14 Potential of Marine Greens for Biofuel Production

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14.1 INTRODUCTION

The global demand for energy is continuously increasing due to increase in population, industrialization, and modernization (International Energy Agency [IEA], 2020). The majority of the world's energy is generated from fossil fuels, leading to an increase in greenhouse gas (GHG) emissions, which contributes to climate change and environmental degradation (Ritchie & Roser, 2021). Recently, there has been rising concern over the development of sustainable and renewable energy sources, particularly biofuels, to ease dependency on fossil fuels and mitigate the negative impacts of GHG emissions (Demirbas, 2009).

Biofuels are derived from organic materials, such as plants and microorganisms, and can be used as alternatives to traditional fossil fuels (Balat, 2011). The potential of biofuels as a renewable energy source has been extensively studied, with particular emphasis on terrestrial plants, such as corn, sugarcane, and oilseed crops (Sims *et al*., 2010). However, concerns have been raised regarding the use of agricultural land and resources for biofuel production, as it may compete with food production and contribute to deforestation (Tilman *et al*., 2009). This has led to a search for alternative feedstocks that do not compete with food production, such as marine greens (Chisti, 2007).

Given the numerous advantages of marine greens for biofuel production, there has been a growing awareness of exploring their prospects for large-scale, sustainable, and economically viable biofuel production (Singh & Olsen, 2011). This chapter aims to provide a comprehensive overview of the potential of marine greens for biofuel production, highlighting their advantages and challenges, recent advances in research and technology, and real-world applications. Additionally, the review will examine the environmental and economic implications of using marine greens as feedstocks for biofuels, as well as future research directions and policy support needed for their successful implementation. This chapter will provide a comprehensive and critical analysis of the current state of knowledge on the potential of marine greens for biofuel production, offering valuable insights for researchers, policymakers, and industry stakeholders.

14.2 MARINE GREENS AS A POTENTIAL SOURCE FOR BIOFUEL PRODUCTION

Marine greens, comprising microalgae and macroalgae (seaweeds), have emerged as a promising feedstock for biofuel production due to their numerous advantages over traditional terrestrial sources, such as higher biomass productivity, non-competition with food crops, and low freshwater requirements (Wijffels & Barbosa, 2010). Biofuels derived from marine greens have the potential to play a substantial role in decreasing GHG emissions and enhancing energy security, thereby contributing to a more sustainable and renewable energy future (Chisti, 2007).

Microalgae are microscopic, photosynthetic organisms that can grow rapidly in a variety of environments, including marine, brackish, and freshwater systems (Mata *et al*., 2010). These organisms have a high lipid content, making them ideal candidates for the production of biodiesel—a renewable and sustainable alternative to fossil-based diesel fuel (Chisti, 2007). Furthermore, some microalgae strains have a high carbohydrate content, which can be utilized to produce bioethanol

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through fermentation processes (Harun *et al*., 2010). Microalgae-based biofuels have the potential to deliver higher energy yields per unit area compared with terrestrial crops, such as corn, sugarcane, and oilseed rape, while avoiding the competition for arable land and freshwater resources (Dismukes *et al*., 2008).

Macroalgae, commonly known as seaweeds, are large, multicellular marine organisms that grow predominantly in coastal areas and can be classified into three groups: green, red, and brown algae (Mann & Steinke, 2012). Seaweeds have a high carbohydrate content and can be used to produce bioethanol, biobutanol, and other biofuels through various fermentation and hydrolysis processes (Adams *et al*., 2011). The advantages of using macroalgae for biofuel production include their rapid growth rates, ability to grow in a wide range of environmental conditions, and capacity to absorb nutrients and carbon dioxide from the surrounding water, thereby providing additional environmental benefits (Horn *et al*., 2014).

One of the key challenges in using marine greens for biofuel production is the efficient and cost-effective extraction of lipids and carbohydrates from these organisms. Recent advancements in cell disruption, solvent extraction, and enzymatic hydrolysis techniques have shown promise in improving the extraction efficiency and reducing the costs related to the production of marine green–based biofuels (Lee *et al*., 2012). Moreover, the development of genetically engineered strains of microalgae and macroalgae with enhanced lipid and carbohydrate content has the potential to further improve the productivity and feasibility of marine green–based biofuels (Radakovits *et al*., 2010).

Another critical challenge in the large-scale production of marine green–based biofuels is the development of sustainable and efficient cultivation systems (Pires *et al*., 2011). While open pond systems are relatively low-cost and easy to operate, they have limitations in terms of contamination risks, evaporation losses, and low biomass productivity. On the other hand, closed photobioreactors offer higher biomass productivity and better control over cultivation conditions, but at a higher capital and operational cost (Posten, 2009). Optimization of cultivation systems, including the integration of wastewater treatment and CO_2 capture technologies, can help improve the sustainability and cost-effectiveness of marine green–based biofuel production (Delrue *et al*., 2016).

Marine greens offer significant potential as a renewable and sustainable feedstock for biofuel production. The utilization of marine greens for biofuel production can help address the global demand for energy while mitigating the negative environmental impacts associated with fossil fuel consumption. Further research and development efforts are needed to overcome the challenges related to the efficient extraction of lipids and carbohydrates from marine greens, as well as the design and optimization of sustainable cultivation systems (Singh *et al*., 2011). By harnessing the potential of marine greens for biofuel production, we can contribute to a cleaner, greener, and more sustainable energy future.

14.3 BIOFUEL PRODUCTION PROCESSES

Biofuel production involves various processes to convert biomass into usable forms of energy, such as bioethanol, biodiesel, and biogas. These processes can be broadly categorized into biochemical, thermochemical, and physicochemical methods (Demirbas, 2009).

a) **Biochemical Processes:** Biochemical processes involve the use of enzymes, bacteria, or other microorganisms to break down biomass into simpler compounds that can be further processed into biofuels. Fermentation is a widely used biochemical process for the production of bioethanol from sugar- or starch-rich feedstocks, such as corn, sugarcane, and wheat (Soccol *et al*., 2010). In this process, sugars are converted into ethanol by yeast or bacteria under anaerobic conditions. For the production of cellulosic ethanol, a pretreatment step is required to break down the complex lignocellulosic structure and release fermentable sugars, which are then fermented by microorganisms (Perlack & Stokes, 2011).

b) **Anaerobic Digestion:** Anaerobic digestion is another biochemical process used for the production of biogas, a mixture of methane and carbon dioxide. This process involves the decomposition of organic matter by various groups of microorganisms in the absence of oxygen, resulting in the production of biogas and nutrient-rich digestate (Angelidaki *et al*., 2011). Anaerobic digestion can be applied to various feedstocks, including agricultural and animal wastes, sewage sludge, and organic fractions of municipal solid waste.
c) **Thermochemical Processes:** Thermochemical processes involve the application of heat to convert biomass into biofuels. Pyrolysis is a thermochemical process that involves the thermal decomposition of biomass in the absence of oxygen, resulting in the production of bio-oil, biochar, and non-condensable gases (Bridgwater, 2003). Bio-oil can be further upgraded and refined into advanced biofuels, such as drop-in biofuels and green chemicals, while biochar can be used as a soil amendment or for carbon sequestration (Lehmann & Joseph, 2009).
d) **Gasification:** Gasification is another thermochemical process, which involves the partial oxidation of biomass at high temperatures to produce a mixture of carbon monoxide, hydrogen, and methane, known as synthesis gas or syngas (McKendry, 2002). Syngas can be further processed into various biofuels and chemicals through catalytic processes, such as Fischer–Tropsch synthesis, methanol synthesis, and mixed alcohol synthesis (Huber *et al*., 2006).
e) **Physicochemical Processes:** Physicochemical processes involve the application of physical and chemical methods to convert biomass into biofuels. Transesterification is a widely used physicochemical process for the production of biodiesel from vegetable oils, animal fats, or waste cooking oils (Ma & Hanna, 1999). In this process, triglycerides are reacted with an alcohol, usually methanol, in the presence of a catalyst, such as sodium or potassium hydroxide, to produce biodiesel and glycerol as a byproduct.
f) **Hydrothermal Liquefaction:** Hydrothermal liquefaction is another physicochemical process, which involves the conversion of biomass into bio-oil under high pressure and temperature in the presence of water (Toor *et al*., 2011). This process is particularly suitable for the conversion of wet biomass, such as microalgae and sewage sludge, into bio-oil, which can be further upgraded into advanced biofuels and green chemicals (Elliott *et al*., 2015).

Biofuel production processes can be broadly categorized into biochemical, thermochemical, and physicochemical methods, each with its advantages and limitations. The selection of the most appropriate process depends on the type and characteristics of the feedstock, as well as the desired biofuel product. Continuous research and development in these processes aim to improve the efficiency, sustainability, and economic viability of biofuel production (Sims *et al*., 2010).

14.4 ADVANTAGES OF MARINE GREENS FOR BIOFUEL PRODUCTION

Marine greens, including macroalgae (seaweeds) and microalgae, have emerged as promising feedstocks for biofuel production due to their unique advantages over traditional terrestrial feedstocks, such as energy crops and agricultural residues (Wijffels & Barbosa, 2010). These advantages include high growth rates, high biomass productivity, reduced land and freshwater use, and the ability to capture and utilize CO_2 efficiently (Chisti, 2008).

One of the main advantages of marine greens is their high growth rate and biomass productivity, which can be several times higher than those of terrestrial plants (Mata *et al*., 2010). This high productivity allows the production of larger amounts of biofuel per unit area compared with traditional feedstocks. Additionally, marine greens can be harvested year-round, providing a continuous and reliable supply of biomass for biofuel production (Potts *et al*., 2012).

Another significant advantage of marine greens is their reduced land and freshwater use, which is particularly important in the context of global concerns over land and water resources. Unlike terrestrial feedstocks that require arable land and freshwater for irrigation, marine greens can be cultivated in saline water or wastewater, reducing the pressure on limited freshwater resources (Roesijadi *et al*., 2010). Moreover, marine greens can be cultivated in open ponds, photobioreactors, or offshore systems, thereby avoiding competition for land with food production and other land-based activities (Xin *et al*., 2017).

Marine greens are efficient at capturing and utilizing CO_2, which contributes to their high productivity and environmental benefits. Many species of microalgae and macroalgae are capable of fixing CO_2 at rates much higher than those of terrestrial plants (Beardall & Raven, 2004). This efficient CO_2 fixation can help mitigate GHG emissions and climate change, as well as potentially provide a sustainable solution for CO_2 capture and utilization from industrial sources, such as power plants and other emission-intensive industries (Markou & Nerantzis, 2013).

Marine greens also have the potential to produce a diverse range of biofuels, including bioethanol, biobutanol, and biogas, through various conversion processes, such as fermentation, anaerobic digestion, and thermochemical conversion (Harun *et al*., 2010). The versatility of marine greens in terms of biofuel production provides an opportunity to develop integrated biorefinery concepts, where multiple products, including biofuels, chemicals, and materials, can be produced from a single feedstock, thereby enhancing the economic viability and sustainability of biofuel production (Enzing *et al*., 2014).

14.5 RECENT ADVANCES AND INNOVATIONS IN MARINE GREENS FOR BIOFUEL PRODUCTION

In recent years, there has been growing interest in the development of marine greens, which include microalgae and macroalgae (seaweeds), as a sustainable and renewable feedstock for biofuel production (Wijffels & Barbosa, 2010). This is mainly due to their high photosynthetic efficiency, rapid growth rates, and ability to accumulate lipids and other energy-rich compounds that can be converted into various types of biofuels, such as biodiesel, bioethanol, and biogas (Hossain *et al*., 2008; Chisti, 2007). Furthermore, marine greens can be cultivated in saltwater or brackish water, which reduces the demand for freshwater resources and mitigates potential conflicts with food production on arable land. This section will provide an overview of the recent advances and innovations in the field of marine greens for biofuel production, focusing on the areas of cultivation, harvesting, and processing technologies.

a) **Cultivation Technologies:** One of the key challenges in the large-scale production of marine greens for biofuel applications is the development of efficient and cost-effective cultivation systems that can optimize growth conditions, maximize biomass productivity, and minimize resource consumption (Singh & Olsen, 2011). Recent advances in this area include the design of innovative photobioreactors (PBRs) and open pond systems for microalgal cultivation, as well as novel cultivation techniques for macroalgae (Posten, 2009).

   For microalgae, PBRs offer several advantages over traditional open pond systems, such as improved light utilization, reduced contamination risks, and better control of cultivation parameters. Recent innovations in PBR design include the development of flat-panel, tubular, and column systems, which can optimize light distribution, gas exchange, and nutrient supply to enhance microalgal growth and lipid accumulation). Additionally, advances in materials science and engineering have led to the creation of PBRs with improved thermal and optical properties, which can further enhance the efficiency and sustainability of microalgal cultivation (Carvalho *et al*., 2011; Grima *et al*., 2003).

   Cultivation techniques have been a major area of innovation, with researchers exploring various methods to enhance the growth and biomass productivity of marine greens. One such approach is the development of photobioreactors, which are closed systems that provide a controlled environment for optimal growth conditions, including nutrients, light, and temperature (Chisti, 2007). These systems can be customized to improve the productivity of specific marine green species, while also minimizing water consumption and land requirements. Additionally, innovative photobioreactor designs, such as flat-panel, tubular, and raceway pond systems, have been developed to maximize light penetration and distribution, further enhancing algal growth and productivity (Grima *et al*., 2003).

Another cultivation strategy involves the use of genetic engineering and selective breeding techniques to optimize marine green strains for biofuel production. By manipulating the genetic makeup of microalgae and macroalgae, researchers have been able to develop strains with higher lipid content, faster growth rates, and improved tolerance to environmental stressors, such as high salinity or nutrient limitation (Grima *et al*., 2003). These advancements have not only improved the potential yield of biofuels from marine greens but also contributed to a better understanding of the underlying biological processes governing their growth and metabolism (Carvalho *et al*., 2011).

b) **Harvesting Technologies:** Another critical aspect of marine green–based biofuel production is the development of efficient and cost-effective harvesting methods, which can separate the algal biomass from the cultivation medium and prepare it for further processing. Traditional harvesting techniques, such as sedimentation, centrifugation, and filtration, are often energy-intensive and expensive, which can significantly increase the overall cost of marine green–based biofuels (Milledge & Heaven, 2013).

Recent innovations in harvesting technologies include the development of novel methods, such as flotation, flocculation, and electrocoagulation, which can enhance the efficiency and sustainability of algal biomass recovery (Garg *et al*., 2012). For example, the use of bio-flocculation agents, such as chitosan and natural polymers, can promote the aggregation and sedimentation of microalgal cells, reducing the energy requirements and environmental impacts of harvesting (Chen *et al*., 2011). Similarly, advances in membrane technology, such as the development of forward osmosis and ultrafiltration systems, have enabled the high-throughput and low-energy separation of algal biomass from the cultivation medium (Bilad *et al*., 2012; Lizzul *et al*., 2014).

c) **Processing Technologies:** The conversion of marine green biomass into biofuels requires the development of efficient and cost-effective processing technologies, which can extract and convert the energy-rich compounds (such as lipids, carbohydrates, and proteins) into various types of fuels (Chisti, 2008; Mata *et al*., 2010). Recent advances in this area include the optimization of traditional processing methods, such as transesterification for biodiesel production and fermentation for bioethanol production, as well as the development of novel techniques, such as hydrothermal liquefaction and gasification for biocrude and bio-syngas production, respectively (Dote *et al*., 1994; Harun *et al*., 2010; Jena *et al*., 2011).

14.6 CASE STUDIES AND REAL-WORLD APPLICATIONS OF MARINE GREENS FOR BIOFUEL PRODUCTION

The potential of marine greens for biofuel production has prompted a variety of case studies and real-world applications, with both large-scale and small-scale projects being implemented to demonstrate the feasibility and benefits of this renewable energy source. This section will highlight some of these case studies, showcasing the diverse applications and successes of marine green-based biofuels in different regions and industries.

a) **Algenol Biofuels (United States):** Algenol, a Florida-based biotechnology company has developed an innovative, patented technology called the Direct to Ethanol® process, which uses photosynthetic microalgae to convert carbon dioxide directly into bioethanol

(Algenol Biofuels, 2016). This process is designed to be both energy-efficient and environmentally friendly, producing minimal waste and utilizing low-cost, non-arable land for algae cultivation. Algenol's integrated biorefinery in Fort Myers, Florida, has demonstrated the scalability and commercial viability of this technology, with the company aiming to expand its operations and further develop its algae-to-ethanol platform (Lane, 2014).

b) **Cellana (United States):** Cellana, a California-based company, is focused on the development of marine microalgae for the production of renewable fuels, feeds, and high-value products (Cellana, n.d.). The company operates a large-scale, outdoor algae cultivation facility in Hawaii, known as the Kona Demonstration Facility, which has produced over 10,000 gallons of algal oil since its inception (McNichol *et al*., 2012). This facility uses proprietary, high-productivity algal strains to maximize biomass and lipid production, while utilizing saltwater and recycled CO_2 to minimize freshwater consumption and GHG emissions (Cellana, n.d.). Cellana has formed partnerships with industry leaders, such as Neste Oil and Living Ink Technologies, to develop and commercialize a range of algae-based products, including biofuels and bioproducts (Neste, 2013).

c) **Seaweed Energy Solutions (Norway):** SES, a Norwegian company, has developed an innovative seaweed cultivation system called the Seaweed Carrier, which is designed for the large-scale production of macroalgae for biofuels and other applications. The Seaweed Carrier is a flexible, modular system that can be deployed in a variety of ocean environments, allowing the efficient and cost-effective cultivation of different seaweed species (Buck *et al*., 2016). SES has successfully demonstrated the scalability and productivity of this system through pilot projects in Norway and Portugal, with plans to expand its operations and commercialize its seaweed-based biofuel technology.

d) **AlgaePARC (Netherlands):** the Algae Production and Research Center (AlgaePARC) is a research facility in the Netherlands, which aims to develop and optimize microalgal cultivation and processing technologies for the production of biofuels and bioproducts. AlgaePARC utilizes a variety of innovative cultivation systems, including flat-panel photobioreactors, raceway ponds, and vertical bag systems, to study the growth and productivity of different microalgal strains under various environmental conditions (Wijffels & Barbosa, 2010). Through its research and demonstration activities, AlgaePARC seeks to overcome the technical and economic barriers to the large-scale production of microalgal biofuels, while promoting collaboration and knowledge exchange among researchers, industry partners, and policymakers.

e) **Bio Architecture Lab (Chile):** BAL, a biotechnology company based in Chile has developed a proprietary platform for the production of biofuels and bioproducts from macroalgae, specifically focusing on the abundant and fast-growing brown seaweed *Macrocystis pyrifera*. BAL's technology involves the enzymatic hydrolysis of the seaweed's complex carbohydrates, such as alginate, to produce fermentable sugars that can be converted into bioethanol and other value-added products (Enquist-Newman *et al*., 2014). The company has successfully demonstrated the feasibility and scalability of this technology through pilot projects in Chile, with plans to commercialize its seaweed-based biofuel process and expand its operations to other regions with abundant macroalgae resources (Bio Architecture Lab, n.d.).

f) **Sapphire Energy (United States):** Sapphire Energy, a California-based company, has developed an innovative platform for the production of renewable crude oil, known as Green Crude, from photosynthetic microalgae (Chen *et al*., 2011). The company operates a large-scale, integrated algal biorefinery in New Mexico, which utilizes open pond cultivation systems, proprietary algal strains, and advanced processing technologies to produce biofuels and bioproducts (Sapphire Energy, n.d.). Sapphire Energy's Green Crude has been successfully tested in various transportation applications, including on-road vehicles and commercial aircraft, demonstrating its potential as a drop-in replacement for conventional fossil fuels (Chen *et al.,* 2011).

g) **Solazyme (United States):** Solazyme, a California-based company, has developed a unique, heterotrophic algae-based platform for the production of renewable oils and other high-value products (Pyle *et al*., 2008). Unlike most algal biofuel production methods, which rely on photosynthetic organisms, Solazyme's technology uses genetically engineered microalgae that can convert a wide range of sugar feedstocks into tailored lipids and other products through fermentation (Stephens *et al*., 2010). The company has successfully demonstrated the commercial viability of its technology through partnerships with industry leaders, such as Chevron and United Airlines, and the construction of large-scale production facilities in the United States and Brazil.

There is a diverse range of technologies and applications being developed for marine green-based biofuel production, with varying degrees of success and commercialization. While some projects, such as Algenol Biofuels and Cellana, focus on the production of bioethanol or biodiesel from photosynthetic microalgae, others, like Seaweed Energy Solutions and Bio Architecture Lab, are exploring the potential of macroalgae as a feedstock for biofuels and bioproducts. Furthermore, companies like Solazyme have developed innovative, non-photosynthetic platforms for the production of tailored lipids and other products from engineered microalgae. Overall, these case studies highlight the significant progress and innovation occurring in the field of marine green-based biofuels, with a growing number of real-world applications and demonstration projects showcasing the feasibility, scalability, and benefits of this renewable energy source. As research and development in this area continue to advance, marine greens are poised to play an increasingly important role in the global transition towards more sustainable and renewable energy systems.

14.7 FUTURE PROSPECTS AND RESEARCH POTENTIAL OF MARINE GREENS FOR BIOFUEL PRODUCTION

Marine greens, including seaweed and microalgae, are a promising source for biofuel production due to their high productivity, abundant supply, and low environmental impact. These aquatic organisms are known for their ability to grow fast, have high lipid and carbohydrate content, and reduce GHG emissions by consuming carbon dioxide. In recent years, researchers have been exploring various ways to optimize the cultivation and processing of marine greens for biofuel production, as well as examining their potential to mitigate climate change and support sustainable development.

One area of research that has been gaining attention is the genetic engineering of marine greens to enhance their biofuel potential. Studies have shown that genetic modification can be used to increase lipid and carbohydrate production, improve stress tolerance and disease resistance, and create novel strains of marine greens for specific biofuel applications (Choi *et al*., 2019). Researchers have also been investigating the use of gene editing technologies, such as CRISPR-Cas9, to precisely manipulate the genomes of marine greens and improve their traits for biofuel production (Kang *et al*., 2021). However, the potential risks associated with the release of genetically modified marine greens into the environment still need to be carefully evaluated.

Another area of research is the development of sustainable and scalable cultivation systems for marine greens. Current cultivation methods, such as open ponds and photobioreactors, have limitations in terms of productivity, efficiency, and cost-effectiveness. Researchers have been exploring alternative cultivation systems, such as integrated multi-trophic aquaculture, which combines the cultivation of marine greens with the production of other aquatic organisms, such as fish and shellfish, to create a more sustainable and diversified food and energy system (Chopin *et al*., 2020). Researchers have also been investigating the use of offshore cultivation systems, such as floating platforms and submerged structures, to expand the cultivation area and reduce the environmental impact of marine green cultivation (Gao *et al*., 2021).

14.8 CONCLUSION

In conclusion, the potential of marine greens for biofuel production is vast and promising. These marine organisms offer several advantages over traditional terrestrial crops, including higher biomass production, faster growth rates, and the ability to grow in a wide range of environments. Furthermore, research has shown that marine greens are a rich source of lipids and carbohydrates, which can be converted into biofuels through various methods such as transesterification and hydrothermal liquefaction. However, significant challenges such as cultivation efficiency, nutrient availability, and processing costs need to be addressed to realize the full potential of marine greens for biofuel production.

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