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Review

Third-generation biodiesel development in Bangladesh: a review of recent trends, prospects, and economic analysis

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ABSTRACT

Researchers worldwide are seeking alternative sources of energy that can meet the future energy demand while significantly mitigating greenhouse gas (GHG) emissions. In addition, increasing the global energy demand at a faster rate, dependency on fossil fuels, and the price of fossil fuels are increasing at an alarming rate day by day. Amongst the options, biodiesel as an environmentally sustainable renewable fuel is considered to make a substantial contribution to the future transport energy demands locally and internationally. Among different biodiesel sources, advanced biodiesel feedstock, so-called 3rd generation biodiesel, which is mainly derived from microalgae, can be taken into account as a promising potential feedstock for biodiesel production due to their fast growth rates, high lipid content, high production rate, and ability to capture carbon dioxide. This paper discusses the selection of 3rd generation biodiesel, recent trends in microalgae-based biodiesel production, challenges in large-scale commercialization, and prospects for its development, particularly in the scenario of Bangladesh. The study estimates biodiesel can produce 10,000 liters per acre per year, with great potential for CO_2 sequestration and job development. The study also looks at how Bangladesh's plentiful freshwater and saline water supplies might be used for microalgae farming in desolate areas. Microalgae biodiesel can be generated at 0.50–0.75 USD per liter, according to a cost study; government subsidies and economies of scale will help to further lower this figure. Microalgae biodiesel can help Bangladesh reach energy security, lower greenhouse gas emissions, and encourage sustainable economic development by being included in their renewable energy plan. This paper will provide a clear understanding of the potential usages of microalgae biodiesel as an alternative source to fossil fuel.

1. Introduction

With the current increase in world energy demand, along with a decline in fossil fuel availability, much attention has been directed toward biofuels as an alternative energy source. The ever-increasing global need for energy, aligned with decreasing supplies of fossil fuels and ecological consequences related to the use of fossil fuels, has consequently increased the search for feasible, renewable sources of energy. Biofuels represent one of the renewable alternatives that could stabilize or reduce dependence on conventional fossil fuels. In addition to meeting the higher energy demand, biofuels have also been considered one of the finest options to help mitigate greenhouse gas emissions and, consequently, deal with climate change [1]. However, it is evident that the transition from fossil fuels to biofuels would not be an easy process; there are considerable differences between the different generations of biofuels according to their advantages and limitations. Biodiesel, being a substitute for fossil fuel, was first derived from food crops, such as corn, sugarcane, soybeans, etc. This type of biodiesel is called 1st generation biodiesel. Large-scale 1st generation biofuel production has received ethical and environmental criticisms due to its competition with food production, apart from using large stretches of land [2]. Food security became increasingly a cause for concern, and therefore, the emphasis started shifting toward the quest for more environmentally friendly alternatives. The disadvantages of the 1st generation biofuels were overcome in the development of 2nd generation biofuels using non-food biomass such as agricultural residues, wood chips, and waste materials (Figure 1). These feedstocks are considered to be in direct competition with food crops; however, in general, the complex processing technologies for the conversion of lignocellulosic biomass to biofuels are costly and inefficient at large scale [3, 4]. The high cost of the conversion processes has so far prevented the wide adoption of 2nd generation biofuels. Due to the disadvantages of both 1st generation and 2nd generation biofuels, attention has been drawn to 3rd generation biofuels, mainly produced from microalgae [5,6]. Compared with terrestrial crops, microalgae have several key advantages: fast growth rates, no requirement for arable land, and far higher potential lipid accumulation for bio-diesel conversion [7].

Under optimal conditions, microalgae can accumulate up to 70% of their biomass as oil, unparalleled by traditional biofuel feedstocks such as soybeans [8]. The environment of Bangladesh has maintained an optimal range for all the most important parameters, such as temperature, salinity, light intensity, photoperiod, and pH, etc., which refers to the potentiality of mass-scale cultivation of microalgae. Bangladesh possesses both freshwater and seawater on its territory. So, water bodies can be used for microalgae cultivation as the land area is limited. Besides, microalgae can capture CO_2 directly from industrial emissions and hence will be a very useful tool to reduce atmospheric CO_2 levels while producing energy. The production of fourth-generation biofuels would involve using genetically modified algae for enhanced production of biofuels. The new biofuels have potential for further gains in productivity and further cost reductions. Fully addressing the environmental and regulatory issues involving genetically modified organisms (GMOs) will be crucial before these technologies can achieve large-scale deployment [8, 9]. With only very limited reserves of natural oil and with very high dependence on imported fossil fuel supplies, the development of biofuels will be of real benefit to Bangladesh, especially 3rd generation biodiesel.

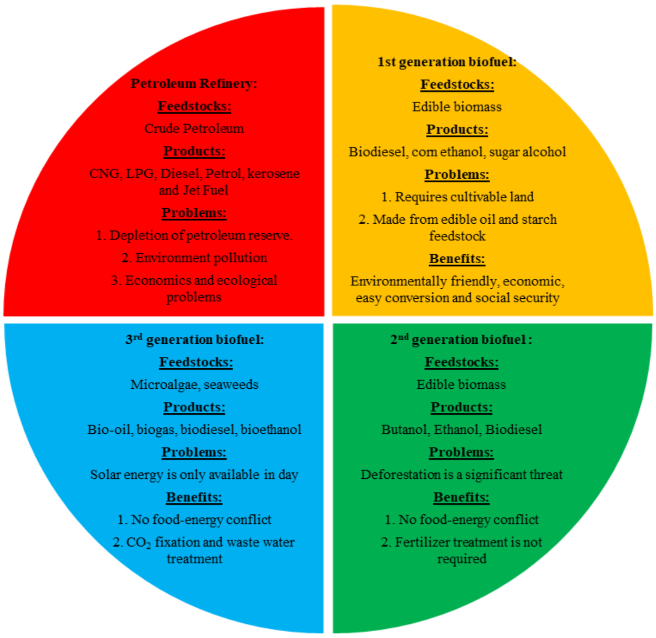

Figure 1. Comparison of 1st, 2nd, and 3rd generation biofuel and petroleum fuel [10, 11]

The high productivity of microalgae, coupled with favorable climatic conditions for the cultivation of algae, opens up a promising avenue toward energy independence and environmental sustainability [12]. This paper is thus committed to discussing trends, challenges, and prospects of third-generation biofuels in Bangladesh and intends to provide valuable knowledge to researchers, policymakers, and stakeholders who are involved in the energy transition of the country.

2. Why third generation biodiesel?

Growing demand for renewable fuels, combined with associated environmental concerns of fossil fuels, has motivated extensive research in the field of alternative energy sources [13]. Biodiesel is a biofuel derived from renewable biological materials that has come into consideration as an alternative to conventional diesel fuel. One of the major arguments against large-scale production of biodiesel is that it will take up millions of acres of farmland for livestock and natural habitats, increase the cost of food, and hardly reduce CO2 emissions. All these arguments are applicable to the 1st and 2nd generation biodiesel. 3rd generation biodiesel using microalgae as livestock has been discovered by the researcher [14].

Table 1 compares the lipid content, oil yield, land use for cultivation and biodiesel productivity per year of 1st ,2nd and 3rd generation biodiesel. It refers to unicellular photosynthetic microorganisms that, by living in either fresh or salt water, possess the capability for rapid growth rates and high lipid content. They convert sunlight, water, and carbon dioxide into algal biomass. Various research works and publications have explained in detail several advantages of using microalgae for biodiesel production compared with other available feedstocks [12-14]. In practical terms, they are easy to grow, grow with little or no attention, use water unsuitable for human consumption, and are easily obtained for nutrients. Microalgae reproduce themselves in different environmental conditions, producing chemical energy from solar energy by photosynthesis, while accomplishing a full development cycle every few days [15]. They grow and produce much faster compared to conventional forestry, agricultural crops, and other aquatic plants because of their higher photosynthesis efficiency. It was reported that the photosynthetic efficiencies of algae are within the range of 3-8%, while for many terrestrial crops, it is only 0.5% [16].

It was estimated through research that the biomass productivity of microalgae could be as high as 50 times that of switchgrass terrestrial plant having the highest growth rate [17]. Microalgae effectively fix CO_2 from various sources, including soluble carbonate salts, industrial flue gasses, and the atmosphere, which is 10–50 times more efficient than terrestrial plants [18]. Since carbon dioxide is transformed into chemical energy by photosynthesis, which can then be transformed into fuels using current technology, microalgae may fully recycle CO2 [19]. About 183 tons of CO_2 can be consumed by 100 tons of algae [20]. Wastewater can be used in microalgae culture for the purpose of wastewater treatment through the absorption of nitrogen and phosphorus [21]. Compared to diesel fuels, biodiesel blend fuels emit lower amounts of exhaust gas [22].

Table 1. Lipid content and productivity of different sources [23-26]

Generation	Feedstocks	Lipid content (% by wt in biomass)	Oil yield (L oil/year)	Land use (m^2 year/kg biodiesel)	Biodiesel productivity (kg biodiesel/year)
1st	Corn (*Zea mays*)	44	172	66	152
1st	Soybean (*Glycine max*)	18	636	18	562
1st	Sunflower (*Helianthus annuus*)	41	1070	11	946
1st	Palm oil (*Elaeis guineensis*)	40	5366	2	4747
1st	Rapeseed (*Brassica napus*)	40	1200	10	1250
2nd	Jatropha (*Jatropha curcas*)	28	741	15	636
2nd	Camelina (*Camelina sativa*)	42	915	12	809
2nd	Castor bean (*Ricinus communis*)	48	1400	9	1238
2nd	Coffee grounds (waste)	15	420	25	371
2nd	Sewage sludge	20	800	0	707
3rd	Microalgae (low oil content)	30	58700	0.2	51927
3rd	Microalgae (medium oil content)	50	97800	0.1	80515
3rd	Microalgae (High oil content)	70	136900	0.1	121104

Figure 2 describes the carbon cycle of biodiesel production from algae biomass. In such a context, microalgae may have the potential to create high-quality biodiesel that could be utilized in traditional diesel engines in an economical and ecologically responsible manner.

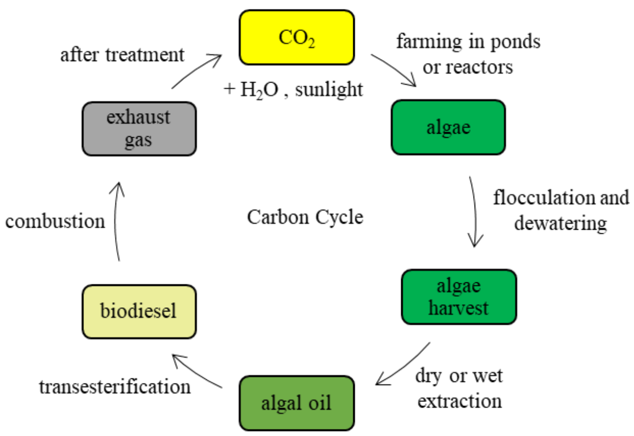

Figure 2. The carbon cycle of biodiesel production from algae biomass [27, 28]

3. Conversion techniques of microalgae biodiesel

Nowadays, biodiesel is being considered as a substitute due to its renewable nature and superior environmental repercussions [18-20] in contrast to traditional diesel oil. The properties that allow a fuel to be used in diesel engines are its ability to burn and evaporate, and some esters made from alcohols and carboxylic acids have these properties.

The alcohols must be mostly methanol or ethanol and have short chains in order to be used in biodiesel applications. Fatty acids that have chain lengths ranging from C14 to C22 are known as carboxylic acids. If biodiesel could take the place of diesel made from fossil fuels, which could become scarcer in the future, it would be highly sought after. However, the potential for a decrease in net carbon dioxide emissions is an even more compelling argument for utilizing it in place of traditional diesel. This is made possible by the fact that the carboxylic component of biodiesel, which makes up the majority of the fuel, comes from plants or algae that take up carbon dioxide from the environment during their growth. Thus, the overall result of using biodiesel and releasing carbon dioxide into the environment is a reduction in carbon dioxide emissions compared to using regular diesel [21, 22, 27]. Microalgae lipids may be trans-esterified into biodiesel using a variety of techniques. Among these techniques are transesterification with homogeneous acid, homogeneous base, heterogeneous acid, heterogeneous base, enzymes, microwave-assisted, ultrasound-assisted, supercritical, reactive distillation, and hydrothermal liquefaction [29]. The triglyceride in the algal oil reacts with the combined methanol and catalyst during the transesterification process, which takes place in a reactor. After that, a separator tank receives the upstream product. Methyl ester, excess alcohol, and the catalyst dominate the top layer when using a base or acid catalyst, whereas glycerol dominates the lower layer [30, 31]. With the exception of the top level's sole methyl ester content, this scenario is comparable to using an immobilized enzymatic catalyst. It also indicates that while the methyl ester obtained from the enzymatic catalysis process is directly fed into the drying unit, the methyl ester is forced to enter a washing column. The conditions upon which enzymatic transesterification relies include pH, enzyme concentration, substrate concentration, and the distance between enzyme molecules and substrates. The form of the enzyme catalyst does not change during the process and can be efficiently recycled. This can reduce the process cost. However, additional downstream processing will be needed to separate the product and solvent if the enzyme combines with them. Furthermore, throughout the process, free alcohols such as excess methanol and the resulting glycerol which is insoluble in crude oil promote dehydrogenases, which in turn prevent catalysis. Before moving on to greater sizes, a laboratory scale experiment can be used to assess the methanol to oil ratio in order to prevent a significant surplus of methanol [32]. The enzyme catalyst has to be immobilized in order to prevent direct interaction with free glycerol. Entrapping the enzyme, cross-linking, and carrier binding are the three methods used to immobilize an enzyme catalyst. Every strategy has benefits and drawbacks. Due to its effectiveness and economic viability, the carrier-binding approach is the most traditional and preferred transesterification technique [33, 34]. Figure 3 illustrates the whole process of biodiesel production in a flow chart.

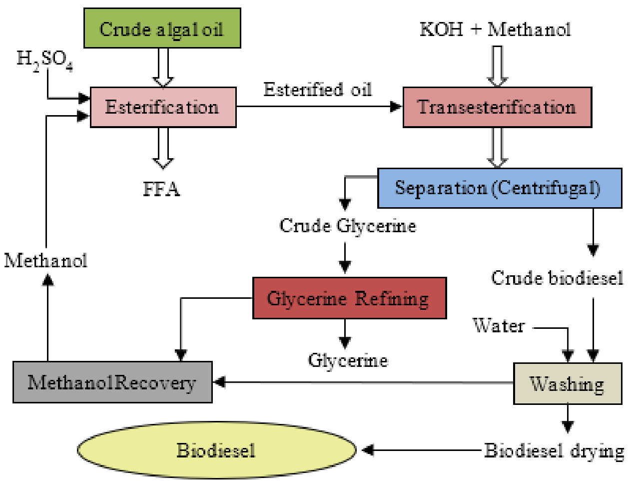

Figure 3. Flow diagram of biodiesel production [28]

4. Recent trends, challenges, and commercial aspects of biodiesel

In the field of biofuels, particularly third-generation biofuels derived from microalgae, significant development has been observed in recent years. It is being upgraded to a new level day by day. There have been various upgrading parameters like physical upgrading, chemical upgrading, etc. Nowadays, esterification, catalytic cracking, and pyrolysis are the most trending methods to upgrade algae oil into biofuel [35]. Among the most promising trends are the searches for seaweed and algae as sources of biofuel due to their rapid growth rates and high oil composition. Seaweed has great potential for the production of biofuel, but efficient fractionation is still amongst the most important bottlenecks to developing marine biorefineries. The whole seaweed process is in need of a rational approach to identify appropriate pretreatment methods for the recovery and valorization of its main fractions. The future of processing will probably be characterized by environmentally friendly technologies, including enzymatic treatments and deep eutectic solvents, playing major roles in seaweed processing [36]. Also, methods for the integration of bioprocessing are continuously being developed. Advanced separation materials and configurations have enabled one-pot production of biofuels from renewable feedstocks [37]. Another widely followed technique is the Fischer-Tropsch synthesis with cobalt catalysts, keeping in view its high hydrogenation activity for the production of linear hydrocarbons and oxygenates such as raw gasoline, diesel, and wax [38].

Despite extensive research, large-scale production of algal biofuels has been believed to be techno-economically unviable. Due to the nature of microalgae cultivation, the resultant costs are higher compared with other biofuel feedstocks, especially with respect to harvesting and dewatering, which account for 20-30% of the total cost of production [39]. Additionally, the rigidity of the algal biomass cell wall results in difficulties during industrial processes since energy-intensive pretreatment methods are required to improve the yield of biofuels. To this date, most technologies related to cell wall disruption and lipid extraction face some major drawbacks related to their costliness, energy consumption, and a lot of time wastage. All these processes, for it to be economically viable for the production of biofuel, have to be optimized by extensive research being done on it [40]. Thermochemical conversion processes, independent of any feedstock improvement, are preferred to the biochemical process in the production of biofuel from algae due to their higher efficiency [41].

Microalgae-derived bio-oil could see commercialization, under most circumstances, only with further research and support from the government. The capability of microalgae for carbon capture and storage, besides rapid growth rates, therefore presents a very interesting environmental and commercial prospect. It finds current applications in cosmetics, animal fodder, and food enrichment owing to its high value as a nutritional source. However, bio-oil production from microalgae is still more expensive compared to conventional production from fossil fuel sources. Although microalgae have given very promising lipid yields and growth rates, large-scale commercialization of microalgae is constrained by the high cost of biofuel production [42].

Besides that, the reduction of production costs needs further technological advancement, economies of scale, and government subsidies. It is also believed that a large array of products in a biorefinery will increase the economic viability of bio-oil from biofuel to chemicals. Co-production of biodiesel with value-added products (VAPs), such as pigments and antioxidants, including astaxanthin, can further reduce costs. This shows the role that integrating multiple product streams can play within biorefineries. These strategies undergird the intent that third-generation biofuels can become economically viable and sustainable, provided technological advancements and supportive policies are in place to scale production [35, 42].

Table 2. Lipid content and productivity of different sources

Water Type	Microalgae Species	Lipid content (% by wt in biomass)	Growth rate (g/L/day)	Biodiesel yield (L/ha/year)	Key Advantages	References
Fresh	*Chlorella vulgaris*	20-30	0.5-1.0	10,000-15,000	Fast growth, high yield	[3, 43]
Fresh	Scenedesmus obliquus	15-25	0.4-0.8	8,000- 12,000	Tolerates wastewater	[44, 45]
Fresh	*Chlorella protothecoides*	25-55	0.7-1.5	12,000–20,000	High lipid under heterotrophy	[46, 47]
Fresh	*Botryococcus braunii*	25–75	0.1–0.3	5,000–10,000	Hydrocarbon rich, long-chain lipids	[48, 49]
Fresh	*Neochloris oleoabundans*	35–54	0.6–1.2	15,000–22,000	High lipid under N-starvation	[50, 51]
Fresh	*Ankistrodesmus falcatus*	20–40	0.5–0.9	9,000–14,000	Adaptable to variable climates	[52, 53]
Fresh	*Tetraselmis suecica*	15–30	0.4–0.8	7,000–11,000	Mixotrophic growth	[54, 55]
Fresh	*Haematococcus pluvialis*	25–45	0.3–0.6	6,000–10,000	High astaxanthin (valuable co-product)	[56, 57]
Fresh	*Euglena gracilis*	20–35	0.5–1.0	8,000–13,000	Grows in organic waste	[58, 59]
Fresh	*Chlamydomonas reinhardtii*	15–25	0.4–0.7	7,000–12,000	Genetic engineering potential	[60, 61]
Salty	*Nannochloropsis oculata*	30-40	0.6-1.2	12,000-18,000	High EPA content	[62, 63]
Salty	*Dunaliella salina*	20-35	0.5-1.0	10,000-14,000	Extreme salt tolerance	[64, 65]
Salty	*Phaeodactylum tricornutum*	20–30	0.4–0.9	9,000–15,000	Silica-rich, marine diatom	[66-68]
Salty	*Isochrysis galbana*	25–40	0.5–1.1	11,000–17,000	High DHA content	[69, 70]
Salty	*Pavlova lutheri*	20–35	0.4–0.8	8,000–13,000	Rich in omega-3 fatty acids	[71, 72]
Salty	*Tetraselmis chuii*	15–25	0.3–0.7	7,000–12,000	Suitable for coastal areas	[73, 74]
Salty	*Chaetoceros muelleri*	20–30	0.5–1.0	10,000–16,000	High lipid productivity	[75, 76]
Salty	*Schizochytrium limacinum*	50–70	0.8–1.5	18,000–25,000	Highest lipid content, DHA-rich	[77-80]
Salty	*Porphyridium cruentum*	20–30	0.4–0.8	8,000–14,000	Produces sulfated polysaccharides	[81, 82]
Salty	*Thalassiosira pseudonana*	15–25	0.3–0.6	6,000–11,000	Model diatom, silica cell walls	[83-86]

5. Proposing actionable solutions to the challenges and prospects of microalgae biodiesel in Bangladesh

The most critical energy challenge of Bangladesh includes its very limited natural oil reserves; the high reliance on imported oil makes it further vulnerable to disorders in the world oil market, which may affect the uninterrupted economic growth of the country [87]. This energy crisis is already hampering socio-economic and industrial development [88].

As a developing country dependent on the use of large amounts of fossil fuels, Bangladesh is increasingly reliant on these non-renewable resources. As fossil fuels, like coal and natural gas, are not infinite, it is important that Bangladesh seeks other methods of energy production before they become scarce. This can be done by utilizing the 0.73 million hectares of unused land in the country for the cultivation of microalgae [36, 89]. Also being a riverine country, Bangladesh is bestowed with abundant fresh water resources, including rivers, ponds, and lakes, as well as saline water from the Bay of Bengal. This unique geographical advantage provides the conditions fit for algae cultivation in Bangladesh because it is able to grow in arid land, in wastewater, in clean water, and even in saline water. Additionally, the availability of barren lands and personal ponds offers a cost-effective and scalable solution for microalgae farming. The several water resources of Bangladesh enable the growth of a great spectrum of microalgae species. Along with their lipid content and growth rates, Table 2 lists some of the most exciting freshwater and saltwater microalgae species for biodiesel production.

Additionally, numerous households have personal ponds that might be used for a small-scale microalgae farming. Because they can survive in effluent and demand little upkeep, microalgae are a cheap option for rural and urban areas. Algae can be cultivated using different systems, such as ponds and photobioreactors, in which they can show high tolerance to pH, salinity, and temperature [90]. To establish the viability and feasibility of microalgae biodiesel in Bangladesh, a projected calculation is given if 10% of the barren land (73,000 hectares) were used for microalgae farming [91].

Freshwater microalgae: 730,000,000–1,095,000,000 liters yearly.

Saltwater microalgae: 876,000,000–1,314,000,000 liters annually.

Given that the average pond size is 0.1 hectare and 1 million households cultivate microalgae in their ponds, the estimated biodiesel production would be:

Freshwater microalgae: 1,000,000,000–1,500,000,000 liters annually.

Saltwater microalgae: 1,200,000,000–1,800,000,000 liters per year.

To address the challenges and facilitate the realization of microalgae-based biodiesel in Bangladesh, technological and socio-economic interventions ought to be adopted. A particular innovation needs development of the catalyst utilized in the esterification and transesterification process when producing biodiesel. The application of heterogeneous catalysts needs to be used in this process for optimal results. Genetic engineering techniques of microalgal strains for enhancing growth rate along with lipid accumulation need to be investigated. Use of local strains with high climatic tolerance for the climate of Bangladesh can further increase productivity levels [92]. Because of the expensive initial outlay of photobioreactors, microalgae growth should be through the use of open pond systems. The ponds will be lined with low-cost materials to prevent contamination and leakage. Emerging technologies in harvesting operations, including flocculation, bioflocculation and membrane filtration, can reduce energy expenditure and related costs [93]. More importantly, algae can be a solution to reduce industrial CO_2 emission, as 1 kilogram of biodiesel from algae requires 1.83 kilograms of CO_2 to produce it, thus it is an eco-friendly substitute [94, 95]. Similarly, novel lipid extraction methods such as supercritical fluid extraction and enzymatic hydrolysis can significantly improve operational efficiency [96].

6. Cost analysis of microalgae biodiesel production

Several elements influence the cost of microalgae biodiesel generation such as, growth systems, harvesting strategies, and lipid extraction processes. The projected expenses for Bangladesh's mass production are listed out in Table 3.

Table 3. Estimated cost for various stages of biodiesel production from microalgae [97-99].

Cost Component	Estimated cost (USD/L)	Remarks
Cultivation	0.20-0.30	Open pond systems are cost-effective for Bangladesh.
Harvesting & Dewatering	0.10-0.15	Flocculation and centrifugation are energy-efficient methods.
Lipid Extraction	0.15-0.20	Mechanical pressing combined with solvent extraction reduces costs.
Transesterification	0.05-0.10	Heterogeneous base catalysts are reusable and cost-effective.
Total Production Cost	0.5-0.75	Economies of scale and government subsidies can reduce costs further.

If the production can make in large scale then the total production cost can be further decreased. Pilot plants can first be introduced, and overall output can then be raised gradually through stepped-up volume, thus providing the potential of achieving scale economies and reducing the overall cost of producing biodiesel. Technical and financial assistance can also be accessed through cooperation with international agencies and research organizations [100]. Bangladesh government has to provide fiscal incentives in terms of tax holidays, grants, and soft loans to promote investment in microalgae biodiesel production. Public-private partnerships have to be promoted for funding research and development. The challenges in the production of biodiesel from microalgae in Bangladesh are enormous but not insurmountable. Through careful application of technology, implementation of beneficial policies, and overcoming socio-economic impediments, Bangladesh can harness the potential of microalgae biodiesel for the achievement of energy security, reducing greenhouse gas emissions and ensuring sustainable economic growth. Adding microalgae biodiesel to the national renewable energy policy may be the key to a greener, cleaner, and more sustainable future [101].

7. Conclusion

The 3rd generation biodiesel derived mainly from microalgae is one of the most promising routes to ensure a better energy future. Due to the very negligible reserve of fossil fuel and ever-growing dependence on imported energy in Bangladesh, switching over to renewable biofuel alternatives is not only advantageous but necessary. Microalgae are an interesting feedstock option considering their high oil yield, rapid growth rate, and possible growth on non-agricultural and even saline lands. Microalgae biodiesel production can be expanded to satisfy a sizable share of Bangladesh's energy needs by using its plentiful freshwater and saline water resources as well as its 0.73 million hectares of barren land. Microalgae biodiesel can be generated at 0.50–0.75 USD per liter, according to cost study; more cost savings are possible with government incentives, economies of scale, and technical developments. Actionable options like genetic engineering, sophisticated harvesting methods, and integrated biorefineries are suggested to help overcome technological constraints and high production costs. Though the commercialization process of algae-based biodiesel is burdened with several technological and financial challenges, continuous research coupled with governmental support will surely make it a plausible option. If algae biodiesel production is incorporated into Bangladesh's renewable energy plan, then it may reach a point of full energy security along with reduced GHG emissions and sustainable economic growth. It can be noted that microalgae-based biodiesel can take a significant role in Bangladesh's future energy scenario with proper investment and policy.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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