

# Key Issues in Biofuel Production from Microalgae: A Review

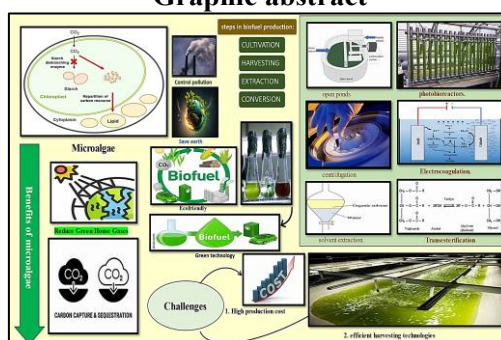
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## Abstract

Approximately 80 percent of the global energy needs are met by fossil fuels. Excessive reliance on these fuels has led to environmental pollution, climate change, and health problems for all living beings. Thus, identifying alternative energy sources is crucial to meeting global energy demands and reducing environmental pollution. It is expected that energy from cost-effective renewable resources will power the world's energy systems in the future. Algae biomass has become a promising source for biofuel, as biofuels derived from microalgae are biodegradable, renewable, and more environmentally friendly compared to fossil fuels. Microalgae are a more sustainable option for biofuel production than traditional biofuel sources because of their high lipid content, rapid growth rates, and capacity to thrive in non-arable land. The processes of microalgae cultivation, harvesting, lipid extraction, and conversion to biodiesel are critically examined in this paper, which also discusses the technological and economic barriers to large-scale implementation. The necessity for effective cultivation systems, the high cost of harvesting and extraction technology, and the need for significant nutrients are the main problems. The findings highlight the need for more study and technological developments to improve the viability of microalgae biofuels, establishing them as an essential part of future renewable energy plans meant to mitigate climate change and advance sustainability.

**Keywords:** Microalgae, biofuels, renewable energy, alternative fuels, climate change, sustainability

## Graphic abstract



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## INTRODUCTION

Biofuels are considered as environmentally friendly as they are renewable and produce a smaller amount of greenhouse gases than fossil fuels [1], because they are made from living biomass, such as plants, algae, and animal waste [2]. They provide an attractive alternative for conventional energy sources, which is critical given the anticipated rise in energy and environmental issues in the coming future [3]. The limitations of biofuels derived from food feedstocks, particularly the food versus fuel debate [4], have spurred

interest in exploring non-food based, low-cost alternative sources of fuel and energy [5]. Additionally, conventional crop-based biofuels place a significant environmental burden [6], due to the extensive amount of arable land and water required for their cultivation [7]. In recent years, there has been significant interest in cultivating [8] growing, harvesting [9, 10] and processing microalgae for biofuel production [11, 12].

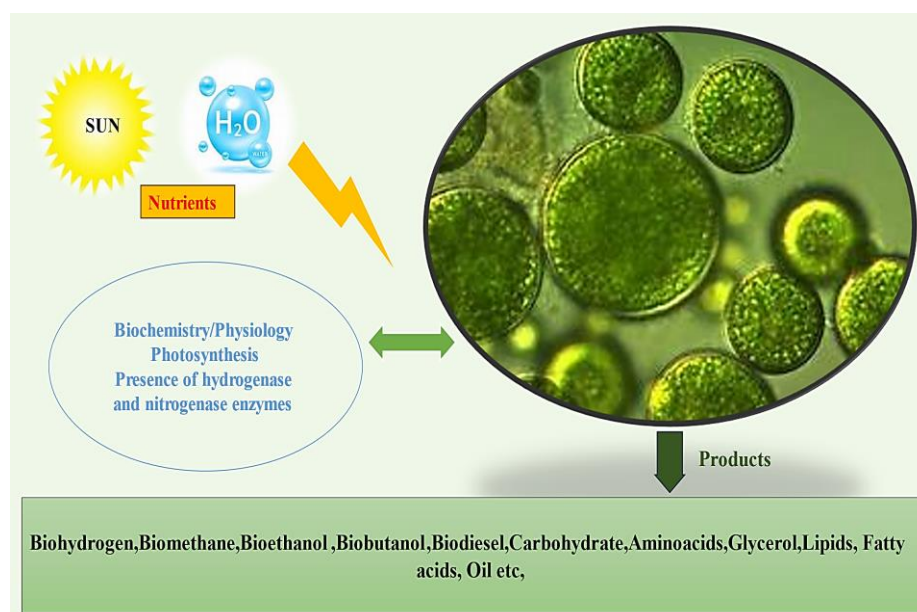
Microalgae are fast-growing and can produce high amounts of lipids and carbohydrates [13], with minimal water and land requirements [14]. They generate more biomass on non-arable land [15], compared to terrestrial crops and trees [16]. As a result, biofuels from microalgae have become a crucial element of today's energy policy [17]. Moreover, microalgae can support year-round production for biofuel plants, as their oil yield per unit area remains consistent compared to oilseed crops [18, 19]. Furthermore, cultivating microalgae does not require pesticides or herbicides [20–22]. Microalgae also help remove carbon dioxide (CO<sub>2</sub>) emissions from flue gases produced by fossil fuels [23], playing a significant role in reducing primary greenhouse gas (GHG) emissions [24]. For instance, 100 tons of algae biomass can sequester approximately 183 tons of CO<sub>2</sub> from the atmosphere, industrial gases, and soluble carbonates [25]. Additionally, microalgae biomass contains about 50% carbon on a dry weight basis [26]. Nonetheless, microalgae cultivation typically takes place in coastal seawater, brackish water, or saline water on non-arable land [27, 28]. The algae biomass is being cultivated locally for energy and fuel production [29]. Therefore, several important technologies have been developed for converting algae biomass into biofuels [30, 31].

Certain microalgae species, under favorable conditions, can accumulate up to 50-70% oil or lipid on a dry weight basis [32]. The fatty acid profile of these microalgae species is highly conducive to biodiesel production [33, 34]. Compared to other energy crops, microalgae grown under optimal conditions can produce up to 20 times more oil [35]. Some microalgae species can yield up to 58,700 liters of oil per hectare [36, 37]. However, technical limitations impact the mass production of biodiesel, making the algae biofuel industry economically unfeasible [38]. The choice of harvesting technology is crucial for the cost-effective production of algae biomass [39]. Similarly, cost-effective technologies for efficient algae biomass harvesting and oil extraction are urgently needed [40]. NRC reported that producing 1 liter of gasoline fuel from microalgae requires at least 3.15 liters of water [41]. In practical terms, meeting just 5% of the United States' fuel demand with microalgae biofuels would require 6–15 million metric tons of nitrogen and up to 2 million metric tons of phosphorus [42, 43]. This is more than twice the amount of nitrogen fertilizers used to grow all the food in the USA [44]. This study aims to assess the significance of microalgae in biofuel production and evaluate the main challenges associated with producing microalgae biofuels.

## EXPLORING THE BIOFUEL PRODUCTION POTENTIAL OF MICROALGAE

The potential of microalgae to produce high lipid content and develop fast has received substantial interest in the generation of biofuel. These microorganisms are a viable substitute for terrestrial plants in the production of sustainable energy because they are more effective at converting sunlight into chemical energy. Microalgae-based biofuel technologies involve identifying optimal growth conditions, developing cost-effective and efficient cultivation systems [45], harvesting and separating microalgae biomass [46] and producing biodiesel (Figure 1) [46, 47]. The biomass production rate of microalgae is significantly faster than that of terrestrial crops. This is because microalgae do not need to produce structural compounds like cellulose for roots, leaves, or stems [48]. Compared to other crops, microalgae offer several advantages, including rapid reproduction cycles [49], high UV radiation resistance [50], and greater efficiency in converting energy into biomass [51], due to lower energy demands for other metabolic functions [52, 53]. The high growth rate, lipid content, and ability to rapidly develop [54], improved strains [55] and produce co-products [56] make microalgae a valuable component of sustainable energy production systems [57, 58]. Additionally, microalgae produce various types of lipids, hydrocarbons, and other complex oils, depending on the species [59, 60]. Optimizing the growth-determining factors of the culture conditions enhances the lipid and fatty acid content in microalgae [61]. Microalgae are favored over macroalgae because macroalgae cultivation is

more complex and less versatile [62, 63], Macroalgae typically use only anaerobic digestion (AD) for biogas production, whereas microalgae can be utilized in sunlight-driven processes to produce a variety of products, including foods, biofuels, high-value bioactives, and animal feed [64]. Microalgae are responsible for over 40% of global carbon fixation [65], with the majority of this productivity linked to marine microalgae. Microalgae biomass contains 50% carbon by dry weight [66], Although the harvesting process releases a significant amount of CO<sub>2</sub>, this CO<sub>2</sub> is absorbed from the atmosphere through the cultivation of additional biofuel sources and microalgae, unlike fossil fuels [67–70].



**Figure 1.** Functioning mechanism of microalgae in the energy industry [100].

### CULTIVATION TECHNIQUES FOR MICROALGAE BIOFUEL PRODUCTION

Microalgae can be cultivated using various methods. Open ponds are the simplest and most cost-effective systems, but they are prone to contamination by other organisms that can harm the microalgae [71]. Alternatively, some systems use a sterile CO<sub>2</sub> source and operate as closed-loop systems [72]. Advanced and high-capital-cost systems, such as photobioreactors, offer high yields and precise control, making them ideal for cultivation. These systems are especially suitable for hot or desert climates where temperatures are high [73]. Land that is unsuitable for traditional crop cultivation can be utilized for growing microalgae [74]. For example, arid and dry land can be used for microalgae production. It has been observed that microalgae growth is 20 to 30 times greater than that of food crops [75]. The Turkey Soley Institute Company has achieved a production rate of 1.7 kg of microalgae per day per cubic meter of water [76].

The cultivation conditions for microalgae are significantly influenced by their composition and growth characteristics [77]. The four main cultivation methods are heterotrophic, photoautotrophic, photoheterotrophic, and mixotrophic [78]. Among these, heterotrophic growth tends to offer better oil productivity, though this can vary depending on the specific microalgae strains, making it a popular choice. However, heterotrophic cultures are prone to contamination, which can impact large-scale production [79]. Photoautotrophic production is technically and economically viable for large-scale microalgae biomass production, particularly for non-energy applications [80].

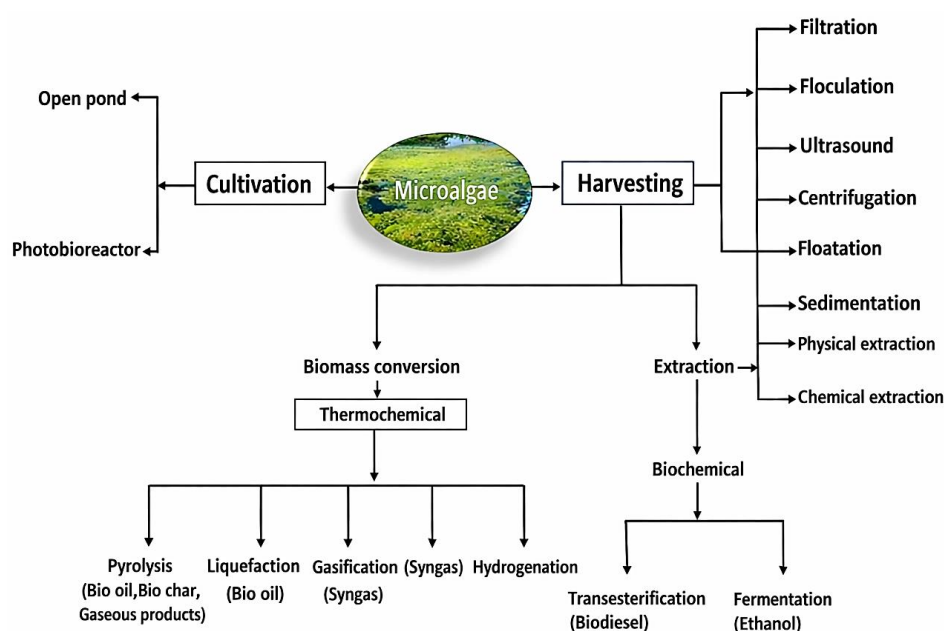
Photoheterotrophic systems require an additional organic carbon source, making them capital-intensive from a commercial perspective [81]. Open pond phototrophic cultivation is the most commonly used method due to its scalability and simplicity [82]. In these ponds, microalgae can absorb CO<sub>2</sub> from factory emissions and convert it into lipids and eventually oil [83]. However, this method faces limitations such as slow cell growth and low biomass production, leading to reduced oil

productivity [84]. Similarly, mixotrophic and photoheterotrophic systems are challenged by contamination risks and light requirements [85], necessitating the use of photobioreactors for scaling up, which increases both capital and operational costs [86, 87].

Microalgae cultivation systems can use sunlight, artificial light, or a combination of both [88]. Laboratory-scale systems using artificial light generally achieve higher oil yields compared to outdoor systems that rely on sunlight [89]. This is because artificial light provides continuous and stable illumination [90]. However, fluorescent lamps used in laboratory photobioreactors consume a lot of energy, leading to high operational costs [91]. To address this, fluorescent lamps are often replaced with multi-LED light sources, which reduce overall power consumption and cost [92]. Solar energy is a more economical lighting option for commercial microalgae cultivation systems, such as open ponds [93]. However, outdoor systems suffer from lower process efficiency and require large land areas. Optical fibers energized by solar energy need only 1.0 kWh of electricity and can serve as internal light sources for cultivation systems [94]. The main drawback of this approach is the variability in solar energy, which limits the application and efficiency of outdoor photobioreactors [95]. Combining LED/optical fiber systems with solar panels or wind-powered generators could significantly cut power consumption. Nonetheless, further technological advancements are needed to improve microalgae growth rates, enhance outdoor cultivation capabilities, and strengthen contamination resistance in large-scale systems [96–100].

## MICROALGAE HARVESTING METHODS

In this process, microalgae biomass is separated from the growing solution based on the type of microalgae. According to the National Algal Biofuels Technology Roadmap (NABTR) and the National Alliance for Advanced Biofuels and Bioproducts (NAABB), harvesting involves concentrating algae in water [101]. The harvesting cycle for microalgae typically ranges from 1 to 10 days [102]. Harvesting technologies differ in production costs for algae farms. Centrifuges have been used for many years to harvest microalgae [103] but the challenge of separating large volumes of water results in high costs and time consumption [104]. Consequently, electrocoagulation is considered more energy-efficient, safer, and cost-effective compared to centrifugation [105]. Nevertheless, the total cost of harvesting microalgae, compared to other industrial processes, includes various factors such as fixed capital (land, buildings, equipment, and piping), plant design and construction, and product costs (including electrical power and raw materials) [106]. The process of biofuel production from microalgae depicts in Figure 2.



**Figure 2.** The process of biofuel production from microalgae.

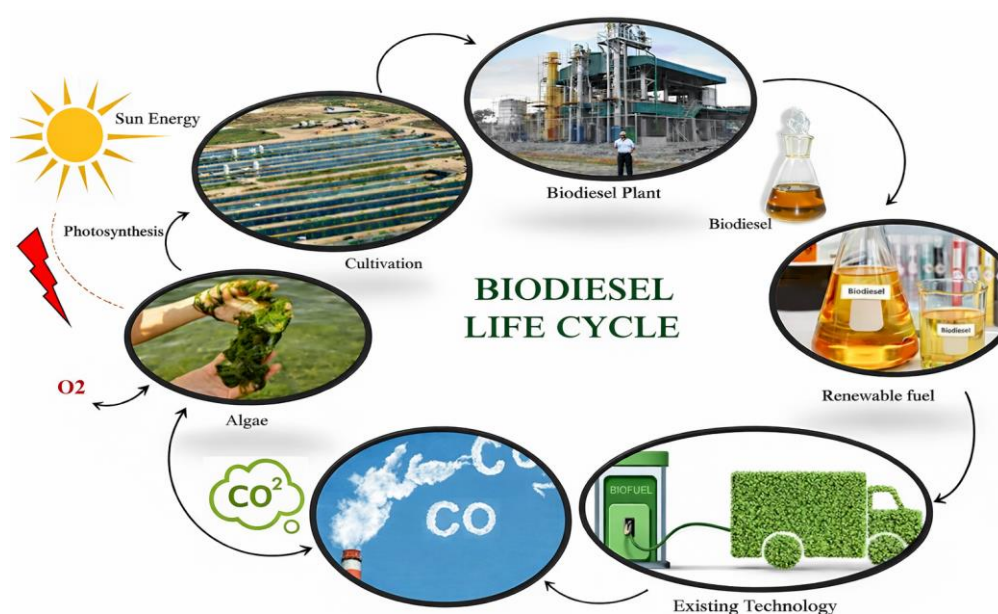
### Fatty Acid and Lipid Extraction

Extraction is used to separate fatty acids and lipids from algae [107]. The National Alliance for Advanced Biofuels and Bioproducts (NAABB) employs a Solvent Recovery System (SRS) using a wet solvent method, which involves several stages [107]. It begins with drying the biomass [108], followed by extracting a mixture of algae lipids and other biomaterials with a solvent [107]. The process concludes with cell disruption or solvent evaporation [108]. Microalgae can produce up to 300 times more oil per acre compared to conventional crops like soybeans, rapeseeds, and palms [109]. The process known as Ultrasonic-Assisted Extraction (UAE) uses ultrasonication to break down cell walls and make it easier for lipids to be released. To increase lipid yield, solvent extraction is commonly used with this method [110]. Supercritical Fluid Extraction (SFE) uses supercritical CO<sub>2</sub> as a solvent and provides a sustainable and effective method for the environment. Lipids from microalgae could be extracted with particular efficiency using this approach [111].

However, further experimental research is needed to refine harvesting and extraction technologies on a larger scale to address existing limitations and meet biofuel cost targets [102]. Traditional techniques, such as solvent extraction, can be time-consuming and detrimental to the environment, despite their effectiveness. More effective and sustainable options are provided by innovations like SFE and UAE. Furthermore, blending several extraction methods can maximize purity and production, increasing the process's viability for industrial uses [112].

### Conversion of Biofuel

Converting organic materials into high-energy fuels that can take the place of traditional fossil fuels is known as biofuel conversion [113]. Usually, there are multiple crucial steps in this procedure. First and foremost, choosing the right feedstock is essential since biofuels can be made from a variety of materials, including plant biomass (such as corn, sugarcane, and algae), animal fats, and agricultural waste [114]. The choice of feedstock depends on factors like availability, cost, and the desired type of fuel. For biodiesel production, lipids (fats and oils) are extracted from the feedstock using methods such as solvent extraction, supercritical fluid extraction, or mechanical methods [115, 116]. The conversion process transforms algae lipids into renewable energy by first converting them into fatty acid methyl esters (FAME) and then into biodiesel [117]. Depending on the fatty acid quality, some methods use a one-step transesterification process with a base catalyst and methanol reagent [118]. Life cycle of biofuel production from microalgae depicts in Figure 3.



**Figure 3.** Life cycle of biofuel production from microalgae.

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## CHALLENGES AND OPPORTUNITIES IN MICROALGAE BIOFUELS

### Features of Microalgae

When green microalgae are cultured under conditions of limited nitrogen or high light, their cellular neutral lipid content increases [119]. These strains with higher lipid contents are more suitable as feedstocks for biofuel production. Biomass yields from cultures in low-nitrogen media are higher compared to those in high-nitrogen media [120]. Microalgae exposed to higher light intensity accumulate more lipids than those under lower light intensity [121]. Using these strategies, lipid content can increase from 0% to 50% on a dry weight basis [122]. However, excessive light can cause photo-oxidative stress, potentially harming the microalgae [123]. Despite this, oil-producing microalgae utilize carbon and energy to synthesize and accumulate lipids under nitrogen stress [124]. Microalgae can double their biomass within 24 hours, with some strains achieving this in as little as 3.5 hours [125]. As thallophytes and some of the oldest living organisms, they contain chlorophyll, the primary photosynthetic pigment, and their photosynthesis process is similar to that of higher plant [126]. Additionally, microalgae cells are cultured in aqueous suspensions, which allows for more efficient access to CO<sub>2</sub>, water, and other nutrients [127]. Classification of microalgae is primarily based on criteria such as pigment types, cell wall constituents, and the chemical nature of their storage products [128].

Additionally, the structure of flagella, the presence of flagellate cells, and the patterns of cell and nuclear division are also important criteria for the classification of microalgae.

Microalgae can be classified as either heterotrophic or autotrophic. They are considered autotrophic when they use inorganic compounds as a source of carbon. Specifically, they are photoautotrophic when they utilize light as an energy source, while they are heterotrophic when they rely on organic compounds for growth [129]. Certain photosynthetic microalgae are mixotrophic, meaning they can combine autotrophy and heterotrophy through photosynthesis [130]. Additionally, microalgae are capable of efficiently fixing CO<sub>2</sub> from various sources, including industrial exhaust gases, soluble carbonate salts, and the atmosphere [131]. CO<sub>2</sub> fixation is the most common and effective technique for capturing carbon, as it involves the transfer of carbon from the air into microalgae during aquatic growth through photosynthesis [132]. For consistent heterologous protein expression, the plastid genome of *Chlamydomonas reinhardtii* has been successfully transformed. However, this technology, while effective in *Chlamydomonas reinhardtii*, may not be ideal for biofuel production and could be better suited for other algae species [133, 134].

### Barriers to Microalgae Biofuel Production

The main barriers to using microalgae for biofuels and achieving widespread commercial use are the challenges of producing lipids at low cost [135] and ensuring a positive energy balance [130–133]. Governments and companies are working to reduce operating and capital costs to make microalgae production commercially viable [136]. A major challenge for commercial-scale biofuel operators is the high expense of installing, operating, and maintaining cultivation systems for oil production [137]. The highest costs are associated with the technologies used for harvesting and converting oil into biofuel [138]. Currently, the production cost of microalgae biofuel needs to be reduced to compete with crude oil prices in the international market [139]. Therefore, there is a pressing need to identify and develop technologies for harvesting microalgae with the goal of achieving a cost of less than \$0.013 per gallon of gasoline equivalent (GGE) at a processing rate of 0.1 to 1 cubic meter of algae water per hour [140]. Researchers are exploring innovative methods for more effective and sustainable extraction of microalgae biofuels [141]. Engineering aspects such as cultivation, harvesting, and processing need to be thoroughly addressed to meet the target of producing at least 36 billion gallons of renewable biofuel from microalgae by 2030, as outlined by the US Renewable Fuels Standard (RFS) [142]. Producing a large volume of microalgae biofuel would require substantial amounts of water, energy, and nutrients. For instance, if nutrients are not recycled, producing a billion gallons of microalgae biofuel would necessitate additional millions of tons of nitrogen and phosphorus annually [143].

Additionally, challenges include developing optimal techniques for selecting the best microalgae strains for growth, collection, oil extraction, and fuel processing [144]. Further research is needed for genetic improvements in algae species. There is a significant technological gap that must be addressed to develop sustainable and environmentally friendly energy from microalgae [145]. It is crucial to explore the maximum production potential, efficiency, and cost of various microalgae biofuel systems [146–149]

### **THE BENEFIT AND DRAWBACKS OF MICROALGAE-BASED BIOFUEL**

Microalgae-based biofuels, with their high lipid content and quick growth rates, present a tremendous potential for sustainable energy production [150]. By using wastewater and cultivating on non-arable land, these microorganism can lessen their rivalry with food crops and have a minimal negative impact on the environment [151]. Furthermore, microalgae can sequester CO<sub>2</sub>, aiding in the pursuit of carbon neutrality [152]. Water-borne nutrients are necessary for the growth of microalgae and can come from fertilizer runoff, natural inputs, wastewater discharges, and other human activities [153]. Microalgae farming can lessen the severe eutrophication that might result from human fertilizers [154].

Algal farming, when coupled with fish farming, has the potential to partially absorb nutrients discharged into the ecosystem via fish feed and waste [155]. In addition, there is considerable potential for sustainability with an advanced concept of algae cultivation in which nutrients are moved to lower water levels with little mixing and eventually come back to the surface via natural upwelling, thus eliminating them from the nutrient cycle [156]. According to [157] there is plenty of nitrogen gas in the atmosphere, therefore this nutrient loss especially nitrogen is not a serious worry.

Nevertheless, there are a number of obstacles to the commercialization of microalgae biofuels, such as expensive cultivation, harvesting, and processing costs. Legal and ethical issues are also brought up by the use of genetically modified strains to improve lipid production [158]. Large-scale microalgae biofuel production is becoming more feasible despite these obstacles thanks to continuous developments in biotechnology and photobioreactor design, which position it as a promising avenue for future renewable energy solutions [120].

### **SUSTAINABILITY ISSUES WITH ALGAE-BASED BIOFUEL**

Even though they present a promising renewable energy source, algae-based biofuels have a number of sustainability concerns [117]. The excessive demand for resources, especially water and fertilizers, is one big worry [131]. Large amounts of water are frequently needed for algae production, which can put a burden on the available water supplies, particularly in arid areas [133]. Furthermore, applying fertilizers to promote growth may result in eutrophication if runoff reaches natural water bodies and creates toxic algal blooms [118]. The significant energy requirements for growing, harvesting, and processing algae can outweigh the environmental advantages of biofuels [95]. This problem is made more difficult by the comparatively low solar energy conversion efficiency of algal photosynthesis [80]. Moreover, large-scale production is economically difficult because of the high expenses associated with downstream processing and harvesting [72]. Ecological and regulatory problems are introduced when lipid production is increased through the use of genetically engineered algae (Wang et al., 2024). It is possible that these altered strains will find their way into natural environments and disturb the biodiversity there [77]. Furthermore, trash and byproducts from the production process may be produced; these must be properly managed to avoid contaminating the environment [60].

Despite these obstacles, new developments in science and technology are working to find solutions for these sustainability problems, opening the door for algae-based biofuels as a sustainable energy source [134].

### **RISKS ASSOCIATED WITH WATER USAGE AND PROSPECTS FOR MICROALGAL BIOFUEL GENERATION**

Water consumption in the process of producing biofuels from microalgae is a major source of both opportunities and concerns [43]. From an opportunity standpoint, wastewater can be used to develop

microalgae [44]. which helps treat and recycle wastewater in addition to lowering the demand for freshwater resources [30]. This dual advantage can relieve pressure on freshwater resources, particularly in areas where water is scarce [70]. Furthermore, improvements in water recycling technology can reduce the water impact of microalgae farming even more [6].

The significant concern associated with large-scale microalgae production is still the high water need [80]. This may make water scarcer in arid areas more problematic and put other vital water usage in risk [22]. Furthermore, applying fertilizers to promote the growth of algae may lead to nutrient runoff, which may eutrophicate adjacent bodies of water [34]. For microalgae-based biofuels to expand sustainably, it is imperative to strike a balance between these opportunities and risks [83].

## CONCLUSIONS

The study on the production of biofuel from microalgae assesses the feasibility and difficulties of this renewable energy source critically. Because of their high lipid content and rapid growth rates, microalgae are a very attractive substitute for traditional biofuels made from food crops. Their capacity to flourish in uncultivated land and make use of diverse water sources, such as brackish and salt water, makes them a viable choice when considering global food security and environmental preservation. The commercialization of microalgae biofuels is confronted with substantial obstacles, notwithstanding its benefits. Due in large part to the high costs of the processes involved in lipid extraction and harvesting, the economic viability of large-scale manufacturing is still a major challenge. It is necessary to develop more economical and efficient technologies because existing procedures, including solvent extraction and centrifugation, are frequently expensive and energy-intensive. Issues regarding the sustainability of large-scale microalgae cultivating are also raised by the demand for significant nutrient inputs, especially phosphorus and nitrogen, which may be higher than those required for traditional agriculture. Furthermore, even though microalgae can help sequester carbon dioxide, large-scale production systems' overall lifecycle emissions and environmental effects need to be carefully evaluated. While the use of sophisticated cultivation methods, like photobioreactors, has the potential to improve biomass yields and lower contamination risks, these systems come with a high investment budget. Although microalgae biofuels present a viable route to sustainable energy solutions, significant technological developments and financial considerations are necessary to get over the present obstacles. In order to overcome these obstacles and realize the full potential of microalgae as a fundamental component of future renewable energy systems, further investigation and innovation are required.

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