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REVIEW ARTICLE

A review on the current status and post-pandemic prospects of third-generation biofuels

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Abstract

The rapid increase in fossil fuel depletion, environmental degradations, and industrialization have encouraged the need and production of sustainable fuel alternatives. This has led to the increase in interest in biofuels, especially third-generation biofuels produced from microalgae since they do not compete with food and land supplies. However, the global share for these biofuels has been inadequate recently, especially due to the ongoing global pandemic. Therefore, this paper offers a review of the state-of-the-art study of the production field of third-generation biofuel from microalgae. The current review aims to focus on the different aspects of algal biofuel production that requires further attention to produce it at a large scale. It was found that several strategies during the life cycle of algal biofuel production can significantly increase its quality and yield while reducing cost, energy, and other related attributes. This paper also focuses on the challenges for large-scale production of third-generation biofuels pre and post COVID-19 to better understand the barriers. The high cost of this fuel's production and sale tends to be the major reason behind the lack of large-scale production, hence, inadequacy to meet the global need. Third-generation biofuel has so much to offer including many integrated applications and advanced uses in the future fuel industry. Therefore, it is important to cope with the ongoing circumstances and emphasize the future of algal biofuel as a sustainable source.

Keywords Algal biomass · Biofuel · Renewable energy · Biodiesel · Third-generation biofuel · Advanced biofuel · COVID-19 · Green recovery

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1 Introduction

We are currently living through a dynamic phase of civilization where technological advancement has made drastic shifts in our lives. The rapid growth of industries, transport systems, and types of machinery leads to a leisurely lifestyle, but they are costing us greatly by depleting the earth's natural resources. The extensive use of fossil fuels and various human activities are the primary causes of the depletion of resources and the global climate crisis [1]. A recent journal article reported that 87% of the global CO_2 emission is resulted from using fossil fuels, in which coal, oil, and natural gas contribute 43%, 36%, and 20% respectively [2]. Specifically, transport systems are accountable for about one-third of the global energy usage, half of which is related to oil. As the world's human population is expected to increase, which will cause a 40% rise in the usage of fossil fuels in the years 2040–2050 [3]. According to a report by the International Renewable Energy Agency (IRENA), around 2 billion vehicles will be on roads in the year 2020, along with the increment in global carbon emission by aviation which alone contributes 3% of the total emission [4]. Therefore, alternative energy sources like solar, wind, and biomass are in high demand to fulfill global energy requirements.

Bioenergy is the oldest known form of renewable energy produced from organic matter, called biomass which is the key for producing biofuels. Initially, biomass is divided into conventional and renewable resources, or feedstocks (Fig. 1) [5]. Renewable biomass is then branched into generations depending on the type of feedstocks. First and second-generation biomass includes food and waste crops such as rice, wheat, sugarcane, barley and their straws, and husks, cultivated energy crops such as woody crops, forest residues, etc. [6]. Currently, a major portion of biofuels is derived from these biomasses, especially from palm oil, corn, and soybean oil.

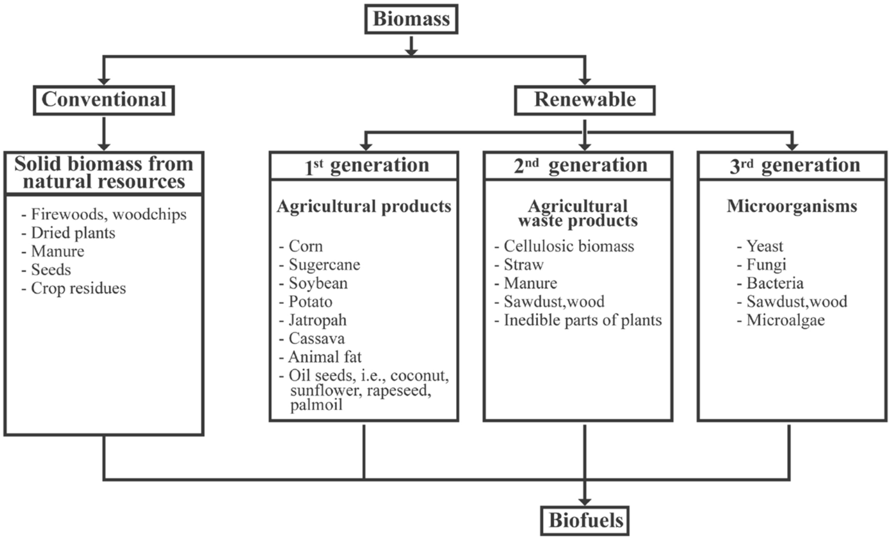


Fig. 1 Classification of biomass into generations [5]

First and second-generation feedstocks require a huge amount of arable lands along with state subsidies and other resource consumption which conflicts with the world's food production. For example, The US biofuel industry highly depends on agricultural products as their biofuel feedstock, which required 24% of their total cropland to meet half of the transport fuel necessity [5]. In this regard, third-generation biofuels, with algae as the feedstock, have been thought to have huge potential to meet future biofuel demands without compromising arable lands and food sources. Particularly, algal biomass is considered a promising candidate for its higher oil contents than oil crops, which exceeds almost 60–70% of the dry weight of biomass in some species [5]. Microalgae have a very high growth rate where it takes only a few days to complete its entire growth cycle and high photosynthetic abilities compared to plants. Biomass production of microalgae is also almost 5–10 times more than terrestrial plants [5]. Moreover, higher adaptability to different environmental situations enables microalgal cultivation independent of fertile lands. *Spirulina* for example can be cultivated in both closed PBR or open-pond systems, therefore, requires less area. Its biomass concentration can double every 2–5 days and yield 20–400 times more protein compared to many food sources [7]. Therefore, microalgal biomass can be considered as a better renewable source of biofuel feedstock. Furthermore, growth conditions for some algal species can also be engineered to maximize their oil content. The biomass leftovers after oil extraction can be used as animal feed, which makes it economically beneficial for mass production [26]. Furthermore, the microalgal efficiency of photosynthesis is high, converting 3–8% of solar energy during the process, which is only 0.5% in terrestrial crops [1]. In addition to being a sustainable feedstock, they can also contribute to CO_2 and nutrient fixation, wastewater treatment, resulting in wide scope for third-generation biofuels to take over conventional fuels.

With the outbreak of the COVID-19, the world has undergone a significant economic crisis, facing a sharp drop in fuel demand and price. Moreover, global precautionary measures have also affected the agricultural practices and transportation of feedstocks, reducing the production of biofuels. Various sustainable organizations worldwide have already started strategies to utilize this situation to shift the global energy and fuel to renewables. Therefore, effective actions are highly needed to develop third-generation biofuel production and gradually promote them to replace the previous generation feedstocks. The importance and scope of biofuels derived from algal biomass have been studied previously in numerous works of literature. This paper aims to study those works of research and analyze the current state amidst COVID-19 to review the prospects of third-generation biofuels.

The rest of the paper is organized as follows: Sect. 2 explores the present status of third-generation biofuel production from algal biomass. The existing technologies for cultivation, harvest, and other applications of algal biomass will be discussed in Sect. 3. In Sects. 4, and 5, the life cycle assessment of third-generation biofuels in terms of cost, water, and CO_2 footprints and energy footprint is discussed followed by future scopes and challenges. Next, these scopes and challenges for the algal biofuel will be assessed through a keen review of the pre-and post- COVID-19 status of the global biofuel sector in Sects. 6, and 7. Furthermore, future scopes and recommendations for third-generation biofuels will be provided based on the reviewed prospects, considering the earlier sections of the paper are discussed in Sect. 8. Finally, Sect. 9 concludes the paper.

2 Algal biomass and their conversions to third-generation biofuels

Algae are aquatic organisms that take CO_2 from the air and convert it into oxygen as well as possess oil through their cell structure breakdown due to the high amount of lipids present in them [8]. In comparison to land plants, algae have higher photosynthesis levels and high growth rates along with high CO_2 sequestering efficiency [5]. They can be either unicellular (Microalgae) or multicellular (Macroalgae). Being the third-generation biomass, microalgae is the one that is used mostly in conversion processes as they contain more lipids than macroalgae and have faster growth [9]. Most species of macroalgae contain lipids less than 5% of their dry weight and can go a maximum of 20% in a specific species call *Dictyotales* [10]. On the contrary, a normal range of lipid content in microalgae is 20–50% of the dry weight and can reach as high as 80% under specific conditions [11]. Apart from lipids, proteins and carbohydrates are the other two main components of algal biomass that can be converted into various by-products, like animal feed, supplements, or biofertilizers (Fig. 2) [1].

Biofuels have a long history of being utilized in transport, power, and energy, so as the use of algae. Production of methane gas from algae was proposed in the 1950s which received attention in the 70s during the energy crisis [12]. Later, the Aquatic Species Program (ASP) supported by the US Department of Energy invested in the goal of producing oil from microalgae between 1980 and 1996, and commercialization for their fatty acids and lipid contents began in the mid-1900s [13]. Algal biomass can also be converted into various third-generation biofuels and other by-products through mainly three types of processes: biochemical, thermochemical, and chemical, utilizing a series of conversion methods [14].

Bioethanol: Production of bioethanol by fermenting crops dates back to the 1800s when the oil crisis led bioethanol to be mixed with petrol [14]. According to a 2018 report, The US accounts for 56% of global ethanol production, the majority of which is produced from first and second-generation feedstocks like maize, sugarcane, and corn [15]. But considering algae as the biomass, they can produce ethanol two times

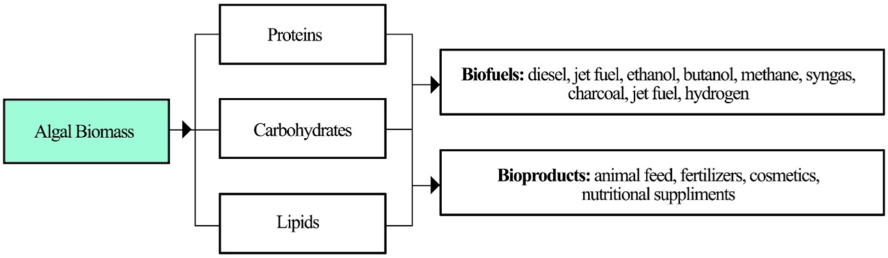


Fig. 2 Major components of microalgae and their products [5]

higher than sugarcane and five times higher than corn [3]. Being low in energy consumption, the pre-treatment of bioethanol is an efficient process to produce bioethanol. Many works of literature developed suggested algae as a promising resource for bioethanol production and can replace food and energy crops.

Biogas: Another ancient use of biomass for using as fuel is the production of biogas for heating purposes. Biogas is also highly used for electricity generation and its usage has been increasing exponentially since the year 2000. Based on a report by International Renewable Energy Agency (IRENA), the cumulative electricity generated by biogas was 13,185 GWh in 2000, which raised to 88,378 GWh in 2018 [16]. Several works of literature over the years have found algae to be an efficient feedstock for biogas production, Marine algae, especially seaweeds, are getting remarkable attention for the production of biogas due to their high amount of polysaccharides [9]. Biogas from algae is produced through various stages of anaerobic transformation. According to a study done by the International Energy Agency (IEA) Bioenergy, biogas from algae (seaweed) can reach up to 20,800 m^3/ha per annum, compared to terrestrial crops yielding a maximum of 6624 m^3/ha per annum [17]. Current methods of algal biogas production still have major potentials for development due to a few limitations like land area for seaweed cultivations, water footprint, etc.

Biodiesel: Biodiesel is the most significant biofuel at present which has been produced and studied widely for development. The first-ever biodiesel was used in the 1890s by Rudolf Diesel who used vegetable oil, which continued its trend after the fossil fuel crisis in the 1930s. From the 1970s onwards there have been more researches and developments in the field of biodiesel from biomass [18]. Biodiesel from algae started to be researched and adopted from the 1978–1996 period which was funded by the U.S. Department of Energy's Office of Fuels Development [19]. Although the global biodiesel industry depends on second-generation biomass, the need for a huge amount of arable lands along with state subsidies has created a challenge to meet their consumption requirements. Researchers have found a wide range of advantages of third-generation biodiesel as algal biomass has a high growth rate and oil productivity [9]. Thus, algal biomass offers a favorable and sustainable solution for issues related to previous generation biomasses.

There are other biofuels derived from algal biomass such as biohydrogen, bio-oil, and syngas, whose contributions are minimal to the overall global production. Algal biohydrogen is a common product in recent years as gaseous fuel or generating electricity. It is usually produced through processes like bio photolysis, where water separates into hydrogen and oxygen molecules in the algal biomass in the presence of light [20], and photo fermentation, a process of hydrogen production from biomass containing organic acids with the help of sunlight [21]. Although, compared to terrestrial plants, biohydrogen yield from algae is low. Thus, to make algal biohydrogen useful in the future, pre-treatment methods are needed to be implemented. Recent studies are also focusing on optimizing enzymatic reactions to produce better biohydrogen yield [9]. Bio-oil and syngas on the other hand are products obtained from various thermochemical conversion routes, like pyrolysis, combustion, hydrothermal liquefaction (HTL), or gasification [9]. However, crude bio-oil cannot be used directly as fuel due to high viscosity, high corrosiveness, and the presence of water, oxygen, and other unsaturated contents [9, 22]. Hence, several steps and treatments can improve their quality, such as fluidized fast pyrolysis for higher yields. For instance, fast pyrolysis of *Chlorella protothecoides* was found to result in the highest 57.9% yield of bio-oil [22].On the other hand, syngas is produced by oxidation at high temperatures and can be used directly as fuel or in gas turbines [9].

Third-generation biofuels have been found by researchers as a remarkable feedstock for biofuel productions than first and second-generation feedstocks. However, it was found after reviewing several works of literature that the technologies for algal biofuel, especially the cultivation and harvesting processes are still required to be developed. Currently, bioethanol and biodiesel are the main biofuels that are produced globally. According to a report published by IEA showing the trend from 2017 to 2020, the production of bioethanol and biodiesel stayed stable which is 1.2–1.3 mb/day and 0.6–08 mb/day respectively [23]. While third-generation biofuels from algal biomass possess great potential for contribution, other aspects of their production need to be explored to identify the barriers to commercialization and scopes of improvement.

3 Current technologies for algal cultivation and harvesting

The latest technology for algal biofuel production involves algal cultivation, harvest, drying, extraction of oil, and transesterification to convert algal oil to biodiesel [8]. These cultivation methods vary according to the type, quality, and commercial value of the biofuel that will be produced [8]. Thus, algae harvesting processes for biofuel production have major significance.

Microalgae being very small in size are usually cultivated by immersing into the water which is checked for important parameters, such as temperature, pH level, CO_2 level, nutrients, and amount of light penetrating the water body and photoperiod. Matured microalgae are then harvested using various mechanical, biological, and chemical-based systems and dried to produce the biomass feedstock for further conversion procedures [24]. Likewise, transesterification can, in turn, be of two types, direct and conventional. In-direct or in-situ transesterification simultaneous extraction of lipid takes place in a single stage, eliminating any form of pre-treatments. It yields more biodiesel compared to the conventional type and is of significance in the further development field. The conventional method, however, is two-staged because they include a mechanical process before the lipid extraction. This method is time-consuming and consumes more energy due to pre-treatment steps [6].

3.1 Algal biomass cultivation

Currently, the algal cultivation method can be mainly photoautotrophic and heterotrophic, among which the photoautotrophic method is of two types, open and closed systems [3]. Open systems are simple and low-cost cultivation methods as they include the oldest and natural systems such as ponds, lakes, lagoons, etc. (Fig. 3) [8]. This cultivation system utilizes atmospheric CO_2. The location of the open pond

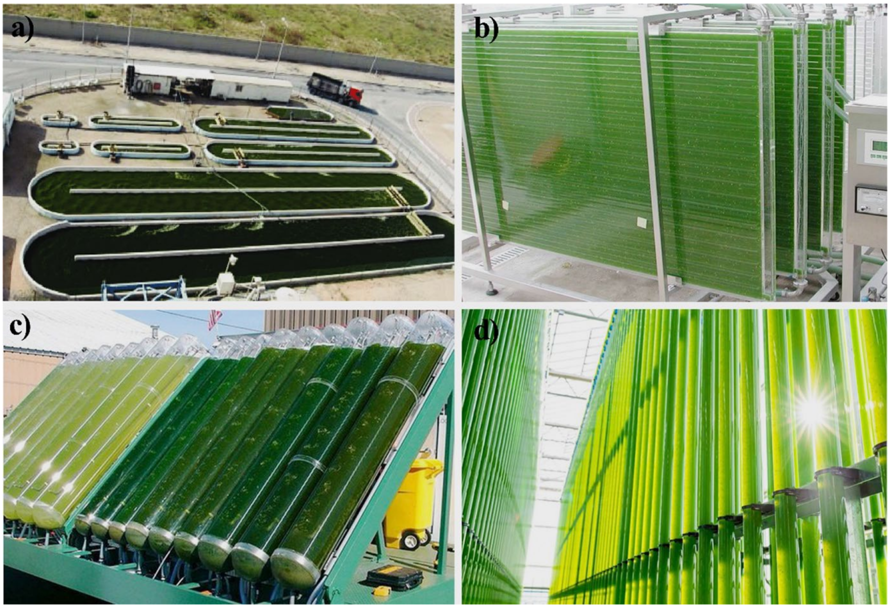


Fig. 3 **a** Open pond, **b** plate photobioreactor, **c** tubular photobioreactor, and **d** bubble column photobioreactor [8]

is the key as the amount of sunlight received depends on it. Light, water temperature, and evaporation are some of the main factors affecting this system since unregulated temperature, lack of sufficient light penetration, evaporation loss, contamination, etc. are some challenges [3]. Since the cultivation process in the open pond system can be done in any suitable open surrounding, it is way cheaper to construct than photobioreactors. However, this system yields very little algal biomass, ranging from 0.02 to 0.20 mg/l/day [25]. On the other hand, closed systems, also known as photobioreactors (PBRs) are high yield-controlled systems that allow the maximum amount of light and mixing of the system according to the biofuel requirements. They are mostly designed with transparent materials such as plastic or glass to allow the light to penetrate and are of various shapes, such as flat plate, tubular, vertical column, bubble column, etc. (Fig. 3) [3]. Auxiliary tanks are used to separate excessive oxygen and other highly maintained control systems are incorporated to ensure maximum efficiency, which makes PBRs expensive to set up and hence only used to produce high-quality biofuel rather than bio-oil only [5].

Attached growth or biofilm systems are simple, low-cost cultivation that does not require dewatering and is often combined with closed systems [17]. Recently, a combination of both closed and open systems has also been established known as a hybrid system which can ensure higher biomass productivity and excessive nutrient removal [3]. These systems are also appropriate for large-scale algae cultivation for commercial purposes. Furthermore, heterotrophic cultivation is another cultivation method mainly for algal species that can survive in the dark and use organic carbon compounds as energy sources [3]. These kinds of algal biomass have a high growth rate, high biomass yield, and are cheaper to harvest. Japan has successfully cultured such heterotrophic algae called *Chlorella* with an annual production of around 1100 tons [5]. However, the high risk of CO_2 during this process makes this system unsuitable for large-scale cultivation [25].

The design and choice of cultivation method selection depend mostly on the final application and the byproducts obtained. The productivity of cultivation methods is also dependent on seasonal variations, the design of the systems, and other factors. There have been numerous techno-economic analyses (TEA) conducted to evaluate the efficiency of cultivation methods to increase biomass yield and lower cost and footprint [17, 26]. In one of such TEA developed by the National Renewable Energy Laboratory (NREL), four different PBRs were analyzed with respect to open systems (Fig. 4) [26]. It was found that all PBR systems cost much higher than open ponds for operations, power generation for mixing, aeration and cooling, and capital cost. However, the annual average productivity of the algal biomass was found to be 25 g/m^2/day for PBRs, which is double the amount in open ponds cases which yielded only 8–12 g/m^2/day.[26]. The cultivation area requirement is also less in PBR than in open systems. These results indicate that the cultivation system selection depends on the aimed scale of algal biomass production. PBRs, although expensive, are more space-efficient that can cultivate algae under customized conditions. In an experimental study conducted recently, a small pilot-scale tubular PBR was tested against a mesh ultra-thin layer (MUTL) PBR with similar scale. After a series of experiments, the MUTL-PBR was found to yield almost three times the biomass than the tubular PBR, which were 6.6 g/L and 2.1 g/L respectively [27]

Furthermore, in recent studies, different bioreactors for algal biomass cultivation were explored. One such system is called a revolving algal biofilm, which was first designed by Prof. Zhiyou Wen, Iowa State University. It is a suspension-based system where algae are cultivated on a material surface and later harvested through

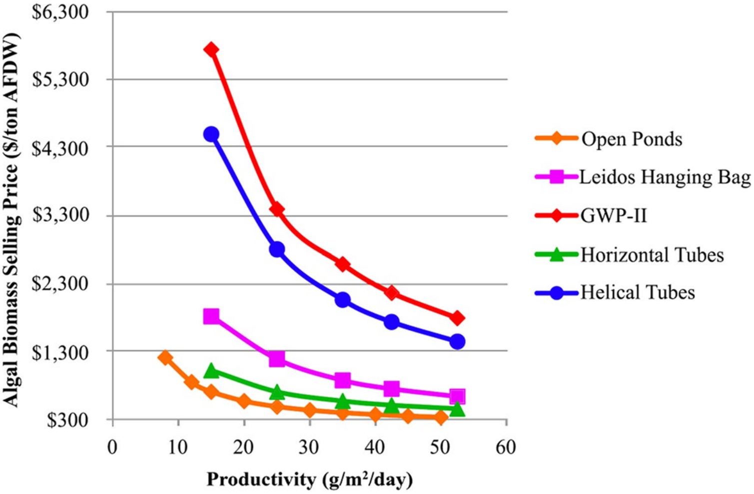


Fig. 4 Algal biomass cultivation productivity for various systems [26]

scraping [28]. This system can yield 40 g/m^2 of biomass, reduces cost, and is currently commercialized in microalgae cultivation [22]. Similarly, a bioreactor cultivation system was developed by the National Aeronautics and Space Administration (NASA) which aimed at Offshore Membrane Enclosures for Growing Algae (OMEGA). This system usually has large flexible plastic tubes, and the mixing process is powered by energy-driven ocean waves. This system yields 4.5 g/m^2/day, with reduced energy consumption and investment cost. However, since it is dependent on ocean waves, the system is highly limited to coastal areas [22].

3.2 Algal biomass harvesting

Algal harvesting is a crucial action that involves the separation and formation of biomass slurry and should be done effectively regardless of the algal species. It is challenging due to several factors like cost, proper utilization, and handling [5]. If the cultivation is done in saline water, the harvesting capital requirement is high. In mass harvesting of algal biomass, flotation, flocculation, and gravity sedimentation methods are used, followed by thickening centrifugation and filtration [29].

Flocculation is a preliminary step for bulk algae harvesting and is suggested to be an excellent method of harvest. This process is done by microbes and chemicals where that flocculant will be algae species-specific, such as cations and its polymers [29]. During this process, algal cells are negatively charged, and flocculants are added which neutralize surface charge resulting in increased particle size and facilitate aggregation [5]. The flocculation method is suitable for handling large-scale algal cultures with less energy consumption than mechanical separation. Next, the floatation process gets facilitated by air/gas bubbles that get attached by algal cells, resulting in the formation of float on the surface for harvesting [5]. This procedure could either be electrolytic or dispersed air floatation. In electrolytic type could be used in salt water and not applicable for microalgae, for which dispersed flotation is used where the air bubbles could be as tiny as 40 µm [29]. Micro-, Macro and Ultra-filtration are designed to harvest algae of smaller sizes using membranes and pushing thickened liquid through it. It is best suited for delicate algal biomass that requires trans-membrane force and flow speed settings [29]. Membrane filtration is economical when compared to flotation but is expensive for large-scale membrane installation and maintenance. On the contrary, gravity sedimentation is a low-efficiency conventional method suitable for large particles and is utilized in wastewater treatment plants. It is also similar to filtration methods that harvest large algae like *Spirulina* [5].

The biomass slurry produced after the harvesting process contains 20–30% of solid content which then undergoes the dewatering process [5]. Usually, in a low humidity climate, this process can be carried out by sun drying. But, due to the small sizes of algal biomass, other methods are used for effective dryings, such as spray, drum, or freeze-drying methods. These methods are also cost and energy-intensive, therefore, often considered as one of the economical obstacles for the whole process [5]. A techno-economic analysis (TEA) published in 2018 on algal biomass harvest and dewatering stated that they comprise 3–15% of the total production costs [30].

Though it was found that the flocculation system is the lowest energy-intensive, the chemicals, and flocculant loss are again added to the total cost. Hence, several research works suggest implementing supplementary systems like pressure filtration and spiral plate technology to overcome the challenges associated with harvesting and dewatering systems [30]. Table 1 below briefly demonstrates the comparisons between the main harvesting techniques:

4 Life cycle assessment

In recent years, the field of third-generation biofuels is deeply explored to find solutions to the global energy and environmental crisis. With limited current technologies, algal biomass often seems to be an expensive choice. Large-scale biofuel production from algae needing advanced types of equipment, water, nutrients, and energy is a challenge, especially from a commercial point of view. On the other hand, a variety of steps, like isolation, purification, and other conversion methods tend to be time-consuming [3]. To consider biofuels being used in current automotive or machine engines, they are required to be compatible with existing petro-fuels. Internationally, certain compatibility standards have been issued, like the American Society for Testing and Materials (ASTM) by the United States and European Nation 14,214 by the European Union [33]. If any algal biofuel does not meet these requirements, they are blended with petro-fuels to be used in engines. For example, the currently available B5–B20 blends of biodiesel (derived from microalgae *Streptomyces platensis*) and petrol. Therefore, producing efficient and cost-effective algal biofuel and using them directly in engines is a current challenge that requires further development.

Life-cycle assessment (LCA) is a strong method for assessing various environmental aspects of a particular system and therefore is a significant part of analyzing the proficiency of third-generation biofuels [34]. LCA has been extensively used previously to assess the environmental impacts of systems related to biomass, such as the production and generation of biofuel, bioenergy, and other byproducts [27]. Likewise, various international organizations and research have investigated the LCA of biofuel production from algae. Therefore, in this paper, some of the major aspects are reviewed to get a broad idea of how much the production of third-generation biofuels is efficient following sustainability, energy consumption, and cost.

4.1 Economic outlook

Cost estimation of algal biofuels is a significant measure to analyze the current status and future scope as a renewable energy source. Several parameters can be evaluated for cost analysis, such as feedstock, cultivation and harvest costs, production cost, energy cost, etc. A study was done by the US Department of Energy (DOE) in 2015 where it was noted that 87% of the total cost of biofuel production was cultivation costs. DOE estimated that 1 ton of dry algal biomass production cost around $1225 in 2015. The cost could be brought down to 60% in 7 years if there is

Table 1 Advantages and disadvantages of different harvesting techniques

Harvesting technique	Advantages	Disadvantages	References
Flocculation	Low-cost and energy Time-saving Can be used as large-scale harvesting	Flocculants like *chitosan* cause contamination at high doses and might be expensive	[3, 27, 31]
Floatation	Time-saving Less space required	High energy consumption	[3, 32]
Filtration	Less expensive compared to other techniques Low energy consumption	Not suitable for large scale Membrane can be clogged easily and needs replacements	[3, 29, 32]
Gravity sedimentation	Suitable for wastewater plants Easy to operate	Limited to bigger microalgae Time-consuming	[3, 32]

a technological improvement [24]. This is because algal biofuel selling prices differ based on cultivation systems.

Techno-economic analysis (TEA) has become a significant tool in recent years to study and estimate the economic feasibility of algal biofuels. There are numerous TEAs conducted that integrate various aspects of third-generation biofuels, such as capital and operation costs, cultivation, harvest and production processes, cash flow, and risk assessments [24]. One of the most widely studied TEA is the cost of open/raceway ponds and the PBRs. It was found that PBR systems are roughly twice more expensive than an open pond, \$8.52–\$12.73 gal, and \$18.10–\$32.57 gal respectively [35]. A 2012 study revealed that PBR systems dominated in total capital cost are 12.7 times higher than the open pond system [36]. Similarly, cost estimation conducted in a recent study on open ponds and different types of PBRs, the total cost of cultivation is least for the open ponds (Fig. 5) [26]. Additionally, operational costs like labor cost, power consumption, water, and nutrient costs are higher in the PBR system. As a result, these expenditure factors affect the final biofuel product extensively. However, in a 2011 study, estimated selling prices for biodiesel from the open pond and closed PRB were \$2.97/L and \$4.93/L respectively [37]. Algal biomass selling price is also higher in PBRs, which can go up to \$1,737/ton in PBRs and \$494/ton in open ponds [26].

Since PBR systems are highly commercialized for algal biomass, their high production costs resulted in increasing the final biofuel product. It was seen that crude oil from algal biomass tends to be expensive progressively. As per a study done in 2011, the production cost of crude oil from algae ranged from \$2.87 to \$3.51/L [24], which increased in 2016, ranging from \$4.40 to \$4.62/L [35]. Therefore, it can be concluded that there is a need for overall improvement in algal biofuel production

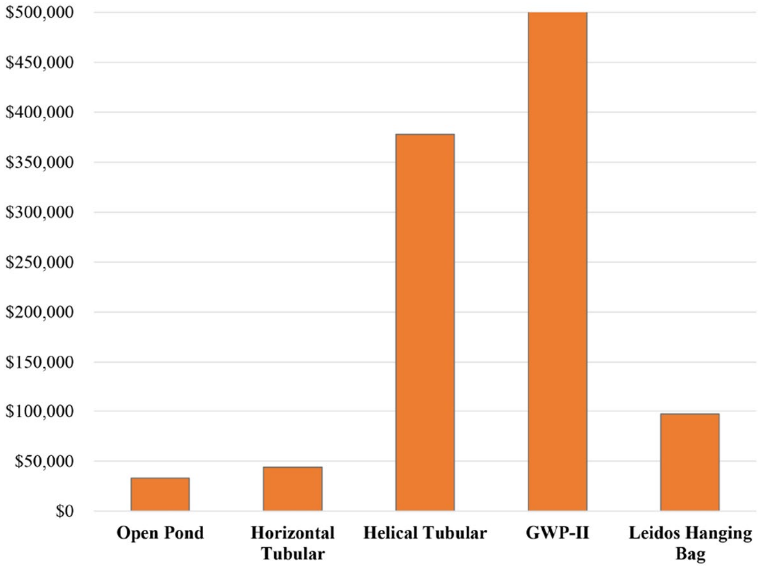


Fig. 5 Capital cost estimation of algal cultivation for open ponds and different PBRs in TEA model [26]

systems that will decrease capital and operating costs while maintaining the end products' quality and efficiency [35].

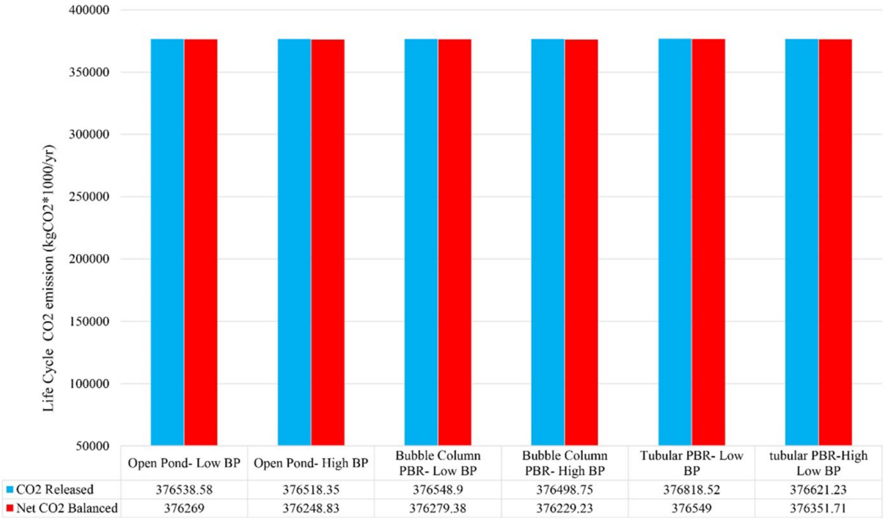
4.2 Water footprint

Water is one of the major elements in the cultivation and harvest of algal biomass because of its significant role in maintaining temperature and delivering nutrients [38]. The estimated requirement for producing 1L of biodiesel is said to be 3000L of water [33]. Therefore, major stress is imposed on water resources around the world because of algal biofuel production. The water footprint (WF) of algal biofuel production is calculated considering the direct and indirect usages of freshwater. Freshwater is directly used in the algae culture mediums, cultivation processes, and as makeup water for the losses during harvesting. Indirectly, they are used in operational processes, such as electricity, culture medium circulation, etc. [39]. According to a study, the WF for algal biomass harvesting for biodiesel is 3726 kg water/kg without reusing the water. Additionally, among all the consumed freshwater, almost 84% is discharged after harvesting, and the remaining is lost through the evaporation or drying process [33]. Hence, if the harvested water is not reused, WF goes very high. It could go down to 591 kg water/kg if 100% harvest water can be recycled. Few recent studies have reported ways of reducing WF in the production of algal biofuels. One such study suggested multiple strategies to reduce freshwater consumption such as recycling the harvested water, alongside using wastewater and seawater in the process [38]. Additionally, this strategy is found to reduce the nutrient requirements by 55% if used wastewater and 90% if used seawater. While using seawater or wastewater can reduce the use of freshwater by 90%, but they cannot replace it. This is due to multiple reasons, such as lower lipid content in marine algae, difficulty in isolation and culture, expensive setup, various harmful components of wastewater [3], etc. Freshwater will still be needed as make-up water for dilution purposes and is also determined by region, climate, and other factors. High-density cultivation can be another method, which states that high biomass productivity species of algae like *Chlorella* sp. and *Spirulina platensis* consume less water than low biomass productivity species. Furthermore, multiple studies have demonstrated that conventional cultivation systems for microalgae consume the most water, and hence making non-suspended growth systems more effective [40]. Due to these reasons, biofilm reactors were suggested as a method to reduce WF, since they target wastewater, swine, and dairy effluents [41]. Another strategy to cultivate high-density algal biomass is to use heterotrophic cultivation. This method was proven to increase lipid content in algal biomass by 55%, which creates a high-density situation and thereby reduces water consumption [42].

Despite implementing the strategies mentioned above, the WF issue of algal biofuel production is a challenge. This is because while methods like recycling reduce water consumption significantly, the production of biomass reduces in subsequent recycling processes [38]. Moreover, non-suspended methods also require special focus for different aspects like nutrients, and maintenance. According to IEA, currently, there is no compliance threshold to include water in the LCA of algal biofuel by the Energy Independence and Security Act (EISA) [17]. However, since water consumption is a sustainability concern, several organizations including EPA are continuously working towards making third-generation biofuel production to be water-efficient.

4.3 CO_2 footprint and fixation

Recently, the evolving biological carbon capture and utilization technologies are stepping towards being carbon negative, that is, the system will reduce its carbon footprint lower than the neutral amount [43]. However, a large amount of CO_2 emissions is associated with various stages of algae cultivation and harvest. Any source of CO_2 can be used for algal biomass cultivation; however, pure CO_2 is needed in most cases since atmospheric air contains less amount [17]. It takes almost 2.0 g of CO_2 to produce 1 g of ash-free dry algal biomass. In the latest research, it was observed that drying and lipid extraction accounted for 57% and 32% of the total CO_2 generated respectively [44]. In the algae bioenergy report published by IEA, it was found that placing an algal cultivation firm near a source of flue gas is an effective way to provide an adequate amount of CO_2 along with incorporating carbon fixation. it was stated that algal biomass can process 30% of a factory's emissions on a peak CO_2 emitting day [17]. Moreover, some literature found algal biofuel production tends to almost balance the CO_2 generated during energy production and consumed during growth, making it carbon neutral [43]. An analysis of carbon fixation done by Dasan et al. 2019 [44] illustrates that there is a CO_2 balance gap of 0.072% with no CO_2 mitigation (Fig. 6). Although this situation is less compared to fossil fuel production, it significantly affects the sustainability of algal biofuel and adds to the overall energy demand, where it is linked with the heat and electricity



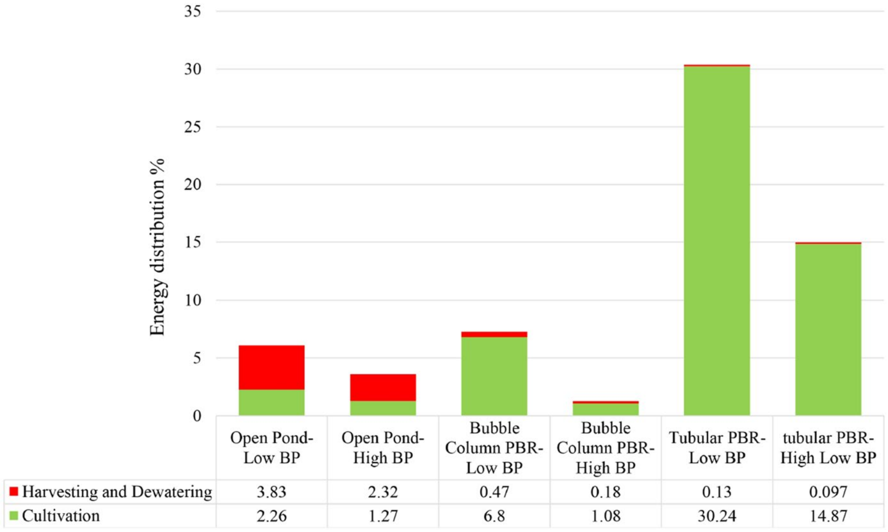
	Open Pond- Low BP	Open Pond- High BP	Bubble Column PBR- Low BP	Bubble Column PBR- High BP	Tubular PBR- Low BP	tubular PBR-High Low BP
🟦 CO2 Released	376538.58	376518.35	376548.9	376498.75	376818.52	376621.23
🟥 Net CO2 Balanced	376269	376248.83	376279.38	376229.23	376549	376351.71

Fig. 6 Net CO_2 emission balance of the various systems [44]

requirements. This leads us to the fact of improved PBR systems which will be energy and cost-efficient. It is also highly suggested that algal cultivation be integrated efficiently with factories and plants for a higher concentrated and pure supply of CO_2 to optimize cost and environmental impact [17].

4.4 Energy demand

Converting microalgal biomass to biofuels in an energy-efficient manner has been a challenge in recent years. In the latest research done on the LCA of microalgal biofuel, it was found that a high amount of energy is consumed during drying and lipid extraction processes [44]. These energies are usually in the form of heat used in evaporating, heating reaction mixtures, and recycling solvents. In Fig. 7, the PBR systems in the study showed almost similar energy distribution in the terms of harvesting and drying processes, whereas it's more for an open pond system. However, PBRs require the highest amount of energy in the cultivation processes than open ponds. Cultivation in tubular PBR consumes the highest amount of energy, 30.24%, and 14.87% for high and low boiling points respectively [44]. Moreover, the tubular PBR system was found to be the most energy-intensive system, accounting for 1446.74 MWh/year and 1777.70 MWh/year for low and high boiling point processes respectively [44]. Likewise, a TEA published by the NREL in 2019 talks about various aspects of algal biomass, and different types of PBRs were investigated. They found the power usage by the PBRs range from 12,967 to 83,155 kW for the total facility, which includes machinery like chillers, generators, and other types of equipment [18]. Open ponds comparatively have very little power consumption which is 9753 kW total power for a facility. Therefore, slower developments in the



	Open Pond-Low BP	Open Pond-High BP	Bubble Column PBR-Low BP	Bubble Column PBR-High BP	Tubular PBR-Low BP	tubular PBR-High Low BP
🟥 Harvesting and Dewatering	3.83	2.32	0.47	0.18	0.13	0.097
🟩 Cultivation	2.26	1.27	6.8	1.08	30.24	14.87

Fig. 7 Energy distribution of algal biofuel production [44]

technological fields of PBRs in algal biofuel production limit its commercial large-scale expansion.

5 Integrated applications and future advancements

5.1 CO_2 fixation through flue gas

Carbon capture and CO_2 mitigation are being widely studied in recent years, and algae are found to be excellent in bioconversion of CO_2. Therefore, bioenergy from algal biomass can be a great source for effective CO_2 mitigation as their processes take away atmospheric CO_2 through photosynthesis, drying, cultivation, etc. However, this benefit is utilized limitedly as CO_2 concentration is lower in water bodies and the air surrounding the algae culture places [24]. Likewise, the type of algal cultivation system plays a key role in CO_2 bioconversion. For instance, open system cultivations are low-cost and widely used, but biofuel efficiency and CO_2 fixation are very limited [25]. This system also has high evaporation losses that contribute to this factor. In comparison, closed PBR systems allow a controlled environment for algal cultivation, hence allowing better CO_2 fixation. Therefore, to make the algal biofuel production effective for CO_2 fixation, PBR systems need to be applied on a commercial scale with further improved designs, which is very expensive. Various research and practices are recently developed to integrate CO_2 capture in algal cultivation processes. Algae can absorb CO_2 from flue gases released from various sources, such as power plants, factories, and industries, power stations, etc.

Additionally, this technique is also beneficial to algal cultivation as it increases algae growth rate and productivity along with implementing CO_2 mitigation to the entire production system. However, transportation of the flue gas gets expensive. Therefore, placing microalgal cultivation facilities near flue gas-emitting sources is a key development goal. Global Algae Innovations (USA) has come up with advanced technologies for optimized CO_2 fixation which was integrated into a powerplant in Brazil [45]. This process of CO_2 fixation can be demonstrated in a simplified way, where the CO_2 produced from any thermal powerplant can be utilized in the adjacent microalgae cultivation plant (Fig. 8) [46]. A very recent feasibility study of CO_2 bio-sequestration through algal biomass was conducted in a gas power plant in Iran, which turned out to be very economical compared to conventional carbon capture systems [47]. Likewise, a thermal power plant in India successfully demonstrated carbon capture through an open pond cultivation system and found 70–90% CO_2 fixation efficiency [1]. Hence, the field of CO_2 fixation using algal cultivation systems have a future scope and deserves further development.

5.2 Wastewater treatment

Algal biomass plays a significant role in wastewater treatment (WWT) by directly absorbing the nitrogen and phosphorus present in the medium. The components in the wastewater stream also have potential benefits in algal growth. Thus, integrating

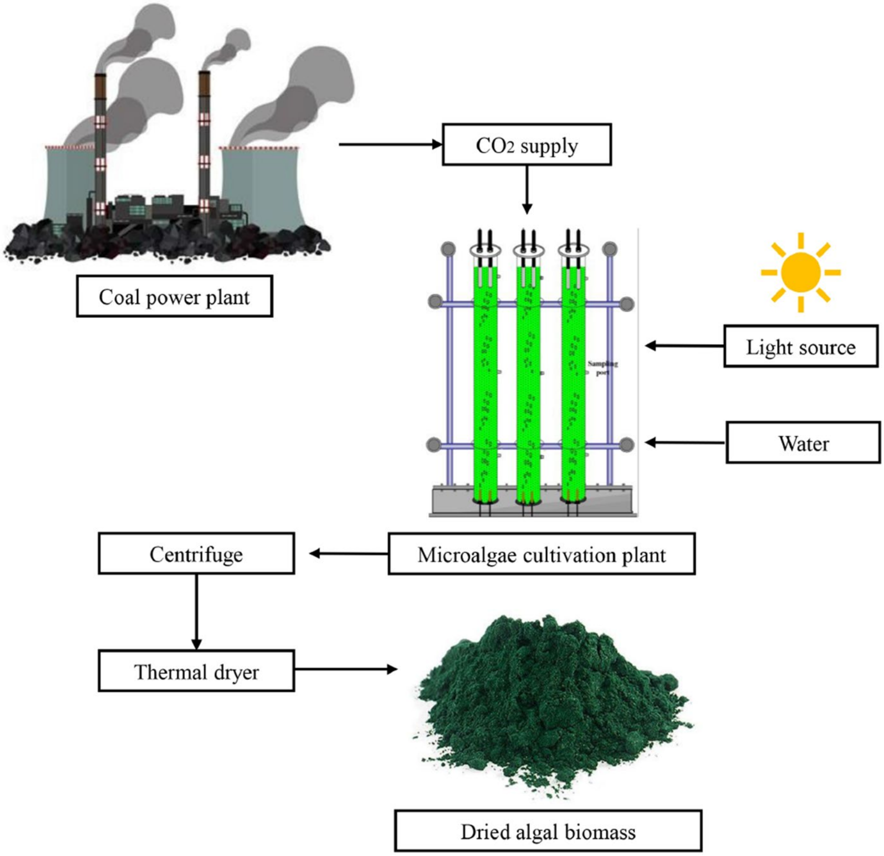


Fig. 8 CO_2 capturing from coal powerplant using microalgal cultivation [46]

algal production in wastewater treatment plants is said to improve the overall economy and sustainability of both processes, especially for the large-scale production of third-generation biofuels [17]. A current inexpensive approach is called a high rate algal pond (HRAP), which includes both PBR and oxidation pond [48]. It is an effective system that removes nutrients and biochemical oxygen demand (BOD) and carries on producing algal biofuel in the following stages. However, it is found that such wastewater resources tend to have low CO_2 concentrations. Thus, researchers have suggested the addition of flue gas to such an algal cultivation method. Integrating additional CO_2 from flue gas serves both CO_2 fixation and wastewater treatment, making the system economic and environment friendly [48]. Similarly, another alternative approach to integrating algae production with WWT is from lignocellulosic ethanol fermentation plants and can be found economically viable [17].

Several studies in the past demonstrated the integration of algal biomass in treating wastewater. In research on wastewater management, algal growth was coupled with hydrothermal liquefaction (HTL) as an environment-friendly method [49]. This method is useful for recovering nitrogen and phosphorus as well as absorb heavy metals like lead, chromium, copper, etc. Since microalgae have a rapid metal uptake, this integration is low cost and energy-saving and produces clean water and crude oil as byproducts (Fig. 9) [50]. Furthermore, a recent study was published where a wetland-microbial fuel cell assisted by algae was integrated for efficient wastewater treatment [51]. In this system, the algal biomass acted as catholyte and passively aerated the cathode ions in the system, improving the performance significantly. This then resulted in the removal of chemical oxygen demand (COD) and other inorganic pollutants from municipal wastewater.

Furthermore, the IEA 2017 report suggests incorporating the WWT with algal biomass biorefinery to deal with the organic and inorganic contents and water usage [17]. This will ensure efficient water management, BOD concentration as well as ammonia level, and other solids. Therefore, efficient integration of WWT with algal production is a potential developmental field for commercializing third-generation biofuels from algal biomass and is broadly researched at present.

5.3 Conversion to bioelectricity

Several studies done in the past few years have found that microalgal biomass can be used as biocathode in a microalgae-assisted microbial fuel cell (MA-MFC) (Fig. 10) [52]. In these kinds of cells, the chemical energy stored in the microalgae biomass is converted into electrical power, which further produces bioelectricity and can be used in various fields. Integrating biofuel productions like biodiesel and bioethanol with bioelectricity is considered one of the most sustainable applications of this

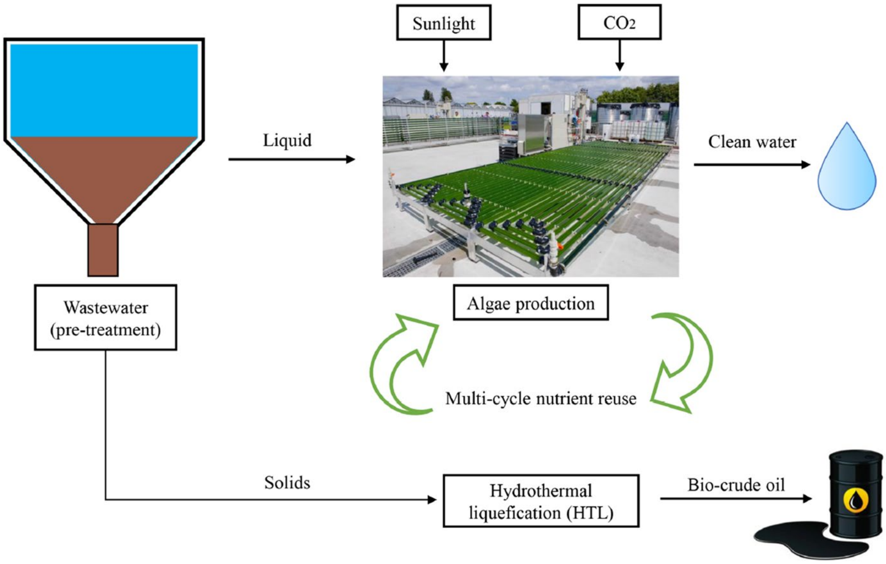


Fig. 9 Process for integrating algal cultivation with WWT plant using HTL [50]

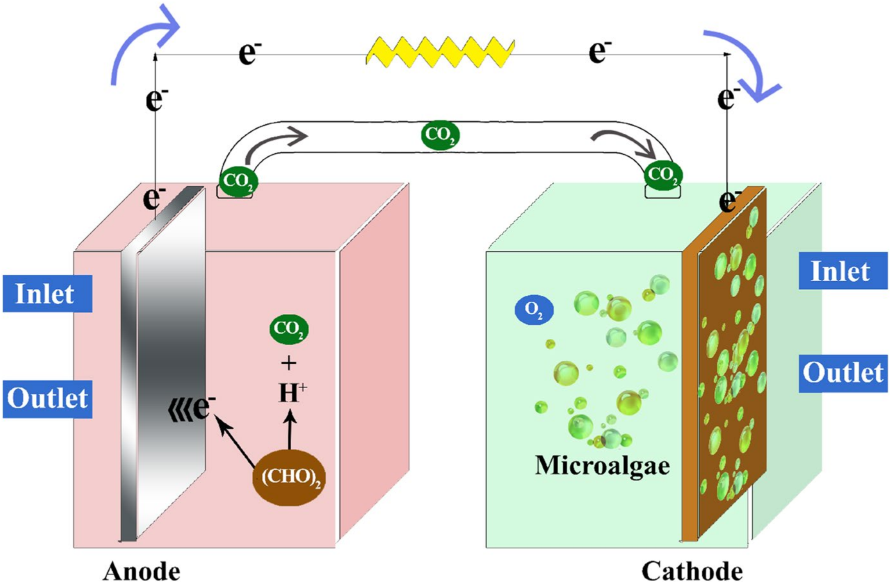


Fig. 10 Schematic diagram of a conventional MA-MFC for bioelectricity conversion [52]

system [52]. Moreover, MFCs are also used as sustainable devices for WWT, using wastewater as a substrate and at the same time produce bioelectricity [53].

This kind of optimized system was proven for high pollutant removal efficiency with 71–92% COD removal from wastewater. Bioenergy can also be produced with the integration of MA-MFC and WWT when varied substrates are used. Several studies reported the various amounts of power densities achieved from such a system, where the maximum yielded power density ranged from 1240 to 4310 mW m^{-2} [52]. Furthermore, MA-MFC can be utilized in other applications alongside the production of bioelectricity, such as seawater desalination, carbon capture, bio-hydrogen production, biosensing, etc. [53]. However, there are few limitations of this sustainable process, such as the slow activity of autotrophic microalgae, energy loss, low performance compared to chemical fuel cells, issues regarding algal biomass harvesting, etc. [52]. The voltage in the MA-MFCs also decreases over time due to various organic activities of the microalgae. Therefore, this approach is still in its infant stage and requires much more research and technological development to be produced on a large scale.

5.4 Future advancements

5.4.1 Implementation of biorefinery

The concept of the biorefinery is to break down biomass into various fuel and non-fuel bioproducts in sustainable methods [3]. Studies have been published stating the future scope of algal biorefinery where the various major components of algae will be extracted into valuable by-products. These components include proteins, carbohydrates, pigments, lipids, and other metabolites. Algal biorefineries have significant scope in the future for maximum optimization of biomass as well as a variety of developed products. One such fuel-based biorefinery is called combined algal processing (CAP), designed by the NREL [54]. In this biorefinery, the fermentation process first produces bioethanol, followed by efficient lip dextran that gives "Green Diesel". Nevertheless, biorefineries could become costly if not properly optimized through techno-economic strategies. Successful integration of algal biorefineries has significant potential with a positive impact on the environment [54].

5.4.2 Genetic modification

One of the main advantages of algae, microalgae to be specific, is that they can be genetically modified for maximum optimization. It is very much possible to genetically modify algae to increase their lipid and fatty acid contents for higher oil yield. With increasing future demand for large-scale algal biofuel production, engineered microalgal biomass has future potential. These future genetic modifications mainly focus on enhancing photosynthesis, higher lipid biosynthesis, metabolic engineering, and other new pathways for desire-specific outcomes [27]. Moreover, these enhanced modifications were found to reduce the cost and energy of microalgal strains and cultivations significantly, up to 85% and 16% reductions respectively in some cases [55]. When Genetic modification of microalgae was studied in recent literature to study its opportunities for implementation in biorefineries. Methods like inserting foreign DNA and directed gene editing have been previously seen as effective in microalgae genetic modification to achieve enhanced quality biomass [54]. Another research was conducted on microalgae genetic engineering in an attempt of improving CO_2 sequestration. Three main targets were established for genetic improvement: improving CO_2 fixation pathways, altering light-harvesting properties, and implementing additional pathways to minimize CO_2 and energy loss [56]. However, this research concluded that these pathways or methods of modifications are currently practiced very minimally, and needed larger focus for scaled-up applications. Currently, genetic modification of microalgae is mainly available in research experiments and small-scale productions due to several existing challenges, such as the pressure of finding the right genome modification for maximum outcomes [57]. Since the effectiveness of each of the genetically modified algae must be delicately explored to successfully increase biofuel productivity, there is a chance of other microalgae production aspects getting overlooked. Thus, further advanced researches are required to find a balance between solving the existing algal biofuel production issues and enhancing the genetic modification technologies.

5.4.3 Green diesel from algae

Green diesel is the hydrocarbon analog, typically containing 15–18 carbon atoms in a molecule [58, 59]. Unlike biodiesel, which is produced from transesterification, green diesel, or "renewable diesel" is produced by hydrotreatment of fats or oils

[1]. Their chemical structure resembles the fossil petroleum diesel, allowing them to be directly used in CI engines as per the US ASTM D975 and EN 590 in Europe specifications [60], and thus, eliminating the need for engine modification. Green diesel composition lack oxygen, which makes it a more stable and higher heating value than biodiesel. Previous research was conducted on green diesel which shows higher savings in fossil energy per ton of biofuel when compared to biodiesel [61]. Table 2 demonstrates the comparison between green diesel, biodiesel, and conventional petroleum diesel. It can be seen that green diesel has the highest heating value, better stability, and cetane value than biodiesel and petroleum diesel [62]. On the contrary, green diesel and biodiesel have the lowest sulfur emission. However, the production of green diesel from algal oil is expensive and development in this field is still an ongoing process. Moreover, a considerable number of studies are also required to further research on green diesel to make this solution economical in large-scale practice [63]. Therefore, further research on crude algal oil purification and advanced hydrotreatment with effective catalysts is highly expected [1].

5.4.4 Bio-jet fuel

Alcohols from algal biomass are considered one of the major feedstocks for creating bio-jet fuel. Algal oil can also produce bio-jet fuel through technologies that are photoautotrophic, heterotrophic, and mixotrophic. They can be blended up to 50% with conventional aviation fuel as per the ASTM D7566 specification [64]. According to an NREL report, the global aviation industry consumed almost 1.5–1.7 billion barrels of conventional jet fuel annually, which greatly contributes to global carbon emissions. Whereas, jet fuel from algal oil has been already approved by EPA and is found to be ecofriendly, reducing 76% of GHG emissions than conventional ones [65]. The global aviation industry has set a future target to achieve carbon-neutrality by 2020 and a 50% reduction in CO_2 emission by 2050 [66]. Although the market for bio-jet fuel is limited in recent years, it is likely to grow in the coming years due to the expected rise of climate change issues [67]. Therefore, algal bio-jet fuel has an important role in gradually replacing conventional jet fuel to achieve global sustainability targets.

Table 2 Comparison between green diesel, biodiesel, and conventional petroleum diesel [62, 63]

Properties	Unit	Green diesel	Biodiesel	Petroleum diesel
Oxygen	%	0	11	0
Cetane	–	70–90	50–65	40–55
Heating value	MJ/kg	44	38	43
Sulfur	ppm	< 2	< 2	< 10
Density	Kg/L	0.864	0.838	0.86–0.90
Viscosity	Mm2/s	5.2	1.9–4.1	3.5–5.0
Cloud point	℃	− 20 to + 20	− 5 to + 15	− 3 to − 12
Oxidative stability	–	Good	Marginal	Baseline

Third-generation biofuels from algal biomass have great futuristic potentials in a variety of fields. along with biofuels, algal biomass provides different byproducts as well which also play significant places. Their integration for WWT and CO_2 fixation is something that is explored quite widely by researchers. However, apart from all these advances, third-generation biofuels are still behind and are not yet commercialized on a large scale. There are few major challenges faced by the algal biofuel industries which need to be addressed and worked forward for.

6 Challenges and barriers for third-generation biofuels

Despite having great potentials, some of the drawbacks of third-generation biofuels hold them back from commercializing, one of which is the production cost. Current data indicate that the production of algal biofuel is comparatively very expensive than first or second-generation fuels [68]. A very recent review article on techno-economic feasibility reported that the production cost of biodiesel from first-generation feedstock ranges ~ 2.57–4.27 US$/GGE (gallon-gasoline equivalent), and second-generation ranges ~ 4.3–6.25 US$/GGE [69]. Compared to first and second generations, the study reported the cost from third-generation feedstock to range ~ 7.0–8.1 US$/GGE. Furthermore, the existing systems for feedstock cultivation and harvesting along with the conversion processes are costly, with other requirements like water, nutrient or energy create a barrier for it to be produced on a large scale. Although various sustainable alternatives have been researched, their implementation is still laid back due to low investments. A report published by IRENA demonstrated the annuals investments in biofuels were more than $20 billion in 2006 and 2007, which however declined sharply and ranged from $10 to 5 billion till 2018. On the other hand, investments for advanced biofuels were comparatively very low, with the highest being $2.5 billion in 2011, and had decreased since then [68]. The IRENA report also conducted surveys to investigate what are the barriers that hold advanced or third-generation biofuels back. The results of this survey showed the US, European and Global perspectives on questions about possible barriers, and three major ones were found to be the cost, policy and regulations, and the investments. Therefore, existing data from works of literature, trials, and experiments, LCA, and TEAs indicate the need for developments in the field of third-generation biofuel production. Several pathways of improvements have been stated in numerous reports and suggest the expected significant role played by algal biofuels in reducing carbon emission by 2050 [68]. If the foremost issues are solved, algal biofuel has great possibilities to contribute to the global biofuel share.

7 Pre and post COVID-19 scenarios for biofuels

The global emergency for the pandemic COVID-19 took many unexpected turns in the world of energy and economy which started its impact at the end of February 2020. Businesses, industries, and agriculture shut down, aviation and transports were banned and a sharp decline in the typical life cycle created lots of changes to this earth. The pandemic induced global economic decline with a huge reduction in petrol and transport fuel consumption, resulting in a reduction of CO_2 in the air. Although this lowered global GHG emission is thought to be unsustainable for the long-term global economy and energy sector [70]. Government associations and economists around the world are extensively assessing the current situation for the prospects of renewable and clean energies once the world starts recovering from the COVID-19.

7.1 Pre COVID-19 plans

Till 2019, global energy and fuel markets had clear estimations on how different renewable sectors are moving forward, what are the forthcoming challenges, and the reasons behind them. Before the global pandemic, economic feasibility has been the major limitation for commercializing algal biofuel production. Despite having numerous research and advancements in newer technologies, large-scale production of biofuel from algae is yet not possible. This was due to several limitations, such as lack of global investments, governmental policies, etc. Research done on the levelized cost of energy (LCOE) of algal biodiesel stated that it was economically infeasible and became profitable only in the late stages of production. The LCOE of algal biodiesel accounts for US$4.86/gallon, which competes with fossil [71]. Numerous studies have found that investment in advanced bioenergy plants is essential to eventually lower the production and selling prices of algal biofuel. An IRENA statistical data (Fig. 11) obtained from the Frankfurt School-UNEP investment statistics shows the in global investments done for biofuels and biomass. It was seen that the investment in biofuels decreased significantly over the years [72]. Developed countries like the US and Europe invested the lowest amount of money into the biofuel sector until 2018 [39]. Hence, hampered initial investment ultimately prevented the development and commercial production of quality algal biofuel.

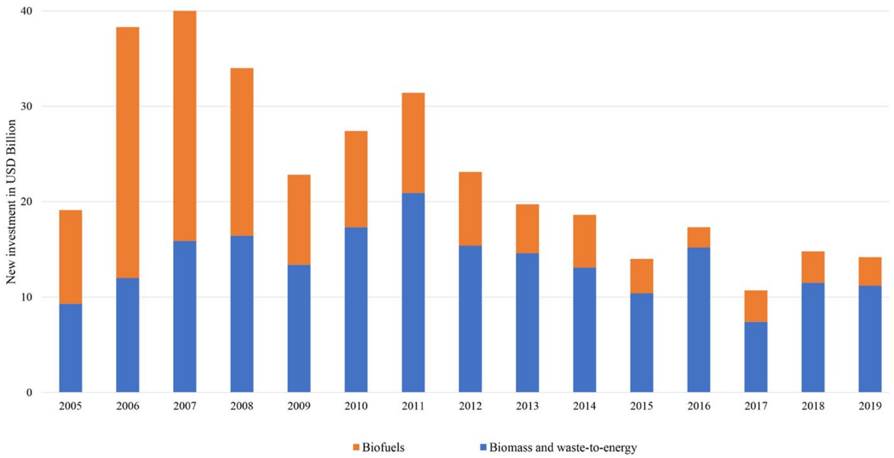


Fig. 11 Global investment trends on biofuels and biomass 2005–2019 [71]

IRENA publishes numerous studies and statistical data in this field, one of which was the 2016 Remap where the trend of biofuel by the years 2030 and 2050 is shown. This report was developed prior to the pandemic claimed that implementation of the REmap strategies can increase 20–70% renewable share in most countries of the world by 2030 [73]. According to IRENA research, global usage and demand for biofuel were expected to increase. Although their share seemed to be lower than solar and wind energy, they still played a significant role as a renewable resource. The main focus of modern renewable energy implementation was anticipated to be in the industrial, building, and transport sectors. It was found that the renewable energy usage share was 11% globally in 2010 and was predicted to be 15% in 2030 in the industrial sector which would increase to 26% with the implementation of IRENA's Remap. However, in the building sector, traditional bioenergy already had the majority of the share but is replaced by advanced biofuels in 2030 estimation. The transport sector, on the other hand, had the smallest share for renewables, which has the highest opportunity to be grown using liquid biofuels. As per the IRENA reference, global transport energy demand will reach 130 EJ/year in 2030 which was 92 EJ/year in 2010 [73].

Consequently, cost issues were stated to be restricting large-scale third-generation biofuel production which could contribute to global biofuel demands. Previously, UAE had proposed to use biofuel in 10% of its transport fuel by 2020. The US also proposed replacing 20% of transport fuel with biofuel by 2022 [3]. According to a report published by the International Energy Agency (IEA), the projected consumption of biofuel blends is higher than the production [41]. Major biofuel-consuming countries except Southeast Asian nations are not on track to meet a sustainable development scenario for biofuel demand by 2030. Similarly, based on IRENA's 2016 Remap, liquid biofuel demand will increase to 500 billion l/year in 2030 [38]. However, currently, there are less than ten commercial advanced biofuel plants are available. Long-term policies are a future challenge that needs to be created to handle this situation.

7.2 Post COVID-19 scenarios

As crude oil prices fell from \$61.14 per barrel in Dec 2019 to \$14.10 per barrel in March 2020, gasoline and ethanol prices faced a decline as well [74]. Due to low gasoline demands and a sharp price decline, ethanol producers are getting low-profit margins, resulting in reduced production. The US ethanol industry uses 40% of the total corn demand [75]. Hence, a reduction in corn production due to the shutdown of agricultural activity and competition for food sources also contributed to the economic drop. Most recent statistics from the Renewable Fuels Association show that the production of ethanol has dropped from 44,268 gals/day in Feb 2020 to 25,914 gal/day in the first week of May 2020 [76]. On the other hand, the impact of COVID-19 on diesel and biodiesel demand reduction is lesser than petrol, gasoline, or ethanol. This is because diesel fuel is used in heavy trucks, machinery, and construction equipment [74]. The monthly biodiesel production report from the U.S. Energy Information Administration (EIA) showed that the production in Feb 2020 was 2 million gallons lower than January 2020 [77]. According to them, soybean oil is the largest feedstock currently for biodiesel production. However, the current situation is estimated to reduce soybean production, leading to a decline in biodiesel at the end of 2020 [74].

In the latest issue of international fiscal affairs, global fiscal policymakers are called for a "green recovery" in response to the pandemic since the induced economic crisis does not change the current climate change challenge [78]. Therefore, decisions are made to address the forthcoming economic drop and recession by focusing on renewable energy transformations, which in turn will open green jobs [79].

7.3 Biofuel in IRENA's post-COVID recovery plan

IRENA published the *Global Renewables Outlook* in April 2020, where it was stated that transforming the energy systems to renewables could contribute to the cumulative global GDP by US$98 trillion between 2020 and 2050 [67]. Biofuels are said to hold a vital position for the end-use sectors and are a significant source of renewable fuel, power, and heat generation. The report urged the replacement of first-generation biofuels with advanced third-generation ones since it is not viable to use food-sourced biomass for fuel conversion at this moment. Its usage is estimated to increase by 23% in shipping, aviation, and industrial sectors in their Transforming Energy Scenario [67]. IRENA proposed the projected liquid biofuel production to rise from 136 billion liters till 2019 to 378 and 652 billion liters in the years 2030 and 2050, respectively [67]. However, noticing the fact that advanced biofuels require larger capital, it is recommended that fossil-fuel investments be shifted towards the production of clean energies. The substantial reduction of fossil fuel prices due to COVID-19 seems to be a great opportunity to enact this recommendation [80].

Currently, however, the impact of COVID-19 is high for biofuel production including 2 million threatened jobs resulted from worldwide lockdown measures and transport fuel demand reduction. Several ethanol industries are facing closure due to pandemic-related disruption in the manufacturing and transport of raw materials. Nevertheless, advanced biofuels were given much attention in the post-COVID recovery plan. Their *Post-COVID Recovery* catalog was published in June 2020 which analyses the impact of the global pandemic and outlines holistic approaches for future economic recovery. The report talks about global energy transition investment and how renewables can boost the global economy over the 2021–2023 recovery phase through GDP and employment expansion [81]. According to the International Monetary Fund (MF), the global GDP can reduce by 3% in the year 2020, leading to a severe recession with the loss of 1.07 million jobs in the fields of fossil fuels and nuclear energy sector over the years 2021–23. IRENA's post-COVID recovery plan states that biofuel supply can play a key role in the 2030 energy transition value chain-related jobs, accounting for 33% of the expected 29.5 million jobs (Fig. 12) [81]. This is one of the reasons investors are shifting their focus to renewables. Based on a market report published by foreign direct investment (fDi)

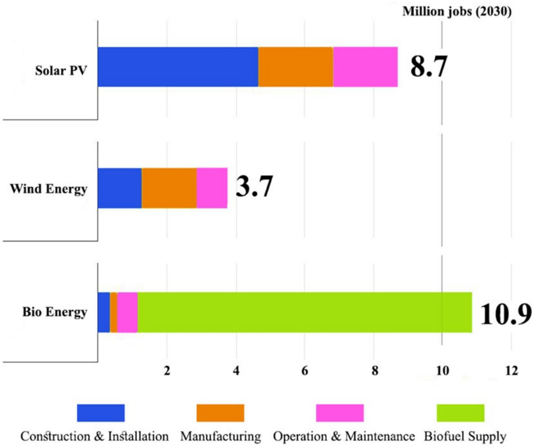


Fig. 12 Distribution of jobs in Transforming Energy Scenario 2030 [81]

intelligence, foreign investors have already announced more than 23 million USD on renewable energy, which is the highest recorded over the past decade [82]. Thus, IRENA highly recommends scaling up the transition of energy, especially in the transport sector by investing and introducing blending mandates for ethanol and biodiesel to boost the biofuel sector.

8 Future scopes and recommendations for third-generation biofuels

Algal biomass production for third-generation biofuels had been seen with various challenges that hold them back from commercializing and replacing the previous biofuel generations. Third-generation biofuels have still not replaced other biofuels due to mainly cost issues. However, the COVID-19 have redirected world organizations to take the opportunity and invest towards a carbon emission-free world. A major focus goes to reforming conventional transport and aviation fuels with advanced or third-generation biofuels. According to the latest report by IEA, biofuel consumption by 2030 is expected to triple (Fig. 13) in the transport sector, which is far more than the amount of biofuel produced [83]. Several countries' biofuel production is obstructed due to the COVID lockdown and restricted movements. Hence, this could be an opportunity to put third-generation forward and promote their usage. The IEA suggests expanding the production of non-food crop feedstocks for producing advanced biofuels since they mitigate land use and offer higher lifecycle GHG emissions. Similarly, IRENA highly recommends the increased use of third-generation biofuels in domestic and international transport, shipping, and aviation. This will not only support the post-pandemic economy but reduce transport and aviation-related emissions by a significant percentage. Long-term cost-reduction and supportive frameworks of bio-jet fuels can slowly terminate conventional jet fuel taking the current pandemic situation's advantage [67].

To scale up the production of third-generation biofuels in the process of coping with COVID-19, governance of sustainability and the establishment of frameworks

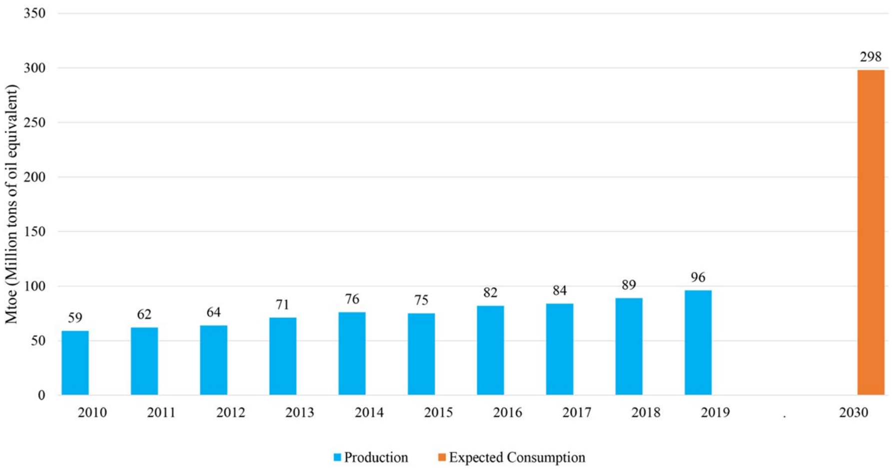


Fig. 13 Global biofuel production compared to expected consumption in 2030 during sustainable reforming [83]

are necessary. Policymakers must develop frameworks, with increased investments are required. Already, the EU, US, and Brazil have established frameworks to ensure biofuel sustainability. however, other countries are needed to be involved as well, along with supported policies and developed technologies to facilitate large-scale production [83]. The IEA also stresses scaling up advanced biofuel share in aviation and marine transports to meet the targets of "Green Recovery" post-COVID. IRENA in their report also recommends stronger regulations, production economy, and feedstock enhancements to enable third-generation biofuels to eventually replace the less sustainable biofuels [68]. Therefore, the enactment of these solutions provided can boost the production of third-generation biofuel from algal biomass and contribute greatly to the sustainable biofuel share.

9 Conclusion

Fossil fuel reserve depletion, CO_2 emissions, and other environmental crises encouraged the world to focus on renewable energy resources. Although biofuel ranks lower than the current usage of solar and wind energy, their contribution to future sustainable development cannot be overlooked. Algal biomass has dynamic characteristics for higher growth rate, production of a variety of products along with the ability to carbon capture and wastewater treatment. However, their cultivation, harvest, and production systems still face several difficulties. Researchers have found several ways to make the total system carbon negative with CO_2 mitigation, low-energy consumption with reduced production costs. However, their application on a large-scale basis is still not performed. Current and potential data show that algal biofuels have a major opportunity to replace fossil fuels with increased use in electricity and heating sectors. Although the COVID-19 crisis anticipates an increase in biofuel production and consumption, the cultivation scope of algae for third-generation biofuels is yet to be set clear. Thus, development in making the production of algal biofuels efficient and cost-effective is highly recommended. Regulations and appropriate policies are required to boost the large-scale production of third-generation biofuels to meet future consumption needs. Similarly, co-products like food, fertilizer, animal feeds, pharmaceuticals, and supplements apart from biofuel production could be manufactured using biorefinery concepts. This, in turn, will aid in reducing production costs while significantly also optimizing algal biomass. Being non-competitive with food sources could give algal cultivation a significant advantage in this current situation. Investments and policies are encouraged to be made globally, which will support research development, improve infrastructure for large-scale production, and establish further genetic engineering for advanced algal biofuels.

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References

1. Raheem, A., Prinsen, P., Vuppaladadiyam, A.K., Zhao, M., Luque, R.: A review on sustainable microalgae based biofuel and bioenergy production: Recent developments. J. Clean. Prod. **181**, 42–59 (2018). https://doi.org/10.1016/j.jclepro.2018.01.125
2. Goli, A., Shamiri, A., Talaiekhozani, A., Eshtiaghi, N., Aghamohammadi, N., Aroua, M.K.: An overview of biological processes and their potential for CO2 capture. J. Environ. Manag. **183**, 41–58 (2016). https://doi.org/10.1016/j.jenvman.2016.08.054
3. Saad, M.G., Dosoky, N.S., Zoromba, M.S., Shafik, H.M.: Algal biofuels: current status and key challenges. Energies (2019). https://doi.org/10.3390/en12101920
4. Renewable, I., Agency, E.: Innovation outlook advanced liquid biofuels. (2016)
5. Sun, Z., Liu, J., Zhou, Z.G.: Algae for biofuels: An emerging feedstock. An emerging feedstock. In: Handb. Biofuels Prod. Process. Technol. Second Ed. 673–698 (2016). https://doi.org/10.1016/B978-0-08-100455-5.00022-9
6. Mat Aron, N.S., Khoo, K.S., Chew, K.W., Show, P.L., Chen, W.H., Nguyen, T.H.P.: Sustainability of the four generations of biofuels—a review. Int. J. Energy Res. **44**, 9266–9282 (2020). https://doi.org/10.1002/er.5557
7. Lim, H.R., Khoo, K.S., Chew, K.W., Chang, C.-K., Munawaroh, H.S.H., Kumar, P.S., Huy, N.D., Show, P.L.: Perspective of Spirulina culture with wastewater into a sustainable circular bioeconomy. Environ. Pollut. **284**, 117492 (2021). https://doi.org/10.1016/j.envpol.2021.117492
8. Adeniyi, O.M., Azimov, U., Burluka, A.: Algae biofuel: current status and future applications. Renew. Sustain. Energy Rev. **90**, 316–335 (2018). https://doi.org/10.1016/j.rser.2018.03.067

9. Behera, S., Singh, R., Arora, R., Sharma, N.K., Shukla, M., Kumar, S.: Scope of algae as third generation biofuels. Front. Bioeng. Biotechnol. (2015). https://doi.org/10.3389/fbioe.2014.00090
10. Gosch, B.J., Magnusson, M., Paul, N.A., de Nys, R.: Total lipid and fatty acid composition of seaweeds for the selection of species for oil-based biofuel and bioproducts. GCB Bioenergy. **4**, 919–930 (2012). https://doi.org/10.1111/j.1757-1707.2012.01175.x
11. Sun, X.M., Ren, L.J., Zhao, Q.Y., Ji, X.J., Huang, H.: Microalgae for the production of lipid and carotenoids: a review with focus on stress regulation and adaptation. Biotechnol. Biofuels. **11**, 1–16 (2018). https://doi.org/10.1186/s13068-018-1275-9
12. Algae Biomass Organization: Algae Basics - History of Algae as Fuel, http://allaboutalgae.com/history/#:~:text=The idea of using algae, fuels (hydrogen and methane). Accessed 10 Jul 2020
13. Hu, I.-C.: Production of potential coproducts from microalgae. Biofuels from Algae. 345–358 (2019). https://doi.org/10.1016/b978-0-444-64192-2.00014-7
14. Guo, M., Song, W., Buhain, J.: Bioenergy and biofuels: history, status, and perspective. Renew. Sustain. Energy Rev. **42**, 712–725 (2015). https://doi.org/10.1016/j.rser.2014.10.013
15. Center for Sustainable Systems, University of Michigan. Biofuels Factsheet. Pub. No. CSS08-09 (2019)
16. IRENA: Workbook: IRENA RE Time Series, https://public.tableau.com/views/IRENARETimeSeries/Charts?:embed=y&:showVizHome=no&publish=yes&:toolbar=no. Accessed 16 Jul 2020
17. IEA: State of Technology Review—Algae Bioenergy. (2017)
18. Gerpen, J. Van: History of Biodiesel – Farm Energy, https://farm-energy.extension.org/history-of-biodiesel/. Accessed 27 Jul 2020
19. Zebrowski, G.: Lookback. Nature. **507**, 528 (2014). https://doi.org/10.1038/507528a
20. Anisha, G.S., John, R.P.: Bio-Engineering Algae as a Source of Hydrogen. Woodhead Publishing Limited (2014)
21. Sağır, E., Hallenbeck, P.C.: Photofermentative hydrogen production. Biohydrogen (2019). https://doi.org/10.1016/b978-0-444-64203-5.00006-x
22. Lam, M.K., Khoo, C.G., Lee, K.T.: Scale-up and commercialization of algal cultivation and biofuels production. In: Pandey, A., Chang, J.S., Soccol, C.R., Lee, D.J., Chisti, Y. (eds.) Biofuels from Algae, pp. 475–506. Elsevier B.V (2019)
23. IEA: Historical and projected global biofuels production, 2017–2020e, https://www.iea.org/data-and-statistics/charts/historical-and-projected-global-biofuels-production-2017-2020e. Accessed 11 Jul 2020
24. Feedstocks, T.G.: Third Generation Feedstocks. (2019)
25. Zhou, W., Lu, Q., Han, P., Li, J.: Microalgae Cultivation and Photobioreactor Design. Elsevier Inc. (2019)
26. Clippinger, J., Davis, R.: Techno-economic analysis for the production of algal biomass via closed photobioreactors: future cost potential evaluated across a range of cultivation system designs. NREL/TP-5100-72716. National Renewable Energy Laboratory, Golden (2019). https://www.nrel.gov/docs/fy19osti/72716.pdf
27. Sandmann, M., Smetana, S., Heinz, V., Rohn, S.: Comparative life cycle assessment of a mesh ultra-thin layer photobioreactor and a tubular glass photobioreactor for the production of bioactive algae extracts. Bioresour. Technol. **340**, 125657 (2021). https://doi.org/10.1016/j.biortech.2021.125657
28. Gross, M., Jarboe, D., Wen, Z.: Biofilm-based algal cultivation systems. Appl. Microbiol. Biotechnol. **99**, 5781–5789 (2015). https://doi.org/10.1007/s00253-015-6736-5
29. Bibi, R., Ahmad, Z., Imran, M., Hussain, S., Ditta, A., Mahmood, S., Khalid, A.: Algal bioethanol production technology: A trend towards sustainable development. Renew. Sustain. Energy Rev. **71**, 976–985 (2017). https://doi.org/10.1016/j.rser.2016.12.126
30. Fasaei, F., Bitter, J.H., Slegers, P.M., van Boxtel, A.J.B.: Techno-economic evaluation of microalgae harvesting and dewatering systems. Algal Res. **31**, 347–362 (2018). https://doi.org/10.1016/j.algal.2017.11.038
31. Mubarak, M., Shaija, A., Suchithra, T.V.: Flocculation: an effective way to harvest microalgae for biodiesel production. J. Environ. Chem. Eng. (2019). https://doi.org/10.1016/j.jece.2019.103221
32. Xu, K., Zou, X., Chang, W., Qu, Y., Li, Y.: Microalgae harvesting technique using ballasted flotation: a review. Sep. Purif. Technol. **276**, 119439 (2021). https://doi.org/10.1016/j.seppur.2021.119439
33. Nagarajan, R., Jain, A., Vora, K.: Biodiesel from Microalgae. SAE Tech. Pap. 2017-Janua, 601–628 (2017). https://doi.org/10.4271/2017-26-0077

34. Sandmann, M., Smetana, S., Heinz, V., Rohn, S.: Comparative life cycle assessment of a mesh ultra-thin layer photobioreactor and a tubular glass photobioreactor for the production of bioactive algae extracts. Bioresour. Technol. **340**, 125657 (2021). https://doi.org/10.1016/j.biortech.2021.125657
35. DOE (U.S. Department of Energy).: National algal biofuels technology review (2016). https://www.energy.gov/sites/prod/files/2016/06/f33/national_algal_biofuels_technology_review.pdf
36. Acién, F.G., Fernández, J.M., Magán, J.J., Molina, E.: Production cost of a real microalgae production plant and strategies to reduce it. Biotechnol. Adv. **30**, 1344–1353 (2012). https://doi.org/10.1016/j.biotechadv.2012.02.005
37. Pandey, A.: Chapter 12. In: Pandey, A., Soccol, C.R., Lee, D.J., Chisti, Y. (eds.) Biofuels from Algae, EBSCO Publishing. Accessed 14 Mar 2020
38. Pugazhendhi, A., Nagappan, S., Bhosale, R.R., Tsai, P.C., Natarajan, S., Devendran, S., Al-Haj, L., Ponnusamy, V.K., Kumar, G.: Various potential techniques to reduce the water footprint of microalgal biomass production for biofuel—a review. Sci. Total Environ. **749**, 142218 (2020). https://doi.org/10.1016/j.scitotenv.2020.142218
39. Martins, A.A., Marques, F., Cameira, M., Santos, E., Badenes, S., Costa, L., Vieira, V.V., Caetano, N.S., Mata, T.M.: Water footprint of microalgae cultivation in photobioreactor. Energy Proc. **153**, 426–431 (2018). https://doi.org/10.1016/j.egypro.2018.10.031
40. Liu, J., Mejia Avendaño, S.: Microbial degradation of polyfluoroalkyl chemicals in the environment: a review. Environ. Int. **61**, 98–114 (2013). https://doi.org/10.1016/j.envint.2013.08.022
41. Mantzorou, A., Ververidis, F.: Microalgal biofilms: a further step over current microalgal cultivation techniques. Sci. Total Environ. **651**, 3187–3201 (2019). https://doi.org/10.1016/j.scitotenv.2018.09.355
42. Shahid, A., Malik, S., Zhu, H., Xu, J., Nawaz, M.Z., Nawaz, S., Asraful Alam, M., Mehmood, M.A.: Cultivating microalgae in wastewater for biomass production, pollutant removal, and atmospheric carbon mitigation; a review. Sci. Total Environ. **704**, 135303 (2020). https://doi.org/10.1016/j.scitotenv.2019.135303
43. Severo, I.A., Deprá, M.C., Zepka, L.Q., Jacob-Lopes, E.: Carbon dioxide capture and use by microalgae in photobioreactors. Bioenergy Carbon Capture Storage. (2019). https://doi.org/10.1016/b978-0-12-816229-3.00008-9
44. Dasan, Y.K., Lam, M.K., Yusup, S., Lim, J.W., Lee, K.T.: Life cycle evaluation of microalgae biofuels production: effect of cultivation system on energy, carbon emission and cost balance analysis. Sci. Total Environ. **688**, 112–128 (2019). https://doi.org/10.1016/j.scitotenv.2019.06.181
45. Duarte, J.H., de Morais, E.G., Radmann, E.M., Costa, J.A.V.: Biological CO2 mitigation from coal power plant by *Chlorella fusca* and *Spirulina* sp. Bioresour. Technol. **234**, 472–475 (2017). https://doi.org/10.1016/j.biortech.2017.03.066
46. Derakhshandeh, M., Atici, T., Tezcan Un, U.: Evaluation of wild-type microalgae species biomass as carbon dioxide sink and renewable energy resource. Waste Biomass Valoriz. **12**, 105–121 (2021). https://doi.org/10.1007/s12649-020-00969-8
47. Olia, A.D.B., Feizollahi, S.: Feasibility study of algae based carbon capture in Tous power plant. In: Conference: 78th EAGE Conference and Exhibition 2016. pp. 1–5. European Association of Geoscientists & Engineers, Vienna, Austria (2016)
48. Molazadeh, M., Ahmadzadeh, H., Pourianfar, H.R., Lyon, S., Rampelotto, P.H.: The use of microalgae for coupling wastewater treatment with CO2 biofixation. Front. Bioeng. Biotechnol. (2019). https://doi.org/10.3389/fbioe.2019.00042
49. Li, H., Watson, J., Zhang, Y., Lu, H., Liu, Z.: Environment-Enhancing Process for Algal Wastewater Treatment, Heavy Metal Control and Hydrothermal Biofuel Production: A Critical Review. Elsevier Ltd (2020)
50. Chen, W.T., Zhang, Y., Zhang, J., Yu, G., Schideman, L.C., Zhang, P., Minarick, M.: Hydrothermal liquefaction of mixed-culture algal biomass from wastewater treatment system into bio-crude oil. Bioresour. Technol. **152**, 130–139 (2014). https://doi.org/10.1016/j.biortech.2013.10.111
51. Gupta, S., Nayak, A., Roy, C., Yadav, A.K.: An algal assisted constructed wetland-microbial fuel cell integrated with sand filter for efficient wastewater treatment and electricity production. Chemosphere **263**, 128132 (2021). https://doi.org/10.1016/j.chemosphere.2020.128132
52. Elshobary, M.E., Zabed, H.M., Yun, J., Zhang, G., Qi, X.: Recent insights into microalgae-assisted microbial fuel cells for generating sustainable bioelectricity. Int. J. Hydrogen Energy. **46**, 3135–3159 (2021). https://doi.org/10.1016/j.ijhydene.2020.06.251

53. Singh, H.M., Pathak, A.K., Chopra, K., Tyagi, V.V., Anand, S., Kothari, R.: Microbial fuel cells: a sustainable solution for bioelectricity generation and wastewater treatment. Biofuels **10**, 11–31 (2019). https://doi.org/10.1080/17597269.2017.1413860
54. di Visconte, G.S., Spicer, A., Chuck, C.J., Allen, M.J.: The microalgae biorefinery: a perspective on the current status and future opportunities using genetic modification. Appl. Sci. (2019). https://doi.org/10.3390/app9224793
55. Fayyaz, M., Chew, K.W., Show, P.L., Ling, T.C., Ng, I.S., Chang, J.S.: Genetic engineering of microalgae for enhanced biorefinery capabilities. Biotechnol. Adv. **43**, 107554 (2020). https://doi.org/10.1016/j.biotechadv.2020.107554
56. Barati, B., Zeng, K., Baeyens, J., Wang, S., Addy, M., Gan, S.Y., El-Fatah Abomohra, A.: Recent progress in genetically modified microalgae for enhanced carbon dioxide sequestration. Biomass Bioenerg. **145**, 105927 (2021). https://doi.org/10.1016/j.biombioe.2020.105927
57. Fajardo, C., De Donato, M., Carrasco, R., Martínez-Rodríguez, G., Mancera, J.M., Fernández-Acero, F.J.: Advances and challenges in genetic engineering of microalgae. Rev. Aquac. **12**, 365–381 (2020). https://doi.org/10.1111/raq.12322
58. Honeywell UOP: Honeywell Green Diesel^{TM} |, https://uop.honeywell.com/en/industry-solutions/renewable-fuels. Accessed 28 Aug 2021
59. Douvartzides, S.L., Charisiou, N.D., Papageridis, K.N., Goula, M.A.: Green diesel: Biomass feedstocks, production technologies, catalytic research, fuel properties and performance in compression ignition internal combustion engines. Energies (2019). https://doi.org/10.3390/en12050809
60. Alternative Fuels Data Center: Alternative Fuels Data Center: Renewable Hydrocarbon Biofuels, https://afdc.energy.gov/fuels/emerging_hydrocarbon.html. Accessed 28 Jul 2020
61. Kalnes, T.N., Marker, T., Shonnard, D.R., Koers, K.P.: Green diesel production by hydrorefining renewable feedstocks. Biofuels Technol. (4), 7–11 (2008)
62. Abdulkareem-Alsultan, G., Asikin-Mijan, N., Lee, H.V., Rashid, U., Islam, A., Taufiq-Yap, Y.H.: Review on thermal conversion of plant oil (Edible and inedible) into green fuel using carbon-based nanocatalyst. Catalysts (2019). https://doi.org/10.3390/catal9040350
63. Azad, K., Rasul, M., Masud, M., Khan, K., Sharma, S., Azad, A.K., Rasul, M.G., Khan, M.M.K., Sharma, S.C.: Review of biodiesel production from microalgae: a novel source of green energy. In: Optimization of biodiesel production process and its production from Australian native plants View project The 9th International Green Energy Conference REVIEW OF BIODIESEL PR. (2014). https://doi.org/10.13140/2.1.3013.0244
64. IRENA: Investment Trends, https://www.irena.org/Statistics/View-Data-by-Topic/Finance-and-Investment/Investment-Trends. Accessed 30 Jul 2020
65. Wang, W.-C., Tao, L., Markham, J., Zhang, Y., Tan, E., Batan, L., Warner, E., Biddy, M.: Biojet fuel conversion technologies. Renew. Sustain. Energy Rev. **53**, 801–822 (2016). https://www.nrel.gov/docs/fy16osti/66291.pdf
66. Rajee, O.: Algal biofuel: the future of green jet fuel in air transportation. J. Appl. Biotechnol. Bioeng. **5**, 5–8 (2018). https://doi.org/10.15406/jabb.2018.05.00127
67. Global Renewables Outlook: Energy transformation 2050. https://www.irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020
68. Advanced biofuels: What holds them back?. https://www.irena.org/publications/2019/Nov/Advancedbiofuels-What-holds-them-back
69. Kargbo, H., Harris, J.S., Phan, A.N.: "Drop-in" fuel production from biomass: Critical review on techno-economic feasibility and sustainability. Renew. Sustain. Energy Rev. **135**, 110168 (2021). https://doi.org/10.1016/j.rser.2020.110168
70. Gordon, J.T.: The implications of the coronavirus crisis on the global energy sector and the environment - Atlantic Council, https://atlanticcouncil.org/blogs/new-atlanticist/the-implications-of-the-coronavirus-crisis-on-the-global-energy-sector-and-the-environment/. Accessed 19 May 2020
71. Lee, D.-H.: Levelized cost of energy and financial evaluation for biobutanol, algal biodiesel and biogydrogen during commercial development. Int. J. Hydrogen Energy. **41**, 21583–21599 (2016)
72. IEA: Investment Trends, https://www.irena.org/Statistics/View-Data-by-Topic/Finance-and-Investment/Investment-Trends. Accessed 30 Jul 2020
73. IRENA: REmap: Roadmap for a Renewable Energy Future, 2016 Edition. 172 (2016). https://doi.org/10.1017/CBO9781107415324.004
74. Taheripour, F., Mintert, J.: Impact of COVID-19 on the Biofuels Industry and Implications for Corn and Soybean Markets-Center for Commercial Agriculture, https://ag.purdue.edu/commercialag/

home/resource/2020/04/impact-of-covid-19-on-the-biofuels-industry-and-implications-for-corn-and-soybeans-markets/. Accessed 19 May 2020
75. Renewable Fuels Association | Leading Trade Association for US Ethanol, https://ethanolrfa.org/. Accessed 19 May 2020
76. Renewable Fuels Association: Weekly & Monthly Ethanol Supply and Demand | Renewable Fuels Association, https://ethanolrfa.org/statistics/weekly-monthly-ethanol-supply-demand/. Accessed 19 May 2020
77. Eia - U.S Energy Information Administration. Monthly Biodiesel Production Report- With data (2020). https://www.eia.gov/biofuels/biodiesel/production/
78. Special Series on Fiscal Policies to Respond to COVID-19. International Monitery Fund. https://www.imf.org/en/Publications/SPROLLs/covid19-special-notes. Accessed 8 June 2020
79. Programme, U. environment: Transforming the energy system—a post-COVID-19 win-win for people and planet, https://www.unenvironment.org/news-and-stories/story/transforming-energy-system-post-covid-19-win-win-people-and-planet. Accessed 28 May 2020
80. DOE April 2020 Monthly Energy Review. eia - U.S Energy Information Administration. https://doi.org/10.1007/s12667-022-00514-7. https://www.eia.gov/totalenergy/data/monthly. https://www.eia.gov/totalenergy/data/monthly/archive/00352004.pdf. Accessed 8 June 2020
81. IRENA: The post-COVID recovery: An agenda for resilience, development and equality, International Renewable Energy Agency, Abu Dhabi (2020). https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Post-COVID_Recovery_2020.pdf
82. Covid-19 accelerates energy investment shift to renewables | fDi Intelligence—Your source for foreign direct investment information—fDi Intelligence.com, https://www.fdiintelligence.com/article/77658. Accessed 11 Jul 2020
83. IEA: Transport Biofuels—Analysis—IEA, https://www.iea.org/reports/transport-biofuels. Accessed 25 Jul 2020