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Biodiesel Production from Spirulina Microalgae and its impact on Diesel Engine Characteristics-Review

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ABSTRACT

This research aims to investigate the literature review on the extraction of algae oil, production of algae methyl ester (AME) biodiesel and the effect of microalgae biodiesel on the performance, combustion and exhaust emissions of diesel engine. The study dealt with researchers who published their reports between 2006 and 2020. Researches now concentrate on renewable energy, and biodiesel is one of the renewable energy sources. Biodiesel is a fuel similar to diesel and has many positive aspects such as quality, renewable energy, lower exhaust emissions, and greater lubricity. In addition to the use of microalgae in the production of fuels, they are used in reducing CO_2 of the atmosphere which in turn results in better air quality to breathe and cleaner environment. Many researchers have paid attention to produce biodiesel derived from microalgae that represents one of the oldest living creatures on the globe. However, by comparing it with diesel, it has some drawbacks like lower heat content, higher density, viscosity, and NOx emissions. Optimization strategies are still recommended to fight the side effects of using biodiesel instead of original diesel fuel.

1. Introduction

For more than a century, the diesel engine engines have deep impact on the industrial economy, as they are used in a wide variety of applications that require mechanical motive power. Increasing tough emissions regulations coupled with fast depleting crude oil resources have caused a stimulation of interest in finding alternative fuels for petroleum-based fuels like diesel and gasoline [1]. Extracting oil from plant resources has attracted considerable attention. In many countries, vegetable oils are used after esterification as "biodiesel" [2]. Researchers have turned their interest towards fuel production from one of the oldest living creatures on the earth, microalgae. Besides their use of producing fuels**, also** for capturing the CO_2 from the environment which gives better air quality to breathe. Algae are one of the most exciting future solutions for our energy crisis, especially that of transportation fuel. Algae need very low requirements to grow including carbon dioxide, sunlight, and water **[3]**. The objective of the present article is to conduct a comprehensive review starts from the oil extraction process, converting the extracted oil to biofuel and ends with the impact of using it as a fuel blended with diesel fuel on the performance, emissions, and combustion parameters of diesel engine.

2. Extraction Algae oil

The oil extraction refers to an operation that transfers one or more components of a solid or liquid phase to another liquid phase. Several methods are used to extract the oil from microalgae, such as mechanical extraction and chemical extraction. Solvent extraction process is more common than mechanical as it extracts almost all the oil and leaves in the

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raw material just (0.5- 0.7) percent of residual oil. The solvent extraction process can apply to any raw oil content materials [4]. The next lines summarize the recent literature papers that deal with the extraction process.

Baig et al. **[5]** explained the oil extraction process from microalgae spirogyra biomass by using n-hexane as a solvent. The authors studied and analyzed the effect of contact time, size of algal biomass, n-Hexane to oil proportion on the percent yield of oil extraction. It was noted that the maximum volume of oil was derived from the biomass of spirogyra using longer contact time, the smaller size of algal biomass, and a greater proportion of solvent to algal biomass. The study registered a 2.5-fold rise in the algae-to-solvent ratios from 1:1 to 1:3 compared with the previous ratio.

Topare et al. **[4]** experimentally studied several methods of oil extraction from algae growing in the open pond system, such as hexane solvent extraction, mechanical pressing, etc. It was noted that the solvent method recovers nearly all the algae oil and leaves only 0.5% to 0.7% oil remaining in the material raw. Solvent extraction method was found to be a better method for the extraction of fats and oils, due to the higher percentage of oil recovered. The study pointed out that the expeller method could recover 75% of the oil from the microalgae.

Shimi et al. **[6]** described in detail the chemical extraction of algae oil from platensis-spirulina using several different solvents subjected to different conditions. The results showed that soxhlet extraction using methanol gives the highest rate of algae oil extraction (98.5%) at 1 hour using biomass to solvent ratio of (1:110). Specifications of oil extracted, showed that viscosity is 58 mPa.s, density is 0.89 kg/L and the acid number is 37.4 mg KOH/g, because of these high values, the algae oil should be transformed to biodiesel by using the appreciated methodology. It was concluded that biodiesel derived from algae oil appears to be golden substitute fuel to reduce the dependence on petroleum fuels. The fatty acid in spirulina is palmitic acid (48.35%) makes it a promising feedstock for the production of biodiesel.

A simple, friendly and energy-efficient method of extraction crude oil from microalgae utilizing dimethyl ether (DME) was presented by Kanda and Li. **[7]**. The authors tested this method on some kinds of natural microalgae (green-blue). As a result, green crude was effectively straight extracted from elevated moisture- microalgae (78.2–93.4 %water content), with an extraction rate changing from (9.9 to 40.1 % dry weight) of the microalgae. The yield extracted by liquefied (DME) was contrasted with the Bligh-Dyer process widely used. The DME technique nearly attained efficient extraction similar to the Bligh-Dyer’s method. It was also found that traditional methods are unable to remove green crude directly from elevated moisture microalgae.

A detailed description of the optimum conditions of the extraction oil method from microalgae- chlorella was presented by Abdullah et al. **[8]**. Soxhlet extraction method is used. It was found that the greatest extraction rate is 61.27% when using heptane as a solvent in the following conditions: 65 °C temperature of reaction, mixing rate of 600 rpm, and extraction time of 5 hours.

Yoo et al. **[9]** applied directly osmotic shock way to wet microalgae biomass with more 99% water content for the extraction of lipids, with both polar and non-polar organic solvents. The results indicated that osmotic shock increases lipid recovery nearly 2 times, and advised that it is a good technique to remove wet lipid from biomass of microalgae. Shah et al. **[10]** discussed the production of oil economics from the algae grown in open ponds by ultrasonic wave, soxhlet and expeller method. About 50% of algae oil was converted to biodiesel by using the transesterification process. The results highlighted that the soxhlet method was the most reliable method for oil extraction.

Shin et al. **[11]** investigated the performance, economic hurdles, special features of different methods to produce microalgae mass involving open pond, photo bioreactor, and immobilized culture procedures. The system of open ponds was considered the easiest, simplest, and least costly method. Despite this, their productivity is poor and easily infected with other microorganisms. The other widely used algal culture systems are the photo bioreactors. It can achieve double biomass efficiency as compared to open ponds along with greater control of pollution with complex designs of gas transfer, light dilution, and thermal insulation. Immobilized algae cultivation systems have huge potential to reduce the harvesting issue of open ponds and photo bioreactors and increase the productivity of biomass.

Wiyarone et al. **[12]** described the characteristics of microalgae oil extracted from Nannochloropsis sp. Two extraction processes were examined, soxhlet-assisted and ultrasonic-assisted. Both methods used ethanol as a solvent. The outcomes revealed that the concentration of ethanol influenced the quality of the algae oil. The better outcome achieved when the concentration of ethanol was 70%. In the meantime, the amount of circulation also affects oil yield quality. The optimum time was 200 minutes. While the use of ultrasonic extraction significantly reduced the temperature and time. The GCMS test of algae oil components indicated that there was no noticeable difference between the two extraction methods is recorded.

Halim et al **[13]** used the supercritical carbon dioxide ($SCCO_2$) and hexane method for the extraction of the lipids from marine Chlorococcum. Various variables affect the efficiency of $SCCO_2$ extraction, such as extraction time, type of algae used, temperature, and pressure. Compared to other lipid-rich microalgae organisms, the chlorococcus used in this study was calculated to have a relatively low lipid yield (7.1 % of dry biomass). The findings showed for $SCCO_2$ extraction, decreasing temperature and increasing pressure resulted in increased lipid yields. The extraction of soxhlets using hexane is significantly less effective than the extraction of $SCCO_2$, resulting in a comparable lipid yield (0.058 gram of lipid extracted per gram of dried microalgae). Table 1 listed the researcher's findings in a summarized way.

3. Production of AME biodiesel

With the ever-increasing demand for energy and impending depletion of fossil fuels, it has become necessary to find out sustainable source of energy. Promising alternatives closer to conventional diesel fuel include algae biofuels, particularly algae biodiesel have been used successfully powered diesel engines. One of the most popular methods used for the production of biodiesel is the transesterification process. The methanol along with sodium hydroxide as the base catalyst used to minimize the raw oil's free fatty acid content The specific parameters that influence the transesterification reaction are: the molar ratio of oil to methanol, the concentration of the catalyst, reaction temperature and time. The next coming studies related to the production of Algae methyl ester (AME) biodiesel via transesterification process.

Karmakar et al. [14] described the preparation of biodiesel from unused algae in two step procedure, acid esterification followed by transesterification. Taguchi’s method was utilized to design the experiment. The best operating conditions for transesterification were selected at (methanol/oil) molar ratio of 6:1, 2.5wt% catalyst KOH,50 °C temperature, and 90 min of reaction time, getting 89.7% of a biodiesel production with 0.25% of content free fatty acid. It was found that diesel engines released less hydrocarbon, CO, CO_2, and higher NOx when using algal biodiesel instead of using petro-diesel. All properties of the produced biodiesel obtained were meeting ASTM standards.

Lardon et al. [15] provided an overview of the possible environmental effects of micro-algae biodiesel production. A virtual facility comparative life cycle assessment analysis was undertaken to assess the energy balance and possible environmental impacts of the entire process started from the processing of biomass up to the combustion of biodiesel as shown in figure (1). The results confirmed the ability of using microalgae as an energy source, but emphasize the imperative need to reduce energy consumption and fertilizer use. The regulation of nitrogen stress during cultivation and the optimization of wet extraction seemed to be useful options.

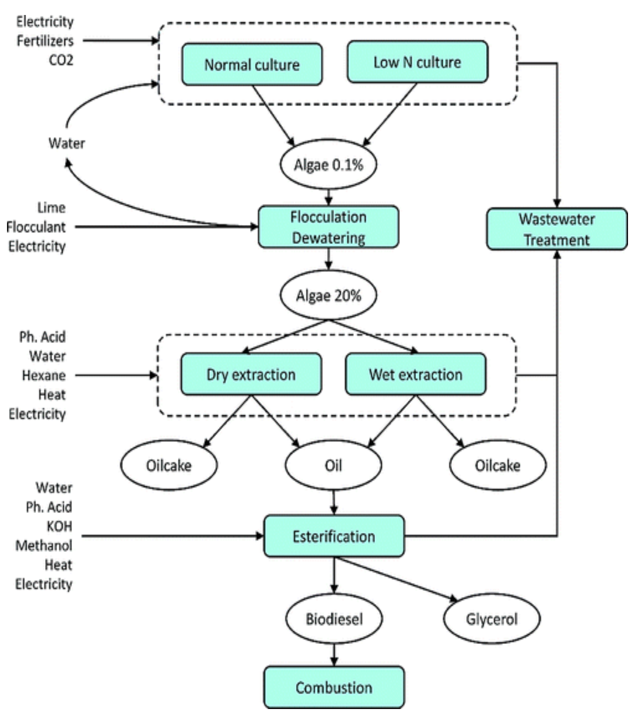

Figure (1) Schematic diagram for the production and testing of AME biodiesel

Sánchez et al. [16] examined the effect of added n-hexane on the transesterification of solid raw materials for the production of biodiesel. Algae oil extraction and reaction were performed concurrently in a batch reactor, incorporating n-hexane with the reactants. The findings revealed that n-hexane has no major effect on the transesterification process. It has been noted that this method requires large amounts of methanol to perform the reaction. The reaction requirements for marine macro-algae transesterification were methanol/oil molar ratio (300:1), 60°C temperature, and around 11 hours reaction time. This resulted in a yield of 17.1 % methyl esters.

Miao et al. [17] developed a coordinate strategy to produce the biodiesel from heterotrophic microalgae oil. With the use of n-hexane, large amounts of microalgae oil were effectively extracted from heterotrophic cells. The best procedure of mixing was 100% catalyst amount, methanol to oil 56:1 molar ratio at a temperature of 30°C in around 4 hours response time, which reduced specific gravity from 0.912 to 0.8637. The outcome indicated that the new technique, which incorporated transesterification and bioengineering, was a feasible and efficient approach for producing high-quality microalgae oil biodiesel.

Scott et al. [18] designed an overview of the potential algal biofuel pipeline and focused on previous researches aimed to improve the production of algal biomass and the fuel molecules contained within the algal cell. Figure (2) shows an approach for algal biodiesel development. Several factors need to be considered and optimized at each point, including inputs of energy and materials (e.g. nutrients and energy for mixing during growth).

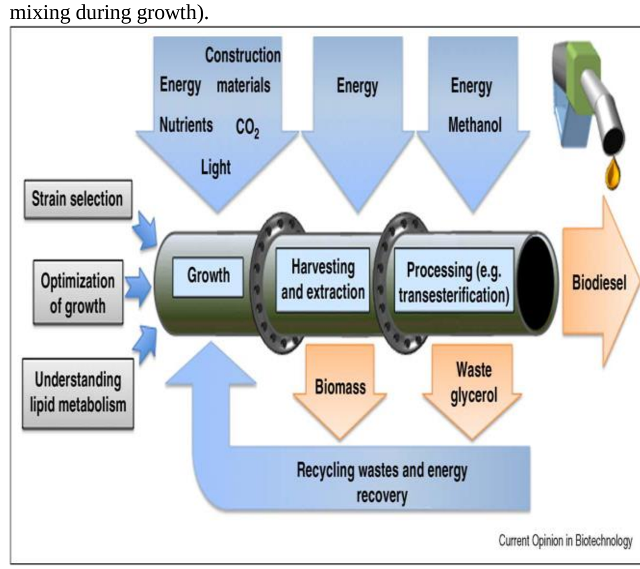

Figure (2) Algal biofuel pipeline

Hariram, et al. [19] derived algae oil methyl ester(AOME), from Spirulina microalgae grown in a photo bioreactor. A two-step solvent extraction method employing ether and hexane solvent was applied to obtain the algae oil. Cyclohexane was put into biomass to eliminate the residual algal oil. The percentage of algal oil was obtained in this method is 92%. The transesterification method was applied to produce algal oil methyl ester by adding methanol and sodium hydroxide. The AOME was mixed with diesel at different blending ratios (5%, 10%, and 15%). It was noted that CO, HC, smoke, and particulates emissions decreased while a slight increase in the NOx emissions is reported.

Recently microalgae have achieved much interest because of their high oil contents and rapid growing rate. Tüccar and Aydın [20] focused on microalgae biodiesel as an alternative fuel in diesel engines. Biodiesel production of microalgae oil was mixed with diesel at (5%, 10%, 20%, and 50%) blending ratio. The results displayed a reduction in brake power and torque values of the engine when using microalgae biodiesel while the emission values were reduced.

Kammakar et al. [21] studied the production of biodiesel from microalgae oil by transesterification reaction. Methanol is used along with KOH as the catalyst. They found that perfect conditions for obtaining minimum viscosity and free fatty acid content with maximum ester when using oil to methanol 1:6 molar ratio, 3 wt% of KOH, 1 hour time, temperature of 60 °C and 2.5 hours of settling time. Most significant properties of ester biodiesel like fire and flash point (158 and 153 °C), viscosity (3.12 mm2/s), carbon residue content (0.03%), pour and cloud point (−6 and −1 °C, respectively) were found within the range of ASTM/BIS standards.

Akubude et al. [22] worked on the production of biodiesel from microalgae via. transesterification process. The authors studied the production of microalgae, economic purposes of microalgae involving production of the fuel, food product extraction, CO_2 capture for bio refinery resulting in the production of bio hydrogen, bio methane, and bioethanol. Issues included various groups of catalysts such as heterogeneous catalysts, homogenous catalysts, and enzymatic catalysts. The use of this technology for the production of biofuels can be commercialized for developing the biodiesel industry.

Gradual rise in carbon dioxide CO_2 concentrations in the atmosphere because of the many anthropogenic activities resulting in major changes in the global carbon cycle. Therefore, microalgae appeared to be an effective medium for capturing extra CO_2 existing in the atmosphere produced from various sources, like automobiles, power plants, and forest fires. Capturing CO_2 through microalgae used as a significant source of carbon to produce lipids from biofuel to replace fossil fuel-derived transportation fuel without influencing crop and food supplies. Various parameters such as time, temperature, light intensity, CO_2 concentration, PH, and flow rate were discussed as a factor affecting on production of biodiesel in photo bioreactors. The results showed that using this method can reduce the proportion of CO_2 in the atmosphere, and thus reduce global warming (Mondal et al. [23]).

Ahmed et al. [24] collected the algae spirogyra spices from various regions of Pakistan and utilized it as a feedstock for production the biodiesel in two stages. During the first stage, the oil was extracted from algae using Di-ethyl Ether and n-hexane as solvents, while in the second step, extracted oil was converted to biodiesel through transesterification process. Almost 95% of biodiesel was obtained using catalyst (Sodium Hydroxide) amount of 0.5wt%, contact time of 25 min at 60 °C and 1:8 molar ratio of oil/methanol.

Fulke et al. [25] explained a feasible technology to convert microalgae lipids lived in a wastewater pond to biodiesel by using photosynthetic CO_2. The highest CO_2 fixation rate was observed in mixed algae samples, followed by chlorella. These findings indicated that biodiesel produced from microalgae lipids can indeed prove profitable, If grown under suitable nutrient and CO_2 conditions, will lead to an ideal high biodiesel yielding cycle and effective sequestration of CO_2.

Aljabarin et al. [26] studied the production of biodiesel from algae. The algae were taken from open ponds and then dried for 12 hours in the oven at 80 °C. Powder was gained by using a disc mill to grind the dried algae. Iron sulphate hydrate is added to the powder to obtain algae oil utilizing a distillation column. Methanol and potassium hydroxide as a catalyst were added to algae oil, the mixture then put in a separated funnel for around 10 hours until two layers of the mixture were obtained, the upper layer represents the biodiesel as shown in figure (3). The outcomes highlighted that biodiesel properties are similar to diesel, except that it decreases carbon dioxide CO_2 emissions and sulfur dioxide SO_2 emissions are not present.

Biodiesel production from algae oil through the transesterification process using methanol and KOH or NaOH as catalyst was presented by Tapore et al. [27]. Three moles from methanol reacted with one mole of triglyceride which creates a mixture of biodiesel and glycerin. It has been discovered that transesterification is a very successful method for reducing the viscosity of vegetable oils and making them suitable for use in such diesel engines without any modification. The finding showed biodiesel from algae oil decreases the greenhouse impact on the atmosphere, by reducing CO_2 gas pollution, and improves the percentage of O_2 in the exhaust gas compared to the ordinary diesel.

Chen et al. [28] developed a novel method for the production of biodiesel from wet microalgae. This method consisted of disrupting the microwave, removing partial water, extracting oil, and transesterification. The wet microalgae biomass with a moisture content of around 80 % was employed as the raw material for the production of biodiesel. Methanol added to algae oil in different ratios such as 10:1, 8:1, 6:1, 4:1, and 2:1. In addition to 25, 35, 45 ,55 and 65°C of reaction temperature and reaction time of 5, 10 ,15 ,20 ,25 and 30 min. The results showed that the moisture content of wet microalgae decreased to approximately 50% after disrupting the microwave, and removing partial water. The recovery of oil from pretreated microalgae reached 90 % and transesterification conversion was greater than 90%.

Hossain et al. [29] presented a study to know the correct transesterification, the amount of biodiesel production and the physical properties of biodiesel. The authors compared the volume of biodiesel production using the popular species Spirogyra and Oedogonium. The findings pointed, In Oedogonium, the production of algae oil and biodiesel was greater than in Spirogyra species as shown in figure (4). The main outcomes of all studies mentioned are listed briefly in Table 2.

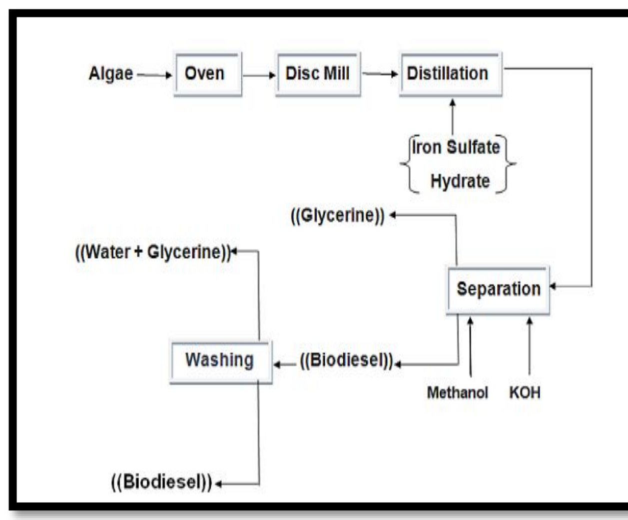

Figure (3) Flow diagram for the production of biodiesel from algae

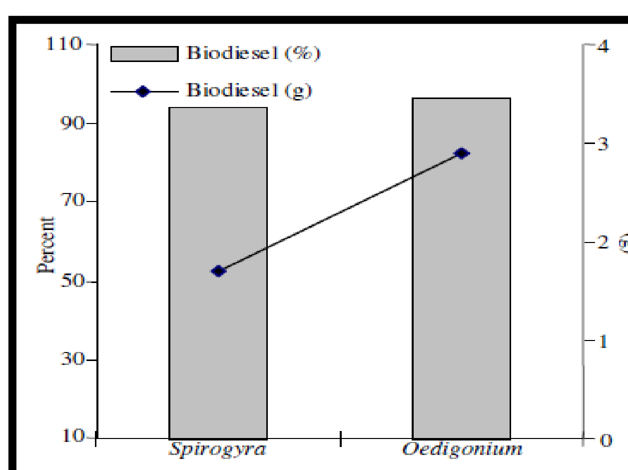

Figure (4) Biodiesel production in Spirogyra and Oedogonium sp.

Table 1 Summary of algae oil extraction studies

Reference	Micro(algae)	Extraction process	Conclusions
Baig et al. [5]	Spirogyra sp.	Solvent extraction process using n-hexane as solvent	Maximum amount of oil obtained as the solvent to algae ratio increased, longer contact time, smaller size of algal biomass
Topare et al. [4]	Not declared	hexane solvent extraction, expeller method	The solvent extraction process can be extended to any products with a low oil content
Shimi et al. [6]	Spirulina-platensis	Solvent extraction process using methanol as solvent (Soxhlet Extraction System)	The fatty acid in Spirulina is palmitic acid (48.35%) makes it a promising feedstock for production the biodiesel
Kanda and Li. [7]	microalgae (green-blue)	dimethyl ether (DME)	This approach has the advantage of reusing the water drained as a microalgae broth.
Abdullah et al.[8]	Chlorella vulgaris	Soxhlet extraction method	Too high temperatures in oil extraction can cause portion decomposition of the microalgae cells and thus reduce oil yields
Yoo et al. [9]	Chlamydomonas reinhardtii	osmotic shock treatment	osmotic shock increase lipid recovery nearly 2 times
Shah et al. [10]	Scenedesmus dimorphus sp.	ultrasonic wave, soxhlet and expeller method	The best way of reduce work was the soxhlet system
Shin et al. [11]	Not declared	Photo bioreactors (PBRs)	Reduced CO_2 emissions, appealing for recycling exhaust gases from power stations
Wiyarone et al. [12]	Nannochloropsis sp.	Ultrasonic and Soxhlet extraction	Ethanol concentration has affected the quality of the algae oil
Halim et al. [13]	marine Chlorococcum	supercritical carbon dioxide (SCCO2)	decreasing temperature and increasing pressure resulted in increased lipid yields

Table 2 Summary of algae biodiesel research works

Reference	Micro(algae)	Production method	Conclusions
Karmakar et al. [14]	unused algae	Acid esterification + transesterification	CO and CO_2 reduction, higher NOx
Lardon et al. [15]	Chlorella vulgaris	Esterification	LCA serves as a critical method for evaluating new energy generation technologies
Sánchez et al. [16]	Marine algae	In Situ Transesterification	N-hexane had no significant effect on the transesterification process
Miao, and Wu [17]	Heterotrophic microalgae(Chlorella protothecoides)	Acidic transesterification	Producing high-quality microalga oil biodiesel using a new technique, which incorporated transesterification and bioengineering
Scott et al. [18]	Species of Chlorella, Haematococcus, and Dunaliella	Transesterification and optimization method	Considered several factors that need to be optimized, including inputs of energy and materials (e.g. nutrients and energy for mixing during growth of algal biomass)
Hariram, and Kumar [19]	microalgae (Spirulina sp.)	Transesterification	CO, HC, smoke and particulates emissions decreased while a slight increase in the NOx emissions
Tüccar, and Aydın [20]	Not declared	Transesterification(using NaOH as the catalyst)	Brake power and torque values decreased, improved Carbon and NOx emission levels
Kammakar et al. [21]	Not declared	Transesterification(using KOH as the catalyst)	CO_2 can be used for microalgae growth and can reduce any kind of emission level
Akubude et al. [22]	Not declared	Nano catalyzed transesterification	less costly, simpler and leaner process. Yield more efficient
Mondal et al. [23]	Not declared	Transesterification	Reduce the proportion of CO_2 in the atmosphere, reduce global warming
Ahmed et al. [24]	Spirogyra sp.	Transesterification	Almost 95% of biodiesel was obtained using catalyst (Sodium Hydroxide) amount of 0.5wt%, contact time of 25 min at 60 °C and 1:8 molar ratio of oil/methanol
Fulke et al. [25]	wastewater microalgae	Not declared	Mixed algae specimens showed the highest levels of CO_2 fixation
Aljabarin and Al jarrah [26]	Not declared	distillation process(using KOH as the catalyst)	decreases carbon dioxide emissions, SO_2 emissions are not present
Tapore et al. [27]	Not declared	Transesterification(using KOH or NaOH as the catalyst)	reducing CO_2 emission, increase O_2 in exhaust gas
Chen et al. [28]	Chlorella Vulgaris	Transesterification(using KOH as the catalyst)	The recovery of oil from microalgae reached 90 % and transesterification conversion was greater than 90%
Hossain et al. [29]	Spirogyra and Oedogonium species	Transesterification(using NaOH as the catalyst)	the production of algae oil and biodiesel from Oedogonium sp. was greater than in Spirogyra species

4. Effect of microalgae biodiesel on the performance, combustion and exhaust emissions of diesel engine

A great number of experiments were conducted by researchers from different parts of the world with biodiesel as a replacement for compression ignition diesel engine fuel.

Rajak et al. [30] investigated the characteristic of diesel engine numerically using the simulation Diesel-RK software. The engine is powered by pure algae biodiesel and diesel at different compression ratios from 16.5 to 18.5. Test engine experiments with an ideal compression ratio of 17.5 were conducted under maximum load conditions, and the results were compared with the numerical results. The products showed a 2.73% reduction in brake thermal efficiency, 6.66% reduction in torque, 1.6 reduction in exhaust gas temperature, 6.1% reduction in carbon dioxide, and 0.5% reduction in nitrogen oxide at full load condition under constant speed. However, SFC was increased by 6.4% at CR 17.5 as compared to pure diesel. Naresh et al. [31] studied the emissions and performance characteristics of a diesel engine (4-stroke, direct injection) using algae methyl ester oil with varying exhaust gas recirculation (EGR) control value of 5 to 20%. Biodiesel and its mixtures displayed a significantly lower thermal brake efficiency relative to diesel fuel under various conditions of load. The energy consumption of fuels decreased as the amount of mixed fuels increases due to the reduced calorific values. NOx and HC are decreased as the amount of EGR increases. With higher rates of exhaust gas recirculation, the emissions and performance parameters are decreased. Therefore, 15 % of EGR is optimal for fuels to improve their performance and emission characteristics. Rajak et al. [32] investigated the effect of spirulina microalgae biodiesel blending ratio on a naturally aspirated diesel engine at various loads. Combustion, emissions, and performance analyses reported a reduction in cylinder pressure, exhaust emissions, exhaust temperature, and brake thermal efficiency relative to diesel fuel. Regarding the emissions parameters, the spirulina microalgae biodiesel blends resulted in lower NOx emissions of 4.9%, PM emissions of 20.7%, and lower smoke of 5.4%, but CO_2 emissions for all loads is increased. Satputaly et al. [33] turned the microalgae oil gained from chlorella to biodiesel using the transesterification process. The produced biodiesel production was tested in Kirloskar diesel engine with capacity 5.2 kW to analyze the combustion, performance and emission. The tests revealed a 3.09% decrease in thermal brake efficiency. The findings showed a decrease in CO, unburned hydrocarbons, nitrogen oxide and smoke opacity emissions when fueled with methyl ester microalgae oil relative to diesel.

Algae oil derived from microalgae using soxhlet having viscosity equal to 8 times that of diesel, was blended in three different amounts with sunflower as follow: 5ml of algae oil + 95ml of sunflower oil (5:95), 10ml of algae oil + 90ml of sunflower oil (10:90) and 15ml of algae oil +85ml of sunflower oil (15:85) respectively, in order to reduce the viscosity. Furthermore, the above mentioned mixture was transformed into biodiesel through two-step transesterification method with methanol. Also, the three biodiesel forms produced were mixed in 10:90 ml with pure diesel (B10A%, B10B%, B10C%) The study involved examination of chemical and physical properties. The biodiesel properties produced conform to ASTM measurements. The results showed that brake thermal efficiency is higher by 2.77% for the B10C% biodiesel than that of the conventional diesel. Likewise, the volumetric efficiency is increased by 1.52% for the B10C% biodiesel when compared with Diesel (Sankar et al. [34]).

El-Baz et al. [35] described the biodiesel preparation from microalgae oil. Blends of 10% and 20% of biodiesel were prepared. The blends under study had physicochemical properties similar to diesel oil. Biodiesel blend B20 indicated declined in specific fuel consumption, exhaust gas temperature, and increased thermal efficiency relative to diesel fuel and B10. The emissions of B20 has been reduced as opposed to B10 and diesel. It could be inferred that microalgae could be used to supply high quality biodiesel which can feed traditional diesel engines efficiently.

Rajak, and Verma [36] investigated the characteristics of emulsion fuel with microalgae biodiesel (B20) and their consequences on exhaust emissions, combustion, and performance of a direct injection, diesel engine. The engine operated at three different engine speeds. The diesel engine powered by B0, B20, and B100 diesel at full load condition. The results showed, 0.55%, 6.2%, 1.63%, 2.6%, and 1.2% reduction in indicated thermal efficiency, oxides of nitrogen, cylinder pressure, smoke emission, and brake thermal efficiency respectively. B20 showed an increase by 4.5%, 5.08%, 2.45%, 2.7%, and 5.08% for peak heat release rate, specific fuel consumption, carbon dioxide emission, and ignition delay period respectively at 1500 rpm with a full load. The numerical results are checked against the results of experiments carried out under the same operating conditions.

Murthy et al. [37] focused on biodiesel production from freshwater chlorella vulgaris algae. The authors used the various blends of algae biodiesel and diesel with variable loads to analyzed the emission, combustion, and performance characteristics of diesel engines. It was noted that B20 has higher brake specific fuel consumption due to the difference in the heating value compared to pure diesel. Reduction in NOx, CO and hydrocarbon emissions are observed.

Mahamudul et al. [38] explained that the usage of biodiesel and its blends marginally decreased engine power and raised fuel consumption but at the same time greatly lowered toxic emissions like hydrocarbons, particulate matter, carbon dioxides. The NOx emission is increased. CO_2 emissions could be ignored as it is consumed by the crops themselves. It was fulfilled that biodiesel has the potential to be used in diesel engines as a substitute fuel for solving the energy and environmental crisis. Makarevičienė et al. [39] conducted an experimental study on the employment of biodiesel containing (30% algae oil methyl esters (AME), and 70% fossil fuel) in VALMET 320 DMG diesel engine onboard ship. It was found that use B30 reduced smoke exhaust emissions to 10–75%, and 5–25% reduction of hydrocarbons emissions (HC) with respect to diesel emissions. The engine thermal efficiency was 2.5–3 % higher while operated on B30 compared to diesel fuel operation. Mathimani et al. [40] investigated the suitability of biodiesel derived from microalga chlorella vulgaris. Biodiesel-diesel blends were tested in a single cylinder diesel engine subjected to variable load operations (0%, 50%, 75%, 100%) to analyze the performance and emission characteristics. Engine powered with B50 reduced the hydrocarbon and CO emissions by 102 ppm and 0.1% respectively compared to baseline diesel. The results showed 6.1% reduction in CO_2, and 376 ppm reduction in nitrogen oxides NOx .

Reddy et al. [41] explained the possibility of using biodiesel derived from Schizochytrium microalgae oil as an alternative fuel for fossil diesel engines. Investigation was carried on diesel engine fuelled with microalgae biodiesel and its blends to evaluate the combustion, performance, and emission characteristics. The properties of biodiesel production were meeting the ASTM standards. The characteristics of the biofuel powered diesel engine compared with fossil fuel diesel engines were considered satisfactory.

Haik et al. [42] conducted an experimental study using the raw algae oil and its methyl esters in a diesel engine. In this study, the effect of heat release, engine speed, injection timing, compression ratio, engine load, combustion noise, and maximum pressure were studied. The properties of the algae oil methyl ester were shown to be similar to diesel fuel and their use has been effective in the smooth running of the diesel engine. However, its use marginally decreased the output torque engine and increased the noise from the combustion. The engine output can be increased and the noise from combustion can be reduced by regulating parameters of the engine design like compression ratio and injection timing. Patel et al. [43] examined the suitability of biodiesel derived from Indian microalgae. Three different algal biodiesel blends namely 10%, 15 %, and 20% with fossil fuel, were tested on a diesel engine. Noticeable reduction in unburned hydrocarbon, brake specific fuel consumption, and carbon monoxide is reported. Moreover, the emissions NOx increased significantly. It can be inferred that diesel fuel can be effectively blended with biodiesel algae to minimize fossil dependence by promising performance characteristics without any engine modification.

The main concerns for the automobile industry are engine performance, emissions, and roughness. An experimental test was undertaken on a Ricardo E6 indirect injection engine with a single cylinder for three different biofuels compared to pure diesel." One of the three fuels used is algae methyl ester AME ". There were two primary sets of experiments; first experiment, the engine torque (load) ranged from 0.5 to 15 Nm, while the other parameters are injection timing, engine speed, and compression ratio. In second experiment, the injection timing ranged from (20° to 45°) BTDC. The findings suggested that to accommodate the variety of biofuel characteristics, the fuel engine load and injection timing have to be adjusted. (Ospina et al. [44]). The results of all discussed studies are described shortly listed in Table 3.

Table 3 Engine performance

Reference	**Algae**	**Biodiesel tested**	**Engine**	**Conclusions**
Rajak et al. [30]	Spirulina sp.	B100	Single cylinder , four stroke, 17.5 Compression ratio, 3.7 kW	Reduction in brake thermal efficiency, , torque, exhaust gas temperature, carbon dioxide nitrogen oxide when using B100, increased in SFC
Naresh et al. [31]	Not declared	B20, B40, B60	direct injection, , four stroke, water cooled , 17.5 compression ratio, 5.9 kW, Kirloskar Engine	Lower thermal brake efficiency, NOx and HC decreases as the amount of EGR increase for biodiesel
Rajak et al. [32]	Spirulina sp.	B0,B20, B40, B100	Kirloskar diesel	Decrease in the ignition delay period as compared to original diesel. decrease in EGT and BTE
Satputaly et al. [33]	chlorella	B0, B100, raw algae oil	Kirloskar diesel engine, single cylinder, water cooled, capacity 5.2 kw	Reduction of CO, Unburned Hydrocarbons, NOx and Smoke Opacity emissions
Sankar et al. [34]	Spirulina sp.	B10A, B10B, B10C	5HP single cylinder,4 stoke, water cooled, diesel engine	Higher brake thermal efficiency for B10C compared to diesel, B10C gives the best result
El-Baz et al. [35]	Scenedesmus obliquus	B10, B20	Kirloskar, single cylinder four stroke, water cooled, diesel engine	Lower BSFC, EGT, higher brake thermal efficiency, lower emissions for B20
Rajak, and Verma [36]	Spirulina sp.	B0, B20, B100	Single cylinder, four stroke, direct injection, diesel engine	.Lower thermal efficiency, NOX, cylinder pressure, smoke emission and particulate matter for B20
Murthy, and Kumar [37]	Chlorella vulgaris	B10, B20	Kirloskar TV-I DI, four stroke, single cylinder, capacity 3.6kw, water cooled	Reduction in NOx ,CO and hydrocarbon emissions for B20
Mahamudul et al. [38]	Not declared	-	diesel engine	Increased in NOx and BSFC, reduction in brake power
Makarevičienė et al. [39]	Chlorella sp.	B30	VALMET 320 .DMG diesel engine onboard ship	Reduced smoke exhaust emissions to 10–75%, 5–25% reduction of hydrocarbons emissions
Mathimani et al. [40]	Chlorella vulgaris	B30, B40, B50, B60, B100	Kirloskar, four stroke, single cylinder, water cooled,	Decreases the hydrocarbon, CO, NOx and CO2 emissions
Reddy et al. [41]	Schizochytrium sp.	B20, B40 and B60	Kirloskar,AV1, single cylinder, vertical, four stroke, capacity 3.7kw	Weak atomization and rising exhaust gas temperatures gave lower thermal efficiency, lower HC, higher BSFC, NOx and CO, decreased in ignition delay
Y. Haik et al.[42]	Ankistrodesmus braunii and Nannochloropsis. A. braunii	B0, B50, raw algae oil	Ricardo E6 single cylinder, indirect injection diesel engine	Decreased the output torque engine and increased the noise from the combustion, decrease in the compression ratio of the engine resulted in diminishing the noise of combustion
Patel et al. [43]	Chlorella Vulgaris	B10, B15, B20	Kirloskar , single cylinder, vertical, four stroke, water cooled	Reduction in unburned hydrocarbon (UBHC), brake specific fuel consumption (BSFC), carbon monoxide (CO).
Ospina et al. [44]	Not declared	B0, B100	Ricardo E6 , single cylinder, four stroke, direct injection, diesel engine	Reduction in peak pressure, higher NOx emissions

5. Conclusion

This paper presents a comprehensive literature review of the most published papers in the field of extraction algae oil, algae biodiesel production, and its effect on performance, emission and combustion. A lot of points could be drawn:

- Although various sources of renewable energy are presently being used, the prospects of generating microalgae biofuels look promising due to their unique characteristics.
- The key of success in the microalgae biofuel production is the cost-efficient and successful extraction of lipids.
- Microalgae cells can produce and extract lipids. This lipid can be utilized in transformation to biofuel particularly biodiesel. This transformation reduces the emissions of petroleum, coal, nuclear power, hydro, and natural gas, which is a significant cause of greenhouse gas (GHG) emissions.
- Due to the higher oxygen content of the biodiesel compared with diesel, early start of combustion is observed.
- Sight reduction in the brake thermal efficiency is reported while the BSFC is increased.
- During the combustion process, biofuels may result in a decrease of toxic emissions such as CO_2, CO, unburnt hydrocarbon and soot.
- NOx is one of the important conditions for the diesel engine studies to be addressed. NOx forming in an engine is determined by the temperature of combustion and the rate of heat release. Consequently, the higher combustion temperature of the engines resulted in increased NOx emissions.
- Most literature papers in this context are based on experimental studies. A clear lack in the theoretical studies is detected, hence more theoretical and simulation works are required to bridge the gap.

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