**Potential of Algae-based Biofuels for Sustainable Energy Security**

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**Abstract**

Fossil fuel supplies are not keeping up with the growing demand and are expected to run out in the near future. As a result, the search for renewable sources of energy has been driven by environmental concerns, such as pollution and global warming, as well as increasing oil prices. Algae has emerged as a potential source of sustainable energy sources, with its high protein, lipid, and carbohydrate content, rapid growth rate, and superior biomass yield. Algae is expected to be a third-generation feedstock for biofuels such as ethanol, biodiesel, and bioethanol, and is expected to outperform the current generation of feedstocks in terms of its potential. There have only been a few thousand algae species examined as potential producers of biofuel, and none of them were perfect. This paper provides an overview of the current state of algae-based biofuels, key phases in their manufacture, and significant production hurdles.

**Key Words**: Microalgae, Biofuels, Algal cultivation, Conservation, Energy.

**1. Introduction**

The main factors influencing the quest for alternative and sustainable renewable biofuels to meet the rising demand for transportation fuels include rising greenhouse gas emissions, depleting fossil resources, energy insecurity, and difficulties with global warming (Owusu and Asumadu-Sarkodie, 2016). Due to the urgent need for energy independence, efforts to produce energy from biomass attracted a lot of interest in the United States during the 1970s (Schelhas *et al*., 2018). Since the middle of the 1990s, there has been a newfound focus on biomass energy as a means of reducing global climate change. The U.S. Department of Energy (DOE) recently established the ambitious target of replacing 25% of organic chemicals with renewable biochemicals by 2025 and 30% of transportation fuel with biofuel .Microalgal biofuels are a third generation biofuel that is viable.Due to the special properties of algae, such as their rapid growth, high oil accumulation, low water requirements, adaptability to a variety of environments, synergy with wastewater treatment, and capacity to sequester carbon dioxide (CO2) through photosynthesis, among other properties, biofuels are promising alternatives (Zhou *et al*., 2014). Additionally, it is anticipated that microalgae will be able to produce enough oil to meet the Energy Independence and Security Act's 2022 "advanced biofuels" output objective and produce an amount of oil equal to over 17% of US transportation fuel imports (Wigmosta *et al*., 2011). Although microalgae cells may be converted into a variety of advanced biofuels, numerous obstacles have prevented the commercialization of algal biofuel. These difficulties include the need for large quantities of freshwater, nutrients like nitrogen (N), phosphorous (P), and trace elements in the current cultivation processes, a lack of energy- and cost-efficient methods for the extraction and conversion of oil from algae, a lack of mature technologies for CO2 mitigation via microalgae, etc.(Koller *et al*., 2012).

Since significant amounts of freshwater and nutrients needed for algae growth could be saved, along with the associated life cycle burdens, combining wastewater treatment with algae cultivation may offer an environmentally responsible and economically viable method for producing sustainable renewable algae-based biofuel and bio-based chemicals (Oliveira *et al*., 2023). In order to provide bioremediation while lowering treatment costs, for example, algae can use nutrients like N and P from a variety of wastewater sources (such as agricultural run-off, concentrated animal production operations, and industrial and municipal wastewaters) (Tambat *et al*., 2023). Additionally, they can combine the generation of carbon-neutral fuel with the sequestration of CO2 from power plants or other emission sources, creating an efficient opportunity for carbon capture and recycling while simultaneously producing carbon credits (Rosa *et al*., 2022).

Growing algae on waste streams offers many advantages over traditional algae farms. Since they are readily available naturally, simple to grow, have high oxygen profiles, can reduce emissions, etc., algae biodiesels are becoming more and more popular all over the world. One of the rapidly expanding biomasses to produce biodiesel is recognized as an algae species, which is known as a clean, renewable fuel. More than 60,000 species of algae are flourishing worldwide, and almost 35,000 species have been identified (El-Sebaaly *et al*., 2021). According to Gundersen et al. (2016), there are seven different types of algae groupings, including red, green, blue-green (*Cyanobacteria*), brown, phytoplankton, seaweeds, and other species. Chlorophyta includes the green microalgae Spirogyra division, which can range in length from 10 to 100 m. Temperature and light exposure are the two key elements that must be taken into account for Spirogyra algae to develop as much as possible. The atmosphere of the world contained CO2 billions of years ago. As a result, there was no life on earth. Algae and cyanobacteria were the first forms of life on Earth. These lowly photosynthetic creatures began releasing oxygen and sucking in ambient CO2. As a result, the CO2 levels began to drop to the point where life began to develop on earth. Once more, these little creatures are ready to protect us from the dangers of global warming.

**2. Algae**

Aquatic creatures known as algae come in a variety of types and sizes, from microalgae to macroalgae. From single cells to multicellular formations like filaments and colonies, they come in a variety of morphologies. The majority of algae can thrive in any habitat and can endure harsh conditions (Kumari *et al*., 2022). The development of algae into cyanoprokaryotes and eukaryotes determines their classification. Chloroplasts and a clearly defined nucleus are absent in cyanoprokaryotes. Eukaryotic algae are further subdivided into the Chlorophyceae, Phaeophyceae, Rhodophyceae, Xanthophyceae, Pyrrophyceae, Euglenophyceae, and Chrysophyceae families based on the composition of their cell walls, pigments, and storage products. Algae lack an embryo, vascular tissues, and a protective membrane covering their sex organs, in contrast to higher plants. A number of industries, including wastewater treatment, energy cogeneration, bioremediation, natural fertilizer, animal feed, pharmaceuticals, and nutraceuticals. Algae can also be used to make a wide range of goods, including proteins, vitamins, pigments, nutraceuticals, and unique oils (omega-3) (Peng *et al*., 2023). In comparison to higher plants like Jatropha, rapeseed, and soybean, algae are 2–15 times more efficient in using light, grow more quickly, and create more lipids (Mehta *et al*., 2023).

**2.1 Microalgal Cultivation**

Algae have rapid growth rates, high levels of photosynthetic activity, and high effectiveness in sequestering carbon dioxide. Additionally, they utilize phosphorus and nitrogen from industrial, agricultural, and municipal wastewater to lessen the nutrient load in the wastewater. They have a sizable amount of lipids, which can be converted into biofuels that are very biodegradable and harmless. Given that algae require only a few basic conditions to develop, algal cultivation for the generation of biofuel seems rather straightforward.

However, a number of variables, including micro- and macronutrients (availability and concentration), CO2, temperature, pH, and light (intensity and photoperiod), affect the best algal development and lipid accumulation. Algae respond differently to these factors, particularly light and temperature. Most algae species are thought to thrive at temperatures between 20°C and 30°C. A physiological adaptation, the amount of unsaturated fatty acids reduces as the temperature rises (Chaisutyakorn *et al.*, 2018). Additionally, the kind of precursor fatty acids affects a number of biodiesel qualities, including lubricity, oxidative stability, melting point, and heating point. It also affects iodine and cetane levels. Palmitic acid (C16:0), palmitoleic acid (C16:1), stearic acid (C18:0), oleic acid (C18:1), linoleic acid (C18:2), and linolenic acid (C18:3) are the typical targets for approved biodiesel production (Fallen *et al*., 2011). Some microalgae change their lipid production route in response to restricting conditions in order to produce significant amounts of neutral lipids (20–50% of dry weight), mainly as triacylglycerol (TAG), which are primarily stored in cytosolic lipid bodies (Rengel et al., 2018). It is preferable to study a large number of algae species for biofuel production before choosing the ones with the highest productivities and then optimizing all circumstances to achieve maximum production for these species. To increase a species' biomass and biofuel production, hundreds of experiments can be run on it. In a bulk-culture in vitro, the selection and optimization stages are often carried out. Microfluidics or on-chip technology became important due to the laborious and time-consuming nature of standard lab techniques. Algae-on-chip is dependent on determining a droplet to be a vessel of culturing starting with a single cell per droplet. One of the striking benefits of this method is the microfluidic device's ability to simultaneously capture more than 100 droplets (this number can be raised depending on the design). These 100 droplets, which were recorded in the same device, represent 100 replicates in a region that is less than 4 cm, which is not possible to do using conventional techniques. To test various growing conditions and even to harvest oil and DNA, many designs can be created. High throughput single cell analysis with microfluidics saves time and labor. This method also enables quick testing of multiple factors. Despite several flaws, this method was able to outweigh all the drawbacks of the earlier methods. Ecotoxicology screening, cell identification, cultivation under various conditions, lipid analysis, sorting, trapping, cell viability, and quantifying self-secreted macromolecules like ethanol and lactate are just a few applications where microfluidic chips have been used(Saad *et al*., 2019).

Growing microalgae is a crucial step in the creation of biofuels. The choice of a cultivation system affects biofuel production. Photoautotrophic systems can, in general, be both closed and open. Photobioreactors (PBRs) are closed systems with perfect stirring and excellent light accessibility (Figure 3C). They are highly controlled, high yield systems. Photobioreactors can be made in a variety of shapes, with the tubular design being the most popular (Singh and sharma, 2012). They can be built as towers, tanks, or plastic or glass bags. According to reports, microalgal biomass was reported to be significantly greater in bubble columns and airlift photobioreactors. An additional tank is typically added to segregate it since too much oxygen can harm algae development (Hargreaves, 2013). Despite the fact that contamination is removed, highly regulated facilities have a significant downside.

Conversely, open systems (also known as ponds) are less expensive than closed systems but offer less control. The raceway pond, the circular pond tank, the closed pond, and the shallow huge pond are the most often utilized designs. The capacity of open systems to exploit atmospheric CO2 is one of its key characteristics. The open system's location is a crucial factor because it influences the amount of sunlight available. Additionally, they frequently have a revolving arm to ensure that the culture is constantly stirred (Carvalho et al., 2006). The main problem with these systems is contamination from bacteria or even from other microalgae.

A hybrid system is a configuration that combines an open system and a closed system. Excellent biomass productivity and high nutrient removal are both achieved by hybrid systems (Zhang *et al*., 2019). They are made to get beyond closed systems' high startup and ongoing expenses as well as their constraints. To increase yield in hybrid systems, microalgae are first cultivated in a closed photobioreactor before being moved to an open system. Large-scale algal cultivation is ideal for hybrid systems. Algae can be autotrophic, heterotrophic, mixotrophic, or photoheterotrophic depending on their metabolic pathways. In the presence of light, inorganic carbon is converted into organic energy by the autotrophic process or photosynthesis (Mallen‐Ponce *et al*., 2022). In contrast to the mixotrophic system, where cells can grow either autotrophically or heterotrophically depending on the available food sources, the heterotrophic pathway requires organic carbon to feed in the dark. Light and organic carbon are both necessary for the photoheterotrophic process to function. When compared to autotrophic metabolism, heterotrophic metabolism promotes faster growth The optimum strategy to get the highest biomass and lipid productivities is said to be mixotrophic metabolism.

**2.2. Algal Harvesting**

Algal cells are harvested by removing them from their medium without affecting the water content (Zuo *et al*., 2022). Algal biomass has been harvested using a variety of methods, including centrifugation, flotation, sonication, flocculation, filtration, flotation, and flotation. In rare circumstances, combining two harvesting techniques can increase biomass. Dewatering may come after harvesting in different circumstances. Dewatering involves taking the water out of cells to produce dried material (Bokov *et al*., 2021).

**2.3. Algal Fuels**

Microalgae have a significant potential for biofuel production as the third generation feedstock because of their rapid growth, excellent biomass output, and high lipid and carbohydrate contents. Among the useful biofuels produced by algae are biodiesel, biogas, bioethanol, and biomethane. Algal oils are utilized to make biodiesel, whereas algal carbohydrates are used to make bioethanol. The biomass that is left over is used to make fuel oil or methane. The leftover biomass can be utilized to make medicines, eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA), biocontrol agents, fertilizers, and animal feed once it has been converted to biofuel. Biodiesel is a biodegradable fuel with engine performance comparable to petroleum while reducing sulfur and particulate matter emissions. Anaerobic digestion of organic material results in the production of biogas or biomethane. Methane (65–75%) and carbon dioxide (25–35%) make up the majority of biogas (Verma *et al*., 2019). The anaerobic digestion process includes the following steps: (1) the hydrolysis of biopolymers by hydrolytic bacteria to monosaccharides; (2) the fermentation of the monosaccharides to acids; (3) the formation of acetate by the action of acetogenic bacteria; and (4) the formation of methane and carbon dioxide by the action of methanogenic bacteria (Li *et al*., 2019). Kerosene, diesel, and gasoline can be produced by converting microalgal hydrocarbons. For instance, Botryococcus braunii generates hydrocarbons outside of the cell that offer great oil production and are easier to extract. Biomass gasification generates bio-syngas, which contains methane, hydrogen, carbon monoxide, water, and ashes when there is air, oxygen, or water vapor present. 800-1200 °C is the required high temperature for the gasification process. The biomass water content should be less than 20% (Sakheta *et al*., 2023). Microalgae can directly create hydrogen from sunlight and water in the absence of oxygen, making it a promising source of clean energy that doesn't release greenhouse gases. The process of yeast fermenting carbohydrates yields bioethanol. There have been reports of microalgae with starch contents above 50%. Seaweeds produced 3.6-11.7 g/L and 179-260 mg/g of polysaccharides. It is possible to turn microalgal cellulose and hemicellulose into sugars and ultimately ethanol (Neeraj and Shashikant, 2022).

**2.4. Conversion Techniques**

Significant candidates for the production of biofuels include algae. Depending on the species, growing method, and biomass processing, several products can be made from algae. Gasoline, ethanol, biodiesel, biokerosene (jet fuel), gasoline, hydrogen, syngas, and methanol are all energy products made from algae (Velidi, 2023). Algae may be processed in many ways to provide a variety of energy products for diverse uses. Algal biomass can be treated via thermochemical, biochemical, transesterification, and photosynthetic microbial fuel cell conversion techniques (Wang *et al*., 2023) after being harvested.

**2.4.1. Thermochemical Conversion**

Biomass is thermally broken down in the process of thermochemical conversion, and then organic chemicals are reformatted into biofuels via pyrolysis, gasification, combustion, or hydrothermal liquefaction . In the absence of oxygen, pyrolysis is the heat degradation of biomass to create solid fuel (biochar), liquid fuel, and gaseous fuel products (Egbosiuba, 2022). Pyrolysis can occur at several heating rates, including slow (0.1-1 C/s for a long time), fast (10-200 C/s for a short time), and flash (above 1000 C/s for a very brief time).

Typically, it proceeds between 300 and 700 C/s . Pyrolysis is the most desired conversion method given the high ash content of algae, although the resulting oil still has some concerns with acidity, viscosity, and stability (Osman *et al*., 2023). A rapid, effective process for producing bio-oil has been suggested: microwave enhanced pyrolysis (MEP) . Gasification is the process of partially oxidizing algal biomass at temperatures between 700 and 1000 °C with a controlled amount of oxygen, steam, or air to produce syngas, a combination of gases primarily composed of H2, CO, CO2, and CH4 (Pandey *et al*., 2019). In order to produce hot gases, direct combustion entails oxygenating biomass in a boiler, furnace, or steam turbine at a temperature of about 1000 °C. Pre-treatments like drying and grinding into smaller particles are necessary before the combustion stage. Algal slurries are subjected to temperatures between 300 and 400 °C and pressures between 40 and 200 bar during the hydrothermal liquefaction process, which results in the production of biocrude, gas, and char (10 to 73, 8 to 20, and 0.2-0.5%, respectively). The algal biomass can be liquefied to extract or depolymerize a number of chemicals. The oil yield via hydrothermal liquefaction is higher than the bio-oil produced by pyrolysis, ranging from 9 to 77% (Venkatachalam *et al*., 2022).

**2.4.2. Biochemical Pathways**

As part of the biochemical conversion process, bacteria hydrolyze cell walls to produce fermentable sugars. Anaerobic digestion of sugars into biogas, bioethanol, or biohydrogen is referred to as fermentation. Through acetogenesis, which involves oxidizing all fermentable materials into acetate, which is then transformed during methanogenesis into methane and CO2, biogas is created (Bhatt and Tao, 2020). The carbon nitrogen (C:N) ratio in the feedstock, time, temperature, pH, solids, and feeding rates all have an impact on the production of biogas. Due to the algal susceptibility to bacterial breakdown and low C:N ratio, which leads to the generation of ammonia (an inhibitor), the biogas yield is quite low. Interestingly, the leftover biomass of Scenedesmus spp. that was free of lipids and amino acids produced more biogas than the raw biomass.The biomass is typically co-digested with waste papers and sewage sludge to compensate for the reduced C:N ratio. According to one study, co-digestion increased CH4 generation by 26% (Lopez *et al*., 2023). It has been suggested that using salt-adapted microbes can lessen the impact of a high protein content on anaerobic digestion. By changing the structure of the cell wall, microwave pre-treatment of biomass can boost biogas output by 56%. Enzymatic, mechanical, and thermal pretreatments can all increase methane generation. Hydrolyzed carbohydrates are fermented by yeast to produce bioethanol. When cyanobacteria containing glycogen were tested for the generation of bioethanol, 6.5 g/L and 350 mg/g were produced (Debnath *et al*., 2021). Due to its high sugar content, Phaeophyceae is regarded as the most suitable feedstock for the manufacture of bioethanol . For effective bioethanol synthesis, pre-treatments such milling, hot water wash, liquefaction, enzymatic hydrolysis, and saccharification or alginate extraction are crucial. Although oxygen, a byproduct of photosynthesis, can inhibit the hydrogenase process, anaerobic digestion can solve this issue. It's interesting to note that continuous flow regime indicated a 20-fold improvement in hydrogen generation over batch production (Sivaranjani *et al*., 2023).

**2.4.3. Transesterification**

To produce biodiesel and glycerol, triglycerides are transesterified with an alcohol (often methanol or ethanol) in the presence of an acidic or basic catalyst. Type of alcohol, catalyst type, and molar ratio all play major roles in the reaction. In order to blend algae oil with petroleum diesel and apply it directly to engines, it is crucial to reduce the viscosity of the oil and improve its fluidity (Wu *et al*., 2020). Direct transesterification is a one-step process where the wet biomass is treated immediately without extraction, in contrast to conventional transesterification which entails the extraction of algal lipids followed by esterification. Despite saving reagents, energy, and time, direct transesterification often produces substantially less biodiesel than conventional processes.

Combining microwave and ultrasound irradiation techniques will boost the yield to 90% while using less energy. Another option to cut costs has been mentioned: in situ supercritical methanol transesterification. Palmitic acid (C16:0), stearic acid (C18:0), oleic acid (C18:1), linoleic acid (C18:2), and linolenic acid (C18:3) are the primary fatty acids utilized in the production of certified biodiesel. The amount of fatty acids in biodiesel has a significant impact on its characteristics. Because saturated lipids tend to increase the cloud point and viscosity of biodiesel (Helwani *et al*., 2023) and polyunsaturated fatty acids (PUFAs) are unfavorable due to their susceptibility to oxidation, monounsaturated fatty acids (MUFAs) are the preferred lipids.

The length of the fatty acid chain has an impact on the heat of combustion, melting temperature, and viscosity of biodiesel, which are all inversely related to unsaturation. With rising unsaturation, lubricity and autoxidation rise. As a transesterification catalyst, lipase helps exclude byproduct recovery and catalyzes both esterification and transesterification simultaneously. High lipid content cyanobacteria, diatoms, and chlorophytes offer enormous potential for producing biodiesel (Dahman *et al*., 2019). Under some extreme stress conditions, such as nitrogen and/or silicon (Si) deprivation, oleaginous strains (at least 20% lipid content on dry weight basis) can overproduce lipids (up to 70% lipids on dry weight basis).

**3. Genetic Engineering Toward Biofuels**

The capacity of genetically engineered algae farming, where all the standardized properties of algae might be tweaked to create large yields of both the primary products and by-products, is necessary for maximizing both of the aforementioned cultivation methods . This approach of growing algae involves purposeful alteration in order to create a better feedstock for synthetic biology (Alishah Aratboni *et al*., 2019). The majority of algal strains use light-harvesting complexes termed antennae in their cells to capture sunlight, and these complexes are what provide the yield. It might be possible to make the genes responsible for these antennae noticeably lighter, allowing more light to enter the cells.

For transferring DNA into algae cells, various transformation techniques have been used, including artificial transposons, electroporation, particle bombardment, viruses, agitation of a cell suspension in the presence of DNA and glass beads, grobacterium infection, silicon carbide whiskers, and most recently, agrobacterium-mediated transformation. The process has produced the maximum transformation rate when using the particle bombardment and electroporation approaches together. For sophisticated techniques of algae DNA rearrangement, algae genetic engineering has gotten steadily more effective and affordable. This is due to the prospect of tolerance to harsh conditions being created by DNA restructuring techniques like sequencing, hybridization, metagenomics, and accelerated evolution (Ben Khedher *et al.*, 2022). Algal genomic DNA can be altered to produce the necessary metabolism at a particular spot, which could enhance performance under difficult conditions. Non-transgenic techniques may also be used to produce new attributes, but these techniques may need to be properly evaluated in order to increase performance and create the best algal strains that could endure a variety of biotic and abiotic circumstances. The metabolic alterations may, however, favor one application over another. For instance, a higher production yield for fuel and energy production could lead to dangerous algae strains for both food and non-food applications (Akram *et al*., 2023). This is due to the fact that the majority of these genetic advancements were initially targeted towards producing beneficial by-products from algae, such as cosmetics and pharmaceuticals, in order to offset the expense of production. Because the majority of algae strains may be screened, rebuilt, and hybridized for quicker development even in harsh settings with the help of dominant molecular techniques, genetically engineered algae technology to supplement both natural and artificial production (Ajingi et al., 2022) . However, this is dependent on funding from the government and private investors to become a reality. The high operational costs of a commercialized PBR, which have been the PBR's main technical challenge, might be greatly reduced with such support. New genes are being developed by organizations like Monsanto and Sapphire Energy to promote rapid growth and other beneficial traits. However, suicide genes are required to prevent harmful algal strains from surviving in an open environment in the event of an unintentional escape (Sebesta et al., 2022). This is due to the fact that these allegedly harmful algal strains pose a significant environmental concern.

It has been observed that reducing the light antenna harvesting size and blocking hydrogenase can improve hydrogen generation through genetic engineering. A mutant strain of Chlamydomonas reinhardtii (Stm6) that had less competition for electrons due to inhibited cyclic electron transport through Photosystem I displayed increased starch accumulation and decreased intracellular oxygen concentrations (hydrogenase inhibitor) . A nuclear transgene that responds to copper can induce anaerobiosis. A single RNAi construct was successfully able to silence all twenty light-harvesting complex (LHC) protein isoforms of C. reinhardtii, which enhanced light transmittance in the culture by 290% (Rojas-Pirela *et al*., 2020). This helped to overcome the light penetration limitation. The changed cell density, however, did not rise . Greater cell densities arise from growing algae in heterotrophic or mixotrophic environments, which lowers the cost of harvesting . *Volvox carteri*, *Phaeodactylum tricornutum, Cylindrotheca fusiformis*, and *C. reinhardtii* were successfully transformed with a hexose transporter (HUP1), causing glucose transfer into the cells (Poonia *et al*., 2022), despite the fact that the majority of algae are stringent autotrophs. Understanding algal behavior and structure is made possible by completed and ongoing initiatives for the whole genome identification of several algae species, such as *C. reinhardtii*, *Thalassiosira pseudonana*, and *Micromonas pusilla*. Synthetic biology, genetic engineering, and metabolic engineering offer the potential to provide sustainable fuels that do not compete with the food business, require fresh water, or use agricultural land.

**4. Current Status and Challenges**

Identification of high-lipid generating microalgae from various habitats according to temperature and location is a part of bioprospecting for microalgae to create economically feasible biofuel. Algal biofuels often have no or very low environmental impact. In fact, other environmental uses including bioremediation (wastewater treatment), power or heat production, bio-fixation (CO2 removal), biofertilizer, animal feed, healthcare, and food products could all be connected to the production of biofuels. The most environmentally friendly fuel source that can aid in reducing greenhouse gas emissions is algae (Merlo *et al*., 2021).

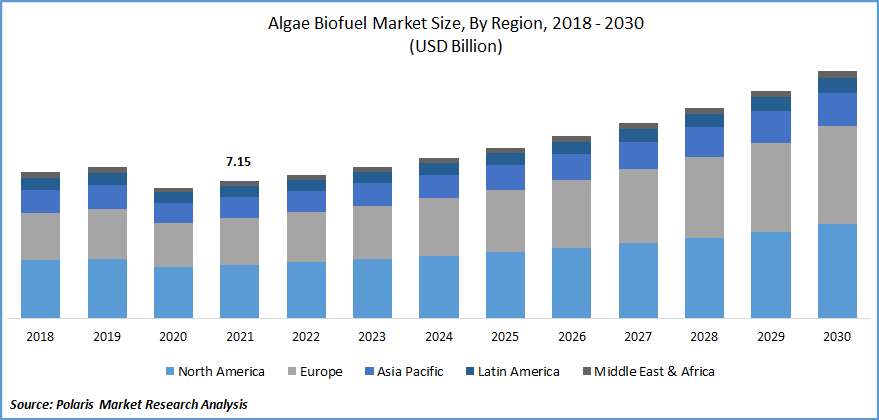


Fig. Algal biofuel market size, global report 2022-2030

The European Union Renewable Energy Directive (RED) recommended using up to 15% of energy from renewable sources in order to significantly reduce greenhouse gas emissions to 20% by 2050 because CO2 emissions from liquid fuels were 36% in 2012 and may increase to 45,000 mega tons by 2040 (Seck *et al*., 2022). UAE suggested using biofuels for 10% of its transportation by 2020. A Renewable Transport Fuel Certificate (RTFC) would be given for meeting the U.S. proposal to replace 20% of its road transport fuel with biofuel by 2022 (De Bhowmick and Sarmah,2021). Renewable energy is anticipated to rule by 2070. Algal biofuels' future depends on the development of commercialization-friendly technology.

However, using genetically modified algae with high rates of precursor overproduction and quick growth is the most alluring alternative. In an open pond close to a contaminated area, these species can be introduced to the environment. This open pond might serve as the facility's initial water treatment stage. The discarded biomass from this pond can be utilized as fertilizer or animal feed, and the biomass slurry will be used to make biofuels. Algal biofuels may appear unaffordable and unsustainable, and they require a lot of water, nitrogen, phosphorus, and CO2 during production. However, as we already noted, they are environmentally friendly and do not compete with other forms of energy for land or water. Large-scale production of algal oil have many effects on the environment, economy, society, and culture. Large-scale cultures for the manufacture of biofuels need a lot of supplies for each stage individually, including tools, machinery, energy, water, and nutrients. The amount of nutrients used by large-scale agriculture and algal cultures could be equivalent. Choosing which algae strains to use is another difficulty. Choosing the best location, isolating, purifying, and identifying natural microalgal assemblies are typically laborious and time-consuming tasks. The media and cultural conditions must be tailored to the target species for superior microalgal multiplication. Identifying a species frequently requires both physical and molecular criteria. To make the in vitro tests as effective as possible, environmental conditions at the sampling site must be noted. The isolated microalgal strain is subsequently cultured in sophisticated systems to produce lipids and biomass (Sun *et al*., 2021). The culture of the organisms in their natural environments with enough inoculum is one method for addressing this issue .

Additionally, algae that thrive in a laboratory setting may not survive in the wild, particularly bioengineered algae that are more susceptible to disease and predators. The energy cost of extracting algae is ten times greater than the energy cost of extracting soybean oil. According to reports, the price was $27 per gallon in 2012 (Davila and Toranzos, 2020). The price of a barrel would be $800 even with perfect setup and planning. One indicator of sustainability is the energy return on investment (EROI). EROI is the proportion of energy produced by a given energy source to the energy required to produce it. When the EROEI is less than 1, more energy is needed to create a fuel than is found in the fuel and coproducts.

EROEI 1 algae fuels are unquestionably unsustainable. For a fuel to be a sustainable energy source, it should have an EROI > 3 . For algal biofuels produced in open ponds or photobioreactors, the estimated EROI ranges from 0.13 to 0.71. Building the facility, chemicals, pumps, cooling, CO2 pipelines, filters, harvesting, centrifuges, storage, surface structure for open ponds, pH, salinity, extraction and conversion, transport, recycling water and nutrients, and supplying fuels are all energy-intensive processes that go into scaling up algal biofuels production (Peter *et al*., 2022).

**5. Conclusion**

Algae is an attractive raw material for biofuel production, as it has the potential to be used for a variety of purposes, including sustainable energy production. Algae can be used to produce biodiesel, biogas, bioethanol, medicines, nutraceuticals, and other useful goods. Biofuels are environmentally benign, renewable, and biodegradable. Numerous advantageous characteristics of algae include their quick development and high lipid content. The majority of algae, known as chlorophytes, are used in bioremediation, water treatment, food production, medicines, and energy production. Chlorophytes include both micro- and macro-algae. Many techniques for cultivation, harvesting, and processing has been discussed here. The primary obstacles seem to be costly infrastructure, operating, and maintenance expenses, the choice of high lipid-containing algae strains, commercial-scale harvesting, and problems with water evaporation. It takes cutting-edge and effective methods to make algae biofuel manufacturing more appealing. Increased biofuel production will aid in the protection of the environment and the preservation of natural resources.

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