

Soxhlet-Assisted Algal Biofuel Production and Diesel Engine Performance Analysis

Kartikey Singh* Toiba Sheikh*

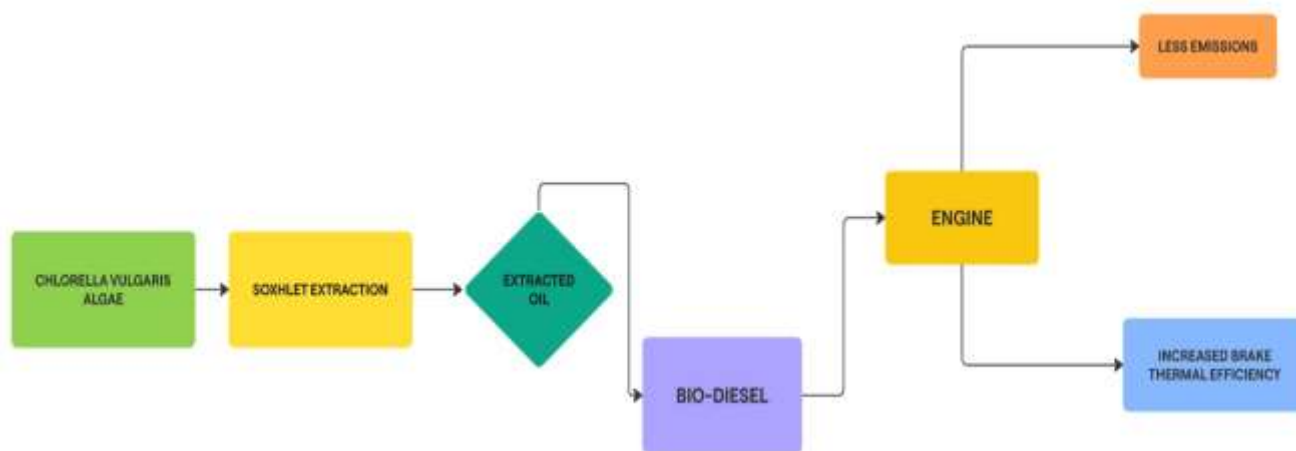
* Department of Mechanical Engineering, Vellore Institute of Technology, Vellore - 632014, Tamil Nadu, India

ABSTRACT

The onus to switch from fossil fuels has revitalized the focus on biofuels, particularly on microalgae. *Chlorella vulgaris* is particularly appealing as it has a very high lipid concentration thus making it a very good biofuel feedstock. However, the focus on oil extraction and the performance of the produced biodiesel on diesel engines is scarce. So, this work fills this gap by using the Soxhlet extraction method but also varying different parameters such as particle size, solvent to solid ratios and reaction time in order to achieve max lipid yield, which is a new idea in algal biofuels. The extracted oil was tested on fuel characteristics and quality check to comply with the biodiesel standard. It also addresses the viability of *Chlorella vulgaris* biodiesel for use in diesel engines, putting together lower emissions and higher brake thermal efficiency than fossil fuel. The evidence offered allow for pathways towards energy autonomy that are also innovative additions to the biofuel landscape by providing the missing link between optimized extraction techniques and real world engine usage.

KEY WORDS

Algae oil
Biodiesel
Engine
Chlorella vulgaris
Soxhlet extraction method



1. INTRODUCTION

A considerable amount of research has been devoted to developing sustainable energy alternatives due to the growing energy crisis and the environmental impacts associated with fossil fuel consumption. Roughly, 88 percent of energy consumed in the world is from sources that are fossil fuels, out of which the more dominant sources are natural gas, coal, and oil at 24 percent, 29 percent, and 35 percent respectively [1]. There is a growing demand for renewable energy sources as it is estimated that the world's energy requirements will increase by 53% by 2030 [2]. Because they emit less greenhouse gases and can help reduce global warming, biofuels have gained great attention in recent years [3][4].

Biofuels can be defined as renewable fuels produced from biological sources such as algae, fats from various animals, and vegetable oils. Biodiesel is a type of biofuel. In most cases to synthesize biodiesel, the process of transesterification of triglycerides into fatty acid methyl esters (FAME) is employed [5]. Since the food industry and biofuel production take place at the same time in many countries, the combination of palm, soybean, and rapeseed oil, which can be used as biodiesel fuel, has raised questions on food security for these countries [6]. Consequently, microalgae such as *Chlorella vulgaris* have provided an alternative as a third generation of biofuels. Algae are regarded as a very effective feedstock because of their rapid growth rates and high lipid content. These plants can survive in wastewater and nonarable land making them grow without food and fuel conflicts [7][8].

Several methods for lipid extraction from algae have been studied, and one of the most commonly used is the Soxhlet extraction method, which successfully separates non-polar lipids using hexane or other solvents [9]. The Soxhlet extraction method has been fully tested on several algae plants, such as *Chlorella vulgaris* and *Acutodesmus obliquus*. It can be concluded that lipid yield is influenced by temperature, time of extraction, and solvent used [10][11]. The optimum conditions are needed to achieve maximum lipid yield [12]. More specifically, temperature, choice of solvent, and time of extraction have to be considered. Furthermore, algae-derived biodiesel has successfully shown performance in diesel engines delivering the same BTE output only with a drastic reduction in emissions of particulate matter, CO₂, and NO_x [13][14].

Microalgae species, such as *Chlorella vulgaris*, have an oil yield that is greater than the conventional oil-bearing crops like soybeans and palm oil trees, which yield around 80000 liters per hectare per year [15]. In addition, microalgae can be grown using saltwater or wastewater, making them an eco-friendly raw material with minimal dependence on freshwater resources [16][17]. The ability of algae to sequester CO₂ while performing photosynthesis adds value to the algae and helps in producing carbon-negative biofuels [18]. Microalgae biofuels are considered to be a more cost-effective and environmentally friendly alternative compared to biodiesels derived from food crops as well as first and second-generation biofuels since it is more environmentally friendly and more productive [19][20].

Algal biodiesel blends with conventional diesel fuel have shown great promise for improving engine performance and reducing emissions. Combining diesel and biodiesel can increase fuel lubricity, which will support injector efficiency and reduce engine component wear [21]. According to studies, blends incorporating algae biodiesel can outperform pure diesel in terms of brake thermal efficiency (BTE) [22]. In addition, algal biodiesel blends tend to reduce particulate matter (PM), unburned hydrocarbons (HC), and carbon monoxide (CO) emissions [23][24]. Using an improved blend, oxygen in algal biodiesel promotes more complete combustion, which reduces nitrogen oxide (NO_x) emissions [25].

Despite these advancements, there is a gap in the literature regarding the optimization of Soxhlet-assisted lipid extraction from *Chlorella vulgaris* and a comprehensive evaluation of its impact on engine performance and emissions. While *Chlorella vulgaris* has been recognized as a valuable source of algal lipids, limited studies focus

on combining optimized extraction techniques with the detailed analysis of biodiesel performance in diesel engines.

The want for opportunity strength assets is rising due to the depletion of fossil fuels and growing environmental concerns. Biofuels have received attention as a promising option to lessen dependency on traditional fossil fuels. Algae, specifically *Chlorella vulgaris*, have emerged as a sustainable biofuel supply because of their rapid growth rate and excessive lipid content material. This research makes a speciality of oil extraction from *Chlorella vulgaris* algae the usage of the Soxhlet extraction technique. The observe cautiously examines parameters such as particle length, solvent-to-strong ratio, and extraction length to optimize oil yield.

In addition to oil manufacturing, this have a look at extends its scope to explore the practical application of *Chlorella vulgaris*-derived bio-oil as a diesel gasoline alternative. By analyzing the biodiesel's overall performance in engine packages, this studies demonstrates the dual benefit of algae-based biofuels, both as an green renewable energy source and as a cleanser option for diesel engines. Through testing engine emissions and thermal efficiency, the take a look at bridges the distance between bio-oil extraction and its real-international utility, emphasizing the potential of algal biofuels to make a contribution to sustainable strength practices.

The purpose of this work is to assess the efficacy of *Chlorella vulgaris* lipid extraction using Soxhlet assistance and optimize its use as biodiesel in diesel engines. This study will specifically concentrate on optimizing lipid output via the Soxhlet extraction method and examining the impact of biodiesel generated from *Chlorella vulgaris* on engine performance, emissions, and combustion characteristics. This research adds to the expanding corpus of knowledge on biofuels derived from algae and their potential to alleviate the world's energy crisis while advancing environmental sustainability.

2. MATERIALS AND METHODOLOGY

The freshwater algae species *Chlorella vulgaris*, which was utilized to extract oil due to its high lipid content, is the subject of this study. Under a microscope, it was determined that the algae samples, which were taken from an open water tank next to the Karpagam campus, belonged to the genus *Chlorella vulgaris*. To guarantee total dehydration, the algae were first air-dried for two to three days to remove moisture. After that, they were dried in an oven at 100°C for twenty-four hours. To achieve uniform particle sizes, the dried algae were next processed into a fine powder using a high-speed grinder (Bajaj, 500W, Speed: 1500 rpm) and sieved through mesh sizes of 30 mm, 40 mm, and 60 mm.

The powdered algae was then dried again, this time for 40 minutes at 100°C in an electric oven, to remove any last traces of moisture. The efficient organic solvent n-Hexane was selected for the extraction procedure due to its characteristics, which include a specific gravity of 0.703 at 28°C and a boiling point between 68 and 71°C. This several-step procedure made sure the algae were ready for effective oil extraction.

2.1 Physicochemical properties of algae oil

The produced oil's physicochemical characteristics were assessed and contrasted with those of biodiesel and regular algal oil. The heating value, saponification value, acid value, iodine value, cetane number, flash point, fire point, and density are the physicochemical properties examined in this paper. The purpose of this investigation was to determine whether the extracted oil might be used in CI engines as an alternative fuel.

Types of Biomass	Solvent Used	Density (kg/m ³)	specific Gravity	Kinematic Viscosity (mm ² /s)	Acid Value (mg KOH/g oil)	Iodine Value (g I ₂ /100 g oil)
ASTM Standard	-	4052-91	D5355	D445	D1980-87	D96
Diesel	-	837	0.835	3.96	-	-
Biodiesel (Standard)	-	860-900	0.903	1.9-6.0	0.8	120
SpirDgyra sp.	n-Hexane	898.2	0.89	4.25	0.5-7	80-110
Botryococcus	Hexane	900	0.9	4.8	1.5	105
Chlorella	Ethanol	890	0.89	5.1	1.8	95
Nannochloropsis	Hexane	910	0.91	3.9	3.2	85
Scenedesmus	Methanol	880	0.88	4.5	2	100
Chlorella vulgaris	Hexane	870	0.87	4.4	1-5	100-130

Table: Effect of dryness level and the particle size of the algae powder in % of oil yield.

S.no	Dryness (%)	Particle size (µm)	Reaction time taken (hours)	Solid solvent ratio (g/ml)	Extraction Temperature (°C)	Oil yield (%)
1	50	0.366	3	1:5	75	33
2	50	0.462	3	1:5	80	35
3	50	0.641	3	1:5	85	35
4	75	0.362	3	1:5	75	33.7
5	75	0.462	3	1:5	80	34
6	75	0.641	3	1:5	85	35

1) Heating Value:

The heating value refers to the amount of energy that is released during the combustion of fuels oil. For instance, the oil from *Chlorella vulgaris*. obtained a heating value of 16.80 MJ/kg to 22.5 MJ/kg which is in the range of algal oils that have been obtained through solvent extraction technique with the use of n-Hexane. However, it should be noted that these values are less than that of diesel (44.8 MJ/kg) and biodiesel (37.27 MJ/kg). As a result, it can be considered to be an alternative energy source microwaving. It may however, enhance it's sp blended use because of the presence of oil do not interfere with the rest.

2) Flash Point:

Flash point is the temperature at which a substance can evaporate in order to form a combustible mixture with air. The oil from *Chlorella vulgaris* shed a flash point of 115°C which was higher than that of diesel which is 72°C and stands to be within the mean of the algal oil flash points which is 65- 115°C. It is advantageous that the flash

point is high in order to avoid hazards of the fuel ending catching fire during storage or handling and this makes *Chlorella vulgaris* oil safer than conventional fossil fuels.

3) *Density:*

The fuel density has an effect on the atomization of fuel in the combustion chamber and also the energy contained in each unit volume of space. The oil of the *Chlorella vulgaris* . was 870 kg/m^3 in density which is slightly lower than the normal range of algal oils ($890\text{-}910 \text{ kg/m}^3$) but comparable to biodiesel which ranges from $860\text{-}900 \text{ kg/m}^3$. Due to its relative low viscosity kinematic ($3.72 \text{ mm}^3/\text{s}$) and low density algal oil can be expected to work well in internal combustion engines and present a good fuel flow.

4) *Saponification Value:*

The saponification value measures the amount of alkali needed to hydrolyze fats and oils, which is an important determinant of biodiesel viability. *Chlorella vulgaris* . The oil is listed as 174 mg KOH/g , which meets ASTM D221 standards and falls within the acceptable range of $170\text{-}195 \text{ mg KOH/g}$ for biodiesel This indicates that this oil is well suited for transesterification, an important process for biodiesel production

5) *Iodine Value:*

The iodine value indicates the insolubility of the oil, with higher values indicating a greater tendency for polymer to form during oxidation *Chlorella vulgaris*. The iodine value of the oil is in the range of $80\text{-}110 \text{ g I}_2/100 \text{ g oil}$, indicating that it is insoluble. This level of neutralization contributes to the stability of the fuel, reducing the risks of oxidation that can cause gum formation and polymerization, thereby increasing the longevity and performance of the fuel

6) *Acid Value:*

The acid value determines the amount of free fatty acids in the oil, and can affect fuel quality, engine performance, and compatibility. *Chlorella vulgaris*. The oil showed an acid value in the range of $0.5\text{-}7 \text{ mg KOH/g}$, making it suitable for biodiesel use. Lower acid levels help prevent corrosion of engine components, extending machine life and reducing maintenance requirements.

7) *Cetane Number:*

Cetane number is an important indicator of fuel combustion quality, with higher numbers indicating better fire quality. The cetane number of *Chlorella vulgaris* oil is often between 50 and 60 which is comparable to the cetane range of 45 to 55 for regular diesel fuel. On the other hand, the cetane number of ordinary biodiesel is around 47. This makes *Chlorella vulgaris* oil suitable for production because its combustion characteristics are moderate when compared to diesel and biodiesel. Albeit it has relatively lower cetane number than those of other types of fuels, when blended with ordinary fuels, it guarantees good ignition and combustion which may improve engine's performance.

Types of Biomass	Solvent used	Density (kg/m ³)	Specific gravity	Kinematic viscosity (mm ² /sec)	Acid value (mg KOH/g oil)	Iodine value (g I/100 g oil)
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Biodiesel	-	860-900	0.903	1.9-6.0	0.8	120
Chlorella vulgaris	Hexane	870	0.87	4.4	1-5	100-130

2.2 Methodology

In this study, a Soxhlet device was used to extract oil from the algae *Chlorella vulgaris*. When contaminants are immiscible and the solubility of the compounds in the solvent is low, this technique works effectively for extracting those chemicals. Fig. 1 illustrates the Soxhlet extractor equipment layout. Because n-Hexane dissolves lipids well, it was used as the solvent for the algal oil extraction.

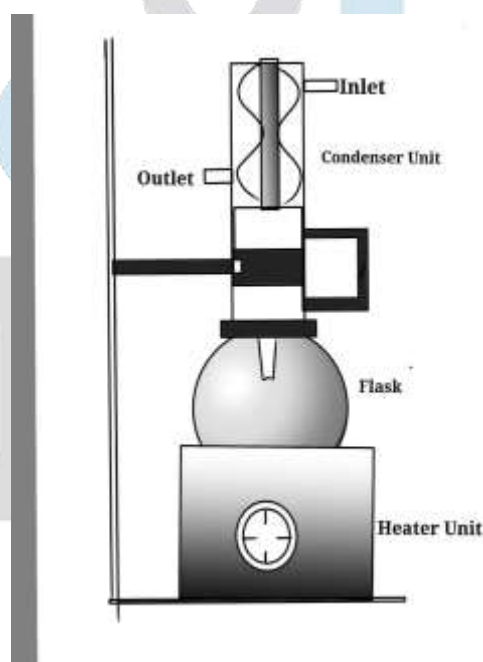
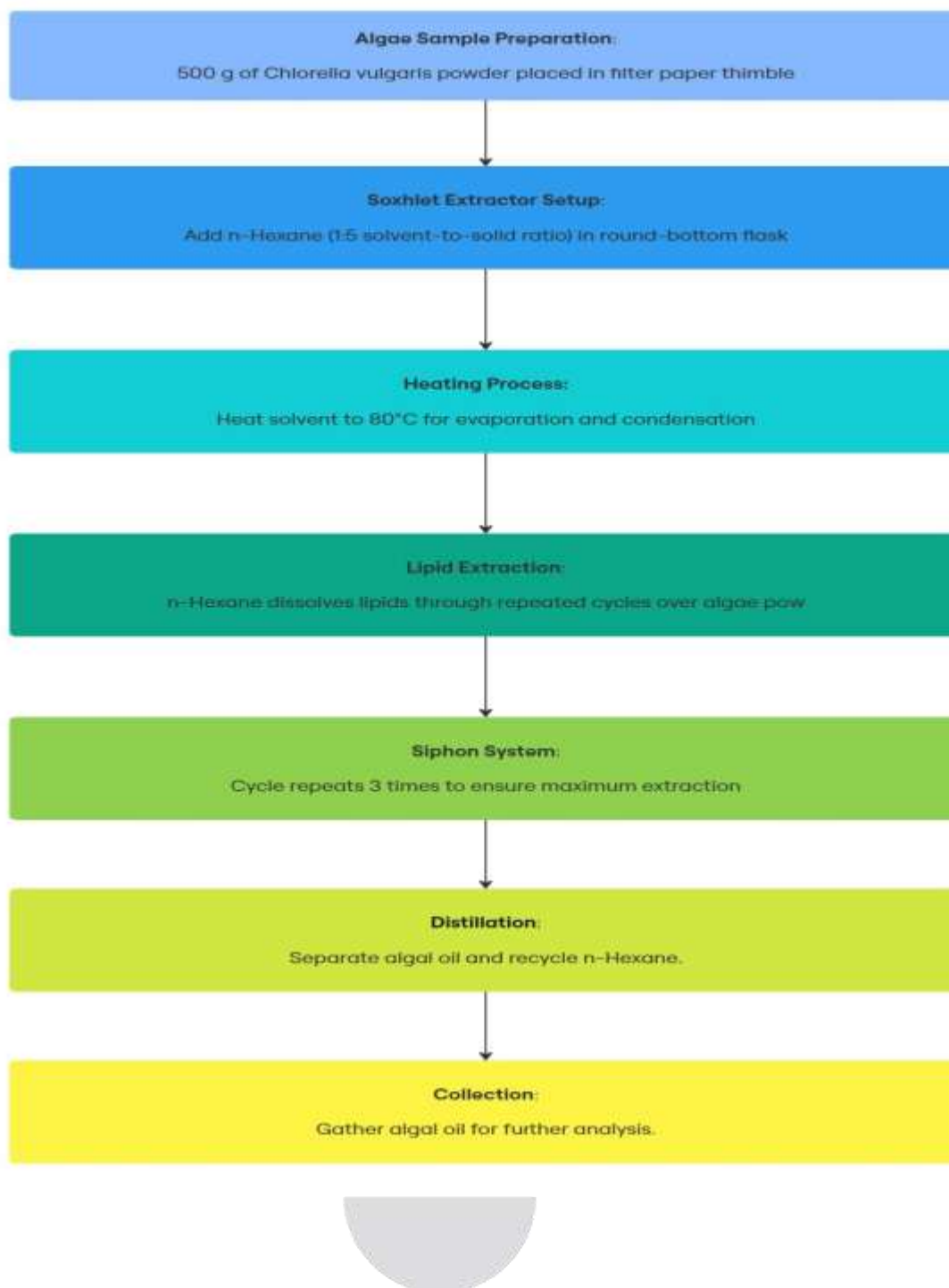


Fig 1: Soxhlet extractor equipment

The processing of the algae sample marked the start of the testing process. 500 g of dehydrated *Chlorella vulgaris* powder, with particle sizes varying from coarse to fine (0.366 μm), were put into a 0.52 mm thick filter paper thimble inside the Soxhlet extractor. Hexane was added to the round-bottom flask beneath the extractor in a 1:5 solvent-to-solid ratio. The evaporation and condensation process was started by heating the solvent to 80°C with an electric heater. The lipids were dissolved and an algal oil-n-hexane combination was formed as the n-hexane repeatedly flowed over the powdered algae as it condensed back into the extractor.

The liquid was constantly heated in the flask until it was emptied back in using a siphon system. To guarantee the highest possible level of lipid extraction, this procedure was performed three times. The mixture of algal oil and

N-hexane was subjected to distillation after extraction to remove the solvent. While the algal oil was gathered for examination, the n-Hexane was condensed and recycled for additional usage.

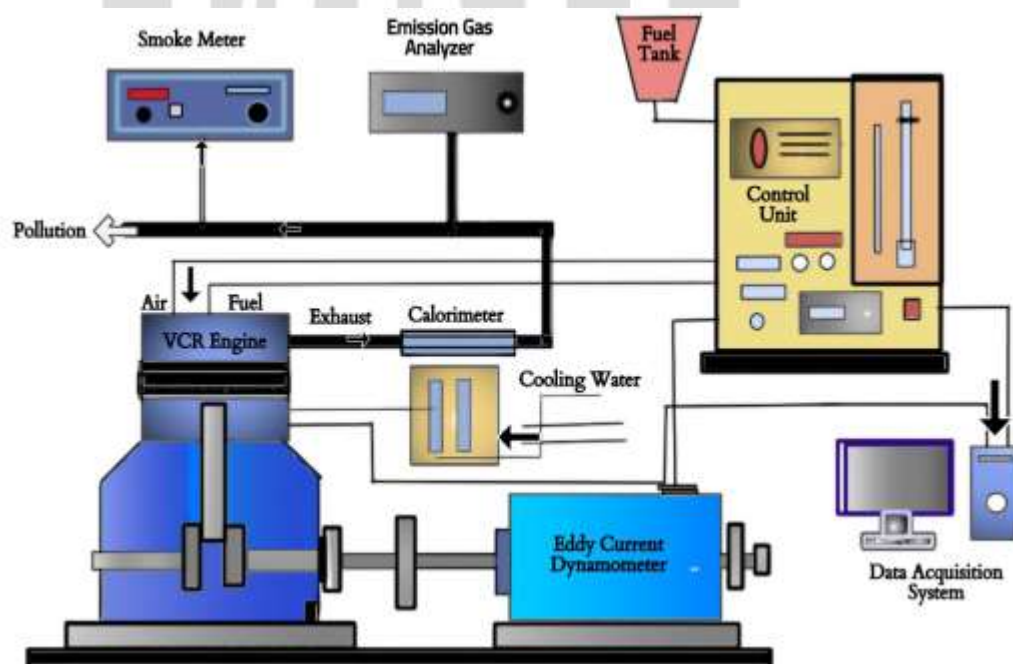


2.3 Engine Specifications, Experiment, and Blend Proportion

This study's experimental setup comprised a four-stroke, single-cylinder direct injection (DI) diesel engine. This engine has air cooling and is naturally aspirated; it is frequently employed for small-scale testing because of its accessibility and simplicity. Because the engine's compression ratio is adjustable it is possible to evaluate various performance results using different kinds of gasoline. Bore diameter of 87.5 mm and stroke length of 110 mm are standard specifications, providing a displacement volume of roughly 661 cubic centimeters. With a rated power of 5.2 kW at 1500 rpm, the engine is appropriate for fuel characterization research on blends, biodiesel, and bio-oils. To monitor performance and emissions, essential sensors and analyzers such as thermocouples, pressure transducers, and gas analyzers were connected to the exhaust system and combustion chamber.

Table: Specifications of the diesel engine

Manufacturer	Kirloskar engines Ltd. Pune, India
Model	TV1
No. of Strokes	4
Stroke Length	110.00 mm
Type of Cooling System	Water Cooling
Compression Ratio	17.5: 1
Rated Power	5.20 kW
Swept Volume	661.45 cc
Rated Speed	1500 rpm
Bore Diameter	87.50 mm
No. of Cylinders	1

**Fig: Photographic view of engine setup****Fig: VCR engine schematic diagram**

The engine was running on a variety of diesel and *Chlorella vulgaris* algae oil blends as part of the testing process. To set a baseline for performance, emissions, and combustion characteristics, the engine was first run on pure diesel fuel. After that, mixtures of diesel and algal oil were added, and the engine's performance was examined under various load scenarios. During these tests, critical parameters such as brake-specific fuel consumption (BSFC), brake thermal efficiency (BTE), and exhaust emissions (CO, NO_x, and particulate matter) were continuously monitored. To evaluate combustion parameters, in-cylinder pressure and heat release rates were recorded in addition to emissions data. The objective was to see how engine performance was affected by the algal oil mixtures in comparison to pure diesel. Post-experiment, engine performance was analyzed using efficiency calculations, and emission trends were evaluated to determine the viability of the algae oil blends for diesel engine applications.

Diesel and algal oil were made in different ratios for the fuel mixes utilized in this study. 10%, 20%, and 30% of the mixes contained algal oil mixed by volume with regular diesel. The predicted stability and algal oil combustion efficiency in a CI engine were taken into consideration when choosing these blends. The purpose of the mixes was to keep fuel qualities including viscosity, calorific value, and flash point within levels that are suitable for diesel engines. The varying ratios made it possible to compare the effects of each mix on emissions, engine performance, and combustion characteristics. The Soxhlet method was employed to extract the algal oil, and controlled conditions were maintained during the preparation of the blends to guarantee uniformity in the testing.

3. RESULTS AND DISCUSSION

3.1 Engine Performance and Combustion Analysis

3.1.1 Brake Specific Fuel Consumption (BSFC) vs Brake Power (BP)

The function shows that specific fuel consumption decreases with an increase in brake power of the engine for all fuel blends. At the curves, the SFC of CL10D90 is nearly aligned to that of diesel through all the load conditions. In contrast, the piece would otherwise give a transmission way up to pure diesel for SP10D90. This is due to the higher viscosity of the number, its greater density, and its lower calorific value.

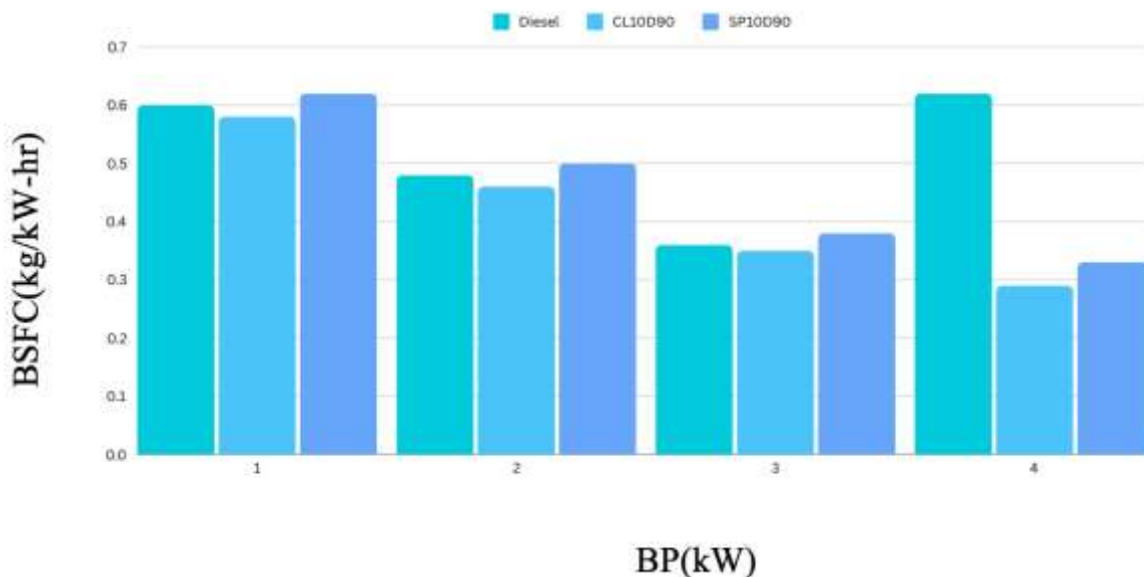


Figure: Brake Specific Fuel Consumption (BSFC) vs Brake Power (BP)

3.1.2 Brake Thermal Efficiency (BTE) vs Brake Power (BP)

Tests of engine performance were conducted over diesel engines making use of various bio-fuel blends (SP10D90, CL10D90) with diesel. Brake thermal efficiency was measured in Spirulina algae bio-fuel, Chlorella bio-fuel blends, and diesel. Among all the blends considered, CL10D90 shows slightly better brake thermal efficiency than SP10D90 and diesel under all loads because of its lower viscosity and high heating value. At full load (100%) of the above blend, CL10D90 showed a maximum efficiency of 30.4; CL10D90 was higher than the efficiency under diesel. The variation in brake thermal efficiency here may be partially attributed to a decrease in the oxygen contents affecting the CL10D90 and SP10D90 blends. This resulted in a marginal decrease in the efficiencies of all the fuels

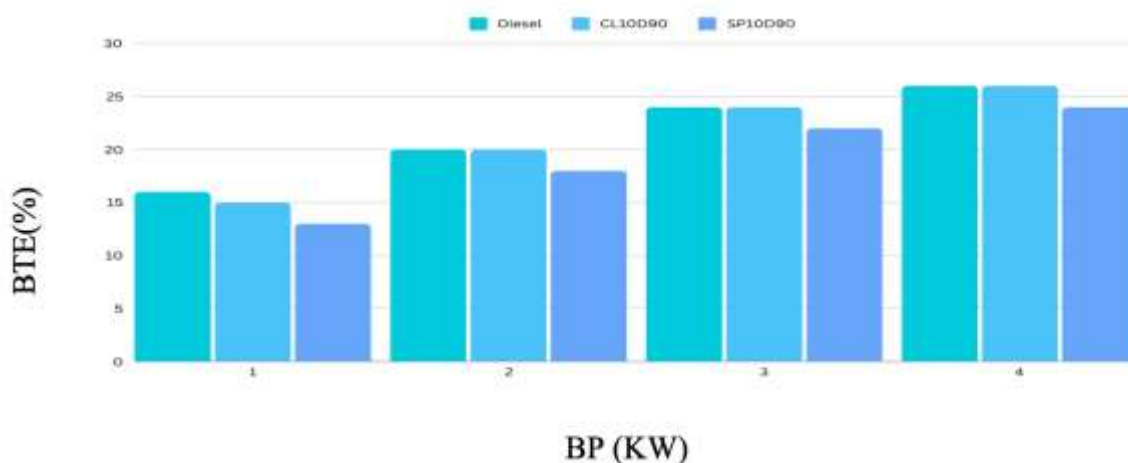


Figure: Brake Thermal Efficiency (BTE) vs Brake Power (BP)

3.2 Emission Performance

3.2.1 Hydrocarbon (HC) Emission vs Brake power

It's the combustion efficiency of the engine which influences hydrocarbon emissions. All the blends except diesel have lower hydrocarbon emissions, with CL10D90 showing greater reductions compared to SP10D90. There is more oxygen chemically bounded with oxygen in biofuel, which is an additional source of oxygen other than oxygen present in the intake air.

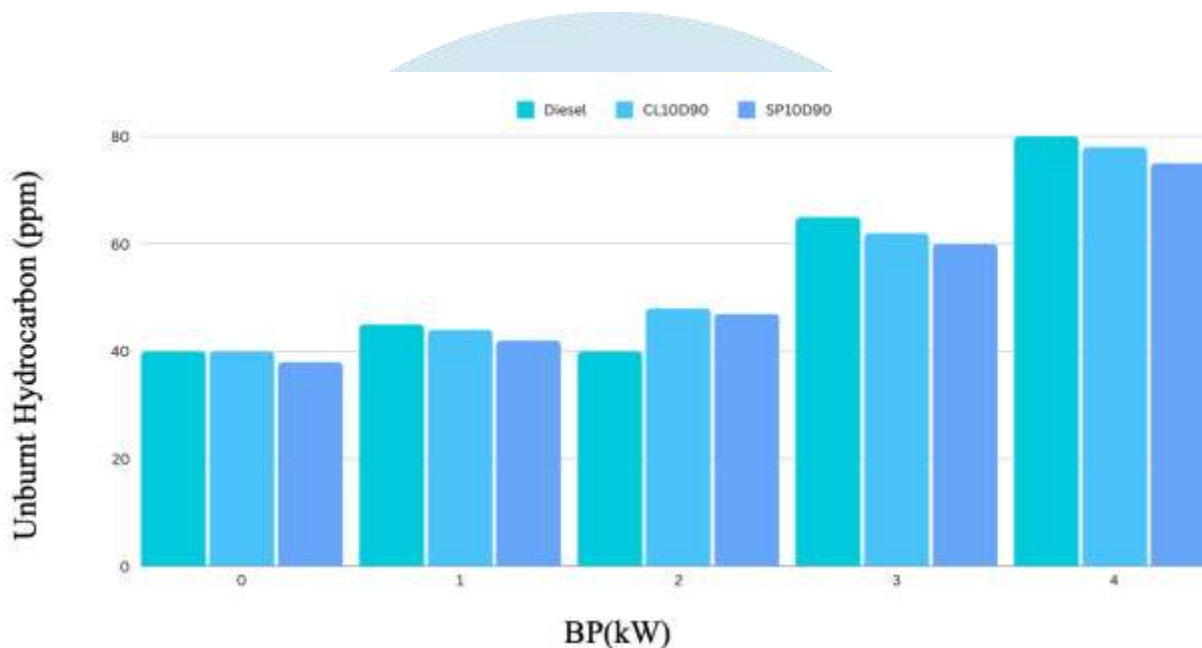


Figure: Hydrocarbon (HC) Emission vs Brake power

3.2.2 Carbon Monoxide (CO) Emission vs Brake power

Carbon monoxide emissions signify incomplete combustion. A reduction in carbon monoxide emissions is observed in one of the blends. Lower emissions are attributed to the higher viscosity of the bio-fuel blends.

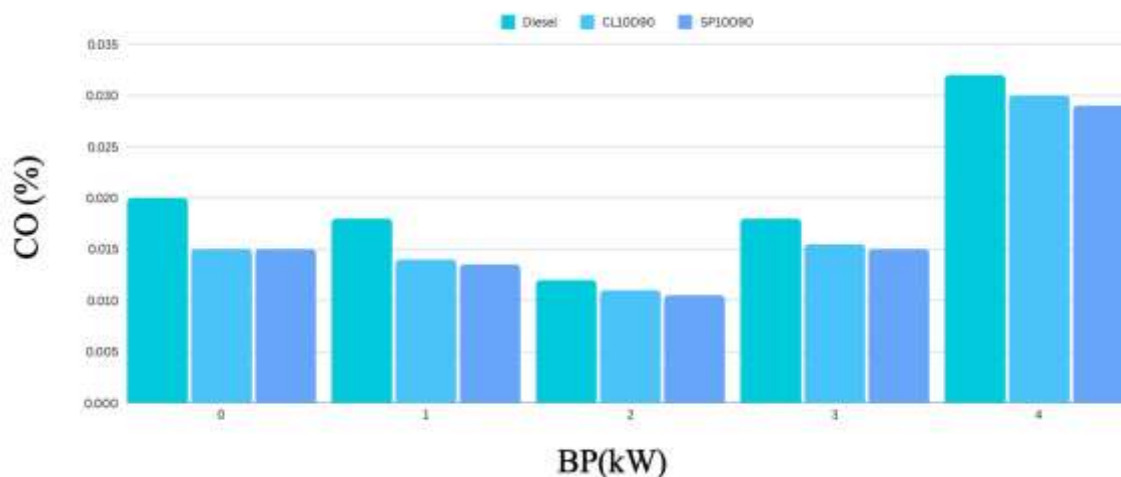


Figure: Carbon Monoxide (CO) Emission vs Brake power

3.2.3 Nitrogen Oxides (NO_x) Emission vs Brake power

NO_x emissions depend on the presence of oxygen in the fuel. It's seen that NO_x emissions are higher in CL10D90 under all load conditions. This is due to the biofuel's high cetane number, which increases the level of early ignition and further enhances premixed combustion herein.

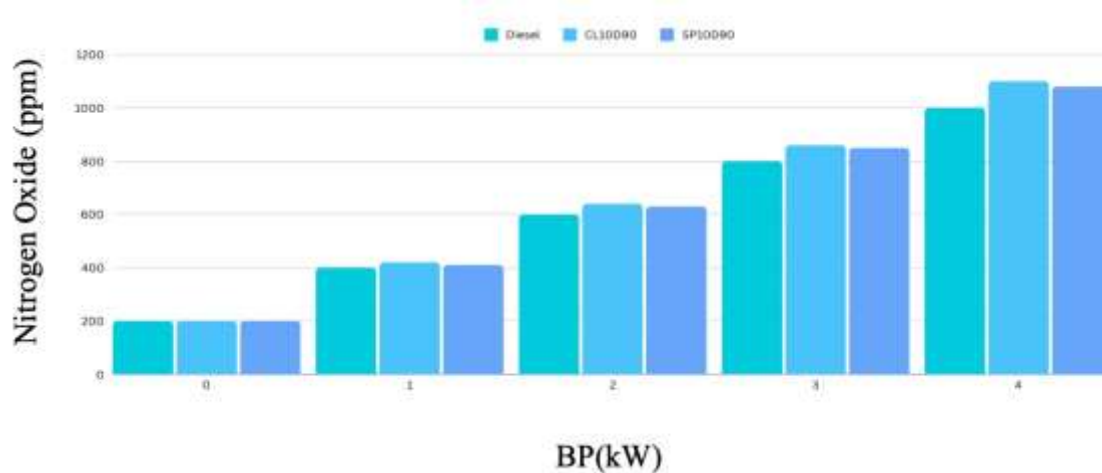


Figure: Nitrogen Oxides (NO_x) Emission vs Brake power

4. CONCLUSION

With maximum oil production of 83% reached for 100% dried algae at 0.322 μm , the Soxhlet method of extracting oil from *Chlorella vulgaris* algae showed that smaller particle sizes and dried algae boosted oil yield. The algae oil's physicochemical characteristics made it an appropriate substitute fuel for internal combustion engines, matching those of biodiesel, diesel, and other biomass oils. An investigation of engine performance revealed that fuel consumption (BSFC) was acceptable for algal oil blends, despite their reduced brake thermal efficiency (BTE) as compared to diesel. Algae oil blends have reduced HC and CO emissions, but increased NO_x and smoke levels, according to an emission study. All things considered, *Chlorella vulgaris* oil appears to be a promising and sustainable substitute for diesel.

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