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Unlocking the Potential of Microalgae: Renewable Biofuel Technologies, Barriers, and Future Directions

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Abstract

Researchers are looking for an alternative source of energy due to the increase in energy demand and environmental pollution caused by fossil fuels. Recent reports said that microalgae are efficient for biofuel production due to their high growth ability, low production cost and potential to grow in severe environments. There are many photosynthetic microalgae that consume CO_2 and sunlight for growth in biomass and thus provide a promising source of bioenergy. This review paper presents the recent technologies to produce microalgal biofuel. Besides this, the cultivation and harvesting processes and environmental factors that influence the microalgal biofuel production have also been discussed. This review paper also discusses how to attain carbon neutrality through several biofuel generations and also discusses their applications and limitations in agriculture and the environment. In future, researchers should give attention to identifying better strains of algae that produce good-quality biofuel of a high yield, better than economically feasible algal biofuel. Future research is needed to produce a higher amount of product because in recent days, most of the algae face the uneconomical higher costs. Finally, this review paper gives an exposure to a better biofuel in future.

Keywords: Algal biomass; Conventional energy; Eco-friendly; Fossil fuel; Renewable energy; Sustainability.

1. Introduction

There are several studies regarding the creation of life. Early studies suggest that the Earth's primitive atmosphere was primarily composed of carbon dioxide (CO_2), making it unsuitable for most life forms. However, the

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emergence of photosynthetic microorganisms, particularly cyanobacteria and algae, marked a critical evolutionary shift. These organisms played a vital role in transforming the Earth's atmosphere by absorbing CO_2 and releasing oxygen, eventually making the planet more conducive to supporting complex life (Elshobary et al., 2022).

Energy has historically played a fundamental role in human progress. Initially, natural resources such as wood and straw served as the primary energy sources. The advent of the industrial revolution introduced a dramatic shift in energy consumption, characterized by the widespread adoption of fossil fuels. By the mid-20th century, coal, petroleum, and natural gas had become the cornerstone of the global energy landscape. However, the prolonged and intensive exploitation of these fossil resources has led to significant environmental degradation, including greenhouse gas emissions, air pollution, and the gradual depletion of finite reserves (Zheng et al., 2025).

In light of escalating environmental concerns and increasing global energy demand, the development of renewable and sustainable alternatives has gained urgency. In recent years, considerable attention has been directed toward biofuels, fuels derived from biological sources as viable substitutes for fossil fuels. These biofuels are renewable, environmentally friendly, and are viewed as critical to ensuring long-term energy security (Eldiehy et al., 2022).

Among the various feedstocks explored for biofuel production, microalgae have emerged as a particularly promising candidate. Microalgae are microscopic, photosynthetic organisms capable of converting sunlight, carbon dioxide, and water into biomass. This biomass is notably rich in valuable components such as lipids, proteins, and carbohydrates, making it highly suitable for energy conversion. Due to their rapid growth rates, high productivity, and minimal land requirements, microalgae present a compelling alternative to traditional bioenergy crops (Zhou et al., 2023; Malik et al., 2024).

Microalgal biomass can be processed into multiple types of biofuels. Methane is produced through anaerobic digestion, biodiesel via lipid extraction and trans esterification, and hydrogen through photobiological pathways. The efficiency of these processes can be enhanced through advanced cultivation techniques, such as biofilm reactors, which enable higher biomass yields and improved energy conversion efficiency (Gupta et al., 2024).

Hydrothermal Liquefaction (HTL) is one of the most promising methods for converting wet algal biomass into bio-crude oil. Unlike traditional thermochemical processes, HTL operates under high temperatures (200-400°C) and moderate pressures (6-15 MPa) in aqueous conditions, thereby eliminating the need for pre-drying. This process yields multiple valuable products, including bio-crude, aqueous by-products, gases, and solid residues. The use of catalysts like titanium dioxide (TiO_2) has been shown to significantly enhance the efficiency and quality of the bio-crude output (Gronwald & Wang, 2024; Santillan-Angeles et al., 2025).

Microalgae offer several benefits over terrestrial bioenergy crops. They demonstrate high photosynthetic efficiency, can grow in saline or wastewater environments, and do not compete with food crops for arable land. These characteristics have led international organizations such as the International Energy Agency (IEA) to acknowledge the potential of algae-based energy systems as key contributors to global renewable energy strategies. Furthermore, advancements in molecular biology, synthetic biology, and genetic engineering are accelerating the development of more efficient and cost-effective algal strains (Balamurugan et al., 2025).

Biofuel production from algal sources typically involves biochemical pathways such as microbial fermentation of lipids, carbohydrates, and alcohols. Among these, biodiesel is a leading alternative fuel, produced primarily through the trans esterification of triglycerides with short-chain alcohols. Microalgae, due to their high oil content and environmental adaptability, are considered ideal feedstocks for the production of both third- and fourth-generation biodiesel (Veza et al., 2022; Muthuraman & Kasianantham, 2023).

Algal biodiesel has demonstrated improved combustion properties, including lower moisture and ash content, higher heating values, and reduced emissions of sulfur and carbon residues. These characteristics not only enhance the efficiency of the fuel but also contribute to a lower environmental footprint compared to traditional fossil-derived fuels (Shweta et al., 2024).

This review aims to provide a comprehensive overview of microalgae as a sustainable biofuel feedstock, focusing on cultivation strategies, conversion technologies such as HTL, and the environmental implications of integrating algal biofuels into the global energy portfolio.

2. Conventional Fuel

In the 18th century, dependency on fossil fuels started after the steam engine was invented. It is not uncertain that fossil fuels are decreasing as they are the most important sources of the world. Petroleum is one of the main sources of conventional fuel. It is a liquid mixture of hydrocarbons and besides this; it also includes gaseous and solid hydrocarbons. It is yellowish-black in colour and also known as crude oil. It is mainly found in geological formations. Petroleum includes both naturally occurring unrefined and refined crude oil.

Petroleum is a fossil fuel which is formed by dead organisms like zooplankton and algae, rooted under sedimentary rock that are buried for a long time with high pressure and heat. Oil drilling is a process by which petroleum is recovered primarily. After the extraction, oil is purified and separated by distillation process into numerous products to use directly in manufacturing. Some of the products are – (a) fuels like gasoline, diesel, kerosene and jet fuel; (b) asphalt and lubricants; (c) chemical reagents used to make plastics, textiles, fertilisers, pesticides etc. Petroleum is used to manufacture a huge variation of materials which is essential for modern life. Under the condition of surface pressure and temperature, lighter hydrocarbons exist as gases, while heavier hydrocarbons exist as solid or liquid form. In the underground oil reservoir, solid, liquid and gas are proportional to surface conditions and phase diagram of petroleum mixture (Norman, 2011). The crude oil contains various hydrocarbons, organic compounds and trace amounts of metals. Mainly alkanes, cycloalkanes and aromatic hydrocarbons; organic compounds like nitrogen, oxygen and sulphur; and trace metals like iron, nickel, copper and vanadium are present in crude oil. Many oil reservoirs consist of live bacteria (Ollivier & Magot, 2005). Though the composition of crude oil varies largely, the ratio of different elements remains almost the same (Bachmann et al., 2014). The production process of crude oil is shown in fig. 1.

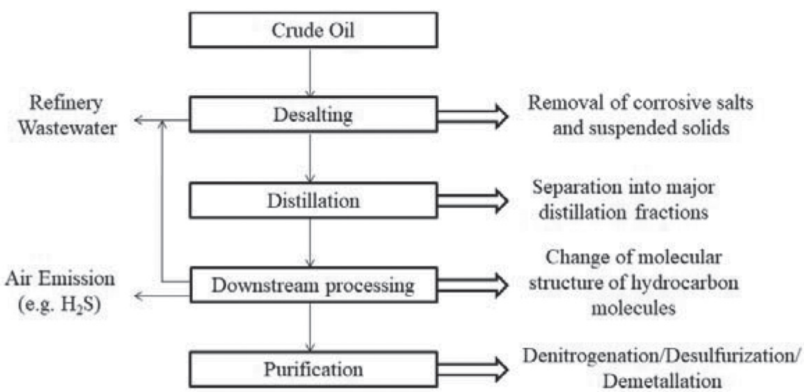

Figure 1: Simplified flow chart of crude oil refinery processes (Bachmann et al., 2014).

2.1. Limitations of Conventional Fuel

Fossil fuels are generally formed from the crust of earth but it takes millions of years to develop. Therefore, fossil fuels are exhausted and non-renewable energy sources are decreasing exponentially. Again, as a result of fossil fuels burning, particulate matter and toxic gases are emitted. This emission is hazardous for life and has a huge contribution to several problems. The increment of the environmental damages looks too small but the consequences have a destructive effect on the environment. Excess use of fossil fuels creates drastic consequences just like air pollution, global warming, acid rain etc. Due to increasing temperature, dry regions are facing shortage of water and heat waves frequently and wet regions are experiencing severe rainfall (Lackner, 2009). Increment of sea level occurs as the glaciers are melting with the variation of sea height. NO_x and SO_x gases mix with water and oxygen and hence create acid rain. Acid rain pollutes soil and damages plants, monuments etc. The burning of fossil fuels results in the release of a large amounts of pollutants and increases the pollution levels in the environment (Ahuja, 2015). Fossil fuels are normally unavailable and thus they are very costly to make them unreachable to underdeveloped countries.

3. Biofuel - An Alternative Source

The fossil fuels are uncertain due to their limited sources and therefore these fuels threaten the development process in every sector (Gorjian et al., 2022). The nations of all over the world are looking for a suitable alternative. Alternative fuels are called non-conventional and advanced fuels. These fuels are derived from many sources other than fossil fuels. Among the alternative fuels, biodiesel and bioethanol are the most promising fuels in the transportation sector as the replacement of fossil fuels and they have the ability to reduce the use of fossil fuels (Sun et al., 2021; Xing et al., 2021). Though we use fossil fuels in the present days therefore the alternative fuels mix with fossil fuels and are used in blended form (Bae & Kim, 2017). So the replacements are different from conventional fuels in origin, properties and procedure of their formation.

3.1. Different Types of Biofuel

On the basis of source, biofuels are mainly classified into two categories viz, primary and secondary biofuels. The secondary biofuels are also sub classified into four sub categories viz, first, second, third and fourth generation (Rodionova et al., 2017). The details of these biofuels are discussed below.

3.1.1. First Generation Biofuels

First-generation biofuels are made from oil-based plants and starch (Aron et al., 2020). It is very difficult to convert the feedstock into first-generation biofuels. To produce first-generation biofuels, biomass is mainly used which is derived from corn and sugarcane (Wang et al., 2012). Corn is used specially for the production of biofuel or ethanol. Maize is used in a traditional way for the people and animals throughout the world. When corn is used for the production of biofuels and electricity, it causes shortage of food (Demirbas, 2011). The utility of first-generation biofuels is increasing day by day due to arable lands and raw materials (Abdulkhani et al., 2017). Some first-generation biofuels are described below

3.1.1.1. Bio-alcohols

It is obtained by the extraction of enzymes and microorganisms. They produce bio-alcohol by fermentation of sugars like starch, cellulose, glucose etc. Some bio-alcohols are bio-methanol, bio-ethanol, bio-propanol bio-butanol etc. (Obergruber et al., 2021).

3.1.1.2. Bio-diesel

Biodiesel is extracted from crops or plants and animals which contain long-chain fatty acid esters. It is made by chemical reaction of lipids with an alcohol and produces methyl, ethyl or propyl ester (Hajjari et al., 2017).

3.1.1.3. Green Diesel

It is another source of energy for the production of first-generation biofuel. It is obtained when triglycerides present in vegetable oils hydrotreating with hydrogen. Some vegetable oils are used as the feedstock of green diesel. There are three main reactions in the hydrotreating process. They are considered as decarbonylation (DCO), decarboxylation (DCO_2) and hydrodeoxygenation (HDO) (Faungnawakij & Suriye, 2013).

3.1.1.4. Vegetable Oil

Castor oil, olive oil, sunflower oil etc. are the sources for the production of vegetable oils. The generated heat through vegetable oil is approximately 90% similar to that of diesel fuel. Recently it has been reported that vegetable oils and waste cooking oil are used as an alternative source for diesel engines and they are used only in some precise applications (Corsini et al., 2015).

3.1.1.5. Biogas

The production of waste material is the main part of activity. The main source of wastes comes from industries, municipalities, medical etc. There are some examples of natural materials like starch, lipid, keratin etc. are converted into biogas by hydrolysis process (Periyasamy et al., 2009).

3.1.1.6. Solid Biofuels

A long time ago, the solid biofuel was used as the most important bio-energy transporter. At that time, animal dung, wood, leaves etc. were used as biofuels commonly. Nowadays, the application of solid biofuels is limited to some particular markets. Normally they are very much useful in the energy system. Those particular markets are classified by the requirements of different fuels and solid biofuel which have different properties like low, medium and high variations of fuel (Kaltschmitt & Weber, 2006).

3.1.2. Second Generation Biofuels

Second generation biofuels are produced from cellulosic or carbohydrate biomass. These types of carbohydrates are repeatedly obtained from inedible plant and agricultural materials (Aron et al., 2020). These materials are accessible, renewable and low in cost to produce the biofuels. They naturally contain cellulose and hemicellulose (Shahzadi et al., 2014). There is a high requirement of chemical pretreatment to dissolve the lignin of cellulose to make easy the formation of these biofuels. After the pretreatment, the biomass further undergoes two steps such as hydrolysis and fermentation. Lignocellulosic biomass has enough potential to produce ethanol (Draude et al., 2001). This biomass does not engage directly with the production of food and has a requirement of land for cultivation. To increase the density of the biomass, a physical densification is needed (Li et al., 2020; Yang & Wyman, 2008). There is some process in the physical densification which includes chopping, grinding, milling and pelleting. These processes help to increase the density of biomass and reduce the size of biomass (Tang et al., 2012). Few 2nd generation biofuels are discussed below.

3.1.2.1. Cellulosic Ethanol

It is a second-generation biofuel which is produced by the fermentation of sugar. The source of this sugar is cellulose and polyose and the biofuel is a lignocellulose compound (Guo et al., 2022).

3.1.2.2. Algae-based Biofuel

Algae are found generally in lakes, ponds etc. Algae is able to be modified into various types of biofuels like biodiesel, biogas etc. Some techniques of the concentration and extraction of biomass are (a) aggregation, (b) centrifugation, (c) floatation, (d) flocculation and (e) purification (Demirbas, 2011).

3.1.2.3. Alcohol

Through the catalytic synthesis, the mixed alcohols are restored from syngas. Syngas also produces alcohol by the fermentation process of biomass with different microbes (Hong et al., 1998).

3.1.2.4. Dimethylfuran

Dimethylfuran is the most oxygenated hydrocarbon in spite of its low carbon content. It is used to lower the emission from the engine because it consists of 17% of oxygen gravimetrically (Xu & Wang, 2016). It is also named as 'sleeping giant' among the renewable chemicals. Besides this, it is used as an alcohol additive in diesel fuel (Chen et al., 2013).

3.1.2.5. Biosynthetic Natural Gas (Bio-SNG)

Some bacteria can generate biogas through the digestion which is active in the absence of free oxygen. The combination of mash gas and carbonic acid gas is used to produce biogas. Bio-SNG is used in cars in Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG) form and it is also used for refuelling the cylinders of natural gas (Zhang et al. 2015).

3.1.3. Third Generation Biofuels

Due to all of the problems of using crops for the production of biofuels, the next suitable alternative source was microalgae. It is used as the major feedstock for the production of third generation biofuels. Microalgae have some characteristics in the application and composition of carbohydrates and lipids. Due to these reasons, microalgae receive lots of attention (Rawat et al., 2011). Using of land, costly pretreatments to remove lignin and the production of food crops are some of the issues of second generation biofuels. Microalgae are a very convenient resource for the supply of biofuels because they have no lignin (Ho et al., 2013). The production cost and investment are much higher for the production of other crops than algae. But microalgae are 10 to 100 times more effective than other crops for the production of fuel, oil, and food (Hussian, 2018). Some third generation biofuels are discussed below.

3.1.3.1. Biomethane

The solid waste and also the industrial sledges are the main source for the production of biomethane. The production techniques are developed to maximise the methane yield (Zacharia et al., 2020). Generally methane is produced by anaerobic digestion. Nowadays, we have seen significant progression the field of biomethane production systems which involves upgradation and digestion.

3.1.3.2. Biohythane

By mixing biogas and biohydrogen (H_2 + CH_4), a new upgraded and good product is formed which is later named as biohythane (Meena et al., 2019). The mixing is held by the fermentation active in the absence of free oxygen. This anaerobic fermentation applies their beneficial effects to minimise the disadvantages and negative effects on the environment. Undoubtedly this is a unique fuel which gains more attention for its properties and positive roles in the environment (Abanades et al., 2021).

3.1.4. Fourth Generation Biofuels

In present days, the feedstocks of 3rd generation biofuel are limited due to the obstacles in the harvesting and cultivation process (Tarafdar et al., 2021). It was believed that the limitations of the third-generation biofuels were rectified by genetically modifying microbes which are the source of 4th generation biofuel. The correction is needed for the improvement of the efficiency of process and yield of the product. The main source of fourth-generation biofuels are cyanobacteria, macroalgae and microalgae (Brennan & Owende, 2010). Cyanobacteria have the ability to produce fourth generation biofuels for their growth ability, genetic tractability and potential to fix the carbon dioxide gas. From the past few years, we have seen a sharp increase in the production of biofuel by the employment of microbial cell factories. Microbial cell factories are the sustainable sources which have the potential to decrease the environmental footprint (Phulara et al., 2018). Various types of fourth generation biofuels are discussed below.

3.1.4.1. Biobutanol

Biobutanol is a substitute of the currently used biofuel. Nowadays, biobutanol is frequently used for its multiple properties like lower absorptive nature, less volatility and the ability to contain a higher amount of energy (Sasaki et al., 2015). Besides these, it can be served as industrial solvent as it needs no modifications (Rakopoulos et al., 2011). The major disadvantage of biobutanol is the cost of production is very high. But on the other hand, production of biobutanol is very useful. As a result, the production cost can be reduced by lignocellulosic biomass (Lee et al., 2008). Biobutanol is produced through the fermentation of alcohols and ketones and from anaerobic digestion (Alias et al., 2021).

3.1.4.2. Biohydrogen

To produce sustainable hydrogen, various biological sources are used. Besides the reformation of biogas, the wastes from organic substances, biomass from algae and agricultural residues are used for biohydrogen production in both biological and thermochemical ways. Recently the efficiency and reliability has been developed for the biohydrogen formation (Maswanna et al., 2020).

3.2. Biofuel from Microalgae

Microalgae has individual yield than other biomass as it is eco-friendly and a renewable feedstock. It is reported that microalgae has a possibility to produce more energy than other types of crops per hectare of land used. As a consequence, the yield of oil is higher than other types of crops. Microalgae have no negative impacts on the environment as they can be cultivated in under-developed land. Microalgal biofuels can be generated throughout the year. Microalgae need light, carbon dioxide gas, water etc. for photosynthetic growth. The temperature of the system is controlled strictly. For the growth of mostly used microalgae, the temperature mainly exists within 20°C to 30°C (Chisti, 2007; Borowitzka, 1999; Borowitzka, 2005). Triacylglycerol is referred to as a store of primary energy in microalgal cells, which forms by the weight of dry cell of 60-70% (Hu et al., 2008). Microalgal biomass can provide a variety of biofuels including biodiesel, bioelectricity, bioethanol, biohydrogen, biomethane etc. Among all the varieties of biofuels, microalgal oils are the most favourable for biofuel production (Shuba and Kifleb, 2018).

3.2.1. Different Types of Algae

Algae are mainly photosynthetic and aquatic plant-like species. Algae are classified into microalgae or macroalgae by their size. Here we focused mainly on microalgae. Microalgae are single cell microscopic organisms which are found mainly in fresh and marine environments. Microalgae is either prokaryotic or cyanobacteria-like which is further known as Chloroxybacteria or eukaryotic and green-algae-like which is further known as Chlorophyta (Khan et al., 2018). *Chlorella* species have the capability to transform the modes of nutrition from phototrophic to heterotrophic among microalgal species (Xu et al., 2006). The biomolecules including carbohydrates, fats, nucleic acids and proteins are the common components present in microalgae (Williams and Laurens, 2010). Microalgae consists of biologically active compounds and they are useful to produce many valuable compounds including fatty acids, polymers, peptides, enzymes etc. (Priyadarshani and Rath, 2012). From the past years the population of the world increased rapidly and also increased the lacking supply of protein. So the research for alternative sources of protein was started. Due to the presence of high quantities of protein in various microalgal species, they are chosen as the unusual sources of proteins (Becker, 2007).

3.2.2. Chemical Composition of Microalgae

Microalgae are characterized by a varied and rich biochemical composition, mainly consisting of proteins, carbohydrates, lipids, and nitrogen-containing compounds. These primary constituents are not only essential for cellular functions but also critically influence the suitability of each species for different biofuel production pathways. The relative abundance of these macromolecules varies across microalgal species, making biochemical profiling an essential step in selecting strains for targeted bioenergy applications (Morais Junior et al., 2020; Abdel-Latif et al., 2022).

The specific type of biofuel that can be efficiently produced from microalgae is largely determined by the dominance of particular biochemical constituents in their biomass:

Lipid-rich species are optimal for biodiesel production. Lipids serve as precursors for fatty acid methyl esters (FAME) through transesterification processes. For example, *Botryococcus braunii* can accumulate lipids up to 75% of its dry weight, making it highly efficient for biodiesel conversion (Morais Junior et al., 2020).

Carbohydrate-dense microalgae are more suitable for bioethanol production. Carbohydrates can be hydrolyzed into fermentable sugars, which are then fermented to ethanol. *Chlamydomonas malina*, with a carbohydrate content of approximately 26.1%, demonstrates strong potential in this regard (Morales-Sánchez et al., 2020).

Protein-rich species are advantageous for biogas generation through anaerobic digestion. Proteins enhance microbial growth and enzymatic activity, thereby improving methane yield. However, high protein content can also lead to elevated ammonia levels, which may inhibit digestion. *Chlorella vulgaris* and *Spirulina platensis* are notable for their high protein levels (61.6% and 76.6%, respectively), making them promising candidates for biogas production in systems that include ammonia mitigation strategies (Abdel-Latif et al., 2022; Seghiri et al., 2019).

In summary, the dominant biochemical trait of each microalgal species plays a decisive role in determining the most suitable biofuel pathway. Understanding and leveraging these variations allows for the strategic selection of microalgae in bioenergy systems optimized for biodiesel, bioethanol, or biogas production.

3.2.3. General Method for Preparation of Biofuel from Microalgae

The cyanobacteria-like Prokaryotic, microalgae-like eukaryotic and the diatoms are examined frequently for biofuel production (Show et al., 2017). As the cost of biofuel production is very high, the freely available sunlight and the daily variations of the natural light levels are used for biofuel production to reduce the production cost (Chisti, 2007; Borowitzka, 1999; Borowitzka, 2005). Microalgal biomass can be converted into bioenergy sources through a number of ways. These processes are biochemical conversion, thermochemical conversion, chemical reaction and direct combustion. Fig. 2 illustrates a schematic diagram of the production processes of biodiesel and bioethanol using microalgal feedstock (Mata et al., 2010). The most convenient way is to extract the vegetable oils from biomass and convert them to biodiesel. The conversion may take place through the transesterification process. Besides this, microalgal biomass can be converted into diesel by hydrocracking process. This type of diesel is commonly named as 'green diesel'. One microalga named *Botrycoccusbraunii* has the ability to produce hydrocarbons which can be further purified like petroleum. Other microalgae are able to accumulate hydrocarbons. Later they are converted into alcohols and other liquid fuels by yeast or other bacteria.

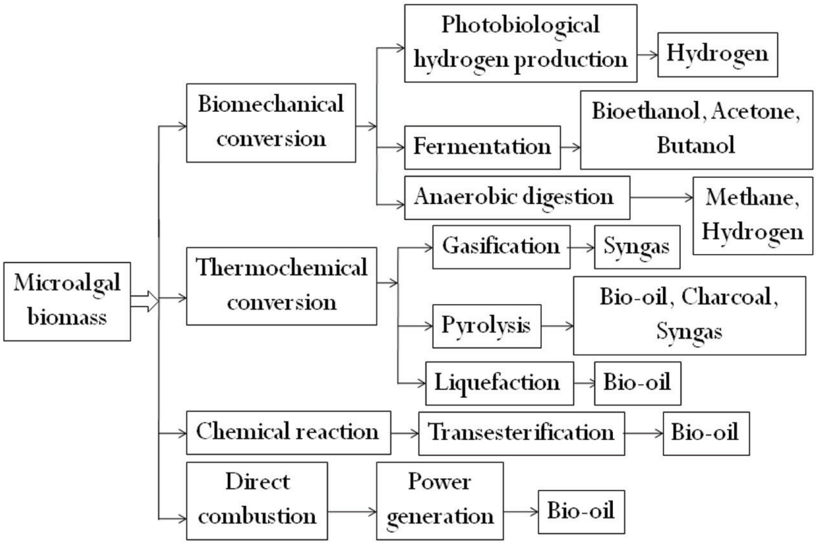

Figure 2: Biofuel production processes from microalgae biomass (Mata et al., 2010; Dragone et al., 2010)

3.3. Comparative Study between different Biofuels

On the basis of different sources, there are different types of biofuels present in our environment. In this section, we are going to discuss the various sources of different biofuels and the microalgal species which help to produce those biofuels. We mainly select some specific examples of biofuels such as bioethanol, biomethane, biohydrogen, biodiesel, bio-jet fuel, biocrude oil and pyrolysis oil. The calorific values of petrol, diesel and CNG are 45000 KJ/Kg, 43000 KJ/Kg and 50000 KJ/Kg respectively. They are the conventional fuel but here we discuss only biofuels. In comparison with diesel, biodiesel has a lower thermal value and in comparison with crude oil, biocrude oil has a lower thermal value (Williams et al., 2018; Shirazi et al., 2017; Biller et al., 2012; Dayananda, 2007). Although the heat values of conventional fuels are very much higher than that of biofuels, the use of biofuels are very much higher than conventional fuels. The main reasons for using biofuels are their biodegradability, renewability, eco-friendly behaviour and their low flammability. The sources, the involved microalgal species for these biofuels and the thermal values of biofuels are discussed in table 2.

4. Utility of Biofuel

Biofuels are increasingly recognized as a sustainable and viable alternative to fossil fuels, driven by growing environmental concerns, fossil fuel depletion, and the need for energy diversification. As renewable energy carriers, biofuels offer a broad array of benefits including reduced greenhouse gas (GHG) emissions, improved energy security, and compatibility with existing energy infrastructure (El-Araby 2024).

One of the most scientifically compelling advantages of biofuels lies in their lower net carbon emissions. Unlike fossil fuels, which release carbon that has been sequestered for millions of years, biofuels particularly those derived from photosynthetic organisms like microalgae and lignocellulosic biomass are part of a short carbon cycle. During growth, these feedstocks absorb atmospheric CO_2 through photosynthesis, which can offset emissions during combustion. Recent life cycle assessment (LCA) models indicate that certain advanced biofuels can reduce GHG emissions by 60–90% compared to petroleum-based fuels, depending on the feedstock and processing technology used (Tibesigwa 2023).

Beyond carbon dioxide, biofuels are associated with lower emissions of other air pollutants such as carbon monoxide (CO), unburned hydrocarbons (HCs), sulfur oxides (SO_x), and nitrogen oxides (NO_x). These reductions are especially evident in biodiesel blends, which are cleaner-burning and contain negligible sulfur content. The combustion of algal biodiesel, for example, produces up to 50% less particulate matter compared to conventional diesel (Ge et al., 2022). This has important implications for urban air quality and public health, as exposure to airborne pollutants has been linked to respiratory and cardiovascular diseases, as well as premature mortality (Shahriyari 2021).

From an energy systems perspective, biofuels also offer favourable energy return on investment (EROI) metrics, especially when integrated with renewable energy sources. The incorporation of solar energy into photobioreactors or thermal processing stages, such as drying and pyrolysis, enhances the overall energy efficiency of biofuel production. Solar-assisted biodiesel production has demonstrated a net energy gain of over 3:1 in recent pilot studies (Malode et al., 2021).

Feedstock flexibility is another critical advantage. Lignocellulosic biomass abundant in agricultural residues, forest waste, and energy crops can be converted into bioethanol, biogas, and bio-oil through biochemical and thermochemical routes. It does not compete directly with food crops, thereby avoiding the food-versus-fuel debate that has challenged first-generation biofuels (Prasad & Ingle, 2023). Similarly, microalgae can be cultivated on non-arable land using saline or wastewater, providing high areal productivity without straining freshwater resources or arable land availability.

Moreover, biofuels exhibit favourable safety and handling characteristics. They are generally biodegradable, possess higher flash points, and pose a lower risk of explosion or environmental contamination compared to fossil fuels. This makes them suitable for use in decentralized and rural energy systems where safety and environmental risks are of paramount concern (Chowdhury et al., 2025).

Nevertheless, despite their promising attributes, several challenges hinder the widespread deployment of biofuels. These include high initial capital costs, variable feedstock supply, land and water requirements, and the need for advanced conversion technologies. However, progress in genetic engineering, strain optimization, and bioprocess integration is rapidly closing these gaps. For instance, Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR)-based genome editing has significantly improved lipid productivity in microalgal strains, thereby enhancing biofuel yield and process economics (Kasai et al., 2024).

In conclusion, biofuels represent a multifaceted solution to energy and environmental challenges. Their ability to reduce emissions, utilize diverse feedstocks, and integrate with renewable technologies positions them as a key component of the global transition to low-carbon energy. Continued innovation in biotechnology, systems integration, and policy support will be essential to unlock their full potential at commercial scales.

5. Future Study

Research is going ahead continuously to differentiate the algal species with higher productivity. These types of algal species can be produced in large quantities and they are also able to reduce the cost of production. The genetically modified microalgae species can generate high amounts of yield and their commercial production and development could lower the cost. In current days, harvesting processes are still expensive despite using biological, chemical, electrical or mechanical techniques. We have needed more research and development to make the harvesting methods low costly and more efficient. These developments also help to reduce the cost of production in the future. Besides these developments, the techniques for production of biomass also needed further research to make the production of microalgae economically and environmentally sustainable. After the summarisation of the considerations, it is clear that in future the researchers must concentrate to fill up the gap of knowledge and address the issues which include the necessity of a cultivating system that increases the production of biomass.

6. Conclusion

In this review, we have discussed the latest update of biofuel production using microalgae and also the processes of production which includes harvesting, cultivation, lipid extraction and conversion. The major advantage of microalgae derived biofuels is that they are highly able to fix CO_2. Microalgae provide some beneficiary properties to recommend them as replaceable feedstock for various bio-refinery applications. In future, we have to go a long way to make algal biofuels as an alternative instead of conventional fuel that is commercially feasible. To meet the energy needs of the world, biofuel plays an important role in the future. We have discussed the four generations of biofuel in terms of their feedstock, conversion processes, environmental effects and economic impacts. The continuous supply of feedstock is necessary primarily to meet the growth of energy. In the present days, the major problem of using biofuels is its high price. To cultivate microalgae which produce biofuels, a favourable environment like suitable light and temperature, proper nutrients, salinity, and pH is needed. If the production cost of biofuel is minimised then the algae-based biofuels can be a perfect alternative of conventional fuels and biofuels are also a better energy source in future days. Overall this review paper summarises that in future days biofuel may be combined with all the four generations of biofuel instead of only one generation. There is a high possibility to achieve a prestigious status in the path of biodiesel production in spite of the presence of export potential, opportunities of jobs and environmental security. This can display the capabilities of our country in an international platform and thus, it can help to increase the self-respect of our country.

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Conflict of Interest

There is no conflict of interest in submission of this manuscript.

Author Contribution Statement

The authors confirm contribution to the paper as follows:

Study conception and Design	Amal Halder
Data Collection	Sampiya Banerjee
Analysis and interpretation of results	Amal Halder
Draft manuscript preparation	Amal Halder & Sampiya Banerjee
Reviewed the results and approved the final version of the manuscript	Amal Halder & Sampiya Banerjee

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