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A Review on Microalgae Biofuel Production and use in CI Engine Applications

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ABSTRACT

Alternative fuel technology of third-generation biofuels in place of conventional fossil fuels is currently being witnessed at a global level. Due to its sustainability and environmental friendliness, in recent years more importance is being given to biodiesel in CI engine applications. Recent trends show that microalgae are promoted as a bio-fuel due to their inherent advantages of abundant availability of oil sources and faster growth rate with ease of cultivation. Particular species of algae such as *Chlorella, Botryococcus braunii*, and *Scenedesmus obliquus* are conventionally favored for biodiesel production as they have a prominent amount of lipids content. This review outlines the current state of experimental investigations on the use of different algae biodiesel blends with diesel for CI engines. Amongst the different algae-based biodiesel, the dual *Calophyllum Inophyllum* methyl ester blend (CIME20) with DEE demonstrated the maximum brake thermal efficiency (BTE) and better brake-specific fuel consumption (BSFC) of CI engines. In terms of emissions, the CO, UBHC, and smoke levels are significantly lower for algae blends in contrast to neat diesel.

INTRODUCTION

Economic growth and development increase the energy demand. Recently global energy requirements are met by fast-depleting fossil fuels. Alternative fuels are particularly important to the transport sector as they address the problems of high demand rates and increasing costs. Furthermore, these fossil fuels emit a huge amount of hazardous substances into the atmosphere contaminating the fragile environment (Enamala et al. 2018). The use of renewable and sustainable energy sources of biofuels for energy production came into existence as a better replacement for conventional fossil fuels. Emissions from vehicles have increased drastically over the past decades (Baral et al. 2015). To achieve environmental and economic sustainability, fuel production must be renewable and capable of reducing CO_2. In these circumstances, microalgae play a vital role in suppressing atmospheric CO_2 to O_2, the primary contributor to global warming and other greenhouse gases (Saratale et al. 2017). Gaseous fuels, biodiesel, and alcohol-based fuels are the most common alternative fuels for IC engines. Most biofuels fall into one of three categories, namely Ist, IInd and IIIrd generation biofuels.

DIFFERENT GENERATIONS OF BIOFUELS

Fig. 1 shows various biodiesel feedstock classified by their generations. Land-based food crops produce first-generation biofuels from cultivated crops known as wheat, barley, corn, and sugarcane produces bioethanol or butanol by fermentation of starch. Transesterification of feedstock like rapeseed, sunflower, palm, castor, and cooking oil (Prakash et al. 2018, Jeyakumar & Narayanasamy 2019) produces biodiesel. Second-generation fuels employ ligno cellulosic non-food biomass such as Jatropha, Mahua, Neem, Karanja, *Aegle marmelos*, Methyl ester from the tannery industry, Safflower, Mesua ferrea, and Rice husk in biodiesel production (Balasubramanian & Purushothaman 2019, Siluvaimuthu et al. 2019, Thiyagarajan et al. 2016, Dhananmurugan & Subramanian 2015, Singh et al. 2015, Kanthasamy et al. 2020, Vinukumar et al. 2017). Ist and IInd generation biofuels with fossil fuels gaining research attention due to their significant benefits. Additionally, soybean, jatropha, canola, corn, and animal fats are being tested as fuels (Xin et al. 2011). Generations of such biofuels require an abundant amount of water and agricultural land for crop cultivation and biofuel production. Third-generation biofuel feedstock like algae, overcome these drawbacks as it does not interact with the food environment. However, the yield of algae biofuel necessarily stepped up to meet the higher demand.

MICROALGAE AS BIOFUEL

Microalgae utilize sunlight and variant micronutrients from the environment for inherent growth (Ramachandra et al.

2013). Climate change legislation and governmental authorities are attempting to minimize greenhouse gases by opting for sustainable algae biofuels. Due to its lowest measure of emitted greenhouse gases, it has tremendous potential for alternative fuel technology. It is photosynthetic in nature without roots, stems, and leaves. Almost three lakhs species of algae are distributed and grown throughout the world in seawater, freshwater, and brackish water. Algae are classified into microalgae and macroalgae. Microalgae are single-celled organisms whereas macroalgae are multicellular organisms. Both kinds of algae can be effectively used in producing the byproducts of biodiesel and bioethanol. However, the yield of biodiesel through the transesterification process from microalgae is better whereas macroalgae are found to be superior in yield of bioethanol. As algae are carbon neutral, their use in biofuels does not result in any detrimental effects on the environment (Zaimes & Khanna 2013). Substances such as proteins, lipids, and carbohydrates are the main constituents of microalgae biomass. Biofuel production from microalgae is a promising field owing to its higher growth rates and potential to accommodate a superior amount of triglycerides. The composition of lipid content determines the yield and quality of biodiesel produced (Ananthi et al. 2021).

STRAIN SELECTION

Fig. 2 shows unique algae species utilized in methyl ester production. Algae cells are neutral lipids. High saturation and rapid accumulations of lipids in the cellular system at different phases of algae growth make them a potential diesel fuel substitute. Strain selection must be cared for, higher accumulation of lipids can lead to the formation of oxides in fuel injector lines during the process of combustion (Piloto-Rodríguez et al. 2017).

PRODUCTION OF OIL AND METHYL ESTER (BIODIESEL)

Algae Cultivation

Fig. 3 represents methyl ester production. For microalgae to grow, the temperature must be between 20°C and 30°C. The intensity of Sunlight is important for biofuel production (Alam et al. 2015). Algae cultivation is accomplished

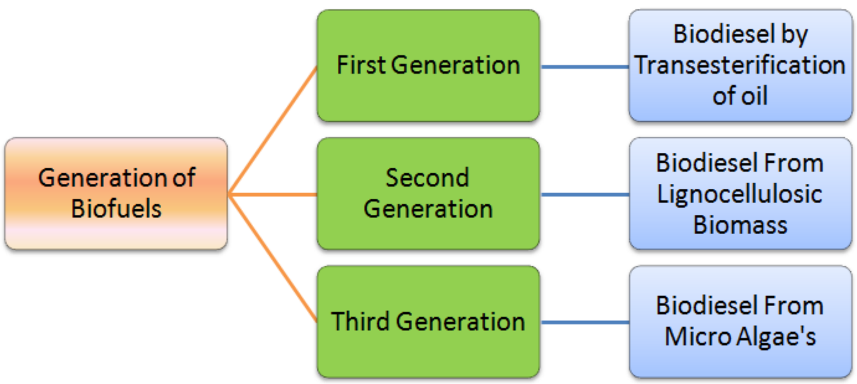

Fig. 1: Generation of biofuels.

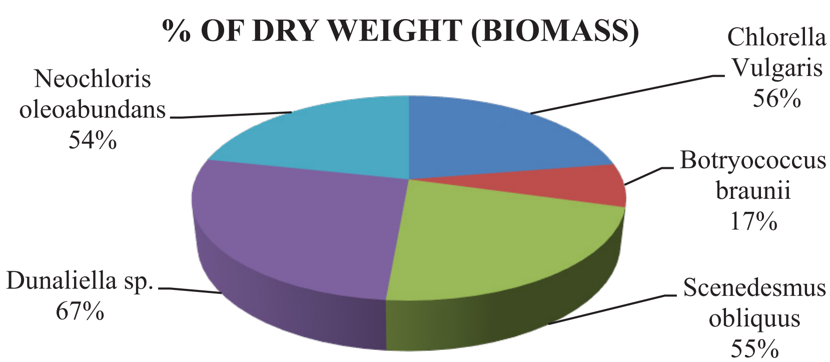

Fig. 2: Unique microalgae species for methyl ester production.

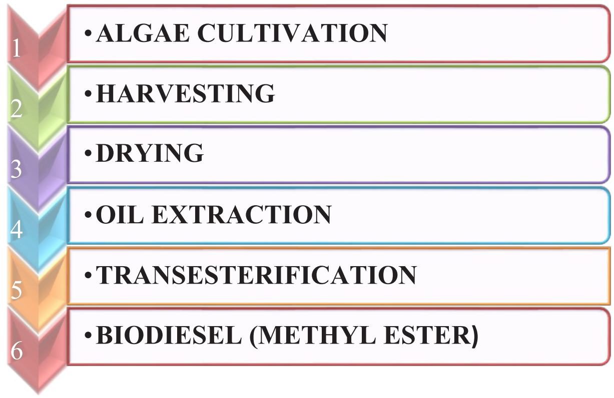

Fig. 3: Biodiesel production from algae.

with two different types of systems including open ponds (raceway) and closed reactors (photobioreactor). Commonly used reactors are Tubular PBR, Flat PBR, and Column PBR, where tubular PBR is less expensive and offers higher biomass productivity (Dragone et al. 2010). The tubular PBR gives superior pH, better temperature control, improved culture strain, finer combination, lesser evaporative losses, and superior cell densities. It is also relatively economical in terms of maintenance (Mata et al. 2010).

Open Cultivation Systems

The earliest type of farming involved a one-foot deep open cultivation system covering many acres that were exposed to natural sun rays. It can be made of concrete or simply excavated into the ground lined with plastic to prevent leakage and contamination (Duran et al. 2018). Nutrients (such as N and P) can be delivered directly by channeling water from water treatment or sewage treatment plants (Saleem & Moe 2014). The cost-effectiveness of the method adopted for manufacturing microalgae biomass is influenced by the algae strain used, local climatic conditions, cost of land, and availability of water. Open cultivation methods have two major drawbacks: first, their output is lower, and second, the environmental factors are more difficult to manage (Spolaore et al. 2006). Raceway-based pond biomass cultivation method tends to cover a total area of 440,000 m^2 (Andersson et al. 2014). Closed cultivation systems are more productive even though open culture systems are more economically viable due to issues such as H_2O, temperature losses, vapor losses, and CO_2 dispersion into the environment resulting in environmental contamination issues (Ho et al. 2011).

Closed Cultivation Systems

Closed culture systems offer a monitored environment that effectively addresses contamination concerns. An open culture method increases carbon dioxide fixation efficiency due to adequate mixing opportunities. However, as a result of its high infrastructure costs, the closed system technology is very expensive. This type of bioreactor is very effective, producing higher biomass concentrations (2–5 $g.L^{-1}$) within two to four weeks with a greater surface area to vol. ratio than open cultivation systems (Wang et al. 2008, Min et al. 2011). Multilayer bioreactor is the most practical and cost-effective way to treat waste H_2O from industrial and agricultural operations, both in terms of scaling up and nutrient removal (Chisti 2008). In terms of commercial production efficiency, the tubular photobioreactor is superior to other closed systems. A series of straight, clear plastic or glass tubes are used to gather solar energy with a diameter of less than 0.10 m, as penetration of sunrays is reduced in larger tubes. The tubes and a reservoir are used to circulate the microalgal broth (Rawat et al. 2011).

Algae Harvesting

In water, algae are frequently seen in a diluted form. Nearly 20-30% of the entire production cost is required for biomass recovery from dilute media. Flocculation, flotation, centrifugation, and filtration are the different harvesting procedures available. Filtration has proven good as it includes passing broth containing algal biomass through filters that collect algae biomass and allow the medium to flow through. A typical filtration procedure is best suited for harvesting algae biomass (>70μm) meanwhile for recovery of algae biomass (<30μm) ultra and microfiltration are technically viable alternatives to traditional filtration (Brennan & Owende 2010). Dewatering cannot be accomplished using a simple filtration approach (dead-end filtration) because of problems with back mixing. However, simple filters can be used in conjunction with centrifugation to improve separation (Harun et al. 2010).

Drying

After the harvesting process, the dry solid concentration of biomass sludge is still modest. Moisture absorption of dewatered slurry is the final step in algae processing, with a moisture level of 12 to 15% Algae slurry is dried or dehydrated at this point to achieve a stable state for future processing Solar, convection, spray and freeze drying are some of the most common drying processes (Chen et al. 2015, Guldhe et al. 2014, Show et al. 2015, 2019).

Solar Drying

Sun drying is the most cost-effective way of drying. It requires a prolonged drying period and might result in deterioration, fermentation, and spilling of the biomass. In as little as 3-5 h, closed sun drying machines can boost the ambient temperature from 35°C to 60°C.

Convective Drying

Oven drying is a sort of hot air medium drying that is commonly used for convective drying. The minimum temperature range of this method is 40-55°C. However, the time required for removing the water content is about 12 h which is shorter than solar drying.

Spray Drying

The spraying technique yields a dark green powder by means of hot gas drying, mostly air. It maintains more nutrients than convective-dried items, which lose 10–20 percent of their protein content.

Freeze Drying

Freeze drying is the most popular method of conserving biomass as it preserves cell contents without damaging the cell wall. It involves the removal of bound water molecules by desorption. The time duration of different drying techniques is revealed in Fig. 4

Oil Extraction from Algae Biomass

The most frequent methods of oil extraction include oil press, solvent, supercritical fluid extraction, and ultrasound technology. Quick, scalable, and efficient extraction techniques are needed as they do not damage the extracted lipids.

Expeller/Oil press

This technique is frequently used to extract oil from dry biomass. To make this procedure easier, it is necessary to dry the algae. A high-pressure approach is utilized to break down cells and squeeze off oil. It removes about 75% of the oil and requires no particular skills. Despite the prolonged extraction time, it's shown to be quite effective.

Solvent Extraction

This technique is relatively inexpensive and is found to yield more amounts of algae oil. In this method, dried algae are treated with organic solvents such as benzene, cyclohexane, hexane, acetone, and chloroform. Though organic solvents are more soluble in organic solvents than water, they break the algal cell wall and extract oil from aqueous media. Amongst different solvents hexane has excellent extraction capacity and inexpensiveness.

Supercritical Fluid Extraction

In this process of extraction, cells are ruptured using high pressure and temperature. This technique utilizes the treatment of liquefied CO_2 under pressure and heated to a temperature as it has both liquid and gas characteristics. However, it's found to be inadequate due to inter-sample interactions.

Ultrasound Technique

This process involves creating high-intensity cavitation bubbles using ultrasonic waves. Shockwaves are generated when bubbles collapse crushing cell walls and expelling desirable chemicals. However, this type of extraction possesses higher interaction of solvents with lesser extraction time. Owing to its technical viability some sort of research must be done.

Soxhlet Extraction Technique – Solvent Extraction

Fig. 5 illustrates the usage of a Soxhlet extractor to extract oil from algae biomass. The constructional arrangement consists of a round bottom flask, thimble, condenser, and

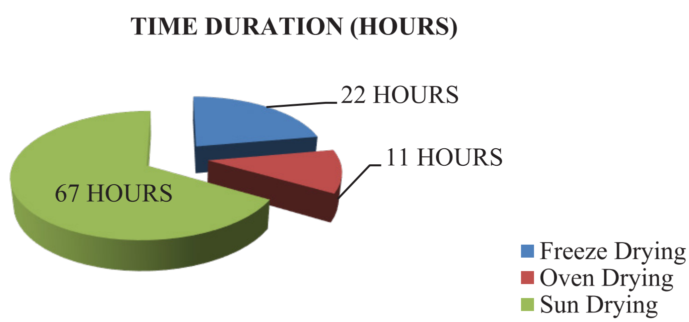

Fig. 4: Duration of drying.

extraction chamber. This apparatus uses a circular bottom flask that is filled with 300 mL of n-hexane, while the dry algae biomass is kept inside the thimble wall. The circular bottom flask is heated to 70°C with the help of the heating unit due to which the n-hexane gets vapourised and enters the condenser. Hexane vapor is condensed in the condenser and gets converted into warm hexane liquid. Once the dried algae biomass is in contact with the warm hexane solvent, oil is extracted from the biomass. The oil and warm hexane liquid are collected in the round bottom flask and the cycle is repeated. After the completion of cycles, the warm hexane liquid and algae oil are transported to a solvent extractor where they are separated.

Determining Free Fatty Acid Percentage Of Algae Oil

Titration is used to assess the free fatty percentage of algae-based oil. A 0.1-0.5 mL of oil sample is taken and weighed using a conical flask. After weighing 50 mL of solvent mixture (95% ethanol and diethyl ether in 1:1 ratio) was added to the sample and is well mixed. Following the dissolving procedure, a burette was filled with 0.1 N potassium hydroxide (KOH) and the initial reading was recorded. Then the dissolved mixture is titrated by the vigorous swirling of the flask with a 1% of phenolphthalein indicator (Karmakar et al. 2017) until the solution turns pale pink. Finally, the end burette reading was observed. The formula described below determines the acid content of algal oil and the percentage of FFA was obtained by multiplying the acid value with the factor of 0.503.

$$\text{Acid Value} = \frac{\text{Molecular weight of KOH} \times \text{Normality of KOH} \times \text{Volume of KOH solution used}}{\text{Weight of algae oil sample}}$$

$$\%\ \text{FFA} = 0.503 \times \text{Acid value}$$

Transesterification Setup and Process

Before commencing this process, the obtained oil is checked for the percentage of FFA (Free Fatty Acid). Transesterification set-up is shown in Fig. 6. It is the most economical chemical process of converting the triglycerides in algae oil into methyl ester in the existence of a catalyst (Kubude et al. 2019). Transesterification is carried out by boiling 100 mL of *Chlorella vulgaris* algae oil in a round bottom flask. 0.95 gm of potassium hydroxide is mixed with 25 mL of methane solution. The prepared mixture is stirred at a temperature of 48-52°C for 30 min. After the stirring process, the mixture is transferred into the separator and left undisturbed to allow settling down at atmospheric temperature for 8-10 h by which the glycerol is separated at the bottom of the separator. The top surface of the biodiesel (methyl ester) is washed with water to minimize the pH value and remove the traces of acid (Emirbas & Demirbas 2011, Satputaley et al. 2018).

Use of Algae in Ci Engines

The following section covers a comprehensive review of

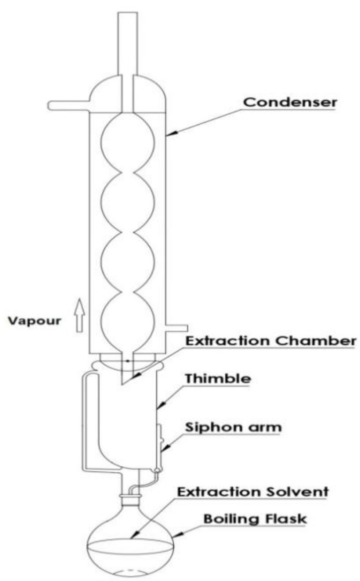

Fig. 5: Soxhlet extractor.

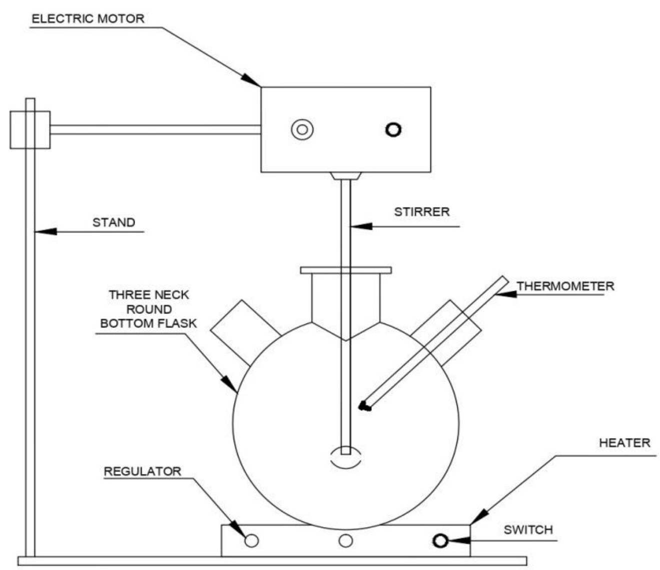

Fig. 6: Transesterification setup.

several research studies conducted by many researchers on various kinds of algae.

Chlorella vulgaris as Neat Oil and Neat Biodiesel (B 100)

The test fuels of *Chlorella vulgaris* oil and biodiesel were experimented with in one cylinder 4 stroke CI engine. BTE of neat oil and methyl ester was lowered and an increase in BSFC was observed for algae oil and methyl ester over diesel. Maximum pressure rise of algae oil and methyl ester were recorded as 63.26 bar and 58.5 bar respectively over diesel of 67.65 bar. However, no drastic variations were observed in Exhaust Gas Temperature (EGT) and NO_x between diesel, neat algae oil, and biodiesel. CO, UBHC, and smoke were found to be lower. This was due to the existence of 10 to 12 percent of additional oxygen content in the oil and methyl ester (Satputaley et al. 2018).

Chlorella vulgaris Oil With Low Viscous Turpentine Oil

Three different test fuels (C90T10, C75T25, C50T50) along with neat diesel (D100) and neat *Chlorella vulgaris* oil (C100) were investigated experimentally to determine their performance characteristics in a single cylinder CI engine with a maximum power of 5.2 KW at 1500 rpm. After adding low-viscosity turpentine oil to *Chlorella vulgaris* oil, the BTE improved considerably. When *Chlorella vulgaris* oil was mixed with turpentine, there was a drastic increase in BSFC because of the low spray-forming characteristics of fuel in the combustion chamber (Karthikeyan et al. 2020a).

Chlorella vulgaris as Methyl Ester

The comparative performance of the CI engine with hydrogen induction technique of micro *Chlorella vulgaris* biodiesel with diesel was investigated experimentally in one cylinder 4 stroke CI engine with a rated output of 9KW at 3000 rpm. The test fuels were investigated for torque, power, and emissions such as CO, HC, and CO_2. The experimental results showed that the addition of 10 LPM hydrogen to methyl ester (MCV20) increased the power and torque of the engine by 7.6% and 10.6%, respectively. A 6% reduction in BSFC was obtained. From an emission point of view, it was noted that the addition of 10 LPM of hydrogen to *Chlorella vulgaris* methyl ester decreased CO, CO_2, and HC by 13.7%, 6.8%, and 34.3%, respectively. However, the addition of hydrogen increased NO_x emissions (Tayari et al. 2019).

A comparative study was carried out on chlorella vulgaris methyl esters in the different blend ratios of (B30, B40, B50, and B60) with diesel in a CI engine at a rated power of 1500 rpm. The test fuels were investigated for BSFC, BTE, CO, CO_2, UHC, and NO_x. The experimental results showed that blending methyl ester blends with diesel showed a decrease in BTE with increased BSFC over diesel at all loading conditions. With higher NOx emissions, all biodiesel blends had lower CO, UHC, and smoke. However, blending higher ratios of methyl ester resulted in a poorer performance when compared to diesel. Hence, an optimum blend of methyl ester is necessary to enhance the performance of a CI engine (Mathimani et al. 2017).

Caulerpa racemosa Algae

Karthikeyan et al. (2020b) investigated the use of *Caulerpa racemosa* algae methyl ester with Bi_2O_3 in a one-cylinder CI engine at a power rating of 1500 rpm. The test fuels were analyzed to examine the combustion, performance, and emission. The experimental outcome showed that the use of nano-additive with B20 improved the performance, lower CD and HRR were observed with Bi_2O_3supplementedblends than B20. From an emission perspective, it was observed that B20 with Bi_2O_3 of 100 ppm gave lower CO (3%vol), HC (200 ppm), and smoke. Emissions of NO_x were found to be higher due to the presence of oxygen at maximum load.

Scenedesmus obliquus Algae

In an experimental study conducted by (Elkelawy et al. 2020), the operational characteristics of a CI engine with a rated speed of 2200 rpm were investigated using the test fuels of *Scenedesmus obliquus* methyl ester blend B50 with three different proportions of n-pentane blends of5%, 10%, and 15%. The experimental results showed that B50 with 15 $mL.L^{-1}$ n-pentane blends increased the BTE by 7.1% and decreased the BSFC by 6.4%. They observed that the

Table 1: Advantages and limitations of various extraction techniques.

Extraction methods	Advantages	Limitations	Reference
Oil Press	Easy to use	Longer extraction time	(Harun et al. 2010, Rajkumar et al. 2013)
Solvent extraction	Solvents are inexpensive	Solvent recovery is expensive and energy-intensive	(Harun et al. 2010, Rajkumar et al. 2013)
Supercritical fluid extraction	Absence of organic solvents and simple operation.	Found insufficient in the interaction between the samples	(Harun et al. 2010, Rajkumar et al. 2013)
Ultrasound technique	High interaction of solvents with less extraction time.	High power consumption	(Harun et al. 2010, Rajkumar et al. 2013)

Table 2: Comparison of performance and combustion characteristics.

Micro Algae Species	Performance parameters		Reference
	BTE	BSFC	
Chlorella vulgaris	Biodiesel and Algae Oil shows reduction in BTE of about 5.2% and 6.4% compared to diesel	Biodiesel and Algae Oil consumes more fuel to give the same power output	(Satputaley et al. 2018)
Chlorella vulgaris	-	BSFC improved by 6.6% with 10 LPM hydrogen gas for the blend B20	(Tayari et al. 2019)
Chlorella vulgaris	BTE diminished with increase in blends	Compared to diesel and other blended fuels BSFC of B60 was higher	(Mathimani et al. 2017)
Caulerpa racemosa	BTE decreased with blend B20 and nano additive	BSFC of blend B20 with 100 ppm was noted to be closer to the diesel	(Karthikeyan et al. 2020c)
Scenedesmus obliquus	BTE increased by 7.1% with 15 mL n-pentane blend	Decrease in BSFC of 6.4% is observed with 15mL n-pentane blend	(Elkelawy et al. 2020)
Chlorella sp.		BSFC of B30 methyl ester is 3.5% higher than diesel.	(Makarevicien et al. 2014)
Calophyllum inophyllum Algae	B20 with DEE improved BTE by 4.4% as compared to neat diesel	BFSC of a micro algal B20 blending with DEE is 3.76% lower than diesel	(Ranjithkumar et al. 2020)
Spirulina	BTE of B20 was found to be lower than diesel	BSFC of blend B20 was found to be 8.42% higher as compared to diesel.	(Krishaniaa et al. 2020)
Spirulina	BTE increased by 1.39% with a 30% butanol blend	The addition of butanol with methyl ester increases BSFC	(Rajak et al. 2019)
Schizochytrium	BTE of B20 was found to be compatible with the diesel	BSFC is found to be higher for all ratios(blends) with respect to diesel.	(Rajendra Prasad Reddy et al. 2020)
Micro Algae Species	Combustion parameters		Reference
	Cylinder Pressure	HRR (Heat Release Rate)	
Chlorella vulgaris	Diesel peak pressure increased by 4% and 14% as compared to algae oil and algae Biodiesel		(Satputaley et al. 2018)
Chlorella vulgaris			(Tayari et al. 2019)
Chlorella vulgaris			(Mathimani et al. 2017)
Caulerpa racemosa			(Karthikeyan et al. 2020a)
Scenedesmus obliquus	Higher cylinder pressure was found with the addition of pentane blends	An increase in HRR was found with the addition of pentane blends	(Elkelawy et al. 2020)
Chlorella sp.			(Makarevicienet al. 2014)
Calophyllum inophyllum Algae			(Ranjithkumar et al. 2020)
Spirulina	Cylinder pressure was found to be dropped with algae biodiesel as compared to diesel	HRR decreased with an impressed percentage of algae biodiesel blends	(Krishaniaa et al. 2020)
Spirulina	Cylinder pressure was increased by combining butanol with algal methyl ester and diesel (ternary blends)	The addition of butanol with algae methyl ester and diesel (ternary blends) increased the HRR	(Rajak et al. 2019)
Schizochytrium	B40 and B60 cylinder pressures were found to be higher than diesel		(Rajendra Prasad Reddy et al. 2020)

blending of n-pentane with methyl ester resulted in longer ignition delay, with high HRR and that cylinder pressure was higher. CO_2 and NO_x were found to be increased for all pentane blends with reduced CO, HC, and O_2 emissions.

Chlorella sp. Algae

An attempt was made by (Makareviciene et al. 2014) to establish the performance and emission characteristics of *Chlorella* sp. methyl ester in a multi-cylinder CI engine at

Table 3: Comparison of Emission Characteristics

Micro Algae Species	Emission Parameters				Reference
	CO	UHC	Smoke	NO_X	
Chlorella vulgaris	10 to 12% of excess oxygen level in methyl ester and algae oil results in reduced CO emissions	10 to 12% of excess oxygen level in methyl ester and algae oil results in reduced. UHC emissions	10 to 12% of excess oxygen level in methyl ester and algae oil results in reduced Smoke Opacity	At 5.15 kW brake power load, algae oil demonstrated the greatest reduction in NO_x of 19 ppm	(Satputaley et al. 2018)
Chlorella vulgaris	CO emissions are reduced by 13.7% as a result of hydrogen enrichment.	UHC emissions are reduced by 34.3% as a result of hydrogen enrichment.		NO_x emissions soared by 5.1 % when hydrogen was enriched	(Tayari et al. 2019)
Chlorella vulgaris	CO emissions fell as biodiesel content in blends increased	The percentage of biodiesel in blends reduced UHC emissions by 14.75%		There was no discernible difference in NO_x emissions between diesel and mixed fuels	(Mathimani et al. 2017)
Caulerpa racemosa	Bi_2O_3 and its blends have lower CO emissions than B20	Bi_2O_3 and its compositions exhale less UHC than B20	Bi_2O_3 and its constituents expel less Smoke than B20	NO_x emissions for Bi_2O_3 nano additions mixed fuel are higher than for B20	(Karthikeyan et al. 2020a)
Scenedesmus obliquus	Excess oxygen in methyl ester with pentane addition lowers CO emissions by 21.19%	Excess oxygen in methyl ester with pentane addition lowers UHC emissions by 9.82%		NO_x emissions are raised owing to increased oxygen when pentane additives are used	(Elkelawy et al. 2020)
Chlorella sp.	CO reductions upto 10% were observed	Reduced UHC emissions by 5-25%		No drastic variations in NO_X emissions were observed	(Makareviciene et al. 2014)
Calophyllum inophyllum Algae	B40 with DEE showed reduced CO emissions by 33% compared to diesel	B40 with DEE showed the lowest UHC emissions by 30.7% compared to diesel		Blend B60 had a 4.91(%) increase in NO_X.	(Ranjithkumar et al. 2020)
Spirulina			B20 reduces smoke emissions by 18.33 %	With B20, NOx emissions are decreased by 10.66%	(Krishaniaa et al. 2020)
Spirulina				NO_x emissions were raised owing to an increase in butanol blends	(Rajendra Prasad Reddy et al. 2020)
Schizochytrium	CO emissions from biodiesel compositions are higher compared to diesel	UHC emissions were decreased by increasing the amount of biodiesel in blends	Smoke emissions from biodiesel compositions are higher compared to diesel	No obvious variations in NO_X emissions were found	(Rajak et al. 2019)

a maximum power of 1500 rpm. The empirical study on chlorella sp methyl ester B30 showed that it had an approximately 3.5 percent greater BSFC than natural petroleum diesel. When the engine was run on B30 methyl ester, there was no noticeable variation in the BSFC readings. Energy utilization of methyl ester was found to be 2.5 to 3 percent superior to diesel-fueled operation. A noticeable improvement in emission factor was seen. The blending of the methyl ester with mineral diesel reduced emissions of HC, CO, and smoke by 75%, 25%, and 10% respectively as compared to diesel, meanwhile, NO_x increases.

Calophyllum lnophyllum Algae

The performance and emission characteristics of dual-blended biodiesel were examined in internal combustion (CI) engine with a power rating of 1500 rpm. Using vol. ratios of 20%, 40 %, and 60 %, methyl ester made from CIME and MAME was mixed with diesel fuel. Comparing (B40 and

B60), B20 with DEE showed a 4.4% higher improvement in BTE when compared to neat diesel. However, the BFSC of the B20 blend with DEE was3.76% less than diesel. Meanwhile, B40 with DEE had the lowest HC and no variations in CO were observed. An increase in NO_x was observed when B60 (30 % CIME + 30% MAME) was blended with DEE (Ranjithkumar et al. 2020)**.**

*Spirulin***a Algae**

Spirulina Methyl Ester

Krishaniaa et al. (2020) experimentally investigated the performance and emission characteristics of spirulina algae methyl ester in a single-cylinder compression ignition engine at a power rating of 1500 rpm. The experimental results obtained showed that blending of *Spirulina* methyl ester B20 with diesel resulted in higher BSFC and lower BTE.EGT was raised as engine load increased due to better combustion quality. Smoke was reduced by 8.3% and a decrease in CO_2 emission was observed for B20. NO_x emission decreased for biodiesel blends by 10.66 percent as a result of the lower combustion process of methyl ester**.**

Spirulina Methyl Ester With Butanol Blend

Rajak et al. (2019) analyzed the emission and performance characteristics with the use of *Spirulina* algae methyl ester with butanol in a one-cylinder CI engine that had a power rating of 1500 rpm. The MSB (40, 30 and 20 percent) n-butanol (10, 20 and 30 percent) blends were 50 percent with low sulphur diesel fuel in volume basis as B1 (LSD 50-MSB 40-nB 10), B2 (LSD 50- MSB 30-nB20) and B3 (LSD50-MSB20-nB30). The results of their experimental work revealed that the addition of 30% butanol to diesel-spirulina methyl ester blends improved the BTE with a high heat release rate and cylinder pressure. The BTE was noted to be 34.57%whereas for petroleum diesel it was found to be 33.18%. The authors noticed that an increase in n-butanol resulted in a corresponding increase in BSFC and relatively low smoke emissions. Contrarily, the NO_x emissions were found to be increased.

***Schizochytrium* Algae**

Rajendra Prasad Reddy et al. (2020) examined the combustion, performance, and emission behavior of *Schizochytrium*-diesel blends in a single cylinder CI engine that had a rated power of 3.7 KW at 1500 rpm. The test fuels of diesel and *Schizochytrium* with ratios of B0, B20, B40, and B60 were prepared and tested. Experimental results showed that the BTE of B20 was found to be similar (24.53%) to the BTE of fossil diesel (25.37%). However, the BSFC was higher with reduced BTE for all the blends which were because of its lower calorific value. The authors determined that there was an improvement as the cylinder pressure was 65 bar for the B60 blend compared to the fossil diesel (63.1 bar) at full load. In addition, the ignition delay of methyl ester blends was reduced due to the presence of intrinsic oxygen and higher CN. On the contrary, they noted that CO and NO_x levels increased with the methyl ester blends. However, there was a decrease in UHC at all loads**.**

CONCLUSION

The purpose of this review study is to provide an overview of algae oil production and its use in CI engine applications. Biodiesel production from microalgae involves identifying the algae species with high oil content and high growth rates, while the second is treating the selected algae with several processing steps. The main advantage of the algae species is that it is carbon neutral and does not release any harmful emissions into the environment. Techniques such as algae cultivation, harvesting, drying, and extraction have been discussed, however, the selection of suitable methods for obtaining biodiesel continues to be a challenge to the research community.

The importance of the photobioreactor in cultivating algae biomass has been highlighted. Open pond cultivation depends on weather conditions whereas the photobioreactor depends on CO_2, sunlight, and nutrients.

The combination of filtration with centrifugation gives better separation of biomass from the broth. The size factor of algae biomass plays a major role in selecting the suitable filtration technique. If algae strain is more than 70µm then conventional filtration is feasible. However, for the recovery of algae biomass, less than 30µm micro filtration and ultra-filtration are widely used.

Among various drying techniques, the freeze drying technique is most widely used as it retains the algae biomass without any damage to cell walls. It is observed that there is a threefold increase in the yield of oil derived from algae dried under natural sunlight in comparison with the oil produced using conventional methods. Dried algae biomass is subjected to extraction to yield oil and later transesterified to obtain biodiesel. Amongst different extraction techniques, the solvent extraction technique is relatively inexpensive and is found to be the best for obtaining more amount of algae oil.

The experimental investigations of different algae have been discussed. It is observed that there is a significant improvement in performance with the use of algae biodiesel. From the review of several experimental studies, it is seen that the addition of butanol and pentanol with methyl ester improves the BTE in contrast with BSFC. An increase in algae methyl ester mix ratios results in poor performance with higher NO_x.

Adding 30 % butanol to the diesel-spirulina methyl ester blends improves the BTE to34.57% with high HRR and cylinder pressure whereas for diesel it is found to be 33.18%. BTE of the dual fuel CI engine is found to be 31% for dual *Calophyllum inophyllum* methyl ester blend (B20) with Diethyl Ether and there is a drop in BSFC of 3.76% in comparison with diesel. This is because the high oxygen concentration of biodiesel might make it burn much more effectively. However, algae methyl ester blends without alcoholic blends are found to have lower BTE with higher BSFC. From the emissions aspect, it is observed that there is a decrease in CO, UHC, and smoke for all algae blends owing to the presence of oxygen sources in the range of 10 to 12 percent in methyl ester and algae oil. No extreme variations are observed in EGT and Nitrous oxide (NO_x) emission between diesel and biodiesel.

Edible species such as *Spirulina* algae are gaining immense popularity of late in the food processing industry. It has however not been widely explored as a possible alternative fuel for CI engines. Only a limited number of research studies have been carried out on its use. The challenging knowledge gap to find the best alternatives to fossil fuels needs to be addressed in future research endeavors. Minor blending (B20) of methyl ester is identified to be the most effective way to improve CI engine performance.

ABBREVIATIONS

BTE - Brake Thermal Efficiency
BSFC – Brake Specific Fuel Consumption
CO – Carbon Monoxide
UBHC – Unburned Hydrocarbon
NO_x – Nitrous Oxide
HRR – Heat Release Rate
CP – In-Cylinder Pressure
EGT – Exhaust Gas Temperature

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