is essential for transitioning seaweed-based bioplastics from laboratory research to commercial production.

2. Technologies for extraction of seaweed-derived bioactive compounds

The richness of carbohydrates in seaweed makes it attractive as a feedstock for producing diverse biochemicals. This interest aligns with global efforts to reduce reliance on fossil fuels and minimize environmental footprints, marking a pivotal shift towards greener alternatives in industrial processes (Michalak 2018). Here, cases are introduced in which seaweed biomass is utilized for chemical production through biological processes. Enzymatic and microbial conversion and development of production strain are described.

Seaweed is a promising source of bioactive compounds suitable for producing a range of high-value biochemicals. Enzyme technologies have facilitated the extraction and conversion of these compounds, enabling applications in foods, nutraceuticals, and pharmaceuticals (Charoensiddhi et al. 2017). Moreover, the exploration of seaweed biomass for the production of lactic acid and hydroxymethylfurfural (HMF) showcases its potential as a feedstock for sustainable biochemical production (Heo, Lee, and Chung 2020; Lin et al. 2020).

Microorganisms play a crucial role in the bioconversion process, with specific strains being utilized to optimize the conversion of seaweed biomass into valuable biochemicals. The development of integrated biorefineries has been proposed to improve the economic viability of seaweed-based biochemical production, enabling the concurrent production of high-value bioproducts alongside biofuels (Buschmann et al. 2017).

Seaweed-based biochemical production presents a viable and sustainable alternative to conventional industrial processes, offering significant environmental benefits and contributing to the circular economy. However, overcoming the technical and economic challenges requires concerted efforts in research and development, focusing on improving biomass yield, optimizing bioconversion processes, and enhancing the quality and consistency of seaweed products. For the seaweed farming industry, this underscores the importance of adopting advanced cultivation techniques, engaging in genetic improvement programs, and exploring integrated biorefinery approaches to maximize the economic potential of seaweed biomass

Given abundant and diverse bioactive profiles of seaweeds, the extraction of bioactive compounds from seaweed is essential for sustainable bioeconomy. These compounds, including antioxidants, polysaccharides, pigments, and fatty acids, offer vast applications in pharmaceuticals, nutraceuticals, and functional foods with significant contributions. The technology for extracting these compounds has evolved to meet the demands for efficiency, sustainability, and scalability. The representative technologies are described below; Enzyme-assisted extraction (EAE), Microwave-Assisted Extraction (MAE), Supercritical Fluid Extraction (SFE), Ultrasound-Assisted Extraction (UAE) (Zhang et al. 2022) (**Figure 10**).

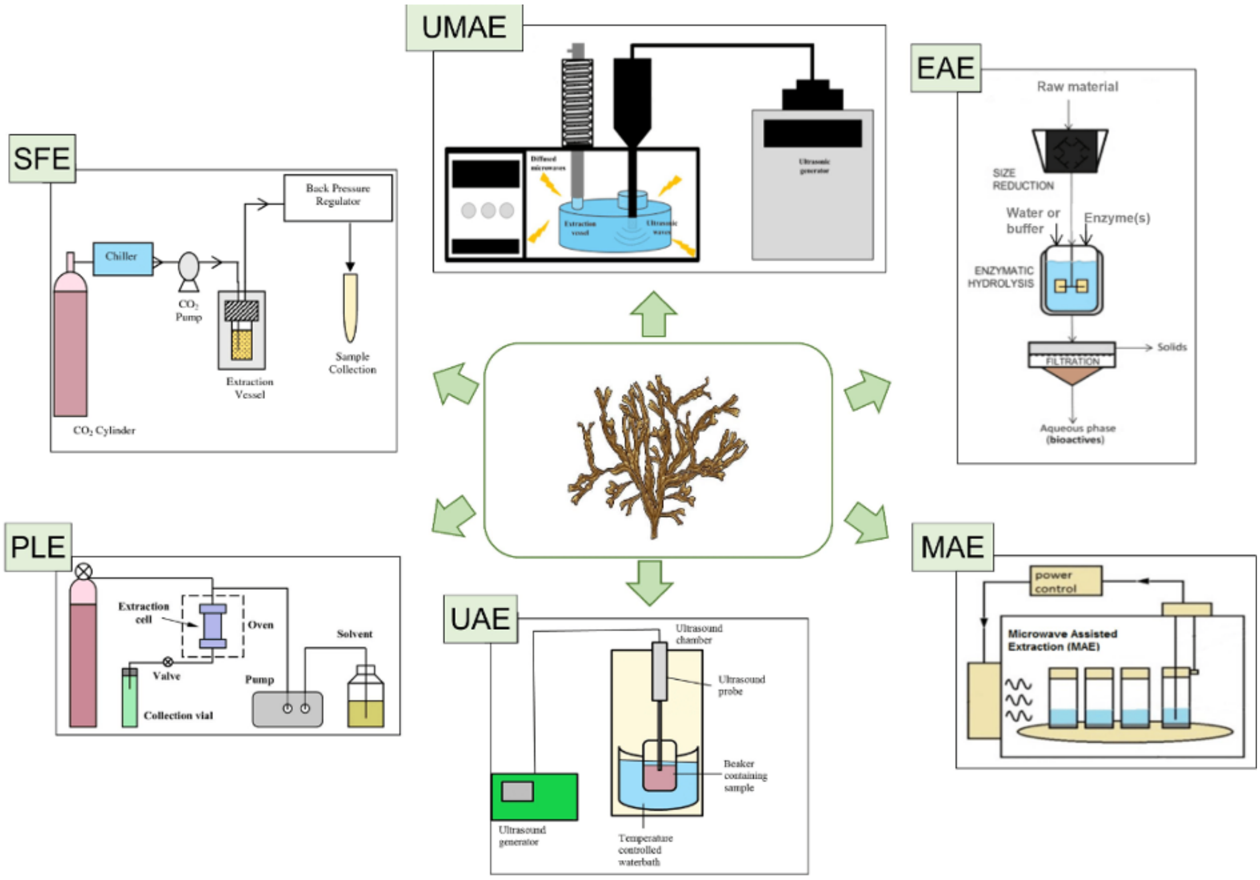

Figure 10. Seaweed bioactive compound extraction methods

This figure was obtained from Quitério et al., 2022 (Quitério et al. 2022)

\

Enzyme-assisted Extraction (EAE): A notable example of advanced extraction technology is enzymatic hydrolysis, which has been successfully implemented by compasses like Ocean Harvest Technology. This method uses specific enzymes to target and break down the complex structures of seaweed polysaccharides into simpler, more soluble forms, efficiently extracting valuable bioactive compounds. The process is highly selective, operates under mild conditions, and preserves the functional integrity of the extracted compounds (Sapatinha et al. 2022). Ocean Harvest Technology utilizes this technology to extract bioactive compounds for use in animal feed, demonstrating the method's scalability and commercial viability.

Microwave-Assisted Extraction (MAE): Another example is the use of Microwave-Assisted Extraction, adopted by companies such as Acadian Seaplants. MAE utilizes microwave energy to effectively heat the seaweed biomass and solvent mixture, significantly reducing extraction time and energy consumption (Quitério et al. 2022). This method enhances the extraction yield and efficiency of bioactive compounds like fucoxanthin and phlorotannins, which are sought after for their potent antioxidant properties. Acadian Seaplants Extracts International has successfully integrated MAE into their production line, producing high-quality extracts for the nutraceutical and cosmetic industries.

Supercritical Fluid Extraction (SFE): Supercritical Fluid Extraction, particularly with CO2, is a green technology employed by enterprises like Algae Biotech (Poojary et al. 2016). SFE uses supercritical CO_2 as a solvent, which has the unique ability to penetrate seaweed biomass and dissolve bioactive compounds efficiently. This method is celebrated for its low environmental impact, absence of toxic solvent residues, and ability to produce pure, high-quality extracts. Algae Biotech utilizes SFE to extract omega-3 fatty acids from seaweed, offering a sustainable alternative to fish oil.

Ultrasound-Assisted Extraction (UAE): Ultrasound-Assisted Extraction is another method, used by entities such as BioMarine Ingredients. UAE employs ultrasonic waves to create cavitation bubbles in the solvent-seaweed mixture, disrupting the cell walls and inducing the release of bioactive compounds (Zhang et al. 2022). This technology is recognized for its rapid processing times, reduced solvent usage, and energy efficiency. BioMarine Ingredients leverages UAE to produce seaweed-based ingredients for the food and beverage industry, demonstrating the technology's adaptability to different market needs.

Bioconversion of seaweed biomass to biochemicals presents both opportunities and challenges. The high carbohydrate content of seaweed makes them suitable for production of chemicals through processes such as anaerobic digestion and fermentation. However, the biochemical composition of seaweeds significantly differs from terrestrial biomass and innovative approaches for efficient conversion are required. Issues such as the recalcitrance of macroalgal components to bioconversion and the variability in bioactive compound concentrations pose notable challenges (Michalak 2018).

Despite these challenges, the industrial production of seaweed bioactives has seen considerable growth, driven by advancements in seaweed cultivation techniques and the domestication of seaweed cultivars. These advancements have facilitated consistent biomass supply, essential for large-scale production. However, entering high-value markets requires stringent quality control, standardization, and traceability of seaweed products, which necessitates further refinement of cultivation techniques and genetic selection of seaweed strains (Hafting et al. 2015).

3. Technologies to manufacture seaweed cosmetics

Seaweed has emerged as a valuable ingredient in the cosmetics industry due to its rich bioactive compounds and sustainable sourcing. Seaweeds are abundant in vitamins, minerals, antioxidants, and polysaccharides, making them highly beneficial for skin care and hair care products. The natural compounds in seaweed, such as alginate, carrageenan, and fucoidan, offer moisturizing, anti-inflammatory, and anti-aging properties that have been shown to improve skin hydration, reduce wrinkles, and protect against environmental stressors. Additionally, seaweed extracts are known for their detoxifying effects, helping to remove impurities from the skin while enhancing its overall texture and appearance. The use of seaweed in cosmetics aligns with the growing demand for natural and eco-friendly products, as seaweed can be sustainably cultivated without the need for synthetic chemicals, fertilizers, or freshwater resources. As research on the bioactive compounds of seaweed expands, the cosmetics industry continues to explore innovative formulations that leverage the unique benefits of seaweed, making it a key ingredient in the development of high-performance, sustainable beauty products.

The interest in utilizing seaweed in the cosmetics industry is growing significantly, facilitated by consumer demand for natural ingredients. Seaweeds are an abundant and renewable resource, offering a diverse array of bioactive compounds that can serve various roles in cosmetics, from active agents in skincare products to technical ingredients that enhance product texture and stability. These compounds include polyphenols, polysaccharides, proteins, peptides, amino acids, lipids, vitamins, and minerals, each contributing unique benefits to cosmeceutical formulations (López-Hortas et al. 2021) (**Figure 11**).

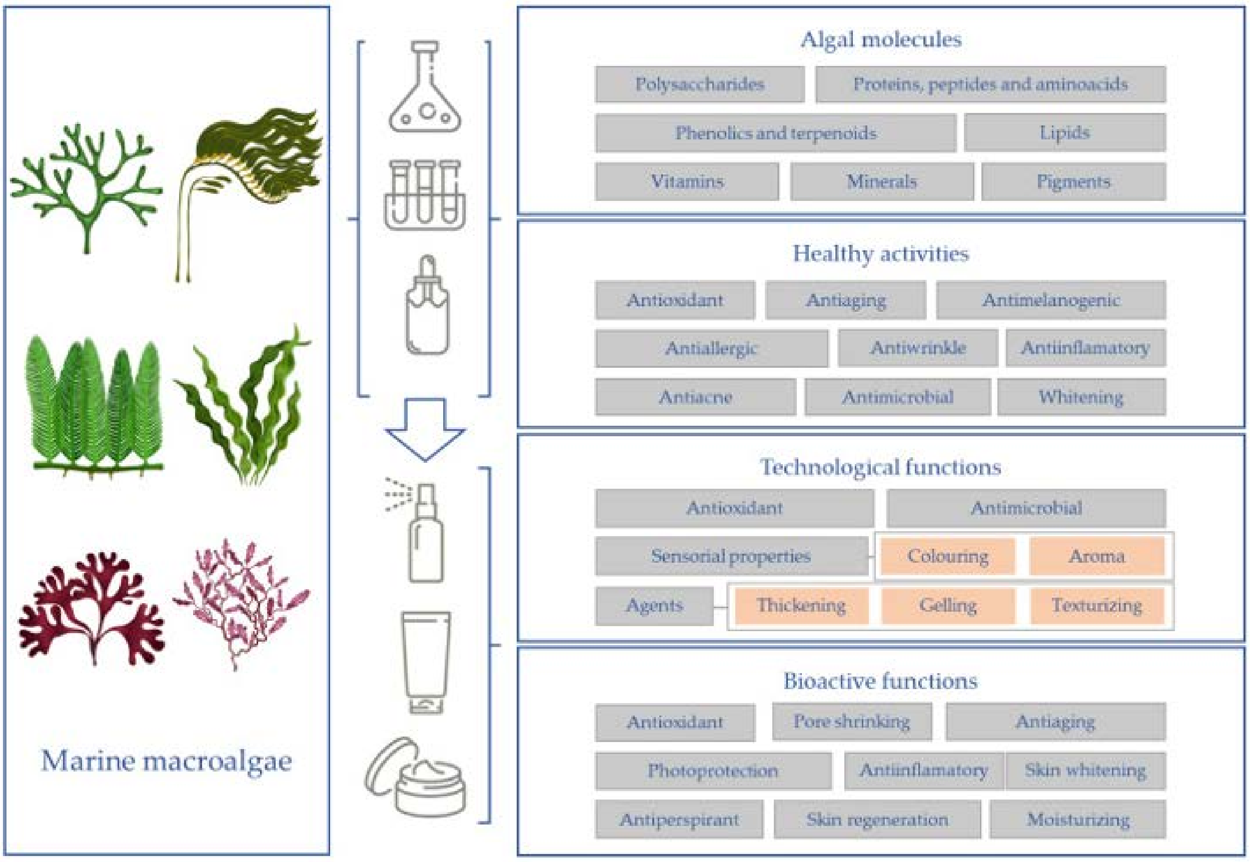

Figure 11. Cosmeceutical potential of marine macroalgae

This figure was obtained from López-Hortas et al., 2021 (López-Hortas et al. 2021)

Seaweeds also provide technical advantages in cosmetics, including antimicrobial properties, antioxidants to prevent oxidative damage, and components that improve the sensorial properties of products (Wijesinghe and Jeon 2011; Ferreres et al. 2012). Polysaccharides from seaweeds serve as thickening, gelling, and stabilizing agents, enhancing the texture and stability of cosmetic formulations (Morais et al. 2021; Xue et al. 1998). In addition, seaweed-derived ingredients are incorporated into cosmetics to offer moisturization, skin whitening effects by inhibiting melanin synthesis, and protection against UV radiation (López-Hortas et al. 2021). Their antioxidant properties help combat oxidative stress and prevent signs of aging. Seaweed components can also stabilize cosmetic formulations and enhance their aesthetic and functional qualities.

Producing cosmetics from seaweeds presents several technical challenges that can hinder large-scale production. One of the primary difficulties is the extraction of bioactive compounds from seaweed's complex cell walls, which requires advanced extraction techniques such as enzymatic hydrolysis, supercritical fluid extraction, or solvent-based methods. These processes must be carefully optimized to preserve the bioactivity of the beneficial compounds, such as polysaccharides, vitamins, and antioxidants, which are sensitive to heat and harsh chemical treatments. Additionally, Its high moisture content creates storage and processing challenges, as it must be rapidly dried or processed to prevent degradation of its valuable components. The seasonal and geographic variability of seaweed also affects the consistency of its composition, leading to fluctuations in the quality and efficacy of the extracted compounds. Moreover, seaweed can accumulate heavy metals and pollutants from its marine environment, necessitating rigorous purification steps to ensure the safety and purity of cosmetic products. These technical hurdles require a combination of advanced processing technologies and strict quality control measures to ensure that seaweed-derived cosmetics meet industry standards for performance and safety. Thus, to fully harness the cosmeceutical potential of seaweed, there is a critical need for the development of advanced cultivation and extraction technologies. These technologies are essential for isolating and refining the bioactive compounds found in seaweeds, ensuring their efficacy and safety when used in cosmetic formulations.

4. Conclusions

There have been attempts to develop technologies to explore the potential of seaweed as a sustainable alternative for various industrial applications, including bioenergy, biochemicals, bioplastics, and cosmetics. This section introduced technologies used in harvesting, pretreatment, and processing seaweed biomass to extract sugars, convert them into biofuels, and produce biodegradable plastics and bioactive compounds for cosmetics. Although there are challenges, such as high moisture content, variability in composition, and the need for advanced extraction techniques, ongoing advancements in microbial engineering, enzymatic hydrolysis, and mechanical processing continue to enhance its industrial viability. Seaweed presents an exciting, scalable resource for producing renewable, eco-friendly materials and reducing environmental impacts across multiple sectors.

References

Adams, Jessica M., Joseph A. Gallagher, and Iain S. Donnison. 2009. "Fermentation Study on Saccharina Latissima for Bioethanol Production Considering Variable Pre-Treatments." *Journal of Applied Phycology* 21 (5): 569–74.

Arias, Ana, Gumersindo Feijoo, and Maria Teresa Moreira. 2023. "Macroalgae Biorefineries as a Sustainable Resource in the Extraction of Value-Added Compounds." *Algal Research* 69 (102954): 102954.

Awogbemi, Omojola, and Daramy Vandi Von Kallon. 2024. "Recent Advances in the Application of Nanomaterials for Improved Biodiesel, Biogas, Biohydrogen, and Bioethanol Production." *Fuel (London, England)* 358 (130261): 130261.

Bak, Urd Grandorf, Ólavur Gregersen, and Javier Infante. 2020. "Technical Challenges for Offshore Cultivation of Kelp Species: Lessons Learned and Future Directions." *Botanica Marina* 63 (4): 341–53.

Buschmann, Alejandro H., Carolina Camus, Javier Infante, Amir Neori, Álvaro Israel, María C. Hernández-González, Sandra V. Pereda, et al. 2017. "Seaweed Production: Overview of the Global State of Exploitation, Farming and Emerging Research Activity." *European Journal of Phycology* 52 (4): 391–406.

Bušić, Arijana, Nenad Marđetko, Semjon Kundas, Galina Morzak, Halina Belskaya, Mirela Ivančić Šantek, Draženka Komes, Srđan Novak, and Božidar Šantek. 2018. "Bioethanol Production from Renewable Raw Materials and Its Separation and Purification: A Review." *Food Technology and Biotechnology* 56 (3): 289–311.

Carlson, Kimberly M., Robert Heilmayr, Holly K. Gibbs, Praveen Noojipady, David N. Burns, Douglas C. Morton, Nathalie F. Walker, Gary D. Paoli, and Claire Kremen. 2018. "Effect of Oil Palm Sustainability Certification on Deforestation and Fire in Indonesia." *Proceedings of the National Academy of Sciences of the United States of America* 115 (1): 121–26.

Charoensiddhi, Suvimol, Michael A. Conlon, Christopher M. M. Franco, and Wei Zhang. 2017. "The Development of Seaweed-Derived Bioactive Compounds for Use as Prebiotics and Nutraceuticals Using Enzyme Technologies." *Trends in Food Science & Technology* 70 (December): 20–33.

Correia, Marta, Isabel Costa Azevedo, Helena Peres, Rui Magalhães, Aires Oliva-Teles, Cristina Marisa Ribeiro Almeida, and Laura Guimarães. 2020. "Integrated Multi-Trophic Aquaculture:

A Laboratory and Hands-on Experimental Activity to Promote Environmental Sustainability Awareness and Value of Aquaculture Products.” *Frontiers in Marine Science* 7 (March): 503978.

Deniz, Irem, Esra Imamoglu, and Tugba Keskin Gundogdu. 2022. *Properties and Applications of Alginates*. BoD – Books on Demand.

Duarte, Carlos M., Jiaping Wu, Xi Xiao, Annette Bruhn, and Dorte Krause-Jensen. 2017. “Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation?” *Frontiers in Marine Science* 4 (April). https://doi.org/10.3389/fmars.2017.00100.

Ferreres, Federico, Graciliana Lopes, Angel Gil-Izquierdo, Paula B. Andrade, Carla Sousa, Teresa Mouga, and Patrícia Valentão. 2012. “Phlorotannin Extracts from Fucales Characterized by HPLC-DAD-ESI-MSn: Approaches to Hyaluronidase Inhibitory Capacity and Antioxidant Properties.” *Marine Drugs* 10 (12): 2766–81.

Forbord, Silje, Siv Anina Etter, Ole Jacob Broch, Vegard Rønning Dahlen, and Yngvar Olsen. 2021. “Initial Short-Term Nitrate Uptake in Juvenile, Cultivated Saccharina Latissima (Phaeophyceae) of Variable Nutritional State.” *Aquatic Botany* 168 (103306): 103306.

Froehlich, Halley E., Jamie C. Afflerbach, Melanie Frazier, and Benjamin S. Halpern. 2019. “Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting.” *Current Biology: CB* 29 (18): 3087-3093.e3.

Fujita, Rod, Simona Augyte, Jennifer Bender, Poppy Brittingham, Alejandro H. Buschmann, Max Chalfin, Jamie Collins, et al. 2023. “Seaweed Blue Carbon: Ready? Or Not?” *Marine Policy* 155 (105747): 105747.

Goldfarb, Jillian L., and Douglas L. Kriner. 2021. “U.S. Public Support for Biofuels Tax Credits: Cost Frames, Local Fuel Prices, and the Moderating Influence of Partisanship.” *Energy Policy* 149 (112098): 112098.

Hafting, Jeff T., James S. Craigie, Dagmar B. Stengel, Rafael R. Loureiro, Alejandro H. Buschmann, Charles Yarish, Maeve D. Edwards, and Alan T. Critchley. 2015. “Prospects and Challenges for Industrial Production of Seaweed Bioactives.” *Journal of Phycology* 51 (5): 821–37.

Heo, Jae Bok, Yong-Suk Lee, and Chung-Han Chung. 2020. “Toward Sustainable Hydroxymethylfurfural Production Using Seaweeds.” *Trends in Biotechnology* 38 (5): 487–96.

Iram, Attia, Deniz Cekmecelioglu, and Ali Demirci. 2020. “Distillers’ Dried Grains with Solubles (DDGS) and Its Potential as Fermentation Feedstock.” *Applied Microbiology and Biotechnology* 104 (14): 6115–28.

Khan, Nida, K. Sudhakar, and R. Mamat. 2024. “Macroalgae Farming for Sustainable Future: Navigating Opportunities and Driving Innovation.” *Heliyon* 10 (7): e28208.

Krause-Jensen, Dorte, and Carlos M. Duarte. 2016. “Substantial Role of Macroalgae in Marine Carbon Sequestration.” *Nature Geoscience* 9 (10): 737–42.

Kung, Chih-Chun, Liguo Zhang, and Fanbin Kong. 2016. “How Government Subsidy Leads to Sustainable Bioenergy Development.” *Technological Forecasting and Social Change* 112 (November): 275–84.

Lian, Yushun, Samuel Obeng Boamah, Zhenghu Pan, Jinhai Zheng, Wenxing Chen, Gang Ma, and Solomon C. Yim. 2024. “Engineering Design and Economic Analysis of Offshore Seaweed Farm.” *Frontiers in Marine Science* 11 (February): 1276552.

Lim, C., S. Yusoff, C. G. Ng, P. E. Lim, and Y. C. Ching. 2021. “Bioplastic Made from Seaweed Polysaccharides with Green Production Methods.” *Journal of Environmental Chemical Engineering* 9 (5): 105895.

Lim, Hyun Gyu, Dong Hun Kwak, Sungwoo Park, Sunghwa Woo, Jae-Seong Yang, Chae Won Kang, Beomhee Kim, Myung Hyun Noh, Sang Woo Seo, and Gyoo Yeol Jung. 2019. “Vibrio Sp. Dhg as a Platform for the Biorefinery of Brown Macroalgae.” *Nature Communications* 10 (1): 2486.

Lin, Hong-Ting Victor, Mei-Ying Huang, Te-Yu Kao, Wen-Jung Lu, Hsuan-Ju Lin, and Chorng-Liang Pan. 2020. “Production of Lactic Acid from Seaweed Hydrolysates via Lactic Acid Bacteria Fermentation.” *Fermentation* 6 (1): 37.

López-Hortas, Lucía, Noelia Flórez-Fernández, Maria D. Torres, Tania Ferreira-Anta, María P. Casas, Elena M. Balboa, Elena Falqué, and Herminia Domínguez. 2021. “Applying Seaweed Compounds in Cosmetics, Cosmeceuticals and Nutricosmetics.” *Marine Drugs* 19 (10). https://doi.org/10.3390/md19100552.

Macreadie, Peter I., Andrea Anton, John A. Raven, Nicola Beaumont, Rod M. Connolly, Daniel A. Friess, Jeffrey J. Kelleway, et al. 2019. “The Future of Blue Carbon Science.” *Nature Communications* 10 (1): 3998.

Mashoreng, S., Y. A. La Nafie, and R. Isyrini. 2019. “Cultivated Seaweed Carbon Sequestration Capacity.” *IOP Conference Series. Earth and Environmental Science* 370 (1): 012017.

Michalak, Izabela. 2018. “Experimental Processing of Seaweeds for Biofuels.” *Wiley Interdisciplinary Reviews Energy and Environment* 7 (3): e288.

Molen, Johan van der, Piet Ruardij, Karen Mooney, Philip Kerrison, Nessa E. O'Connor, Emma Gorman, Klaas Timmermans, et al. 2018. "Modelling Potential Production of Macroalgae Farms in UK and Dutch Coastal Waters." *Biogeosciences* 15 (4): 1123–47.

Morais, Tiago, João Cotas, Diana Pacheco, and Leonel Pereira. 2021. "Seaweeds Compounds: An Ecosustainable Source of Cosmetic Ingredients?" *Cosmetics and Toiletries* 8 (1): 8.

Nakhate, Pranav, and Yvonne van der Meer. 2021. "A Systematic Review on Seaweed Functionality: A Sustainable Bio-Based Material." *Sustainability* 13 (11): 6174.

Nissar, Sinan, Yahya Bakhtiyar, Mohammad Yasir Arafat, Saima Andrabi, Zahoor Ahmad Mir, Niyaz Ali Khan, and Seema Langer. 2023. "The Evolution of Integrated Multi-Trophic Aquaculture in Context of Its Design and Components Paving Way to Valorization via Optimization and Diversification." *Aquaculture* 565 (February): 739074.

Peteiro, César, Noemí Sánchez, and Brezo Martínez. 2016. "Mariculture of the Asian Kelp Undaria Pinnatifida and the Native Kelp Saccharina Latissima along the Atlantic Coast of Southern Europe: An Overview." *Algal Research* 15 (April): 9–23.

Poojary, Mahesha M., Francisco J. Barba, Bahar Aliakbarian, Francesco Donsì, Gianpiero Pataro, Daniel A. Dias, and Pablo Juliano. 2016. "Innovative Alternative Technologies to Extract Carotenoids from Microalgae and Seaweeds." *Marine Drugs* 14 (11). https://doi.org/10.3390/md14110214.

Quinn, Jason C., and Ryan Davis. 2015. "The Potentials and Challenges of Algae Based Biofuels: A Review of the Techno-Economic, Life Cycle, and Resource Assessment Modeling." *Bioresource Technology* 184 (May): 444–52.

Quitério, Eva, Clara Grosso, Ricardo Ferraz, Cristina Delerue-Matos, and Cristina Soares. 2022. "A Critical Comparison of the Advanced Extraction Techniques Applied to Obtain Health-Promoting Compounds from Seaweeds." *Marine Drugs* 20 (11): 677.

Ramachandra, T. V., and Deepthi Hebbale. 2020. "Bioethanol from Macroalgae: Prospects and Challenges." *Renewable and Sustainable Energy Reviews* 117 (January): 109479.

Ramsey, Steven, Brian Williams, Philip Jarrell, and Todd Hubbs. 2023. "Global Demand for Fuel Ethanol Through 2030." USDA. https://www.ers.usda.gov/webdocs/outlooks/105762/bio-05.pdf?v=5239.1.

Samoraj, Mateusz, Derya Çalış, Krzysztof Trzaska, Małgorzata Mironiuk, and Katarzyna Chojnacka. 2024. "Advancements in Algal Biorefineries for Sustainable Agriculture: Biofuels, High-

Value Products, and Environmental Solutions." *Biocatalysis and Agricultural Biotechnology* 58 (103224): 103224.

Sapatinha, M., A. Oliveira, S. Costa, S. Pedro, A. Gonçalves, R. Mendes, N. M. Bandarra, and C. Pires. 2022. "Red and Brown Seaweeds Extracts: A Source of Biologically Active Compounds." *Food Chemistry* 393 (November): 133453.

Scarlat, Nicolae, and Jean-François Dallemand. 2011. "Recent Developments of Biofuels/Bioenergy Sustainability Certification: A Global Overview." *Energy Policy* 39 (3): 1630–46.

Schiener, Peter, Kenneth D. Black, Michele S. Stanley, and David H. Green. 2015. "The Seasonal Variation in the Chemical Composition of the Kelp Species Laminaria Digitata, Laminaria Hyperborea, Saccharina Latissima and Alaria Esculenta." *Journal of Applied Phycology* 27 (1): 363–73.

Solvang, Torfinn, Emil Scott Bale, Ole Jacob Broch, Aleksander Handå, and Morten Omholt Alver. 2021. "Automation Concepts for Industrial-Scale Production of Seaweed." *Frontiers in Marine Science* 8 (April): 613093.

Sudhakar, Muthiyal Prabakaran, Rahulkumar Maurya, Sanjeet Mehariya, Obulisamy Parthiba Karthikeyan, Gopal Dharani, Kulanthiyesu Arunkumar, Sandra V. Pereda, María C. Hernández-González, Alejandro H. Buschmann, and Arivalagan Pugazhendhi. 2024. "Feasibility of Bioplastic Production Using Micro- and Macroalgae- A Review." *Environmental Research* 240 (Pt 2): 117465.

Tullberg, Robert Maxwell, Huu Phu Nguyen, and Chien Ming Wang. 2022. "Review of the Status and Developments in Seaweed Farming Infrastructure." *Journal of Marine Science and Engineering* 10 (10): 1447.

V, Godvin Sharmila, Dinesh Kumar M, Arulazhagan Pugazhendi, Amit Kumar Bajhaiya, Poornachander Gugulothu, and Rajesh Banu J. 2021. "Biofuel Production from Macroalgae: Present Scenario and Future Scope." *Bioengineered* 12 (2): 9216–38.

Venier, Chiara, Stefano Menegon, Hugh P. Possingham, Elena Gissi, Andrea Zanella, Daniel Depellegrin, Alessandro Sarretta, Andrea Barbanti, and Jennifer McGowan. 2021. "Multi-Objective Zoning for Aquaculture and Biodiversity." *The Science of the Total Environment* 785 (146997): 146997.

Walls, A. M., M. D. Edwards, L. B. Firth, and M. P. Johnson. 2017. "Successional Changes of Epibiont Fouling Communities of the Cultivated Kelp Alaria Esculenta: Predictability and Influences." *Aquaculture Environment Interactions* 9 (February): 57–71.

Wang, Zhaoqin, Bruce S. Dien, Kent D. Rausch, M. E. Tumbleson, and Vijay Singh. 2019. “Improving Ethanol Yields with Deacetylated and Two-Stage Pretreated Corn Stover and Sugarcane Bagasse by Blending Commercial Xylose-Fermenting and Wild Type Saccharomyces Yeast.” *Bioresource Technology* 282 (June): 103–9.

Wargacki, Adam J., Effendi Leonard, Maung Nyan Win, Drew D. Regitsky, Christine Nicole S. Santos, Peter B. Kim, Susan R. Cooper, et al. 2012. “An Engineered Microbial Platform for Direct Biofuel Production from Brown Macroalgae.” *Science* 335 (6066): 308–13.

Wijesinghe, W. A. J. P., and You-Jin Jeon. 2011. “Biological Activities and Potential Cosmeceutical Applications of Bioactive Components from Brown Seaweeds: A Review.” *Phytochemistry Reviews* 10 (3): 431–43.

Wu, Jiaping, Haibo Zhang, Yiwen Pan, Dorte Krause-Jensen, Zhiguo He, Wei Fan, Xi Xiao, et al. 2020. “Opportunities for Blue Carbon Strategies in China.” *Ocean & Coastal Management* 194 (105241): 105241.

Xue, C., G. Yu, T. Hirata, J. Terao, and H. Lin. 1998. “Antioxidative Activities of Several Marine Polysaccharides Evaluated in a Phosphatidylcholine-Liposomal Suspension and Organic Solvents.” *Bioscience, Biotechnology, and Biochemistry* 62 (2): 206–9.

Yacobucci, Brent D. 2013. *Biofuels Incentives: A Summary of Federal Programs*. Bibliogov.

Yong, Wilson Thau Lym, Vun Yee Thien, Mailin Misson, Grace Joy Wei Lie Chin, Siti Nahdatul Isnaini Said Hussin, Harry Lye Hin Chong, Nur Athirah Yusof, Nyuk Ling Ma, and Kenneth Francis Rodrigues. 2024. “Seaweed: A Bioindustrial Game-Changer for the Green Revolution.” *Biomass & Bioenergy* 183 (107122): 107122.

Zhang, Lizhu, Wei Liao, Yajun Huang, Yuxi Wen, Yaoyao Chu, and Chao Zhao. 2022. “Global Seaweed Farming and Processing in the Past 20 Years.” *Food Production, Processing and Nutrition* 4 (1). https://doi.org/10.1186/s43014-022-00103-2.

Zheng, Zhiguo, Ali Dai, Yonggui Liu, and Tingting Li. 2022. “Sustainable Alginate Lyases Catalyzed Degradation of Bio-Based Carbohydrates.” *Frontiers in Chemistry* 10 (September): 1008010.

Zhu, Ben-Wei, Li-Shu-Xin Huang, Hai-Dong Tan, Yu-Qi Qin, Yu-Guang Du, and Heng Yin. 2015. “Characterization of a New Endo-Type PolyM-Specific Alginate Lyase from Pseudomonas Sp.” *Biotechnology Letters* 37 (2): 409–15.