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Review Article

Palm Oil Biodiesel: Unlocking a Sustainable Energy Alternative to Fossil Fuels for a Greener Future

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ABSTRACT

Biodiesel has gained popularity in the last decade and is claimed to be an important weapon to combat the climate crisis. Many sources, such as Jatropha, soybean, karanja, and canola, among others, have been identified for biodiesel production. This study aimed to discover the potential of *Elaeis guineensis* (oil palm) as a promising alternative for biodiesel production. The main objective of this review study was to find out the potential of oil palm as a biodiesel feedstock. The biodiesel industry's market price and profit margin have also been considered for this study. The net energy ratio of biodiesel has been calculated by life cycle analysis (LCA). The result showed that oil palm is an economically viable choice of biodiesel feedstock. Oil palm biodiesel showed an average net energy ratio (NER) of 3; for Jatropha, canola, and soybean, the values are 4.7, 2.2, and 3.2, respectively. Internationally, pure-grade biodiesel, marked B99/B100, is priced at 4.30 USD/gallon. Industrially, with the implementation of sustainable approaches in the production process, a profit of 1.08 USD/gallon (>22% of the production cost) is attainable. Understanding the current issues and approaching them with research-based alternatives might eradicate the present issues and make biodiesel a viable alternative to fossil fuels.

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1. Introduction

Energy is a key determinant of economic development in the modern era of urbanization and globalization [1]. However, the energy demand is mainly met by the depletion of fossil fuels, eventually causing environmental pollution. Presently, fossil fuels meet 79% of the total global energy needs [2]. Another recent study has predicted that 84% of our total global energy demand will be met by fossil fuels alone by the end of 2030 [3]. Presently, one-third of the total carbon dioxide produced is due to anthropogenic activity [4]. This dependency on fossil fuels might be proven to be costly for humanity, as burning fossil fuels not only poses major environmental concerns, such as greenhouse gas emission, nitrogen oxide, and sulfur oxide production, and production of secondary pollutants, but also, according to estimates by various scientists, the global reserve of major fossil fuels will be depleted in the near future. As per the prediction, coal, gas, and oil reserves are to be completely depleted in 100, 37, and 35 years, respectively [3].

1.1. Energy Crisis Scenario in India

The Indian economy is constantly growing and evolving. Being a country with 17.7% of the total world population, India is the fifth-largest generator and sixth-largest consumer of energy. Over the past three decades, India's demand for energy has grown at a rate of 3.6% per annum. The pre-pandemic valuation was 916 million tons equivalent of oil [5]. Although during the pandemic, worldwide energy demand witnessed a sharp decrease, it has increased again since the economic year 2022-23 [6]. In a situation where both the demand for energy and global warming are on a steep rise, using renewable sources is the only possible way out of the problem. In the global scenario, 18% of the total energy comes from renewable sources [2]. The Indian government, under its National Electricity Plan 2023-2032, has set a goal of meeting a peak demand of 458 GW of energy by 2032, and 24.2% of energy requirements would be fulfilled by renewable energy by 2027 [6].

1.2. Biofuel as an Alternative

Biofuel is one source of energy that is sustainable and technically renewable due to the abundance of biomass on Earth. It has the same calorific value as diesel but creates no sulfur or nitrogen oxides (SO_x, NO_x) after combustion in the presence of oxygen [3]. It is worth noting that the biodiesel-yielding procedures can absorb more carbon dioxide (CO_2) than they produce after the combustion of fuel [7] . Four widely used categories of biofuel are biodiesel, bioethanol, bio-oil, and biogas. Biodiesel is considered more favorable than the other three options, as it is used as a replacement for diesel and can be used as a blend with mineral diesel or directly as combustion oil [8]. Bioethanol is also a popular energy source as a replacement for petroleum, but this fuel cannot replace the mineral oil industry, primarily because bioethanol is designed to be used as a blend with petroleum. The specialized engine that can run on 100% bioethanol is neither cost-effective nor available industrially. Besides, the production procedure for bioethanol is fermentation, which is responsible for carbon loss during production [9]. Biogas is a newly popular energy source with high potential, but this source of energy is not ready to be used yet. First, the production procedure is not cost-effective, and large-scale application of the method seems impossible with so little technological advancement available in countries like India. Second, the gas is highly flammable and poses a risk of toxic cloud formation; thus, it is not suitable to be used in densely populated metropolitan areas [10]. However, with proper implementation methods, biogas can be produced from industrial and household waste materials as well [11]. The pyrolysis-derived bio-oil shows a negative NER (Net Energy Ratio), and the product stream makes it almost impossible for alternative treatment [7,12].

1.3. Feedstock for Biodiesel

Biodiesel can be derived from any potential source of biomass, but feedstock selection plays a vital role in the market value and efficiency of the product. In different studies, different feedstocks have been used, such as microalgae, animal fats, cooking oil, or oil-producing plants. Before discussing oil palm and its potential, some other viable options are discussed below.

1.3.1. Jatropha

In India, *Jatropha curcas* L., a native species, is often considered to be a potential source of biodiesel (Figure 1). In local languages, the plant has many names, such as ‘ratanjot’ in Hindi and ‘kattamanakku’ in Tamil, among others. In the year 2009, the Government of India declared *Jatropha sp.* as the most suitable source of biodiesel in the sub-continent in an attachment announcing the country’s national biodiesel mission. The goal of this government project was to achieve a 20% blend of biodiesel to crude mineral oil by the year 2017 in six states of the country and bring down the pollution level, as well as the surging price of petrol. Unfortunately, seeds of the said plant could not be proven to be the “most suitable feedstock” as claimed by the Government of India. Reasons cited for the failure of this project include many, although the uncertainty of the monsoon and lack of knowledge about proper cultivation remained at the top of that list [13].

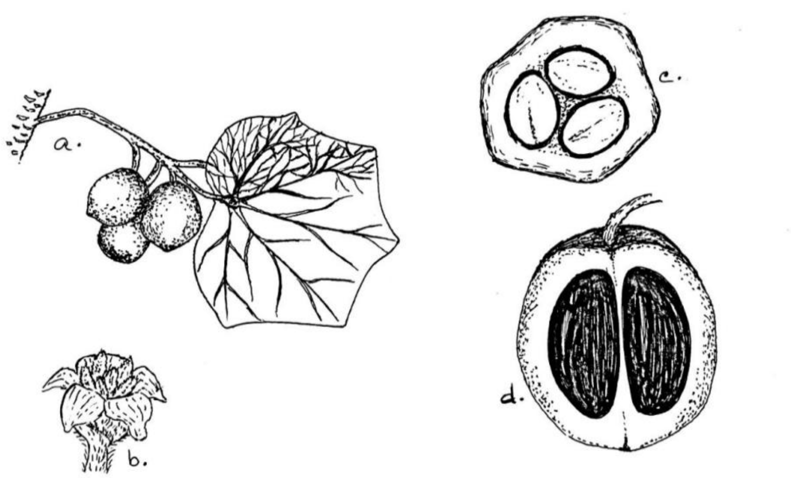

Figure 1. *Jatropha curcas*: a) fruit-bearing branch; b) flower; c) transverse section of fruit; d) longitudinal section of fruit

1.3.2. Karanja

Millettia pinnata, or Pongame oil tree or Karanja, as shown in Figure 2, which belongs to the Leguminosae family, is another feasible source of biodiesel in India. This plant, as well, is a non-edible source of biodiesel and thus preferable. *Madhukalongipholia* or Mahua plants are also a worthwhile source for biodiesel production in the country. The Indian Biodiesel Corporation, situated in Baramati, is currently working with 300 non-edible species like Karanja and testing their potential to emerge as an exclusive source of biodiesel in the country [14].

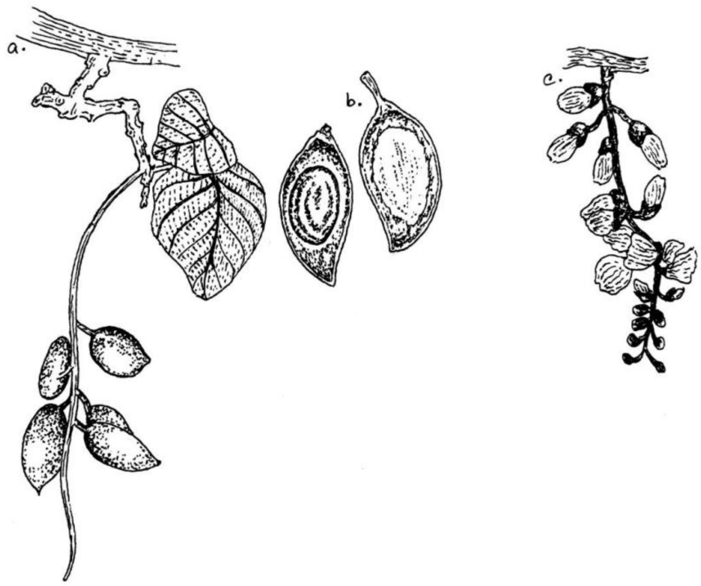

Figure 2. *Millettia pinnata*: a) fruit-bearing branch; b) transverse section of fruit exposing whole seed; c) inflorescence

1.3.3. Cooking Oil

Another interesting source of biodiesel is cooking oil. This procedure, though, has little to no drawbacks, and is still not accepted nationally as the production of biodiesel from this source requires pre-treatment to reduce the free fatty acid content of the cooking oil and some extra pre-treatment procedures to rectify or purify the feedstock. Hopefully, with proper training and skill enhancement in laborers, equipped factories using cooking oil may emerge as the primary source of biodiesel in the country [15].

1.3.4. Oil Palm Tree

Elaeis guineensis, or oil palm of Palmaceae, has a high-yielding capacity to meet the growing energy demand of India, as shown in Figures 3 and 4. An oil palm tree can live up to 30 years and yield feedstock at a high rate regularly. Especially, the southern part of India possesses optimum climatic conditions for the growth of oil palm trees. Presently, 9 Indian states, Andhra Pradesh, Chhattisgarh, Karnataka, Rajasthan, Odisha, Uttarakhand, Tamil Nadu, Punjab, and Haryana, are actively implementing biofuel (both biodiesel and bioethanol) regulations to promote their usage [16].

Palm, being a potential power source in biodiesel production in India, satisfies all the criteria of being studied as a source of biodiesel production worldwide.

Figure 3. *Elaeis guineensis* or oil palm

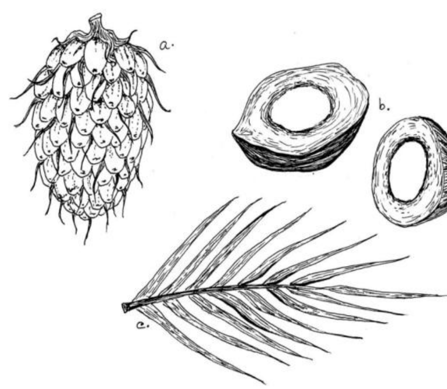

Figure 4. *Elaeis guineensis*: a) fresh fruit bunch; b) transverse and longitudinal sections of fruit; c) pinnate compound leaves named fronds

In the year 2018, India declared its national policy regarding biodiesel that promotes the use of biodiesel for a better and sustainable future. Although only six plants have been established in the country thus far, the government has certain plans for the industry. Around a hundred small biodiesel plants are to be built by oil marketing companies. Purchase of biodiesel has already started (51 INR/Litre). "Zomato", an Indian company, has proposed a project of collecting used cooking oil from households as biodiesel feedstock. With the help of advancing technologies and the concerned authority, it can be expected that the Indian biodiesel industry will flourish soon [15].

Presently, oil palm is the most promising feedstock for biodiesel production. This study discussed the potential of it both environmentally and economically. A comparative study of feedstock was done to find out if oil palm is a sustainable feedstock for biodiesel production, compared to other available options (e.g., *Jatropha*, soybean, etc.). From an ample number of research works, life cycle analysis (LCA) of oil palm was done to find out the average net energy ratio (NER) of the said fuel and to compare the result with diesel. A depth analysis of the market price and profit margin of the oil palm-based biodiesel industry was taken into consideration.

2. Materials and Methods

The study was focused on the global environmental and economic status of biodiesel, mainly biodiesel derived from oil palm. The evaluation was done by reviewing peer-reviewed literatures and official websites. The entire methodology can be divided into subparts for better understanding.

2.1. Selection of Scientific Literature

Reviewing literature can follow two major methods: either a systematic review of scientific journals or a meta-analysis. For this study, a systematic review was conducted gathering various scientific journals. As the original study started in 2021, the papers used for data analysis in this study were published over ten years before the study (2010–2020). Although some old papers were cited in this study, none of those papers were used for data analysis. Most of the published papers are from Indonesia and Malaysia, but some of those are also from other regions of the world. Papers were downloaded with the help of the "Google Scholar" search handle. Most of the papers are open source in nature, but there are a few exceptions as well, which were accessed with the help of the guide of this study. While selecting the paper, the following route was followed, as shown in Figure 5.

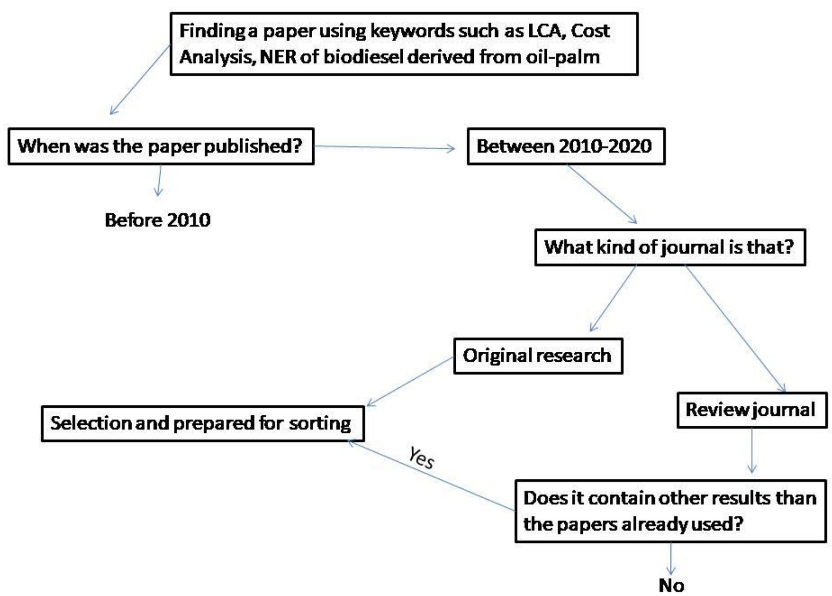

Figure 5. Flow-chart of the selection process for papers

After selecting the papers on the topic of oil-palm-derived biodiesel from different parts of the world, a country-wise sorting of the selected papers was done.

Table 1 shows the simulation models other than SimaPro used for the life cycle analysis in this study, along with their working principles.

Table 1. Software Used In LCA

GREET model	The Greenhouse Gas, Regulated Emissions, and Energy Use in Technologies Model is an LCA tool made by Argonne National Laboratory, which is publicly available
LEAP	Long Range Energy Alternative Planning System is a tool made in Stockholm. The window-based tool helps in LCA studies by creating a simulation.

Papers that contain similar data were studied thoroughly for equal-weight values. For example, all the papers that dealt with life-cycle analysis were evaluated to obtain parameters of interest, net energy ratio values, and net energy balance values (in a few cases). Then, a simple average value was derived from the obtained value. The papers selected from this study are not from one region or continent, giving the derived average value a global aspect. For cost analysis, the average profit value plays the same role as NER for LCA. Thus, this review paper aimed to give directions towards the overall scenario and potential of this industry.

2.2. Calculation of Life Cycle Analysis

LCA is a popular way of analysis that is generally used to determine the environmental impact of a procedure. LCA consists of four basic steps or pillars: a) goal and scope definition, b) inventory analysis, c) impact assessment, and d) interpretation. Although biodiesel derived from oil palm can be successfully used as a replacement for mineral crude oil, the question remains whether it fits into our desired economic standards. To answer this question, some factors must be considered, like the production of oil palm, the market price of methanol, the selling price of glycerol and crude palm oil (CPO), and finally, the market price of crude petroleum oil [17]. Life cycle analysis, a cradle-to-grave procedure to understand the environmental impact of a product, is usually calculated using software. Most of the articles reviewed in this study have reported using SimaPro; in some instances, locally popular software is used as well [18,19]. The functional unit of LCA is calories, as it deals with the total energy input in the production process. There are also instances where CO_2eqv (Carbon dioxide equivalent) was used as a unit to understand the carbon production, as well as the environmental impact of the product in question [20]. But, to avoid confusion and get a unidirectional answer to the question in this review work, journals have been chosen where calorie/kilocalorie was used as the standard unit.

2.3. Calculation of Net Energy Ratio

Net energy ratio is the ratio of total energy output from the product, or in this case, the energy that we gain from the combustion of biofuel based on oil palm, and the input or energy requirement to produce the same amount of biodiesel used for combustion. The ratio is more than one (1), which denotes that the product in question produces more energy than it consumes in the process of production [21]. Naturally, NER is a unitless number. To get a clear idea, NER for fossil fuel is always less than 1 [22]. This denotes that fossil fuels consume more energy in the process of production and extraction than they give back during combustion.

2.4. Energy Input, Output & Ratio

To analyze the energy requirements, this study evaluated each step of the biodiesel production method, from plantation to combustion. The overall procedure can be divided into four main categories: 1) plantation, 2) oil milling, 3) transesterification, and 4) combustion. Apart from the mentioned steps, sometimes nursery care of young saplings and transportation of FFB (Fresh Fruit Bunch), and crude oil from feedstock are other factors considered while calculating the overall energy expenditure. Sunlight is considered as a free source of energy. Various products are used and retained as input and output materials in different stages of biodiesel production (Table 2).

Table 2. Input and output of oil palm in the biodiesel process [23]

Stage of Biodiesel Production	Input materials	Output materials
I. Agricultural stage	Palm oil seed	Fresh Fruit Bunches/FFB

II. Oil Milling	FFB	Crude Palm Oil/CPO
		Empty Fruit Bunches/EFB
		Fibers and Shells
		Palm Oil Milling Effluent/ POME
III. Transesterification	CPO	Biodiesel
	Methanol/CH_4OH	Glycerol
	Sodium Hydroxide/NaOH	

2.5. Calculation of Life Cycle Cost

Life cycle cost can be simply calculated by adding the total cost of production of one unit of biofuel and subtracting that from the market price. To get the international picture, the international standard currency (USD) and the idea of local Indian currency (INR) were used in this study. A comparative study of the market growth in biodiesel/biofuel and recent government policies that might help in the growth of the industry was also discussed in the results and discussion section.

3.Results/Observations and Discussion

3.1. Comparing Oil Palm with Other Feedstock Options

Biodiesel is a recent innovation in fuel technology; a renewable energy source that can be derived from any potential biomass and can fight greenhouse gas (GHG) emissions and pollution issues. Throughout the paper, various sources of biodiesel were discussed, among them rapeseed, sugarcane, jatropha, soybean, and oil palm were discussed repeatedly.

Among the aforesaid sources of biodiesel, oil palm and jatropha are perennial plants. While high-quality oil palm trees can live 25-30 years, *Jatropha* sp. has a longer lifespan of 40 years. A perennial stock of biodiesel has a greater impact on the biodiesel industry as it can not only provide feedstock for a longer time, but also the amount of production does not fluctuate drastically like annual crops. Soybean and rapeseed (belonging to the mustard family, Brassicaceae) are annual crops. Although sugarcane is a perennial grass, it cannot provide feedstock annually like *Jatropha* sp. or palm species. On the other hand, the perennial plants have disadvantages too. In Malaysia, the largest producer of crude palm oil (CPO), a large area of rainforest was cleared for oil palm cultivation. Research showed that 80% of Borneo's rainforest in Malaysia was compromised due to the large-scale cultivation of oil palm [24]. The situation not only creates an imbalance in the ecological scale but also destroys carbon sinks in Malaysian island areas. Although oil palm biodiesel is not yet popular in India, the National Policy of the country in 2018 indicates an inclination toward biodiesel-based transportation. The major point to be considered here is that plant members of Arecaceae or any other source of the aforesaid biodiesel should not harm the indigenous species of the region. The question arises as to what the point of biodiesel is if the production process destroys the environment. In some disputed studies, it was also claimed that oil palm as a feedstock of the biodiesel industry is harmful to the environment if "forest land usage" is considered while calculating the LCA [17]. Although the situation is not the same for *Jatropha* sp. in India, being an indigenous species, it might not harm the ecological balance even on large-scale cultivation and can be grown without disrupting environmental stability. However, the failure of the Jatropha mission questions its potential as a biodiesel feedstock [25] (Table 3).

Table 3. Brief Analysis of Important Biodiesel Feedstock in India [26-28]

Name of Feedstock	Advantages	Disadvantages

Oil palm	Perennial; contains 56% oil; the NER value is high; market demand ensures success	Requires a massive land area; invasive species in India; requires a high number of fertilizers & pesticides; Low freezing point
Jatropha	Perennial; Indigenous species; can be grown on roadside, sidewalks, unused swampy land, etc.; shows high yield with proper care	Not suitable for industrial use yet; requires genetic modification for a high-yielding variety
Soybean	High oil content; High value of NER; Does not require a large land area & does not disrupt the ecological balance	It is a food crop; requires agricultural land; not suitable for any agriculture-based country
Sugarcane	Does not require a large area; NER positive; A good source of bioethanol, not biodiesel	It is a food crop; requires agricultural land; FFA content is lower
Rapeseed/ Canola	High oil content; High value of NER; Does not require a large land area & does not disrupt ecological balance	It is a food crop; requires agricultural land; not suitable for any agriculture-based country

3.2. Comparing the Net Energy Ratio (NER) Values

NER or net energy ratio clarifies the feasibility of an energy source. It is a ratio of output energy vs. input energy; the higher the value, the more energy-efficient the source. For the aforesaid feedstock, a positive value (more than 1) is obtained. In fossil fuels, the value is less than 1 [22,29].

3.3. Life Cycle Analysis of Oil Palm–Derived Biodiesel

The production of crude palm oil in a unit area of land surpasses the production of rapeseed or soybean on that same land by 5% and 10%, respectively [14]. The market price of soybean oil is almost 20% higher than that of the CPO; the rapeseed oil price, though it fluctuates sometimes, is also much higher than that of palm crude oil [26,30].

This work was based on previous research carried out in this specific field. The goal of this work was to assess the energy requirement for biodiesel production from oil palm, to find out the Net Energy Ratio (NER), and to find out the cost of the entire process. Most of the research reviewed under this study was performed in Malaysia, Thailand, or Indonesia.

3.3.1. System Boundary

The study covered the process of biodiesel production from oil palm. Each step involved in the process of production, from plantation of oil palm trees to harvesting fresh fruit bunch (FFB), transporting the fresh fruit bunch to an oil mill, and extraction of crude palm oil (CPO), refining crude palm oil, and transesterification, was studied for the occurrence of possible input and output of energy. Thus, the cradle of this experiment was the cultivation of palm trees, and the grave was the production of biodiesel by transesterification of CPO. All the possible inputs and outputs were then calculated by their energy equivalents and noted down [19].

The system boundary defines the scope of the study. In the case of biodiesel production from first-generation feedstock, the generalized steps were taken into consideration while calculating the LCA. The standard procedure of production is stated below as a schematic diagram [31] (Figure 6).

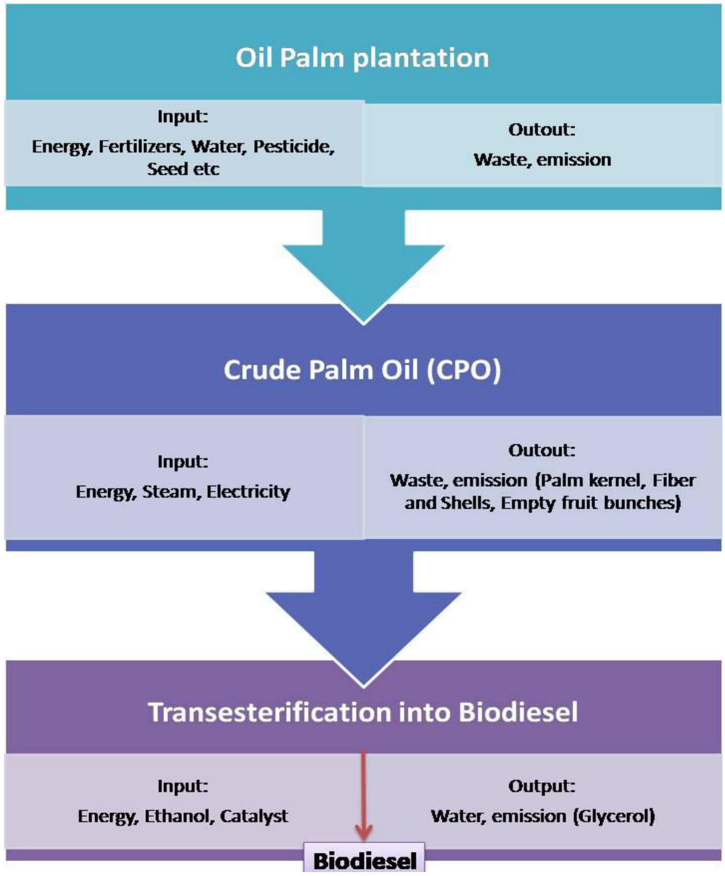

Figure 6. System boundary

3.3.2. Inventory Analysis

Oil palm Cultivation: Oil palm has an average life span of 25 years, which may exceed 30 years if proper care and a favorable atmosphere persist. Some general plantation data are provided below (Table 4).

Table 4. Cultivation potential of oil palm in brief [32-34]

Total Number of trees per Ha	136-160
FFB per plant per year	140 kg
FFB per Ha per year	19 Tonnes/Ha
FFB required for 1 Ton CPO	5.2 Ton
FFB required for 1 Ton PME	5.5 Ton
Area to produce 1 Ton PME	0.28 Ha
Production of CPO per Ha	3.70 T/Ha
FFB= fresh fruit bunch, CPO= crude palm oil, PME= palm methyl ester	

Generally, old trees are replaced by young ones to keep the total oil yield consistent. FFB harvesting requires experienced cultivators to avoid damage to fresh fruit bunches. Inexperience may lead to a loss in oil yield [35].

FFB milling: In the standard milling procedure, 1 ton of CPO is collected from 5.2 tons of fresh fruit bunches. Oil palm trees require a bare minimum application of chemicals. The FFB is first heated by a steaming process, and then oil is extracted from the FFB. In this process, natural gas is released, which consists of 65% methane and 30% CO_2. The gas is called Palm Oil Mill Effluent (POME) and can be used as biogas [23].

PME production: The reaction to produce Palm Methyl Ester or PME from Crude Palm Oil (CPO) requires certain chemicals like methanol, sodium hydroxide, and CPO. The step also requires electricity. Combustion of PME may release 760 CO_2equiv. / ton [20].

Market Scenario: In March 2015, the average price of palm crude oil on the international market was 607.5 US dollars (USD) per metric ton. The European Union has reported 41% use of palm-based oil biodiesel with respect to total oil usage. The Netherlands and Germany were the highest consumers of oil palm-based biodiesel [36].

3.3.2. Energy Input, Output & Ratio

After dividing the entire process from plantation to production of biodiesel into 1) plantation, 2) oil milling, 3) transesterification, and 4) combustion, the energy balance of each step was calculated.

Plantation: The assessment of energy balance must be calculated from the ground level and the agricultural stage. For this stage, we must calculate both the transportation and production of fertilizers and pesticides. To simplify the calculation, we must consider that all the transportation is done with the help of fossil fuel, not biofuel. An oil palm tree requires various micro and macronutrients to attain optimum yield and growth. Oil palm or *Elaeis sp.* needs nitrogen, phosphorus, and potassium fertilizers, and being prone to pests, it also requires pesticides (preferably glyphosate). By calculating the equivalent energetic value of such ingredients, we may attain the total energy expenditure of this stage [37].

According to a study that evaluated the biodiesel scenario in Malaysia, Indonesia, and Singapore, the total energy used in farming is 3200 MJ/Ha in a farm where the yield is 17.8 tons of FFB per hectare [38]. In another study from Malaysia, the total expenditure of diesel is evaluated to be 644.24 MJ, and electricity purpose is 5.17 MJ; these numbers, after being added with the energy equivalent of fertilizers used, make a total of 2404.47 MJ [26]. Another study on the Malaysian biodiesel production industry showed that diesel and electric-based energy used in the plantation procedure in a year is near about 730 MJ, whereas fertilizers and pesticides cover most of the energy expenses, the total energy expense for such is 2182 MJ [32]. An average of 5.31 MJ to 8.57 MJ of energy is used per kg of palm methyl ester (PME) [23,39]. The total amount of energy required in the agricultural stage depends on the boundary set by the research workers. When tractors, machinery, and human labor are excluded, the amount of total energy expenditure drops. A study showed that the amount of energy required to prepare land for oil palm cultivation is 163.41 MJ, and the same for Jatropha is 161.66 MJ per ton of oil production. While this energy is a one-time investment, the land must be kept free from any kind of weeds and pests throughout the lifespan of the plant. Maintaining that cultivating land requires around 6211.61 MJ energy per ton of biodiesel, while the requirement of Jatropha for that purpose is as low as 1178.64 MJ per ton of biodiesel produced [28].

During this whole procedure, some components act as the deciding factor for energy expenditure. Oil palm, like many other plants, needs nitrogen as a major growth-inductive molecule. The environmental and other impacts of this much use of mineral fertilizers are estimated to be huge. Though the energy equivalent of such fertilizers cannot be evaluated properly, the revelation is shocking. In the oil palm industry, 48.7% of the total greenhouse gas (GHG) emission occurred to produce a ton of biodiesel comes from the nitrogen fertilizers used in the cultivation procedure alone [40]. Some general data is provided in Table 5.

Table 5. Nitrogen Fertilizer in Oil Palm Cultivation

Sl no.	Amount of N-fertilizer used (unit)	Equivalent energy(unit)	Source

1.	76 kg/Ha	---	[26]
2.	25.5 kg/Ha	1773 MJ	[32]
3.	105 kg/Ha/Year	1.21 MJ/kg PME	[39]
4.	128 kg/Ha	48.9 MJ/kg	[23]
5.	64.35 kg/Ha	1196202 kcal/Ha/year	[41]
6.	83.30 kg/Ha	1548464 kcal/Ha/year	[41]
7.	54.01 kg/ton PME	3.10 MJ/PME	[18]

The other two main fertilizers widely used in oil palm cultivation are phosphorus pentoxide (P_2O_5) and potassium oxide (K_2O). According to a study based on the Malaysian oil palm-based industry, on average, 86 kg P_2O_5 and 119 kg of K_2O fertilizers are used in one hectare of land in a year. These values cost around 180.16 MJ and 207.20 MJ of energy per ton of CPO production [26]. In another study, these fertilizers are held accountable for 1094 MJ/ton CPO of energy expense a year. Glyphosate is the most commonly used pesticide used for oil palm cultivation. According to a study conducted in Iran, the annual application rates of insecticides, fungicides, and herbicides required for oil palm cultivation were 0.43 kg ha^{-1}, 0.88 kg ha^{-1}, and 1.28 kg ha^{-1}, respectively [42]. These amounts of pesticides account for a total of 555.2MJ/Ha energy. Another study reported that pesticide application accounts for approximately 315 MJ of energy consumption per hectare per year [32,42]. Harvesting is usually done manually for oil palm trees. A palm tree can live up to 25-30 years and keeps producing FFB till the end of its lifespan [43].

Oil Milling: After collecting FFB from fields, they are transported to an oil mill where Crude Palm Oil or CPO is extracted from the fresh palm fruits. The oil extraction procedure is quite simple; the collected FFB are heated and pressurized inside a vessel, and then the fruitlets are pressed to extract oil from them. The amount of chemicals required to operate the process from oil palm fruits is negligible and does not provide additional energy data to the total expenditure. According to standard data, a healthy tree can provide around 140 kg of FFB every year, and altogether 19 tons of FFB can be collected per hectare of a field. Around 1000 kg or 1 ton of CPO can be produced from 5.2 tons of FFB [32]. While producing CPO, another by-product, POME or Palm Oil Mill Effluent, is produced. This is a biogas which is made of, on average, 65% methane with 30% carbon-dioxide. POME can produce energy at a rate of 23 MJ/m [34]. Using this POME as an alternative source of energy can save energy as well as the cost expenditure of any palm oil-based biodiesel industry. Unfortunately, in most cases, only 15% of the total biogas produced is collected and reused, leaving the majority to be released into the atmosphere [20]. In an oil mill, the main energy expenditure is caused by the electricity required to operate machinery and diesel to start the turbine. To produce one ton of PME or Palm Methyl Ester, 22.58MJ energy is required for electricity in an oil mill; for the same amount of PME production 5.25MJ energy is required as diesel is used to operate the turbine of an oil mill. The refining process of the oil costs 61.36 MJ of energy in the form of diesel and electricity [18]. Combining the energy inputs of both the processes of oil extraction and refining, the energy value accounts for 78.58 MJ/ton CPO/year energy as diesel, 339.2MJ/ton CPO/year energy as electricity, and 9723 MJ/ton CPO/year energy for the steaming system of FFB [32]. Another study revealed that the steaming procedure costs 9826MJ energy per ton CPO per year, a total of 270.22 MJ energy is spent as electricity per ton CPO per year, and 109.37MJ energy for diesel per ton CPO per year [26]. However, using any other feedstock other than oil palm FFB can provide different data. For instance, rapeseed oil requires hexane as an extraction solvent, which costs around 53.17MJ energy/ton CPO/year [42,44]. The energy requirement for the extraction of rapeseed oil is also much lower than that of CPO due to the difference in feedstock quality.

Transesterification: This is the final step that produces the PME or Palm Methyl Ester from Crude Palm Oil (CPO). The CPO is refined, bleached, and deodorized (RBD) before entering the transesterification process. Transesterification is a chemical reaction where the glycerides present in the CPO react with a primary alcohol (methanol or ethanol) in the presence of a strong acidic or basic catalyst and produce fatty esters and glycerol [45].

In a commercial biodiesel production process, methanol is used for its cost efficiency and easy availability; sodium hydroxide (NaOH) and potassium hydroxide (KOH) are usually used as catalysts for the same reason. The input materials are refined CPO, methanol, and catalysts, which are put into the system. It typically takes 8 hours for a 6000 L capacity biodiesel plant to produce biodiesel and glycerol at a temperature of 50-60°C [34].

The whole process of transesterification in biodiesel production is operated via electricity using conventional energy sources. Thus, energy expenditure in this stage is higher than in the other two. A standard system of biodiesel production requires 180kg of methanol, 10kg of NaOH (100%), 297MJ electricity, and 1.73kg of diesel to produce 1 ton of PME. The total energy required for the aforesaid is 5.98MJ/kg of PME [18]. Another study revealed that 1 ton of oil palm fatty acid distillate or PFAD can produce 921 kg of PME, and the amount of methanol required to produce 1 ton of PME is 103 kg. The data showed that 3.75MJ energy is required to produce 1 kg of PME from PFAD [39]. In a study based in Malaysia, it was claimed that 6599.7 MJ of energy is required to produce one ton of CPO, with methanol being the most energy-expensive material (costs 4870MJ/ton CPO).

The end products of the biodiesel production procedure are biodiesel, glycerol, fiber, and shells. While the main output material can be used in multiple ways, glycerol is quite versatile in the chemical and cosmetic markets. Fibers and shells are also used as minimal energy sources. Biodiesel gives back a huge amount of energy, i.e., 39204 MJ/ton CPO/year. Glycerol can produce an energy equivalent of 181.38 MJ/ton CPO/year, and fibers and shells produce 19534.74 MJ energy per ton of CPO. The total energy output is 60.72 GJ/ton of CPO [26,46]. According to another set of data, 39.70 MJ/kg of PME is produced from all the end products. Using other feedstock may result in different data; for instance, if rapeseed is used as feedstock, 107.8 GJ of energy is produced from the output material per ton of CPO [39]. Based on a study in Thailand's biodiesel industry, PME can produce 38.07 MJ of energy per kg, glycerol produces 3.42 MJ per kg of energy, and oil palm kernel and shells produce 6.36 and 8.45 MJ per kg of energy, respectively [18].

NER or net energy ratio stands for the ratio of output energy and input energy. This value defines the sustainability of a compound. For oil palm-based biodiesel, the value typically ranges between 2.42 and 3.58. For conventional diesel or mineral diesel, the value is 0.8, defining its negative impact [22]. For soybean-biodiesel, the value is 3.9; canola-biodiesel shows a value of 2.9 [22,26]. Tallow-biodiesel shows a value of 3.2, and for rapeseed, the value is 1.45 [26]. Some studies suggest soybeans can give an NER value of 2.55 [47]. In the case of Jatropha, the value can be anywhere between 1.4 and 8, based on the method used for production, although the Indian scenario is more inclined to a value near 1.85 [25,48]. With the advancement of technology, the value is expected to increase. Using green sources of energy to produce green fuel can ensure sustainability and a better environment for the future of mankind. According to a joint research study performed in Malaysia, Indonesia, and Singapore, the total life cycle fossil energy consumption for petroleum is around 1.2 MJ per MJ fuel consumed. According to research, if POME is considered as a by-product of the procedure, the FER may increase by a lot. Natural gas produced during the production procedure can provide 94% of the energy requirement of the whole process [38].

3.3.3. Average Value of Net Energy Ratio

After deriving net energy ratio values from various studies, an average value was calculated. As studies were conducted in various countries all over the world, the average values indicate a global picture. The average values are documented in a tabular form in Table 6.

Table 6. Average NER as obtained from previous papers

Feedstock	NER value range found in different studies	Mean value
Oil Palm	2.42-3.58	3
Jatropha	1.4-8.0	4.7
Canola/ Rapeseed	1.45-2.9	2.175
Soybean	2.55-3.9	3.225

3.4. Cost Estimation of The Biodiesel Production Process

The energy balance and environmental aspects are not the only concerns in any industry; the economic system also plays a major role. The palm-based biodiesel industry is considered an economic driver due to its high yield, long lifespan of palm trees, production of many economically important by-products, and other factors [49]. In comparison to other vegetable oils, palm oil has a relatively lower production rate per ton of CPO [36,50]. Some of the well-known indicators of the economic performance of a product are NPV (net present value), IRR (internal rate of return), CAPEX (capital expenditure), and OPEX (operational expenditure) [21]. However, the most simplified and commonly used term in this field is LCC or Life Cycle Cost, which refers to a simple addition and subtraction method to show the feasibility of any industry [51]. The simplified expression of the term is stated below-

LCC = (Capital cost + Operating cost + Feedstock cost + Maintenance cost) – (Salvage value + By-product credits)

However, the calculation has a further elaborate mathematical expression. The palm industry requires a high investment in the first year of production. According to a study in Colombia, the project had a lifetime of 30 years and required 100% investment in the very first year [51]. The initial capital includes outlays required for the land for cultivation, and construction of buildings, instruments, and equipment [21]. The amount varies to a wide range based on the capacity of the diesel plant and the type of feedstock used.

Plantation: The operational cost of this stage is further distributed between the steps followed in this stage. A Colombian plant showed data that if the total operational cost during this stage alone is a total of 100%, the crop establishment process costs around 4%, while the major part (96%) comes from the crop maintenance steps. Fertilizers and pesticides account for 29%, harvest and transportation of fresh fruit bunches account for 25%, workers and machinery costs around 22%, and the final 20% is spent on land area and management of the cultivating yard [21,52].

Palm Oil Mill: A study from the Colombian plant discussed above showed that if the total expense of POM is considered to be 100%, the fixed costs account for 42%, labor cost is around 28% of the total POM cost, maintenance cost of the equipment and infrastructure costs 16%, electricity expense is around 9%, and management cost is 5% [21].

Biodiesel Plant: The same study shows that the feedstock costs around 73% (a major part) of the total biodiesel plant expense. Supplies and labor cost 21%, and 2% respectively, quality analysis studies and maintenance procedures cost 1% each, and electricity accounts for 2% of the total biodiesel plant expenditure [21,52].

3.4.1. Amount of Expenses According to Various Sources

Determining the exact amount of expense for each step is not possible, as the amount may vary drastically depending on the location, type of feedstock used, and market price of the raw materials required. A study in Colombia showed that FFB as a raw material can cost 125 USD/ton, and CPO can cost up to 735 USD/ton [21]. Another source showed that feedstocks may cost 2.72 USD/gallon, supplies and labor cost 0.79 and 0.09 USD per gallon, respectively, electricity accounts for 0.07 USD, quality analysis costs 0.05 USD, and maintenance cost is

0.03 USD per gallon [53]. PFAD costs 0.57 USD/kg, methanol costs 0.33 USD per kg, and sulfuric acid (H_2SO_4) and NaOH cost 0.22USD/per kg and 0.54 USD per kg, respectively, according to another data source [33]. The total production cost of one gallon of biodiesel from soybeans is 2.95 USD in the United States of America, and the amount for the same amount of production is 5.85 USD per gallon in Brazil, where castor oil is used as feedstock. In Malaysia, using palm as feedstock, the amount varies from 2.39 to 3.75 USD per gallon [51]. Another study showed that FFB costs 0.12 USD/kg of biodiesel, 0.38 USD for diesel, 0.43 USD for other HFO, 0.35 USD for methanol, catalyst, and NaOH, 0.635 USD per kg [54]. The CAPEX is around 37.8 USD/ ton CPO (51% from the Palm oil mill and 49% from crop and feedstock), and OPEX is 519.2 USD/ ton CPO [21]. Also, another data showed that OPEX is 0.369 USD per liter of biodiesel produced [55].

3.4.2. Gains from Biodiesel Production

The gain depends on the market price of the end products. The market value of biodiesel depends solely on the government schemes of a country and the demand in the market of a location. During the past few decades, civilized countries have become increasingly concerned about the hazardous changes happening to the environment, causing a rapid surge in demand for biodiesel.

Data shows the growing need and popularity of biodiesel worldwide. According to a study performed in 2016, biodiesel has a market value of 0.813 USD per liter, and as the main by-product, glycerol has a market price of 0.062 USD per kg [52]. Another research-based study showed that the total income can be 800 USD per ton, of which 92% comes from the CPO, 5% from the power supplies, and 2% from the palm kernel pellets [21]. Overall, palm-based biodiesel has proven to have a profit value almost always higher than 22.4%, which indicates a 1.08 USD profit margin per gallon of biodiesel [33]. Besides, biodiesel glycerol and other by-products, if used properly, are proven to be economically useful. Palm kernels have a market value of 0.41 USD per kg, and bio-fertilizers provide a 0.09 USD per kg market price [54]. Bio-energy-based electricity costs around 0.085 USD per kWh, which is less than conventional electricity and is economically sustainable for the producers as well [54]. Depending on the facilities available in any plant, the total amount of profit and expense to gain ratio often varies a lot.

3.4.3. Profit

There is absolutely no doubt that the palm oil-based biodiesel industry is economically profitable, looking at its rising popularity in the modern era. The industry requires a massive amount of capital cost during the very first year, the payback time or time to regain that amount from the very same industry varies from 5-7 years in most of the cases [54]. In a conventional biodiesel plant with a capacity of producing 30 kt CPO per year and 25 kt biodiesel per year, the annual profit (income-outcome) is nearly 602 USD per ton [52]. But if plants can undergo certain changes, the amount can rise to 2699 USD, for instance, installing a co-composting plant and bio-energy cogeneration plant may require a larger amount of initial capital cost, but this ensures a much higher income and shortens the payback time by 1-2 years on average [54].

4. Conclusions

4.1. Key Findings

Oil palm biodiesel showed an average net energy ratio (NER) of 3; for Jatropha, canola, and soybean, the values are 4.7, 2.2, and 3.2, respectively. Most of the production is based in Thailand, Malaysia, and Indonesia. In terms of environmental value, SO_x and NO_x production is observed to be lower than those of fossil fuels. The other environmental aspects, such as land use, rainforest degradation, and invasive species, raised questions, but not enough research has been done in this area. In one study, it is reported that a bio-based approach for biofuel production from oil palm can give an NER value as high as 17.7 to 22.9 [56].

Presently, the price of biofuel in India varies greatly based on the quality and purity of the end product, within a range of 35–75 INR per litre. Internationally, the price follows a much more stable trend: in March of 2026, the international benchmark was about USD 1.14/kg in Northeast Asia, USD 1.50/kg in Europe, USD 1.37/kg in South America, and USD 1.18/kg in North America. As reported in the U.S. retail alternative-fuel report, B99–B100 biodiesel price was listed at USD 4.30/gallon, which is about USD 1.14/litre [57]. So, globally, biodiesel pricing is usually clustered around a little above USD 1/litre equivalent, with Europe on the higher end and Northeast Asia on the lower end [58]. Considering the present exchange rate of INR to USD, the Indian market price of biodiesel is much cheaper compared to the international standard, leaving room for growth of the industry in the subcontinent. Industrially, there is a hypothetical profit value of 1.08 USD/gallon, which is 22.4% of the production cost as reported in one Colombian study [33]. Despite some issues regarding agricultural methods used in feedstock cultivation, Oil palm-derived biodiesel is a viable alternative to fossil fuels. Biodiesel price highly varies based on the government policies and involvement regarding sustainable energy promotion, and in 2022, the government of India has demonstrated a positive approach toward biodiesel or biesel (blend of biofuel and diesel) utilization by promoting oil palm importation in their Biofuel Policy 2022 [59,60].

4.2. Future Scopes

The growing concerns about global warming and climate change can be addressed through scientific advances in fuel technology. This study aimed to understand the actual potential of oil palm as a feedstock for biodiesel. The value of the net energy ratio (NER) can be determined entirely; hence, average values of NERs from the research articles studied for this review work have been presented before. For oil palm, the mean NER value is 3, except for rapeseed, which showed a higher value than that of oil palm. With conscious policies and hands-on approaches, biofuel from oil palm can be a sustainable alternative to fossil fuels [61]. In Nigeria, the reuse of biowaste was reported recently with significant success [62]. In another study, a microalgal-oil palm hybrid approach was taken to reduce the waste production [63]. Research has been going on in this very field to make this model of fuel production more environmentally friendly, and with the help of scientific advancements and thoughtful usage of such inventions, the biodiesel industry can gain the potential to fully replace fossil fuels. The key concerns of this growing industry should be to lean toward a more sustainable production path by reducing waste and reusing the by-products as alternative resources, incorporating other renewable energies, such as solar/geothermal, in the production process, and focusing on holistic growth of the industry, among others [64].

4.3. Limitations and ecological concerns

Even though life cycle analysis usually covers an intensive cradle-to-grave study of the entire process of production, many environmental issues are overlooked during the calculation. While a reduction of fossil fuel dependency can result in various positive outcomes, introducing a foreign/invasive species into a new environment comes with many short- as well as long-term ecological impacts. As reported in a few case studies, in many areas of Malaysia, rainforests are being cut to plant oil palm, which not only entirely disrupts the biodiversity of the said ecosystem, but also might cause a huge environmental havoc [65]. Another issue with using oil palm as the primary feedstock in biofuel comes from an ethical concern of global food security. In addition, water consumption of oil palm and soil component alteration needs to be further studied to ensure safe, ethical, and sustainable production practices [66].

The environment is already going through rapid changes due to anthropogenic activities, many animals are facing the risk of extinction, and if scientific advancements do not come forward to reduce fossil fuel depletion, the situation might get worse. Oil palm might be one of the many ways to bring the desired change. But like any other industry, the industry has its drawbacks as well. Combining multiple feedstocks or using biofuel in combination with other renewable sources might yield a higher NER while preserving the ecological balance.

5. Limitations of the Study

This study aimed to evaluate the viability of oil palm as a primary feedstock option in the production of biofuel. However, the study lacks information in various fields. For instance, most case studies as well as original research papers are based on Malaysia, Indonesia, and Colombia, lacking a truly global view of the issue. In addition, although various feedstocks were taken into consideration while conducting this review work, some high-yielding alternatives were overlooked for the sake of maintaining the equilibrium; microalgae-based biodiesel production and fuel production from food waste showed promising outcomes in several recent studies [67]. In the future, such studies should be incorporated to have a broader picture of the present scenario in biofuel production.

Author's Contributions

Dr. Om Prakash Chaturvedi and Dr. Krishnendu Kundu conceptualized and supervised the study. Dr. Abhishek RoyChowdhury, Dr. Sayanti Kar, and Dr. Kaizar Hossain supervised and visualized the study. Dristi Majumdar investigated, collected data, and wrote the initial manuscript. Dipsita Hati helped in the investigation and revision of the manuscript.

Conflicts of Interest

There was no conflict of interest.

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