EXPERIMENTAL INVESTIGATION OF COFFEE HUSK BIODIESEL AS A RENEWABLE FUEL IN COMPRESSION IGNITION ENGINE

Thesis

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

ADDISU FRINJO EMMA

DEPARTMENT OF MECHANICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA

SURATHKAL, MANGALORE – 575025

JULY, 2022

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(187099/187ME002)

Under the guidance of

Dr. SATHYABHAMA A **Dr. AJAY KUMAR YADAV**

DEPARTMENT OF MECHANICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA
SURATHKAL, MANGALORE – 575025

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DECLARATION

I hereby declare that the Research Thesis entitled **"EXPERIMENTAL INVESTIGATION OF COFFEE HUSK BIODIESEL AS A RENEWABLE FUEL IN COMPRESSION IGNITION ENGINE"** which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in **Mechanical Engineering** *is a bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any other Universities or Institutes for the award of any degree.

Register Number: 187099/187ME002

Name of the Research Scholar: ADDISU FRINJO EMMA

Signature of the Research Scholar:

Department of Mechanical Engineering

Place: NITK-Surathkal

Date: 13/07/2022

CERTIFICATE

This is to certify that the research thesis entitled **"EXPERIMENTAL INVESTIGATION OF COFFEE HUSK BIODIESEL AS A RENEWABLE FUEL IN COMPRESSION IGNITION ENGINE"** submitted by **Mr. ADDISU FRINJO EMMA (Register Number: 187099**/187ME002 as the record of the research work carried out by him, *is accepted as the research thesis submission* in partial fulfillment of the requirements for the award of the Degree Of **Doctor of Philosophy.**

Sathy

Dr. SATHYABHAMA A

Research Guide

Date: 13/07/2022

National Institute of Technology Karnataka * Dept. of Mechanical Engineering *

Dr. AJAY KUMAR YADAV

Research Guide

Date: 13/07/2022

Chairman, DRPC

Department of Mechanical Engineering

Date: 13.7.2022

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Addisu Frinjo Emma

DEDICATED TO

My kind and decent wife Kasech Daniel, my daughter Mahder, my son Natnael and my little angel Emmy

ABSTRACT

In the present study, coffee husk (CH) and spent coffee ground (SCG) are used for the production of biodiesel. The CH is a by-product of the coffee processing industry, and SCG is obtained after the coffee is brewed. Field Emission Gun Scanning Electron Microscope (FEG-SEM) is used to investigate the elemental composition of the CH and the SCG samples and identify the presence of different elements with their distribution and concentration. The compositional analysis indicates that the CH comprised 49.84% of carbon and 48.06% of oxygen by weight. On the other hand, it is found that the SCG had 67.72% of carbon and 26.18% of oxygen by weight. The CH is selected for further study for the production of oil due to its higher oxygen distribution than SCG. From 1Kg of CH, 250g of oil is produced. By using the transesterification process, the produced oil is converted into biodiesel. Subsequently, 700 mL of coffee husk oil methyl ester (CHOME) biodiesel was produced from 1000 mL of coffee husk oil. After characterization of obtained biodiesel, the experiments are conducted in a single-cylinder direct injection diesel engine at a constant speed by varying the loads (0%, 25%, 50%, 75%, and 100%) for different biodiesel-diesel blends (B10, B20, B30, B40, B50, B80, and B100), and the results are compared with the baseline diesel. The brake thermal efficiency (BTE) of the blends, B10, B20, B30, and B50, is reduced by 0.6, 0.7, 1.29, and 3%, respectively, compared to the regular diesel. Similarly, the brake specific energy consumption (BSEC) is increased by 0.1, 0.3, 0.44, and 0.77% for B10, B20, B30, and B50, respectively. Exhaust gas emissions are reduced for all biodiesel-diesel blends with a marginal increase in NO_x emission. Compared to regular diesel, at full load, CO, HC, and smoke opacity of B30 are reduced by 13.2%, 4%, and 12%, respectively. Whereas NO_x and CO_2 of B30 at full load are increased by 3.8% and 8.63% respectively

The viscosity of CHOME biodiesel is found to be higher than diesel; hence a preheating mechanism is set to reduce the viscosity and density of the fuel before injecting it into the combustion chamber. Preheating the neat CHOME biodiesel (B100) to 95 °C decreased its viscosity and density by 49.5% and 3.7%, respectively. Running the engine with preheated B100 reduces CO, HC, and smoke opacity by 34%, 34%, and 35%, respectively, compared to unheated regular diesel. The percentage of CO_2 in the exhaust gas is increased by 45.5% for preheated B100 compared with unheated B0 at 100% load. Furthermore, the injection timing of the engine is altered to find the optimum injection timing of the biodiesel-diesel blend. The BSEC is increased by 0.53 kg/kWh and reduced by 1.4 kg/kWh for advanced and retarded injection timing, respectively. By advancing injection timing, the HC, CO, and smoke opacity were reduced by 7.4%, 36%, 5.7%, and 7%, respectively, compared to the B30 at standard injection timing.

Keywords: Biomass, Coffee husk, transesterification, Biodiesel, Preheating, Injection timing, Combustion, Performance, Emission

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NOMENCLATURE

B0	0% CHOME biodiesel + 100% regular diesel
B10	10% CHOME biodiesel + 90% regular diesel
B20	20% CHOME biodiesel + 80% regular diesel
B30	30% CHOME biodiesel + 70% regular diesel
B40	40% CHOME biodiesel + 60% regular diesel
B50	50% CHOME biodiesel + 50% regular diesel
B80	80% CHOME biodiesel + 20% regular diesel
B100	100% CHOME biodiesel + 0% regular diesel
BSEC	Brake specific energy consumption
BSFC	Brake specific fuel consumption
bTDC	Before top dead center
BTE	Brake thermal efficiency
CA	Crank Angle
CCS	Coffee cut-stem
CH	Coffee husk
CHOME	Coffee husk oil methyl ester
CI	Compression ignition
CM	Coffee mucilage
CO	Carbon monoxide
CO_2	Carbon dioxide
CP	Coffee pulp
CS	Coffee silverskin
DI	Direct injection
FEG-SEM	Field Emission Gun Scanning Electron Microscope
FFA	Free fatty acid
FTIR	Fourier transform infrared
H_2SO_4	Sulfuric acid
HC	Unburned hydrocarbon
IC	Internal combustion
KOH	Potassium hydroxide

NaOH	Sodium hydroxide
NHRR	Net heat release rate
NO_x	Oxides of nitrogen
ppm	Parts per million
RPM	Revolution per minute
SCG	Spent coffee ground
U	Uncertainty
U_T	Total uncertainty

CHAPTER 1

INTRODUCTION

1.1 Background

Global energy consumption is increasing for a variety of reasons, including transportation of people and goods, excess population, and industrial uses. The dramatic increase in automobile ownership has increased the demand for petroleum products in recent years. The rise in energy consumption, the depletion of petroleum-based fuel reserves, the resulting increase in pollution, and the rising cost of petroleum has refocused attention of researchers on alternate energy sources. The amount of oil consumed continues to rise year after year. Research findings anticipate fossil oil reserves will run out in 2052 (Martins et al. 2019). Fig. 1.1 shows the global energy reserve and consumption rate.

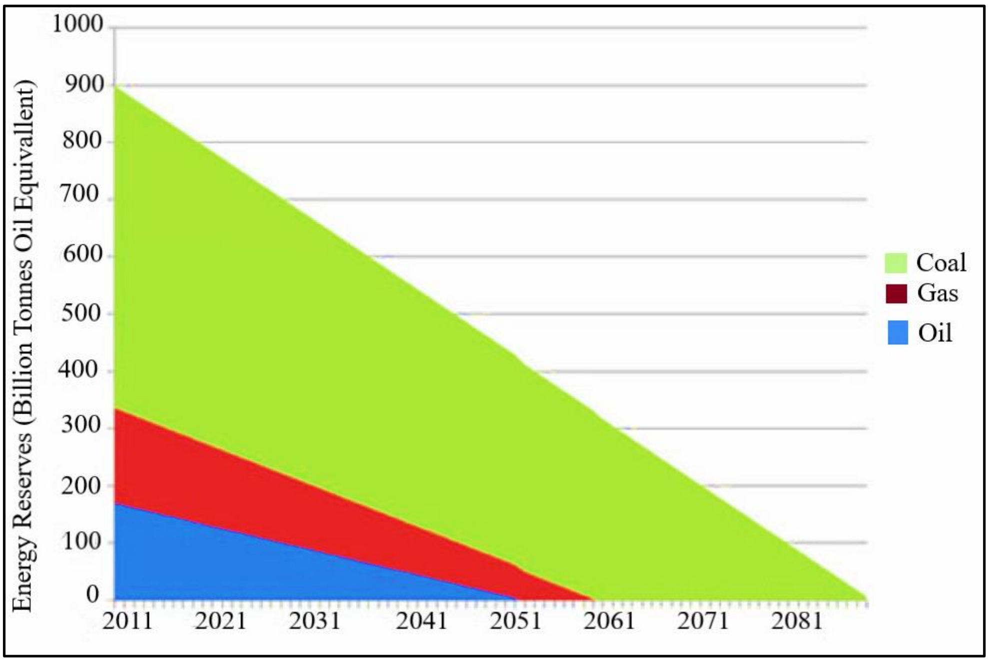


Fig. 1.1 Global oil reserve and depletion period
https://mahb.stanford.edu/library-item/fossil-fuels-run/ (2019)

The rate of fossil fuel consumption is not steady; it is increasing. This is because the global population continues to grow. More people equals increased demand for fossil fuels since the number of things that use fossil fuels continues to grow. Globally, 11 billion metric tonnes of oil (approximately) as fuel is consumed yearly, and it rises year after year (Huo et al. 2007). As it is indicated in Fig. 1.1, the oil reserve will end in 2052, the gas reserve in 2060, and coal in 2090 (Vairamuthu et al. 2016; Dresselhaus and Thomas 2001; Deepankumar et al. 2017).

Excessive reliance on fossil fuels has wreaked havoc on the global ecosystem and caused health risks. With rising environmental concerns and stiffer rules on exhaust emissions, engine fuel system improvement has made decreasing engine emissions a priority. Additionally, efforts must be made to reduce reliance on petroleum fuels, which are limited in supply. There is boundless social and political pressure to reduce emissions in the exhaust gas of compression ignition (CI) engines. Another major issue of the modern era is the rapid destruction of the biotic environment, which is the habitat of flora and wildlife caused by industrialization.

Almost all developed, developing, and underdeveloped countries are trying to respond by changing their production methods to recycle industrial waste. As a result, most large industries no longer categorize their chemical residues as waste but as raw materials for other processes (Mussatto et al. 2011).

Energy sources for the Internal Combustion (IC) engine are the main challenges the world face today and in the future. This energy source is a significant problem impacting the economic wing of every developing country since most countries in the world are importing oil from outside, influencing their country's economy as a whole.

Reducing global warming and environmental pollution and building a green world is the slogan of the world's developed, developing, and industrialized countries. Alternative energy sources have increasingly arisen over the last decades to replace non-renewable energy sources.

1.2 Effect of exhaust gas emissions

Air pollution is created by a variety of factors, including urbanization and increasing industrialization, and manifests itself in a variety of ways, including vehicular emissions and industrial smoke. Exhaust emissions and their influence on human health constitute a second major concern next to fuel depletion. The carbon monoxide (CO), unburned hydrocarbons (HC), particulate matter (PM), and nitrogen oxides (NO_x) are the primary pollutants produced by IC engines during the burning of fuel. Exhaust gas pollutants are particularly hazardous to human health.

To address these challenges that threaten economic development to meet human needs, it is of utmost importance to look at alternative and renewable energy sources. Interest in renewable energy has increased significantly, and it has emerged as a key source of energy generation. As an energy source, biomass is a type of renewable energy produced from non-fossil organic masses. Agricultural biowastes, forest debris, bioscraps, landfills, and certain agricultural seeds are a few examples of biomass sources considered for alternative energy generation.

Using agriculture waste as a source of alternative energy address various environmental issues, including environmentally friendly alternative energy, pollution control, greenhouse effect, energy efficiency, and climate change policies (Savariraj et al. 2011; Maki and Prabhakaran 2011).

The key objectives of biofuel policies are to encourage the use of biofuel in transport and other biomass-based fuels to promote people's interest in finding new sources of energy rather than being solely dependent on fossil fuels. On the other hand, the plan shifts the philosophy of the world to focus exclusively on what we have rather than on a single source of energy. Furthermore, searching for alternative sources of energy and investigating new ways to replace the non-renewable sources of energy is of utmost importance.

1.3 Biodiesel

Biodiesel is defined as a fuel consisting of mono-alkyl esters of long-chain fatty acids generated from vegetable oils or animal fats and exhibits similar qualities to regular diesel. In the presence of a catalyst, biodiesel is typically produced via the reaction of vegetable oils or animal fats with methanol or ethanol. Biodiesel is a methyl or ethyl ester of fatty acids that are abundant in vegetable oil or animal fat. In compression ignition (CI) engines, biodiesel can be used as a straight substitute, extender, or supplement for fossil diesel fuel. Biodiesel can be utilized in diesel engines with minimal or no modification. Nevertheless, biodiesel is currently more expensive than petroleum diesel. The greater price of biodiesel is mostly attributable to the cost of raw materials.

Biodiesel has been established as a viable alternative to conventional fuels in the global energy market. This energy is generated through plant growth rather than drilling it from the ground. Since it is composed of plants and other organic materials, it can be generated wherever there is available ground, and it helps both farmers and consumers.

Because of environmental concerns, socioeconomic, and foreign exchange, saving the share of biofuel in the automotive industry is increasing rapidly during the 21st century (Demirbas 2008; Coyle 2007). The energy of biofuel is derived from the biological fixation of carbon. Fossil fuels are not known to be biofuels because they initially have carbon fixation that has been "out" of the carbon cycle for a very long time.

Many biodiesels have been used in diesel engines to produce energy as an alternative to conventional diesel. Biodiesel is produced from various vegetable oils, both edible and non-edible. Sources of biodiesel include soybean, palm, sunflower, rapeseed, peanut, coconut, jatropha, cottonseed, Karanja, Dhupa seed, Simarouba, Rubber seed, Neem, and Mahua (Ghadge and Raheman 2006; Richard et al. 2013). Another source of biodiesel is oil produced from agricultural biomass residues such as corn stover, wheat straw, rice husk, coffee husk, crop peels, pulps, etc. (Abbas and Ansumali 2010; Gouvea et al. 2009b; Karlsson et al. 2016; Tyndall et al. 2011).

Biodiesel production is increasing at a rate of about 40% each year. Other ingredients, such as animal fats, palm oil, and coffee grounds, are also used, although the latter is a very new addition. These goods are primarily designed for use as fuel, but they can also be found in industrial waste, such as fryer oil, which is utilized in a large number of restaurants.

The majority of vegetable oils are edible in nature, and their continued use as a substitute for fossil fuels contributes to a food crisis. In order to address this, non-edible vegetable oils have been tested in diesel engines, resulting in the same engine performance, combustion, and emission characteristics compared to edible oil.

1.4 Advantages of using biodiesel as an alternate fuel

Biodiesel is a renewable, domestically produced alternative to petroleum fuel. Using biodiesel in IC engines as a fuel has substantial benefits such as;

- Biodiesel is a sustainable fuel that can be regenerated multiple times within a single generation.
- Biodiesel can be produced from reclaimed vegetable oils and animal fats, and it is becoming popular day by day.
- In contrast to diesel, biodiesel is harmless and degrades swiftly in a biological environment. Biodiesel spills are significantly less dangerous than diesel spills.
- Because biodiesel has a higher ignition temperature than diesel, it is safer to handle than petroleum-based diesel.
- Biodiesel can be created from vegetable seeds, biomass, and animal fats, it can be produced anywhere in the country whenever there is a requirement for it.
- It is recommended that the fuel injector and combustion chamber be modified in order to burn pure biodiesel. However, for 20% biodiesel blend, modification in the engine is not needed.
- Because biodiesel is made from plants and has oxygen in its molecules, it burns cleaner than gasoline and diesel (Sastry et al. 2006)

1.5 Disadvantages of using biodiesel

The use of plant and animal oils as an alternate fuel is the first outcome of the revelation of biodiesel. However, using edible and non-edible as a substrate for the production of biofuel has several drawbacks, including

- Coking and creation of trumpets on the fuel injector
- Carbon deposision on valves
- Oil ring sticking
- Lubricant oil thickening
- Lubrication issues and
- Not suitable at low temperature

Other disadvantages of using edible and non-edible oils are the high viscosity and lower volatility content, which causes the formation of deposits in engines due to incomplete combustion and incorrect vaporization characteristics. Some of these problems have been fixed by using some of the following methods:

- Blending the biodiesel with regular diesel (Subramani and Karuppusamy 2021).
- Adding nano particles to improve the spray characteristics and increase the volatility of the fuel (Ghanbari et al. 2021; Sathasivam et al. 2018).
- Preheating the fuel before injection to reduces the viscosity and density (Ranjit and Chintala 2021; Sivasubramanian and Sajin 2021; Viswanathan and Wang 2021).
- Varying injection timing (Gaddigoudar et al. 2021; Rami Reddy et al. 2021; Ranganatha Swamy et al. 2021).
- Using exhaust gas recirculation to reduce NO_x emission (Dhana Raju and Kishore 2019; Rami Reddy et al. 2021).

Biomass-based fuels are gaining global interest due to their sustainability, zero carbon emission, and ability to create new jobs in rural regions. As a result, many developed countries have put in place new rules to encourage the use of biofuels made from grains, vegetable oil, or biomass in the transportation sector.

Biomasses can be used to produce a variety of fuels, including liquid fuels like ethanol, methanol, biodiesel, and gaseous fuels like hydrogen and biogas. Liquid biofuels are generally used to power automobiles, but they can also be used to power engines or fuel cells for electricity generation. Biofuels may be made easily from typical biomass resources. They provide significant environmental benefits, as they are biodegradable and contribute to long-term sustainability.

1.6 Sources of biomass

Biomasses have real potential in nations with limited oil and gas reserves to minimize energy reliance on other countries. In its various forms, biomass nowadays supplies about 1250 million tonnes of oil, equivalent to about 14% of the world's annual energy consumption. It is one form of energy source for emerging countries, supplying 35% of all energy demands. In developed countries, biomass energy usage practice is also substantial (Werther et al. 2017).

The biomass can be obtained from various sources, as shown in Fig. 1.2. Biomasses are said to have a high potential, especially in nations with limited oil and gas reserves, as they minimize the energy dependency on the oil industry of other countries.

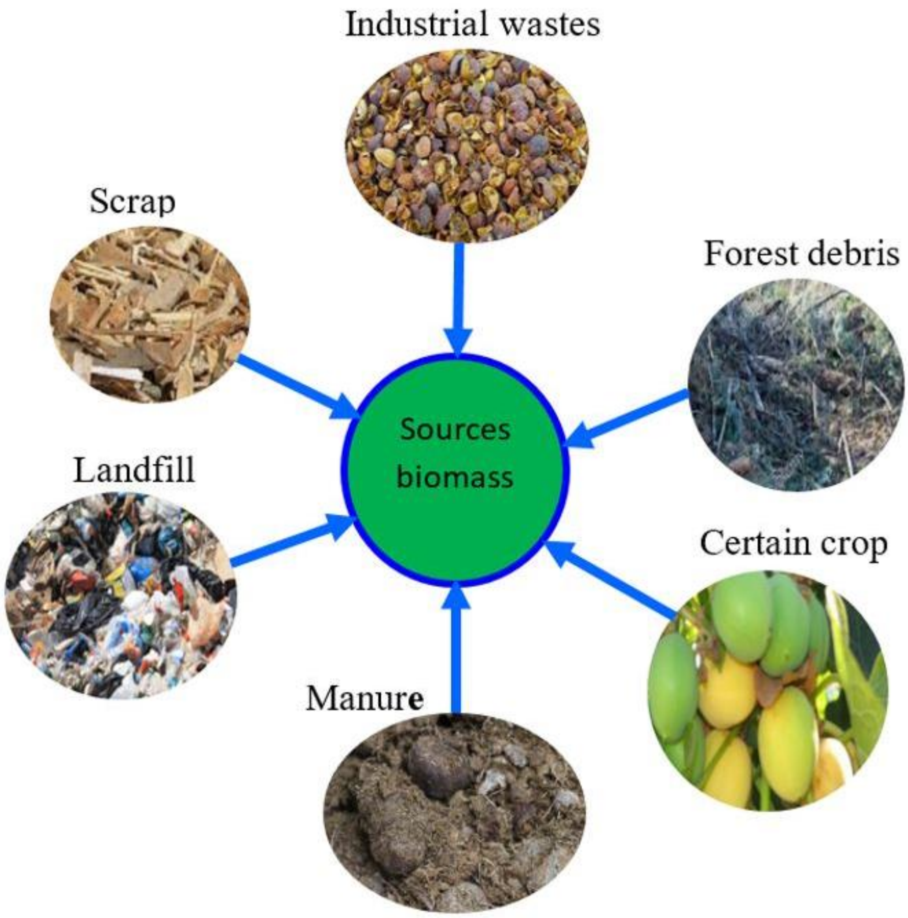


Fig. 1.2 Sources of biomass

The primary biomass sources currently used are sugar cane, rice husk, and maize for bioethanol production. In addition, certain products that can be used to produce biofuel are sunflower seeds, soybean, canola, peanuts, Jatropha, coconut and palm oil, sugar beet, sweet sorghum, and cassava. The second-generation biofuel mainly comprises cellulose resources such as grassy crops, woody plants, forestry, agricultural by-products (such as wood residues, stems, and stalks), and urban garbage. The technology for the conversion of this feedstock still needs improvement and is under investigation.

Biofuel is a form of fuel whose energy is derived from organic carbon fixation. Biofuels comprises fuels derived from biomass conversion, as well as solid biomass, liquid fuels, and various biogases. Figure 1.3 illustrates the usage of biomass in a cascade.

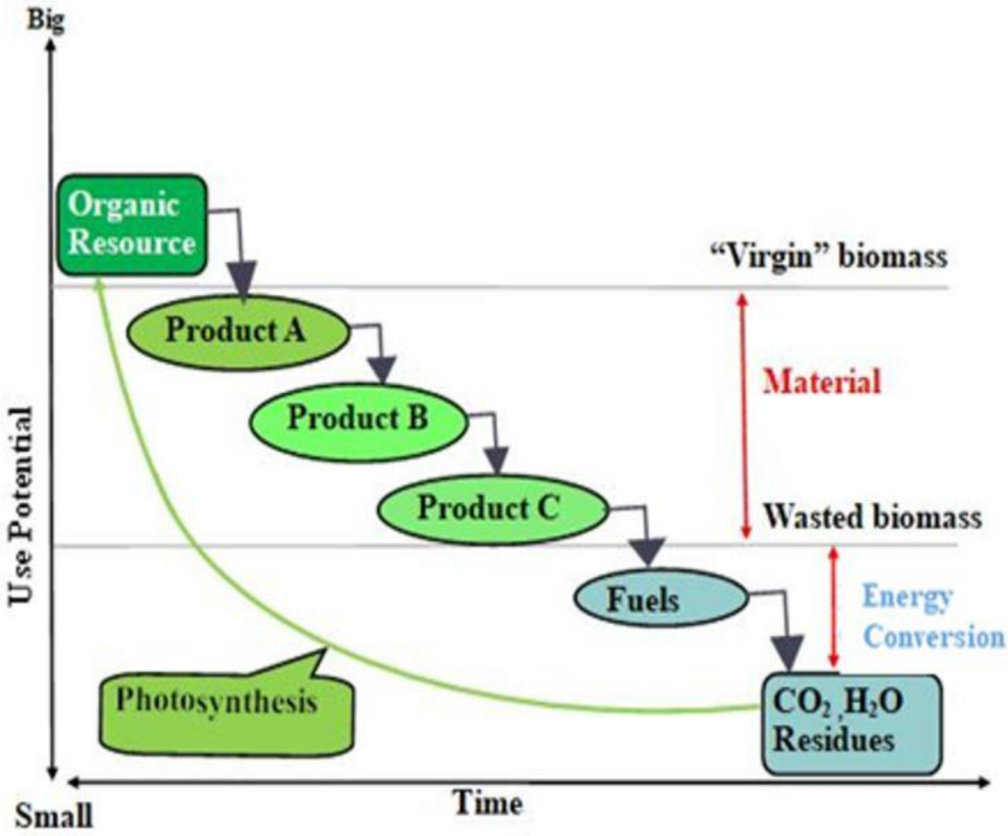


Fig. 1.3 Cascade use of biomass

Because biomass fuels are renewable and generate lower pollutants than fossil fuels, they represent a compelling alternative to fossil fuels. Renewable biomass energies are closed-loop, non-radioactive energy systems that do not contribute additional carbon or heat to the geosphere.

The prospect for biomass fuels is very promising in the long run because of their availability and sustainability. In addition to replacing fossil fuels in engines, biomass has a favourable impact on the environment. Extensive utilization of biomass fuels can reduce the dependency on fossil fuels, which are currently the main source of energy in the world. In countries without petroleum reserves, the use of biomass fuels can reduce energy imports, resulting in significant foreign exchange savings.

1.7 Coffee waste biomass

Coffee is widely used due to its refreshing properties. Coffee processing is one of the industrial processes in which coffee products are processed and sold to the market. Those coffee production industries are significant resources of agricultural waste. For instance, in a coffee bean weighing 0.75 g, approximately 0.36 g, i.e., 50% is removed as waste from its total weight (Gouvea et al. 2009). Those wastes are abundantly available in most of the coffee processing industries. Also, they cause pollution and environmental issues in the countries producing coffee. When the coffee wastes are carelessly disposed of on the land during the summer, they flow into rivers which causes pollution by changing the quality of the streams. And it produces a foul smell in the entire region surrounding the coffee industry. Wastewater from those industries has a high concentration of chemical contaminants. It also causes more harm to the local water bodies, human health, and marine life when it is inattentively released into the rivers and streams.

Figure 1.4 shows the compositional percentages of a coffee cherry. The main products of the coffee plants are the coffee cherries which consist of a pair of coffee beans that are coated and surrounded by pulp. The pulp is covered by a thin parchment-like shell called the outer skin.

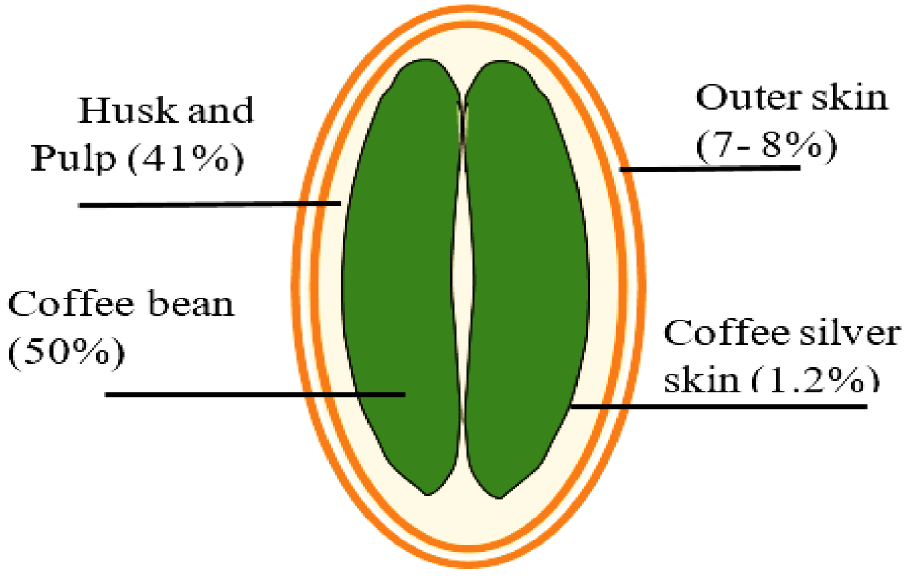


Fig. 1.4 Compositional percentages of a coffee cherry

There is a significant amount of waste products at each stage of coffee processing that adds a quantity to the total residues of the coffee processing industry. In addition to reducing the total profit of the overall manufacturing revenue, improper disposal of these wastes have an environmental impact.

Figure 1.5 shows a flow chart of methods involved in the processing of coffee and the waste products obtained at different stages. The coffee processing method is typically classified into dry and wet. In the dry processing method, the collected coffee beans are dried, crushed, and spread over a different size plate sieve of the coffee processing machine according to the thickness of the coffee bean. During this process, dry coffee wastes such as coffee husk (CH) and coffee pulp (CP) are mixed and stored in the same place. The waste products generated in each step of processing collectively increase the total waste residue of the industry.

The quality of waste produced depends on the type and moisture content of the coffee bean. Meanwhile, in the wet method, the coffee fruit is fermented, and then the pulper machine is used to remove the pulp that covers the bean before it is dried.

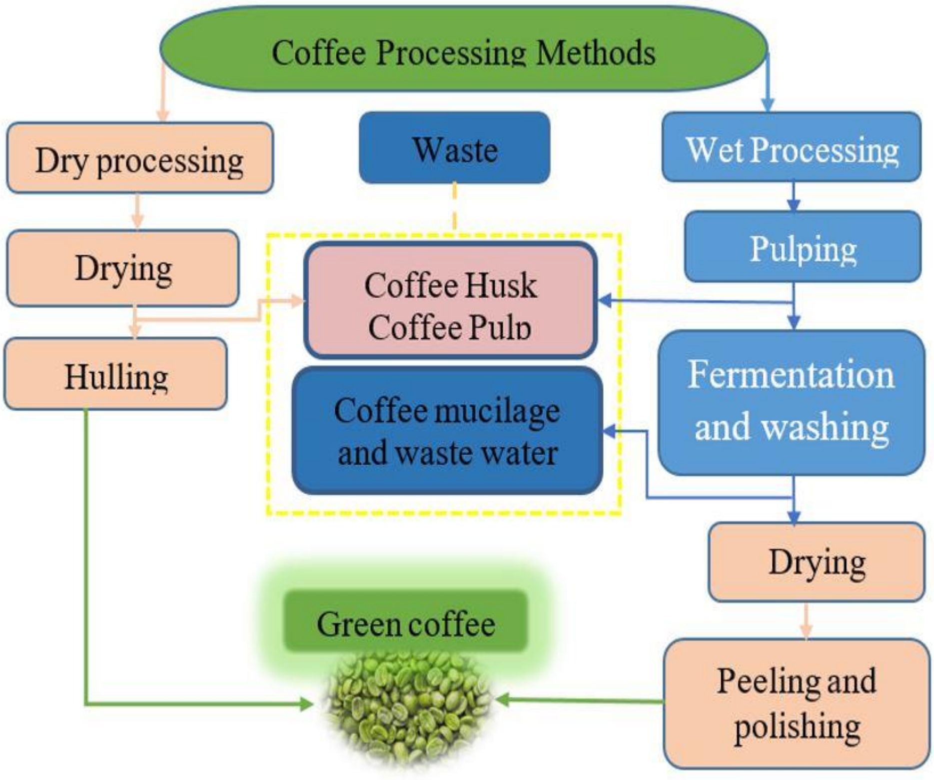


Fig. 1.5 Flowchart of coffee processing methods and their waste products

The wet method of coffee processing is also known as the washed coffee processing method. Coffee mucilage, which can be used as a substrate for hydrogen generation, is also produced as coffee husk and pulp during dry coffee processing (Galanakis 2017).

Globally, 102 tonnes (approx.) of oil equivalent biomass of coffee waste is burned in the open air without energy exploitation, thereby providing substantial environmental pollution annually. In some countries, like Ethiopia, nearly 192000 metric tons of CH and CP are obtained as waste products every year (Merete et al. 2014).

As the wastes from the industrial process obstruct ecological developments, using those products to produce another form of energy that will reduce environmental pollution would upgrade the viability of the coffee processing industries (Hernández et al., 2014). Most of the studies (Orrego et al., 2018; Tehrani et al., 2015; Wilson et al., 2010) have shown that the coffee waste biomass may be utilized as a feedstock for generating alternate energy. Productive utilization of these wastes has been lagging. A few studies have shown that the coffee husk biomass can also be used as alternative to conventional energy surces to produce biofuels. However, reliable references on the extraction of coffee husk biofuel and its characterization are still insufficient (Miito and Banadda, 2017; Sime et al., 2017).

Figure 1.6 shows the burning of waste produced by coffee processing industries. The CH and CP are poorly utilized or spent on the land to decompose (Fig. 1.6a). Figure 1.6b shows the waste from the coffee processing industry being incinerated in an open environment.

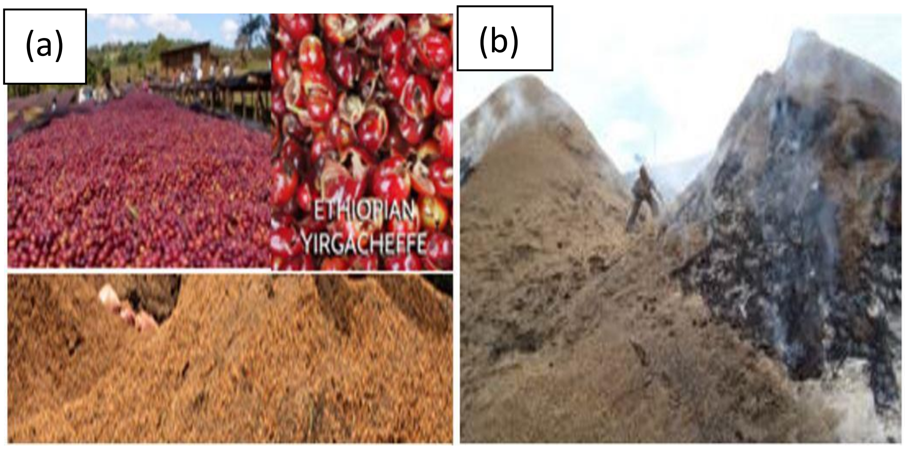


Fig. 1.6 Coffee wastes at the coffee processing industry (a) coffee waste pile at coffee processing industry (b)coffee waste burning in an open environment

1.8 Major coffee processing waste

Coffee processing is one of the industrial processes in which coffee products from agriculture are processed and made ready to market for consumers at a different level. The coffee industry produces an enormous amount of waste like CH, CP, coffee silverskin (CS), spent coffee ground (SCG), coffee mucilage (CM), and coffee cut-stems (CCS) (Galanakis 2017). These sectors generate an estimated 6 million tons of SCG, 6.08 tons of CH and CP per year, and 0.68 tons of CH and CP produced per ton of coffee cherry (Janissen and Huynh 2018).

The CH is a by-product of the coffee manufacturing industry, which contains a high concentration of carbon-based materials, minerals, and chemicals such as caffeine, tannins, and polyphenols. Due to its detrimental chemical quality, these residues cause environmental pollution and inhibit animal feed use (Oliveira and Franca 2015). Thus, the CH is considered as the main solid waste generated from the dry coffee processing method. The CH and CP's chemical constituents were obtained for 100 g dry bases. In this study, it was found that the CH produced from the dry processing method contained 8% to 11% of protein lipids and 58% to 85% of carbohydrates. In contrast, CP produced by the wet processing method contained 4% to 12% of protein lipids and 45% to 89% of carbohydrates. These are essential substances in the production of biofuels (Sajjadi et al., 2018).

The SCG is a coffee waste produced either by domestic brewing in the places like coffee shops, restaurants, and households or from the industrial preparation of instant coffee powder. The chemical composition (elements, distribution, and concentration) of the CH and the SCG samples is determined in the current study, followed by oil extraction from CH, production of biodiesel from the oil, and its characterization is also established. Fig. 1.7 shows the SCG damped as waste in coffee brewing shops.

Fig. 1.7 SCG in coffee brewing industries

1.9 Fuel injection system

A fuel injection system regulates the injection timing and the amount of fuel injected into the combustion chamber. Fuel injection should start and end at a predetermined time to avoid the subsequent injection that could affect the engine's performance. In the case of diesel engines, the fuel is taken from the fuel tank by an injection pump via feed pump and fed into the combustion chamber at high pressure. To get better engine performance and emission characteristics, advancing or retarding an engine's timing is possible. Advancing injection timing causes the injection process to occur earlier than the standard injection timing (manufacturer) settings. In contrast, retarding means injection timing is changed, so the fuel is injected after the standard injection timing. Although advancing is common compared to retarding, it can fix a lag or smoking problem, except for NO_x and support combustion and performance issues.

1.10 The purpose of preheating the fuel in diesel engine

In a conventional diesel engine, diesel is injected into the combustion chamber of the engine in its liquid form. Prior to ignition, diesel fuel is atomized, vaporized, and mixed with air during the injection process. When diesel fuel is burned in a conventional diesel engine, there is a big challenge with how quickly the droplets evaporate because combustion reactions happen much faster than fuel mixing with air. Similar problems will happen using biodiesel as an alternate fuel in the CI engine. This is because biodiesels have higher viscosity and density than regular diesel. Various techniques used to minimize these problems are preheating the fuel before injection, increasing the pressure of the injection, preheating the intake air, and mixing nanoparticles as additives. Figure 1.8 shows the schematic diagram of the fuel preheating arrangement.

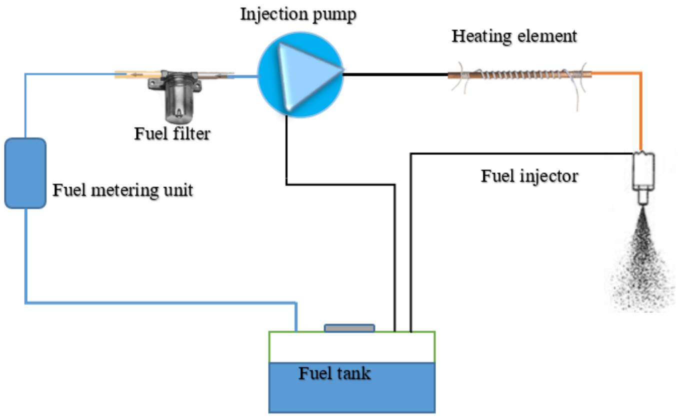


Fig. 1.8 Schematic diagram of preheating injection system

Preheating the fuel before injection significantly reduces the viscosity and density of the fuel. As shown in Fig. 1.9, the fuel from the fuel tank is pumped by an injection pump through a fuel filter at high pressure. The camshaft of the engine drives the fuel injection pump. By wrapping the heating cord around the injection fuel line, the temperature of fuel flowing through the line increases on to the way the fuel injector. The overflow fuel from both the injection pump and injector is returned to the fuel tank after the injection.

Preheating the fuel prior to injection improves the air/fuel mixture, enhances vaporization and atomization, and results in better combustion and emission characteristics for the engine.

In the present study, Kirloskar TV1 engine is used. The injection system of this engine includes a fuel tank, fuel metering mechanism (burette), injection pump, fuel lines, and injector. A pump is placed close to the cylinder mounting to the engine. The plunger of the high-pressure pump is actuated by the cam lobe, which delivers the proper amount of fuel with the proper pressure to open the injector valve at the right time and crank angle. The amount of fuel that is injected into the engine depends on the stroke the plunger in the injection pump.

1.11 Exhaust emission and its control

Various techniques have been adopted in recent decades to reduce exhaust emissions and increase thermal efficiency. Low-temperature combustion (LTC) is a recently invented engine concept that lowers combustion chamber temperature than the temperature at which the NO_x emission is formed. The local equivalence ratios must be lower than those for which diesel smoke opacity gets formed. It includes some advanced combustion mechanisms, comprising homogeneous charge injection (HCCI) or premixed charge compression ignition (PCCI). HCCI is the first stage where the combustion process is no longer linked to the engine's injection timing. Instead, the kinematics of the chemical starts to play a more significant role in combustion. PCCI is a second stage that is inextricably linked to fuel injection occurrence. In the first stage (HCCI), air and fuel are mixed in such a way that at the start of the combustion, fuel is sprayed on the air in the combustion chamber, and it is a homogenous mixture categorized by an equivalent ratio less than unity everywhere. Recently, other new techniques of LTC ignition called Reactivity Controlled Compression Ignition (RCCI) is being formed. Compression ignition with reactivity control is a relatively new approach in which several fuels with varying reactivity are injected at predetermined intervals to control the reactivity of the charge in the cylinder for the required combustion period and magnitude.

In the second category, combustion phasing is tightly closed to the fuel injection event which is termed as premixed charge compression ignition (PCCI) mode. Figure 1.9 shows the local equivalent ratio (φ) plot to flame temperature (T) with different combustion strategies.

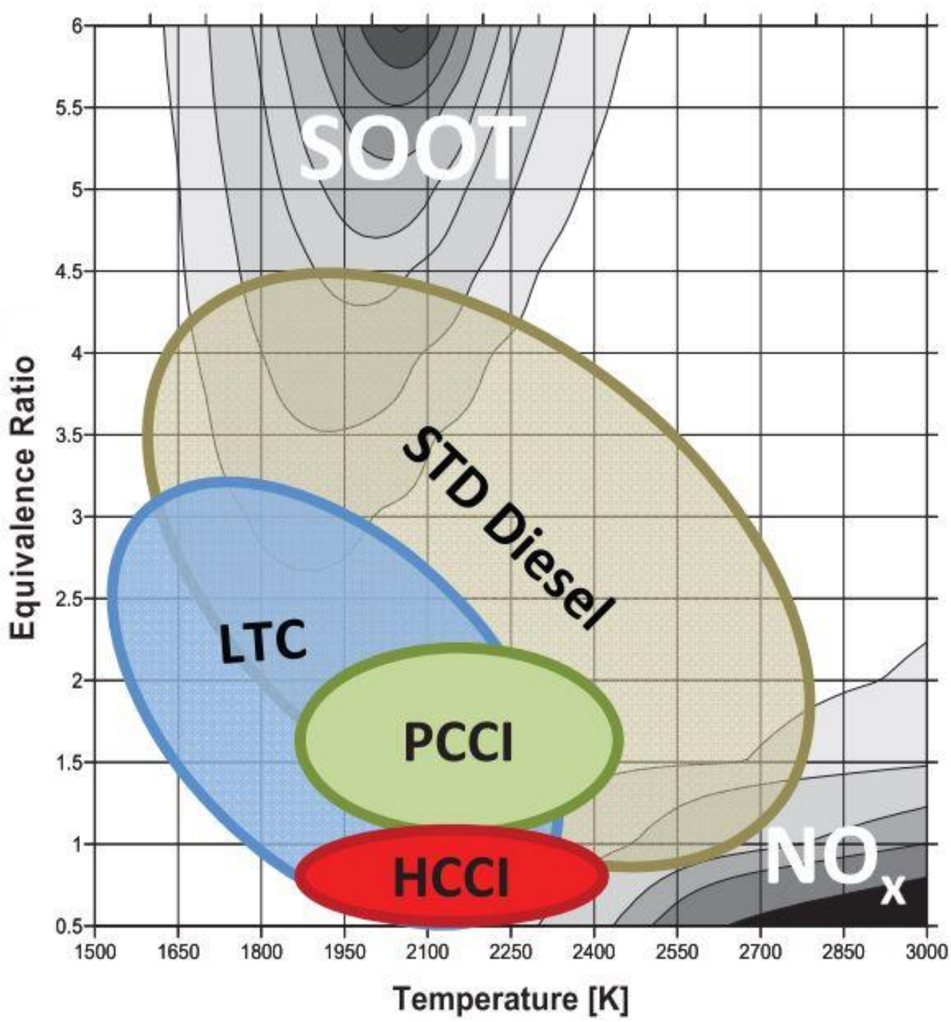


Fig. 1.9 Predominant φ–T working conditions for combustion modes (Desantes et al. 2012)

Essentially, this strategy involves injecting relatively low reactive fuel (port injection), extremely early in the engine cycle, where it mixes homogeneously with the air. Later, a more reactive fuel is pumped directly into the cylinder, forming pockets of varying air-fuel ratios and reactivity that govern the beginning of combustion at varying times and rates (Imtenan et al., 2014).

To achieve LTC mode in IC engines, exhaust gas recirculation (EGR), variable valve timing (VVT), and different types of fuel injection mechanisms are developed.

Apart from the mentioned methods, several investigations have been conducted to address some of the disadvantages of biofuels. Yet more findings are underway to find ways to optimize engine performance, combustion, and emission characteristics while biofuels are used.

1.12 Organization of the thesis

The main aim of the present investigation is to find the effect of coffee husk oil methyl ester (CHOME) biodiesel diesel blends on combustion, performance, and emission characteristics of the CI engine. The thesis includes a comprehensive experimental analysis of coffee waste biomass, biodiesel extraction, and combustion, performance, and emission characteristics of the Kirloskar TV1 single-cylinder diesel engine by using CHOME biodiesel diesel blends. The thesis is divided into seven chapters, which are explained below.

Chapter 1: Introduction: This chapter provides a comprehensive overview of the present energy sources, energy supply and demand challenges, available alternative fuels to diesel fuel, fossil fuel reserves, and fossil fuel depletion. It highlights the current scenario of biodiesel, biomass, biofuels, and fuel injection system for diesel engines. Coffee waste biomass, the fuel injection system of the engine used in this research work and exhaust gas emission reduction mechanisms are also overviewed.

Chapter 2: Literature review: This chapter presents an extensive literature review containing biodiesel production, investigating the engine's performance, combustion, and emission characteristics by using different biodiesel. Mechanisms to improve the biodiesel characteristics to advance the engine performance, combustion, and emission characteristics are also reviewed. The motivation for the present research work and its contribution and objectives are also covered in this chapter.

Chapter 3: Deals with investigating the compositional elements and distribution in coffee waste (Coffee husk and spent coffee ground), extraction, and characterization of biodiesel from the coffee husk. The methodology applied in biodiesel production and materials used are discussed as well.

Chapter 4: This chapter discusses the experimental analysis of engine performance, combustion, and exhaust gas emission characteristics by using CHOME biodiesel-diesel blends. The experimental setups, biodiesel diesel blends used to perform the experiment, and results obtained are discussed. Load on the engine is varied to study the effects of the fuel blends on overall engine characteristics.

Chapter 5: This chapter presents the effect of preheating the fuel on engine performance, combustion and emission characteristics. Three blends (B10, B30, and B50) neat CHOME biodiesel (B100) and regular diesel (B0) are used for the experiments. Preheating system is developed to heat the fuel to 95 °C before injection. The performance, combustion and emission characteristics of the engine fuelled with preheated and unheated fuel at different loading conditions are discussed.

Chapter 6: In this chapter, the effect of varying injection timing on the performance and emission characteristics of the engine using CHOME biodiesel-diesel blend is discussed. B30 and regular diesel are used to perform the experiments. Three different injection timings are used (standard, advanced and retarded). Regular diesel results of the engine characteristics at standard injection timing are used to compare the results obtained from B30 at advanced, standard, and retarded injection timings.

Chapter 7: This chapter provides the overall conclusions of the work that has been done and the scope for future research.

CHAPTER 2

LITERATURE REVIEW

In this chapter, a comprehensive review of the literature is which includes the production and use of various biodiesel in CI engines, the effects of preheating the fuel before injection and varying the injection timings on the performance combustion and emission characteristics of the engine.

2.1 Using biodiesel in an IC engine

Different biodiesels have been utilized to generate power as an alternative energy source in diesel engines. Various vegetable oils, both edible and non-edible oils, have been used as sources of biodiesel. Soybean, Palm, Sunflower, Rapeseed, Peanut, Coconut, Jatropha, Cottonseed, Karanja, Dhupa seed, Simarouba, Rubber seed, Neem, and Mahua are some of the sources of biodiesel that were investigated. Another source of biodiesel is the oil produced from agricultural biomass residues such as corn stover, wheat straw, rice husk, coffee husk, crop peels, pulps, etc.

Buyukkaya (2010) conducted an experiment on the performance, emissions, and combustion of a diesel engine fuelled with rapeseed oil biodiesel and its blends of 5%, 20%, and 70% with diesel. The findings showed that the usage of biodiesel resulted in reduced smoke opacity (up to 60%) and increased BSFC (up to 11%) compared to diesel. The CO emissions of B5 and B100 fuels were found to be 9 and 32% less than those of diesel, respectively. The BSFC of biodiesel was discovered to be 8.5% and 8% greater than that of diesel, respectively. The combustion result revealed that the ignition delay of rapeseed oil and its tested blends was longer than that of diesel.

Karabektas and Hosoz (2009) conducted an experiment on direct injection, single-cylinder diesel engine fuelled with diesel and isobutanol blends. In addition to regular diesel, four different isobutanol-diesel fuel blends containing 5, 10, 15, and 20% isobutanol were prepared and used in the experiments. The experiment was conducted at speeds between 1200 and 2800 rpm, with 200 rpm intervals. The test results showed that the BSFC increases proportionally with the isobutanol percentage of the blends.

BTE of the engine by using regular diesel was greater than the other four blends. With the use of the blends, CO and NO_x emissions were reduced; however, HC emissions increased significantly.

Anandhan et al. (2021) tested jojoba oil biodiesel to analyze the performance and emission characteristics of diesel engine. This study observed that while increasing the load, B20 had the highest BTE and the lowest smoke, CO, and HC emissions of all the biodiesel diesel blends evaluated. However, compared to other fuel blends, a higher concentration of NO_x emission was observed at B20.

Gad et al. (2018) investigated the performance and emissions characteristics of CI engine fueled with palm oil/palm oil methyl ester blended with diesel. In this report, it was concluded that by fueling the engine with palm oil methyl ester, the BTE of the engine was reduced, and BSFC was increased compared to regular diesel. HC and CO emissions are reduced except slight increment in NO_x emission. The NO_x emissions for diesel, B20, and B100 are 174, 190, and 285 ppm, respectively, at full load operation.

Aydin and Ilkiliç (2011) investigated the performance of CI engine by using biodiesel produced from cotton seed oil and neem oil. In this experimental investigation, it was reported that cottonseed and neem oil might be used as a resource to obtain biodiesel. According to their conclusion, fueling the engine with cotton seed oil methyl ester (B20) increased the BTE of the engine compared to diesel fuel due to the complete combustion.

Mendoza et al. (2019) characterized residual biomass from the production of coffee for energy purposes. This study shows that this biomass is an excellent raw material for thermochemical conversion processes with lower moisture content, higher average heating efficiency, and volatile content. The results of the experimental sample conducted as part of this study reveal that the thermochemical conversion that was carried out successfully produced a valuable output from the waste generated by the coffee industry.

Seong et al. (2012) used popping pretreatment to convert coffee residue into bioethanol. The results of this experiment it is concluded that the biomass of coffee residue (SCG) is an attractive resource for bioethanol production since they are mainly composed of fermentable sugars such as mannose, glucose, and galactose.

Sime et al. (2017) extracted bioethanol from the coffee husk. From 100g of coffee husk powder, 69% of bioethanol was produced in the laboratory, and the properties were comparable with the commercially available bioethanol.

Ga et al. (2016) performed an experimental investigation on the characterization of coffee husk for the fast pyrolysis process. In their preliminary investigation, coffee husk bio-oil was used as a fuel in the pyrolytic process. In this report it was concluded that, indicated that using coffee husk oil, the final product of the pyrolytic process had a good calorific value.

Couto et al. (2013) conducted an experiment in a gasification pilot plant, running at a temperature up to 850 ºC under the pressure of one bar with a maximum pellet feeding rate of 70 kg/h. Tests were made using feeds of the different coffee husk at 800ºC. Feedstock admission rates of 40 and 63 kg/h were tested to study syngas composition as a function of feedstock composition and operational conditions.

Table 2.1 Coffee husk biomass properties

Elementary Analysis (%)				**Humidity (%)**	**Density (kg/m^3)**	**Net Heat Value (MJ/kg biomass)**
N	C	H	O			
5.2	40.1	5.6	49.1	25.3	500	20.9

Table 2.1 shows the properties of coffee husk biomass, such as humidity, density, net heat value, and primary constituents (carbon, nitrogen, oxygen, and hydrogen) in terms of their volume percentage. The Net Heat Values (NHV) of biomass was determined with an IKA Laboratory Equipment C 200 Calorimeter system. This study showed that the biofuel produced was rich in carbon monoxide, hydrogen, and a small amount of methane. These gases are accountable for the heat content in the produced syngas.

Mbugua et al. (2014) investigated the potential of the coffee husk as a source of fuel for power generation. According to their investigations, the calorific value of the coffee husk was found to be 19.98 MJ/kg, which shows that the coffee husk is an encouraging source of renewable energy.

Gouvea et al. (2009) studied the physical properties of the coffee husk and concluded that the solid waste of the coffee husk is quite promising for ethanol production. The coffee husk used in the study was denominated as a unique type of coffee husk. Some characteristics that distinguish this specific type of coffee husks from the ordinary dry-processed ones include their protein, higher density, and lower fiber contents.

Oliveira and Franca (2015) overviewed the possible uses of coffee husk for biofuel production. The researchers reviewed a worldwide survey of coffee cultivation and statistical production. The review extensively covered the processing of coffee, chemical composition identification of coffee, solid biofuel, production of ethanol, production of biogas, fermentation studies, adsorbents production, and recovery of bioactive compounds. In this study, the moisture content of the coffee husk was found to be 7%-18%. The authors also recommended researching alternative and profitable coffee husk and pulp uses.

Orrego et al. (2018) conducted an experimental study on coffee mucilage for optimization, fermentation, and ethanol production. The result demonstrated that coffee mucilage, a waste of the coffee processing industry, can be used as a substrate for the production of ethanol without any pre-treatment process. Besides that, this study proved that these industrial wastes attractive for other applications such as fermentation processes.

Kamil et al. (2019) assessed and quantified the potential benefits of coffee waste fuels throughout the life cycle. This study showed that coffee biodiesel, during its life time, contributes to a CO_2 emission reduction of 80.5% compared to hydrocarbon diesel. Therefore, coffee biodiesel has significant benefits and potential.

Miito and Banadda (2017) shortly reviewed the coffee husk gasification for sustainable energy in the Uganda region. In this review it is concluded that gasification can convert coffee husks to clean gas fuels for industrial energy generation.

Yadira et al. (2014) developed a methodology for the production of bioethanol from coffee mucilage (CM) which is one of the waste products of the coffee processing industries. In this report it was concluded that the mucilage of the coffee has the potential to produce biofuel.

Kukana and Jakhar (2022) investigated the effects of biodiesel derived from ambadi oil and waste cooking oil on CI engine performance, combustion, and emission characteristics. It was reported that the brake thermal efficiency (BTE) of the engine at full load by using B20 of ambadi oil biodiesel, B20 of waste cooking oil biodiesel, and neat regular diesel were 32.96%, 32.50%, 33.76%, respectively. The results of BTE of both biodiesels were closer to regular diesel. As reported in the study, HC and CO emissions were reduced, and NO_x emission was increase while using this biodiesel and its blends with regular diesel.

Gowthaman and Thangavel (2022) utilized coconut shell oil-diesel blends in the CI engine and investigated the engine's performance, combustion, and emission characteristics. In this experimental investigation, it was reported that the BTE of the engine was slightly reduced while using coconut oil diesel blends compared to BTE of regular diesel. Brake specific fuel consumption (BSFC) increased as the blending volume of the coconut shell oil increased. B20 shows better BSFC and pollutant gas emissions compared to other blends. It was revealed that both pure coconut shell oil and its blend with conventional diesel can be effectively used in CI engines with enhanced thermal efficiency and reduced emissions of harmful pollutants.

Adam et al. (2017) analyzed combustion, performance, and exhaust emissions characteristics of IC engine fuelled with upgraded waste source fuel. In this work, upgraded waste cooking oil showed 14% higher power and 13.8% higher torque than regular diesel. Waste plastic disposal fuel produced the lowest NO_x due to its low-pressure curve during combustion.

Kannan et al. (2020) performed experimental investigations on CI engine's performance and emission characteristics with neem oil biodiesel and its blends instead of diesel fuel. They concluded that CI engine using neam oil biodiesel blend (B20) and diesel (B0) showed nearly similar BTE results.

Machacon et al. (2001) investigated the influence of pure coconut oil as an alternative fuel on the efficiency and emissions of a single-cylinder DI diesel engine. From a performance perspective, it was discovered that the combustion efficiency was reduced due to lower atomization features lower, and poorer mixing, resulting in lower combustion efficiency in the case of neat coconut oil operation. The emission study revealed that virgin coconut oil produced lower smoke and NO_x emissions but more HC and CO emissions. According to the reports, if the same injector is to be utilized, the neat oil's viscosity values should be lowered to match the mean droplet diameter values of diesel spray.

Doğan (2011) conducted an experiment to determine the effect of n-butanol-diesel blends on the performance and emissions of a small CI engine running at a constant speed of 2,600 rpm. It was discovered that the BSFC and BTE increased slightly as the percentage of n-butanol blended in the diesel up surged. As the percentage of n-butanol in fuel blends increased, the exhaust gas temperature decreased, CO, NOx, and smoke were simultaneously reduced, and the percentage of HC emissions increased.

Suresh et al. (2021) investigated a diesel engine's performance and emission characteristics with cardanol-based hybrid biodiesel-diesel blends. As per the results, the brake thermal efficiency of hybrid biodiesel was nearly similar to that of diesel at full load. In this report it was reported that lower emissions of CO, HC except NO_x are encouraging to recognize 5C5H (5% cardanol + 5% Honge oil + 90% diesel) as an optimized fuel blend for a CI engine.

Elkelawy et al. (2021) studied the performance, combustion, and emissions parameter of DI diesel engine fueled with algae biodiesel/diesel/n-pentane blends. In their study, they used 50% algal biodiesel and 50% regular diesel to run the experiment. To enhance the engine performance, n-pentane was used. It was concluded that adding n-pentane to a biodiesel blend significantly improves engine performance, surpassing regular diesel.

Rajasekar et al. (2020) investigated an engine's performance and emission characteristics fueled with biodiesel derived from coconut acid oil. This investigation proved that coconut oil biodiesel could be directly used in diesel engines without any modification. When utilizing these biodiesels, the performance of the engine is somewhat improved while BSFC is increased.

Dubey and Gupta (2016) studied the performance and emission characteristics of a dual fuel-powered single-cylinder diesel engine. According to the findings of this study, the use of Jatropha biodiesel and turpentine oil provided good performance and low emissions except HC.

Wang et al. (2012) conducted an experiment on a four cylinder DI diesel engine using lowest sulphur diesel combined with ethanol, biodiesel, and diglyme to measure the particle matter emissions of engine at a maximum torque speed of 1800 rpm under five engine loads. Results showed that particulate matter (PM) emission reduces as oxygenate concentration in blends increases. Adding ethanol to diesel fuel increases HC, CO, NOx, and NO2 emissions while reducing particle concentration. The addition of diglyme to diesel has the opposite effect of ethanol. Emissions of diesel–biodiesel fall between diesel–ethanol and diesel–diglyme. Various oxygenates exhibit different effects on emissions, particularly on particulate matter reduction efficiency, demonstrating that the physical qualities and chemical structure also affect PM emissions. The addition of diglyme to diesel can concurrently reduce particulate matter and NOx emissions.

An et al. (2013) investigated the performance, combustion, and emission characteristics of the engine by using biodiesel produced from discarded cooking oil. Euro IV 4-stroke diesel engine with a common rail fuel injection system was used to perform the experiments. The impacts of different biodiesel blends (10, 20, 50, and 100%), on engine speed, performance and emissions characteristics were explored. Experiments indicated that engines running at low speeds and under partial load had a considerable impact on the combustion and exhaust emission processes. The BSFC of B10 was the same as diesel; however, there was some better performance under particular engine operating situations and a slight increase in BSFC when compared to B50 blend. When the engine was run at 25% load at 800 and 1200 rpm, the BSFC increased by 42% and 35%, respectively compared to B10. Because of the improved combustion coming from oxygenated biodiesel, the higher thermal efficiency of biofuel was reported at 50 and 100% loads; compared in comparison with 25% load.

Çelik et al. (2017) investigated the impact of the addition of bioethanol in cottonseed and grapeseed biodiesels on performance, combustion, and emission characteristics of a diesel engine. This study proved that the addition of bioethanol into cotton and canola biodiesel reduces the viscosity of the biodiesel and increases the cylinder pressure. In addition, it was concluded that incorporating bioethanol into specified biodiesel reduces the NO_x emission.

Sivalakshmi and Balusamy (2014) investigated the performance, combustion, and emission characteristics of neem oil methyl ester and its diesel blends in a diesel engine. In this study, it was reported that a lower percentage of biodiesel blends (B10 and B20) gave better engine performance and improved engine emissions. Higher percentages of biodiesel blends (B30, B50, and B100) reduced CO, HC, and smoke emissions. In addition to environmental benefits, utilizing neem oil methyl ester as a diesel engine fuel can enhance agricultural economy and minimize the uncertainty of fuel supplies. The results of the experiments also indicated that using neem oil methyl ester in diesel engines is a feasible alternative to regular diesel.

Viswanathan and Thomai (2021) analyzed the performance combustion and emission characteristics of the single-cylinder diesel engine Elaeocarpus Ganitrus (EG) biodiesel blend. In the experiment, it was reported that use of EG biodiesel improved the combustion characteristics of the engine due to the excess amount of oxygen in the biodiesel. It was reported that using B0.5 at 100% load BTE of the engine was increased by 32.23% and the BSFC is reduced by 24.1% compared with regular diesel. The exhaust gas emissions of the engine were improved. Smoke density, CO, HC, were reduced by 11.6%, 50%, 49.15% respectively. It was also reported that NO_x and CO_2 emissions were decreased by 19.14%, and 15.25%, respectively. As a result, it was discovered that the emissions from EG biodiesel are lower than those from standard diesel for all blends.

Shrivastava et al. (2019) evaluated a 4-stroke single cylinder CI engine performance and emission characteristics fueled with roselle and Karanja biodiesel. According to the findings of this study, the use of Karanja biodiesel (20% blend) improved the BTE of the engine by 1.5% under all loading situations. The engine's heat release rate and peak cylinder pressure using biodiesel were lower than normal diesel. It is also reported that the smoke emission of the engine by using Roselle biodiesel (20% blend) was reduced by 15.8%, and it got increased as the load on the engine increased. CO_2 emissions were found to be higher in all blends. NO_x emissions were reduced by 11.2%, 10.4%, 5.6%, 3.69%, 14.2%, and 18.3% for roselle (10% blend), Karanja (10% blend), roselle (20% blend), Karanja (20% blend), roselle (100%), Karanja (100%), respectively compared to diesel.

Raheman and Ghadge (2007) evaluated the engine's performance and emission characteristics using mahua (Madhuca indica) biodiesel as an alternate fuel. This report concluded that as the blending ratio of the biodiesel in the blend (mahua) increases, the BSFC increases, and the BTE reduce. The smoke and CO emissions in the exhaust gas were reduced, whereas the NO_x emission increased as the blending share of the biodiesel increased. Overall, blending the mahua biodiesel up to 20% was recommended as it did not significantly affect the engine performance and emission characteristics.

Adaileh and Alqdah (2012) used biodiesel extracted from a waste cooking oil and measured the performance and emission characteristics of a single-cylinder 4-stroke CI engine. The results indicated that fuel consumption rate, BTE, and exhaust gas temperature was increased. Compared to regular diesel, BSFC for biodiesel increased by 5.95%. When compared to regular diesel, the experimental results indicate that biodiesel significantly reduced CO and HC emissions while increasing NO_x.

Tizvir et al. (2022) investigated the performance and emission characteristics of the engine fuelled with biodiesel fuel produced from Dunaliella tertiolecta microalgae. An internal combustion 4-stroke single-cylinder CI engine was used for the experimentation, and the resulting biodiesel was evaluated as B10 and B20 blends. Their report concluded that CO, HC, and NO_x emissions in all tests decreased by an average of 23.54%, 18.28%, and 6.97% compared to pure diesel, respectively, using B20 CO_2 emission was averagely increased by 5.43% using B20. However, BSFC was increased by 3.46%, and the engine output power was decreased by 2.64%, using B20 fuel. This experimental analysis concluded that the B10 and B20 biofuels derived from Dunaliella tertiolecta microalgae can be successfully employed as an alternative fuel. Singh and Sandhu (2020) studied the performance, emission, and combustion characteristics of a 4-cylinder turbocharged, inter-cooled, common rail direct injection engine using argemone biodiesel-diesel blends. They reported that this biodiesel blends perform better at part load and full load compared to low loading conditions. Using argemone biodiesel diesel blends, the BTE of the engine was improved by 5.58% and specific fuel consumption by 7.88% for B20 at higher load compared to lower load with same blends. Significant reductions in exhaust emissions (excluding NOx) were observed at part load and high load up to 30% blending of argemone biodiesel in diesel. Lower NOx emissions and higher HC and CO emissions were observed at low load for all biodiesel-diesel blends. At all testing conditions except low load, it was concluded that increasing the proportion of biodiesel in diesel up to 30% reduces both HC and CO emissions. On the other hand, NO_x emissions from biodiesel blends are low at low loads and high at larger loads. Due to lower thermal efficiency and higher specific fuel consumption of argemone biodiesel blends in this condition, biodiesel blends have lower maximum cylinder pressure, heat release rate, and rate of pressure rise than diesel at low load.

Das et al. (2018) experimentally studied the performance combustion and emission characteristics of CI engine fuelled with diesel-castor biodiesel blends. This study revealed that the combustion of biodiesel diesel blends starts early than diesel, and the rate of pressure rise is also faster. It is also shown that there was no significant change in the engine BTE, BSFC, and exhaust gas emissions. The engine performance and emission characteristics did not fluctuate much whether diesel or any of the three biodiesel blends (B05, B10, and B20) were used. At maximum load, the BTE of the engine running on fuel blends was somewhat greater than that of diesel. These engine parameters demonstrate that a blend of diesel and 20% castor oil methyl ester may be utilized to run the engine effectively.

Qi et al. (2014) investigated the combustion and emission characteristics of rapeseed oil–diesel blends in a two-cylinder agricultural diesel engine. BSFC and BSEC of rapeseed oil blends were slightly higher compared to regular diesel. The lower blends showed improved starting characteristics at lower loading levels. Peak cylinder pressure and heat release rate were both greater at low engine loads but nearly similar at high engine loads. It was concluded that blending rapeseed oil with diesel reduces fuel viscosity and may be used as alternative biodiesel in diesel fuel up to 20% without engine modification.

Kousoulidou et al. (2010) performed an experimental investigation to study the effect of biodiesel on a latest diesel engine equipped with common-rail fuel system. The combustion parameters were investigated by measuring in-cylinder pressure and net heat release rate (NHRR) during combustion with regular diesel and a 10% blend of palm oil origin biodiesel (PME) and rapeseed oil (RME). Over steady-state tests, hazardous pollutants and fuel economy were measured. There was marginal increase in BSFC when using biodiesel versus normal diesel, which could be due to inefficient ignition timing. NO_x and particulate matter (PM) emissions were completely determined by local conditions, speed, and load capacity.

2.2 Preheating fuel before injection

Different findings proved that preheating the fuel before injecting it into the combustion chamber reduces the viscosity of the fuel. The fuel preheating technique has the advantage of making it simple to convert a standard diesel engine to run on heavier fuels. The engine does not require any modifications. Engines that use fuel preheating have better performance than engines that use unheated fuel.

Ranjit and Chintala (2021) investigated the engine's performance and emission characteristics by preheating deep-fried oil from 60 °C to 130 °C in an direct injection CI engine with a waste heat recovery framework. It was found that preheating to 130°C improves the BTE and reduces BSFC from all other tested fuels. It was also reported that a good pressure rise was noticed at this temperature, which is particularly important in using deep-fried oil as an acceptable alternative for diesel in the short term. As concluded in this report, NO_x was increased with the temperature mentioned above, and CO, HC, and smoke were reduced compared to regular diesel.

Viswanathan and Wang (2021) investigated the application of preheated fish oil ethyl ester in a direct injection diesel engine. Heat energy available in the exhaust gas was trapped and utilized to preheat the fuel before injection. This experimental investigation used three heating temperatures (60 °C, 70 °C, and 80 °C). At a higher preheating temperature (80 °C), the fish oil ethyl ester enhanced engine characteristics. Similarly, it was found that preheating the testing fuel to 80 °C produces less smoke compared to diesel as well as lower preheating temperatures (60 °C and 70 °C). This decrease in smoke emission occurred due to the increased combustion chamber temperature generated by fuel preheating.

Kodate et al. (2021) investigated the engine's performance, combustion, and emission characteristics by preheating Dhupa seed oil biodiesel as a substitute fuel in a single cylinder diesel engine. In this experimental investigation, it was reported that preheating the biodiesel reduces the viscosity of the fuel; it encourages the diffusion characteristics of the fuel during injection and combustion, leading to enhanced performance and combustion of the engine. Preheating the testing fuel to 95 ° reduced CO and HC emissions by 28.08% and 42.7% at 75% load, as concluded in this investigation.

Sivasubramanian and Sajin (2021) investigated the effect of neat biodiesel prior to fuel injection. In their work, cashew nut shell biodiesel was preheated to three different temperatures (70°C, 80°C, and 90°C), and the result was compared with unheated biodiesel and diesel. According to their results, the cashew nut shell biodiesel preheated to 90°C before injection had the lowest emissions of harmful gases. By preheating the fuel, HC, smoke, and CO emissions were reduced by 6.7%, 5.2%, and 8.6%, respectively. This report concluded that preheating the cashew nut shell biodiesel during the fuel injection can be an exceptional way for using it in CI engines.

Reddy et al. (2020) evaluated diesel engines' performance and emission characteristics by preheating castor oil methyl esters (CAOME) biodiesel blends with regular diesel. As reported in this experimental evaluation, maintaining the temperature of CAOME biodiesel at 70 °C by exhaust gas resulted in an increase in thermal efficiency by 7.3% compared to unheated CAOME. This work concluded that using preheated CAOME biodiesel reduces CO, HC, and smoke emissions with slight increase in NO_x emissions.

Praveena et al. (2020) investigated the CI engine's performance and emission characteristics using preheated Azadirachta indica biofuel. Exhaust gas temperature was used to preheat the test fuel. As reported in this experimental investigation, preheating the testing fuel to 80 °C before injecting it into the combustion chamber reduces CO and CH emissions by 23.3 and 19%. The BTE of preheated biodiesel was improved by 5.5% compared to unheated biodiesel used in the experiment.

Mourad and Noureldeen (2019) studied the performance and emission characteristics of a diesel engine fuelled with preheated biodiesel using exhaust waste energy. This study used exhaust gas to preheat the fuel before injecting it into the combustion chamber. A heat exchanger was designed to enhance the biodiesel fuel temperature prior to the combustion process. Under different operating situations, including varying engine loads and speeds, the performance characteristics of diesel engines and the emissions of pollutants caused by this modification were evaluated. The results revealed significant improvements in engine performance, including increased output power, specific fuel consumption, and reduced emissions of pollutant gases except nitrogen oxide. It was reported that preheating the fuel prior to combustion process, the engine power and specific fuel consumption increased by 1.3% and 8.27%, respectively. Carbon monoxide and hydrocarbon emissions were reduced by 12.95 % and 12.85 %, respectively, indicating a significant reduction in pollution emissions. However, nitrogen oxide emissions climbed by 4.39 %.

Gangwar et al. (2019) investigated the engine's performance, exhaust, and combustion-related parameters by utilizing unheated and preheated rice bran methyl ester (RBME). According to the results of this experimental investigation, preheating the testing fuel to 60 °C increased the BTE of the engine from 24.19 - 26.11% at maximum load. Similarly, the BSFC also reduced from 0.3652 kg/kWh to 0.3487kg/kWh for unheated and preheated RBME biodiesel at full load. It was also reported that preheating the RBME to 60 °C before injection reduced HC, CO, and CO_2; however, NO_x emissions increased considerably.

Kumar et al. (2005) investigated the use of preheated animal fat as a fuel in a CI engine. In their report, the effect of inlet temperature on performance, combustion and emission characteristics was evaluated. The fuel was preheated to 30 °C, 40 °C, 50 °C, 60 °C, and 70 °C. It was reported that animal fat has a longer ignition delay and combustion duration than diesel at low temperatures. The ignition delay and duration of burning in preheated animal fat were lowered. At high fuel inlet temperatures, peak pressure and percentage of pressure rise were shown to be as high as animal fat. When compared to regular diesel at standard temperature, the heat release pattern indicated a reduced premixed combustion phase with animal fat. Preheating increased the rate of premixed combustion. Animal fat produced fewer smoke emissions than diesel at low temperatures. When compared to diesel, animal fat emitted more unburned hydrocarbons and carbon monoxide at low temperatures. Preheating the fuel minimized these pollutants. Animal fat emitted as little NO_x as possible at low temperatures. Increased NO_x emissions aroused from fuel preheating. Overall, it was determined that preheated animal fat can be utilized in diesel engines to minimize smoke, hydrocarbon, and carbon monoxide emissions while maintaining engine performance.

Acharya et al. (2014) investigated the performance and emission characteristics of the engine by preheating Karanja oil as a diesel blend. In this investigation, 10 and 20% of Karanja oil were used and preheated before being injected into the combustion chamber. The electric heater was used to preheat the fuel to 120 °C to reduce the viscosity of the fuel. This experimental investigation concluded that preheating the Karanja oil-diesel blend improves the engine's performance and emission characteristics.

Nasim et al. (2013) investigated the performance of the engine by using neat jatropha oil methyl ester by preheating before injection at different temperatures (30 °C to 110 °C). This experimental investigation proved that the BSFC increases as the inlet fuel temperature increases up to 70 °C and starts to reduce up to 90 °C. The maximum fuel consumption value was observed at 110 °C, which might be due to leakages. As it was shown in the result of this research work, the BTE of the engine is increased for jatropha oil methyl ester (JOME). By preheating the inlet fuel, the BTE of JOME reduces except for 90 °C temperature. Based on the results obtained, it can be concluded that preheating at 90°C is sufficient to bring jatropha oil's physical and chemical properties to close to diesel levels, allowing the fuel to be used in diesel engines without modification.

Dinesha P. (2012) investigated performance combustions and emission characteristics on an indirect injection diesel engine using preheated JOME biodiesel as an alternate fuel. An online electronic preheating system was used to heat the fuel to 60, 70, 80, 90, and 100 °C. This experimental investigation reported enhanced performance and emission characteristics were attained with biodiesel preheated to 60 °C and showed increase in BTE over unheated biodiesel at 80% load.

Agarwal et al. (2007) studied the effect of reducing the jatropha oil viscosity by increasing the fuel temperature using waste heat of the exhaust gas and thereby eliminating its effect on the performance and emission characteristics of the engine. They reported that heating Jatropha oil between 90 °C and 100 °C is sufficient to reduce its viscosity to levels comparable to diesel. The viscosity of Jatropha blends (up to 30%) was found to be comparable to diesel. The optimal fuel injection pressure for diesel and preheated Jatropha oil was 200 bar. While running the engine on Jatropha oil (preheated and blended), performance and emission indicators were observed to be remarkably similar to those of mineral diesel at lower blend proportions. However, performance and emissions were found to be slightly lower at higher blend percentages.

Augustine et al. (2012) evaluated a DI diesel engine performance and emission characteristics using preheated cottonseed oil methyl ester (CSOME) biodiesel. This investigation concluded that preheating the CSOME biodiesel reduces its viscosity from 7.75 to 1.8 cSt, which is lower than regular diesel. The reduction of the viscosity improved the combustion process resulting in lower HC, CO, and smoke. As it was concluded in the report, CO emission in the exhaust gas was reduced by 34% by preheating the CSOME to 80 °C. Similarly, HC emission was reduced by 16% at the same temperature compared to unheated CSOME biodiesel.

Chauhan et al. (2010) investigated the performance and emission characteristics of diesel engine using preheated and unheated jatropha oil methyl ester biodiesel. This report concluded that preheating the biodiesel before injection improves the engine performance compared to unheated biodiesel. Exhaust gas emissions such as CO, HC, and smoke opacity were reduced. It was also concluded that preheating the inlet temperature of the biodiesel to 100 °C creates leakage of lubricating oil. The optimum inlet temperature recommended in this investigation was 80°C.

Karabektas et al. (2008) investigated the effect of preheating cotton seed methyl ester biodiesel on diesel engines' performance and emission characteristics. They carried out the investigation on a single-cylinder four-stroke direct injection diesel engine at full load. In this study, the cottonseed oil methyl ester was preheated to four different temperatures, namely 30, 60, 90, and 120 °C. According to the results, preheating cottonseed oil methyl ester to 90 °C has favourable effects on BTE and CO emissions but increases NO_x emissions. In this report, it was concluded that as the preheating temperature rises to 90 °C, the brake power increases slightly. There was a significant decrease in brake power when the cottonseed methyl ester was preheated to 120 °C due to excessive fuel leakage caused by decreased fuel viscosity. The results show that cottonseed methyl ester that was heated up to 90°C can be used in place of diesel fuel without any major changes, but NO_x emissions will be higher.

2.3 Varying injection timing

Belagur and Chitimini (2012)investigated the effects of static injection timing on the performance, combustion, and emissions of a CI engine fueled with honne oil methyl ester. The static injection timing of 23° bTDC was varied to 28° bTDC. The smoke opacity, CO, HC and NOx emissions of oil methyl ester were dropped when the engine operated between static injection timing of 23–28° bTDC, at all loads.

Appavu et al. (2018) portrayed the effects of injection timing on the performance and emission characteristics of the engine fuelled with palm biodiesel and diesel blends. In their experimental investigation, B20 with the addition of cerium oxides of nanoparticles at 30 ppm, 60 ppm, and 90 ppm were used. The injection timing was varied from 19° CA bTDC to 23° CA bTDC. According to this investigation, the engine's performance (BTE and BSFC) was enhanced for fuel blends at advanced injection timing (23° CA bTDC). It is also revealed that by fuelling the engine with upgraded palm biodiesel diesel blends at advanced injection timing, the exhaust gas emissions (CO and HC) are significantly reduced, and NOx emission increased slightly under all working circumstances.

Kumar et al. (2020) investigated the performance combustion and emission characteristics of a diesel engine fuelled with a tamarind seed biodiesel blend. They used a blend of 20% tamarind biodiesel and 80% regular diesel at various injection timings and engine loads. As it was concluded in this study, delaying the injection time by 4° CA bTDC improves the BTE by 3.18% compared to conventional injection timing. It was also concluded that retarding the injection timing reduces the BSFC and significantly reduces exhaust gas emissions.

Reddy et al. (2021) evaluated a diesel engine operated by mango seed biodiesel by altering injection timing and exhaust gas recirculation. In the study, it was reported that advancing the injection timing by 2° CA bTDC improves the BTE of the engine by 4.54%, and exhaust gas emissions were also reduced considerably except NO_x emission. To mitigate the NO_x emissions caused by advancing the injection timing, 5% exhaust gas recirculation was employed.

Babu et al. (2022) evaluated the performance and emission characteristics of a direct injection diesel engine running by acacia biodiesel. This experimental evaluation determined that the engine emits lower emissions when the main injection angle is 15° bTDC and the pilot injection angle is 23° bTDC. The performance of this biodiesel was satisfactory whether single or split injection strategies are employed.

Senthil and Thirumalini (2020) investigated the effect of split and retarded injection timing on diesel engine performance combustion and emission characteristics with cashew nut shell biodiesel blends. The blends, delayed timings, and split injections used were B5 and B10; 2° crank angle (CA) and 4° CA from the existing timing; 5%, 10%, and 15% of the mass of the main injection at 2200 rpm, respectively. In this experimental investigation, NO_x was reduced by 17.8%,11.8%, and 27.5% for diesel, B5, and B10, respectively, at 4° retarded CA with a 10% split compared to base injection timing with a single injection. At 4° retarded CA and 15% split, smoke was reduced by 19.5% for diesel and 73.8% for B5. With split injections and delayed injection timing, it was found that emissions can be reduced without affecting performance for all fuel blends.

Jayaprabakar et al. (2017) conducted an experimental analysis to investigate the effect of injection timing on the combustion characteristics of the engine. It was found that advancing the engine injection timing increases the cylinder pressure and heat release rate, which will directly be related to BTE and BSFC.

Nwafor (2000) investigated the influence of advanced injection timing on the engine performance running with rapeseed oil. The experimental investigation were conducted on a single-cylinder high-speed CI engine that produced 4.8 kW at 3600 rpm utilizing rapeseed oil and diesel as fuel with standard injection timing of 30° bTDC and advanced injection timing of 35.5° bTDC. The experimental results showed that the engine performance was increased at 35.5° bDTC, although it was smooth at low loads.

The study was done with injection timings of 25° CA bTDC (advanced injection timing), 20° CA bTDC (standard injection timing), and 15° CA bTDC (delayed injection timing) by using five different methanol/ethanol-diesel blends under the same operating conditions. An increase in maximum pressure rise, combustion duration, and ignition lag was recorded at advanced injection timings. At 25° CA and 20° CA BTDC, blends exhibited longer ignition delays compared to diesel (Turkcan and Canakci 2011).

Deep et al. (2017) investigated the influence of fuel injection timing and injection pressure on single cylinder CI engine. The engine was fueled with 20% castor biodiesel with regular diesel. The experimental inquiry indicates that advancing and retarding the engine injection timing resulted in a reduction in BTE. The higher cylinder pressure at advanced injection timing did not contribute to increasing the BTE. NOx emission was reduced by a small amount.

Datta and Mandal (2015) conducted an experiment on the effects of injection timing on the performance and emission characteristics of CI engine by using regular diesel and methyl soyate biodiesel. The injection timing was varied by advancing 3° CA and retarding 3° CA from and on, the standard injection timing of the engine. This report showed that by advancing the injection timing, the BSFC increases while the BTE decreases. By delaying the injection timing, the BTE got increased, and the BSFC got decreased.

Arunprasad and Balusamy (2018) investigated the performance and emission characteristics of the engine by altering the injection timing and injection pressure using mixed biodiesel. The report showed that at full load, advancing the injection timing increases the BTE of the engine by 1.5% compared to standard injection timing. Higher injection pressure and advanced injection timing reduced the BSFC by 5.08% at a higher load.

Datla et al. (2021) investigated the performance combustion and emission characteristics of variable geometry turbocharger CI engine using neem biodiesel varying with injection timing. According to the report, by increasing the injection timing, BSFC was significantly decreased, and BTE was improved. Advancing the injection timing by 10° CA bTDC increased the engine's BTE by 13% and reduced BSFC by 21% compared with standard injection timing. It was noticed that the cylinder pressure of the engine increases with advancing the injection timings for both regular diesel and biodiesel diesel blends. Similarly advancing injection timing improves the heat release rate of both tested fuels in the experiment. Furthermore, it was noticed that the emissions of CO and HC were reduced by advancing the injection timing and CO_2 and NO_x emissions got increased.

Indudhar et al. (2019) investigated the impact of split injection on the combustion and emission parameters of a CRDI engine fueled with diesel and honge oil biodiesel at injection pressures of 900 bar and injection timings of 10° bTDC. At optimal operating circumstances, a split injection of Honge oil biodiesel results in a 24 – 27% reduction in NO_x emissions, a reduction in HC emissions, and a small increase in BTE.

Jamuna Rani et al. (2020) assessed the engine performance combustion and emission characteristics with advanced and retarded injection timing, using a single-cylinder CI engine fueled with rice bran and algal biodiesel blends. It is reported in this experimental assessment that advancing the injection timing of the engine by 4° CA bTDC improved BTE, and retarding the injection timing by 4° CA bTDC reduced the BTE of the engine. Cylinder pressure and net heat release rate are also increased for advanced shifting the maximum cylinder pressure angle back by some degree CA and reduced for retarded injection timing forwarding the maximum injection timing angle forward by some degree CA compared to standard injection timing. CO, HC, and smoke opacity are all reduced for advanced injection timing and NO_x emission increased by advancing the injection timing.

Sayin et al. (2009) investigated the effect of injection timing on exhaust emissions of diesel engines by using diesel methanol blends. A single-cylinder, naturally aspirated four-stroke diesel engine was used to conduct the experimental investigation. The tests were conducted for three different injection timings (15 °CA, 20 °CA, and 25 °CA bTDC) at four different engine loads (5 Nm, 10 Nm, 15 Nm, 20 Nm) at 2200 rpm. Their experimental test results showed that BSFC, NO_x, and CO_2 emissions increased as BTE, smoke opacity, CO, and UHC emissions decreased with an increasing amount of methanol in the fuel blend. Compared to original injection timing, at retarded injection timing (15 °CA bTDC), NO_x and CO_2 emissions reduced, whereas smoke opacity, HC, and CO emissions were increased. With the advanced injection timing (25 °CA bTDC), smoke opacity, HC and CO emissions were decreased and NO_x and CO_2 emissions were increased under all test conditions.

2.4 Summary of the literature

The extensive literature assessments indicate that energy demand and supply are out of sync due to population growth and development, and that the fossil fuels upon which all sectors rely will eventually run out. Looking to other sources of energy than fossil fuels is of utmost importance. Biodiesels are some of the renewable energy sources that have been used in the IC engine blending with diesel fuel. Biodiesels are produced from seeds (eatable/non eatable), biomass, and animal fats through transesterification. Due to their lower calorific value, higher density, higher viscosity, and higher flash and fire points, using biodiesel in CI engines result in lower BTE than regular diesel. Researchers are making systematic efforts to enhance the engine performance, combustion, and emission characteristics while using biodiesels from different sources. Several approaches such as fuel preheating, varying injection timing, exhaust emission control, blending the fuel with additives etc. to mitigate the disadvantages of applying biodiesel in CI engines.

2.5 Research gap

Many previous studies (Choi et al. 2012; Miito and Banadda 2017b; Orrego et al. 2018; Tehrani et al. 2015; Wilson et al. 2010) have shown that the coffee waste biomass can be used as a feedstock to produce biofuels. However, reliable references on the extraction of biofuel from coffee waste biomass and its characterization are still inadequate (Sime et al., 2017; Suarez and Beaton, 2003). CH is one of the waste products of the coffee processing industry. This waste is abundantly available in all coffee processing industries and is considered to be a waste product for the sector. A feasibility study on CH for ethanol production was conducted by (Gouvea et al. 2009b). The results showed that the property of CH biomass as a feedstock produces incredible results in biofuel generation. The biochemical conversion method was used to produce biofuel, and the results were encouraging. The extracted biofuel properties were comparable to the ethyl alcohol already in use.

Based on the literature review and summary of the literature detailed above, research gaps are identified.

- Biodiesel produced from edible seeds are recently not economically feasible as the extensive use of edible oils for biodiesel production may lead to food crisis.
- There have been limited studies on the wastes generated in most coffee processing industries and how they influence the environment.
- A limited work has been done on the utilization of coffee waste as a substrate for the production of alternative energy.
- Limited work was done on the production and characterization of biodiesel produced from CH and the effect of utilizing the biodiesel on engine performance, combustion and emission characteristics.
- The effect of fuelling the engine with high temperature fuel before the combustion process needs to be explored more.
- Effect of varying injection timing on performance combustion and emission characteristics of the engine by using CH oil biodiesel-diesel blends are limited.

2.6 Motivation

As coffee-producing industries generate substantial agricultural waste, it can be used as an energy source. For instance, in a coffee bean weighing 0.75 g, approximately 0.36 g, i.e., 50% is removed as waste from its total weight (Gouvea et al. 2009a). These wastes are abundantly available in all coffee processing companies. They also contribute to environmental pollution when coffee wastes get discarded indiscriminately on the land throughout the summer, they run into rivers, causing pollution by altering the quality of the waterways. Furthermore, it emits a terrible odor across the coffee industry region. Chemical pollutants are widespread in wastewater from these industries. When it is inadvertently discharged into rivers and streams, it also causes greater harm to local water systems, human health, and marine life. Therefore producing useful energy from this waste is of utmost importance. There have been limited studies on the wastes generated in most coffee processing industries and how they influence the environment.

Recent research focuses on spent coffee grounds (SCG) and CH. A massive amount of CH residue is available in the coffee processing industry. Only a few studies find evidence of the utilization of this biomass as an alternative source of energy (Choi et al. 2012b; Sime et al. 2017; Summers et al. 2014).

2.7 Contribution

The caffeine chemicals in the waste have an adverse effect on the environment including inhibition of seeds, autotoxic effects in plants, and toxicity to insects and bacteria. Therefore, changing this coffee waste into a useful form of energy is the best way to reduce environmental pollution and upgrade the profitability of the coffee processing industries (Merete et al. 2014).

The present work focuses on extracting oil from the CH and converting it into biodiesel, i.e., coffee husk oil methyl ester (CHOME). It is a novel biofuel generated from coffee waste and is not yet in use. Produced biodiesel is characterized in the laboratory to obtain various properties. After characterization, the CHOME biodiesel is blended with regular diesel, and fundamental properties such as viscosity, density, flash point, and fire points are tested for all blends before fuelling in a single-cylinder direct injection diesel engine. The engine combustion, performance, and emission characteristics are carried out with various blending ratios of B10, B20, B30, B40, B50, and B80 at different engine loading conditions. The blending ratio was started with 10% CHOME biodiesel and continued until 80% by investigating the effect of the blend on engine performance, combustion and emission characteristics. The results are comprehensively analyzed and compared for a single-cylinder four-stroke direct injection diesel engine without modification.

2.8 Objectives of the present work

- To extract the oil from CH to produce biodiesel through transesterification, and to carry out the characterization of obtained biodiesel.

- To investigate the effect of CHOME biodiesel-diesel blends on engine performance, combustion, and emission characteristics at different engine loading conditions.
- To investigate the effect of preheating the fuel on performance combustion and emission characteristics of a CI engine using CH oil biodiesel-diesel blends.
- To investigate the effect of varying injection timing on performance, combustion, and emission characteristics of CI engine fuelled with CHOME biodiesel.

CHAPTER 3

EXTRACTION AND CHARACTERIZATION OF COFFEE HUSK BIODIESEL

This chapter focuses on investigating the compositional elements of CH and SCG biomass and the production of alternate fuel to be used in IC engines. The oil is extracted from the CH and then the biodiesel is produced. The physicochemical properties of the biodiesel produced have been tested for the feasibility of the fuel to be utilized in IC engines.

3.1 Experimental set up and methodology

An ultra-high-resolution image scanning Gemini 300 Field Emission Gun Scanning Electron Microscope (FEG-SEM) is used to determine the constituents of the coffee wastes (CH and SCG). The element and composition of the sample are determined using a 20 kV acceleration voltage, a working distance of 1 m, resolution of (eV)127.3, and magnification of (eV)127.3.

The coffee wastes, such as CH and SCG, are collected from NKG India Coffee Pvt. Ltd., Hassan, India, and coffee brewing shops in Mangalore, India. Initially, the coffee husk collected from the coffee processing industry is cleaned with water to eliminate unwanted components, dried at room temperature in a laboratory, and left for three days. Then, the particle size is reduced by crushing, and it is prepared for elemental analysis. The conversion of raw CH to CH powder is shown in

. The SCG collected from the coffee brewing shops was dried and cleaned to eliminate the undesirable particles. Finally, the bigger particles were removed by the process of sieving.

Fig. 3.1 Conversion of CH to CH powder

3.2 Results and discussion

3.2.1 The elemental analysis of CH

This section discusses the compositional analysis of the coffee wastes using FEG-SEM. Fig. 3.2 and Fig. 3.3 portray the morphology of the sample illustrated by electro-microscopic micrographs, the selected area of the sample. Table 3.1 illustrates carbon, oxygen, potassium, and calcium compositional percentages of CH. Fig. 3.2(a) shows CH FEG-SEM at a magnification power of 40kx, and Fig. 3.2(b) shows a magnification power of 7.8kx.

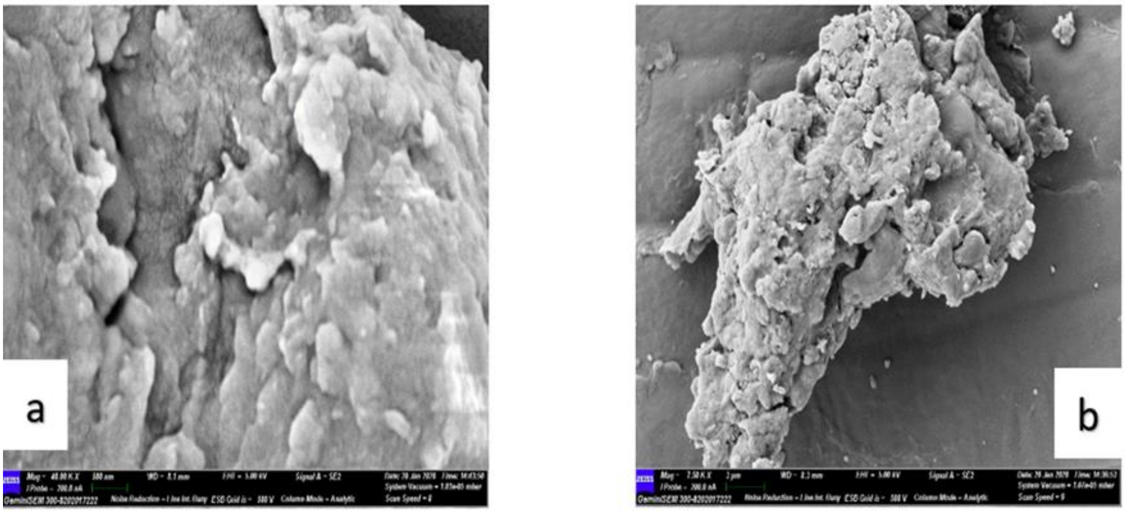


Fig. 3.2 Scanning electron micrographs (scale bar 20 μm) of the CH sample

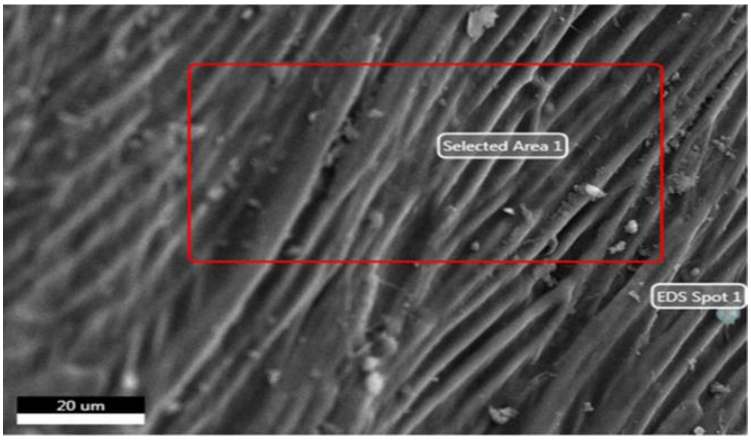


Fig. 3.3 FEG-SEM image of CH at scale bar of 20 μm

Table 3.1 eZAF Smart Quant Results of CH

Element	Weight %	Atomic %	Error %
C	49.84	57.48	7.09
O	48.06	41.61	6.58
K	4.46	1.65	2.05
Ca	1.85	0.67	3.14
S	0.68	0.31	3.88

From Table 3.1, the overall concentration of oxygen and carbon is 48.06% and 49.84% by weight, respectively. This leads to the conclusion that CH contains a higher concentration of oxygen and carbon than other elements available in the waste. These elements are the base elements for the production of biofuels since diesel is a long chain of carbon and hydrogen. The electron micrographs (scale bar 20 μm) of the CH sample for surface topography and structure are shown in Fig. 3.3.

Fig. 3.4 demonstrates the chemical compositions, distributions of the elements and their percentages. The carbon and oxygen elements are the focus of the present investigation.

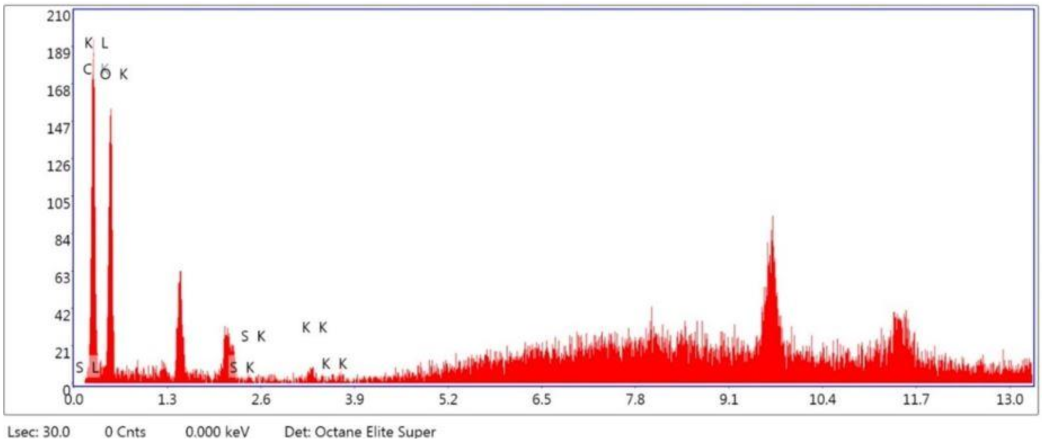


Fig. 3.4 Compositional elements and their distribution in the CH

The distribution of carbon and oxygen is in a higher ratio compared to the other elements, along with a small amount of sulfur.

3.2.2 The elemental analysis of SCG

The compositional percentage of carbon, oxygen, potassium, and calcium are shown in Table 3.2 and Fig. 3.5 shows the selected area of the investigation for the composition and distribution of the elements chosen for this study.

The elemental concentration of the biomass is investigated by applying different magnifying powers of the instrument. Fig. 3.6(a) depicts SCG FEG-SEM at a magnification power of 6.53 kx, while Fig. 3.6(b) depicts it at a magnification power of 1.09 kx.

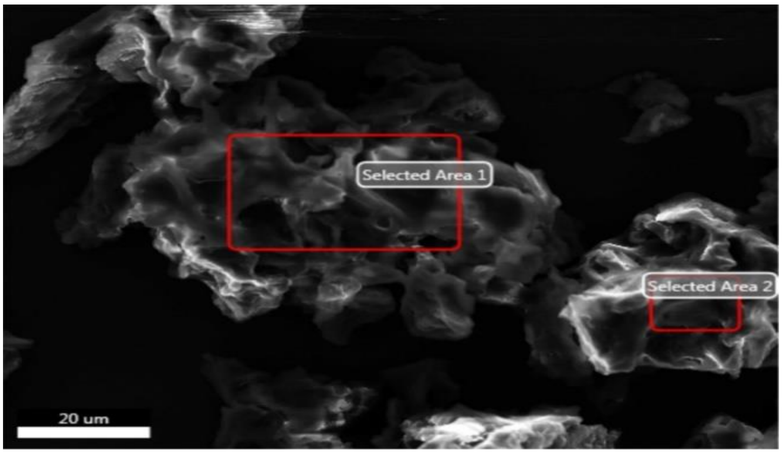


Fig. 3.5 FEG-SEM image of SCG at scale bar of 20 µm

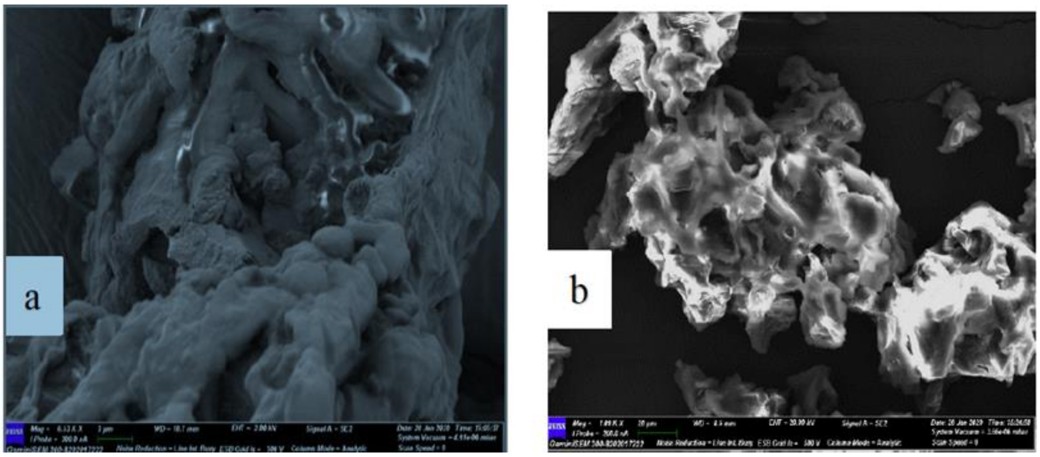


Fig. 3.6 Electron micrographs of the SCG sample

Table 3.2 eZAF Smart Quant Results of SCG

Element	Weight %	Atomic %	Error %
C	67.72	76.54	10.80
O	26.18	22.21	11.37
K	1.54	0.53	6.39
Ca	0.22	0.08	31.63
S	2.61	1.14	4.40

From the total weight of the sample, the compositional distribution of carbon and oxygen were 67.72% and 26.18%, respectively. These values were found to be much higher than the composition of the rest of the elements. From Fig. 3.7, it can be determined that the sample's chemical composition contained more carbon and oxygen as obtained through the FEG-SEM study. The FEG-SEM analytical results of carbon and oxygen were found to agree with their corresponding anticipated molar ratios within the limits of the experimental error, as indicated in Table 3.2

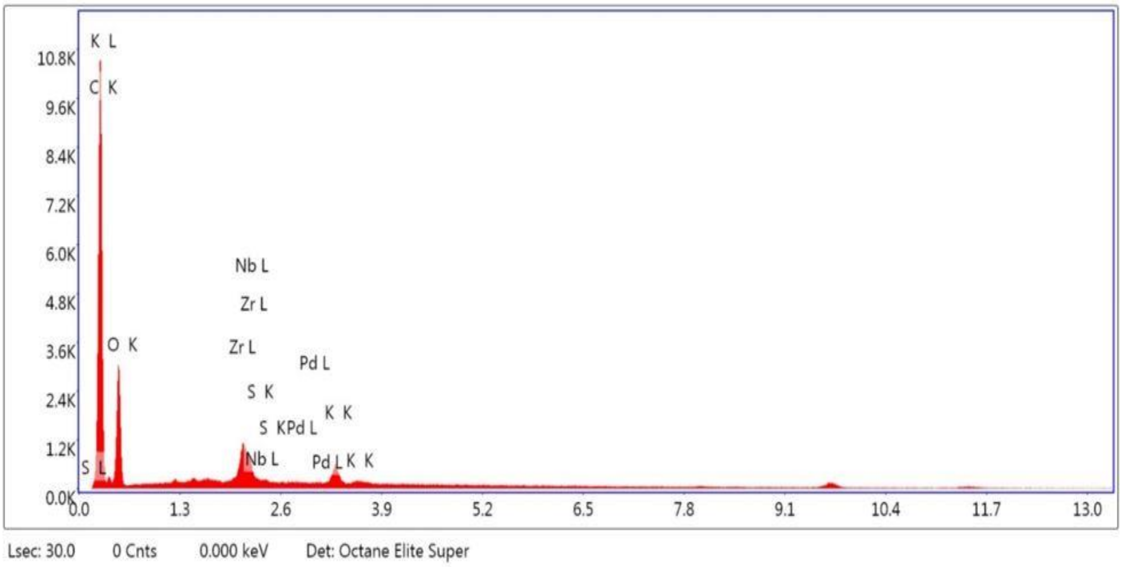


Fig. 3.7 Composition and distribution of elements in an SCG

3.3 Production of oil from CH

The CH contains high carbon and oxygen and can be used as a base element for biofuel production. A screw-type expeller press machine is used to extract oil from CH. For lubricating the screw during the oil production process, the CH powder is mixed with 10% defective coffee bean oil. Fig. 3.8 shows the flow chart of oil and biodiesel production steps from CH.

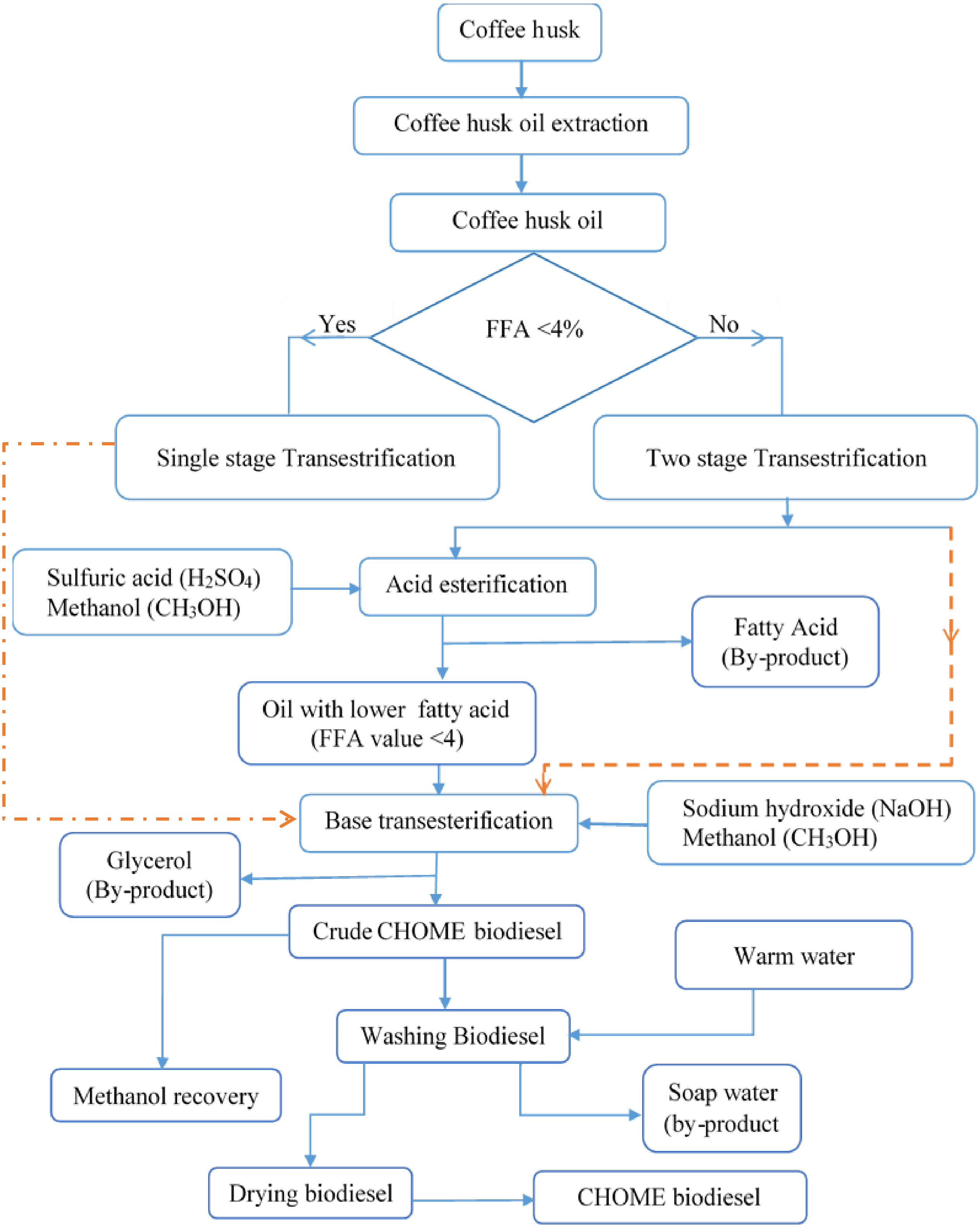


Fig. 3.8 Biodiesel production flow chart

The photographic views of the CH powder oil production setups and extraction are shown in Fig. 3.9. The oil production yield of the sample is ~25%, as 250 grams of oil was produced from 1 kg of CH.

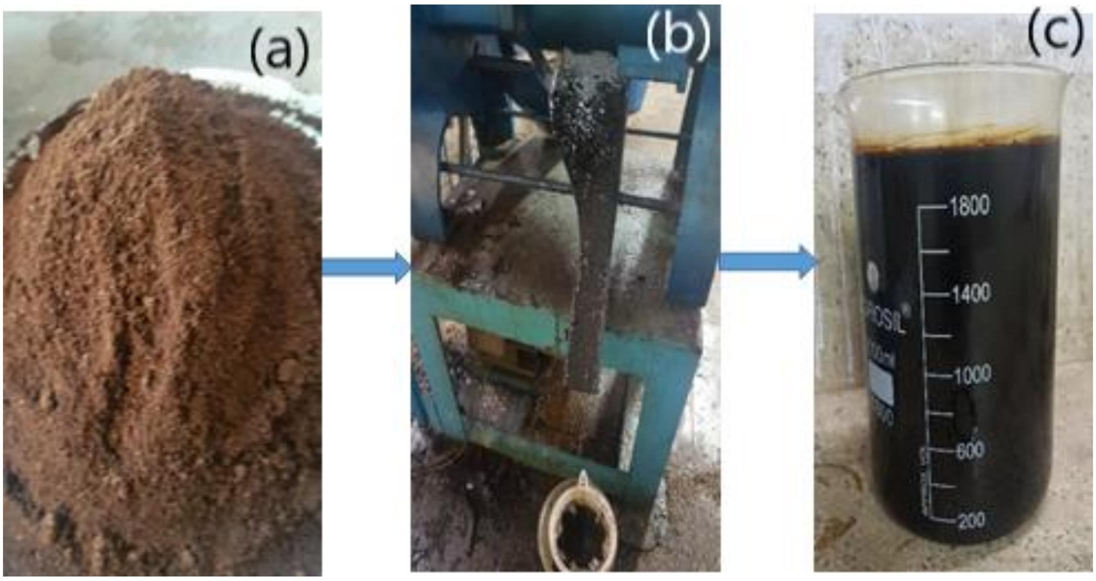


Fig. 3.9 CH oil extraction (a) crushed CH, (b) oil production and (c) CH oil

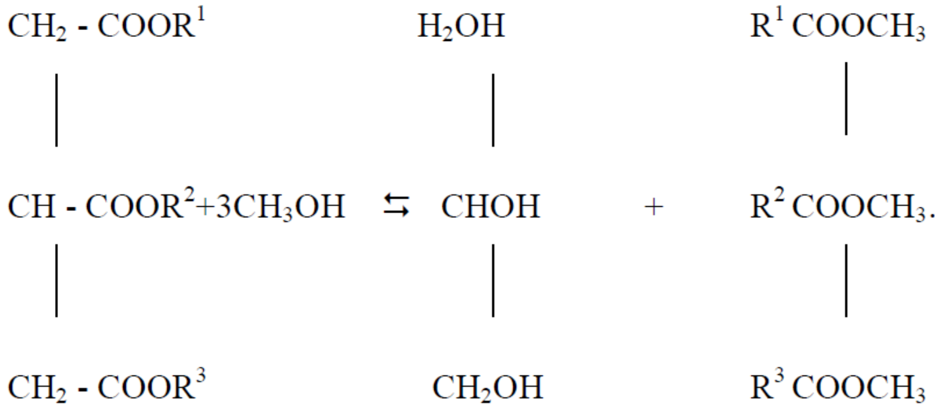
CH oil is converted into CH oil methyl ester (CHOME) through the transesterification mechanism. It is a process by which oil breaks down into esters and glycerol in the presence of alcohol and a catalyst. The transesterification parameters can be different based on the quality and type of the oil, particularly its free fatty acid (FFA) concentration.

3.4 Biofuel production

Biofuels are a broad category of fuels derived from eatable or non-eatable seeds, animal fats, and biomass and are gaining increased public and scientific interest and concern due to fossil fuels' contribution to greenhouse gas emissions. There are various types of biofuels, with bioethanol (which is used to partially or completely replace gasoline) and biodiesel being the most important.

3.5 Biodiesel production

According to (Freedman et al. 1986), biodiesel is produced via transesterification of vegetable oil or animal fat feedstock. There are various forms of transesterification procedures, such as batch processes, supercritical processes, ultrasonic methods, and even microwave processes. Biodiesel that has been transesterified is a combination of mono-alkyl esters of long-chain fatty acids. In most of the transesterification processes, methanol (converted to sodium methoxide) is used to make methyl esters (commonly known as Fatty Acid Methyl Ester-FAME) or ethanol to produce ethyl ester (commonly known as Fatty Acid Ethyl Ester - FAEE). Using alcohols with a higher molecular weight makes the resultant ester flow better at low temperatures. Since the reaction is reversible, excess methanol is required to reduce the activation energy, thereby shifting the equilibrium to the product side. The triglycerides present in the vegetable oil are converted into alkyl esters (biodiesel). Fig. 3.10 indicates the reaction equation of the transesterification process used to convert oil to biodiesel in the presence of methanol and catalyst. The presence of a Catalyst (Strong acid or base) Accelerates the conversion (Murugesan et al. 2009)



Vegetable oil + Alcohol ⇄ Glycerol + methyl ester

Fig. 3.10 Reaction equation of the transesterification process

Transesterification produces biodiesel with considerably lower viscosity, allowing it to be used in diesel engines instead of petroleum diesel. Prior to the discovery of the transesterification process, the viscosity of vegetable oil prevented its use as a fuel due to its poor combustibility. Glycerin, the result of the chemical reaction that has been separated during transesterification is released. Depending on its phase, glycerin will either sink to the bottom of the reaction vessel or rise to the surface. It may be separated readily by centrifugation. Thus, nothing is wasted during the transesterification process; the products and by-products are employed for various purposes.

The CH oil is converted to the desired ester by lipid transesterification. The FFA in the oil should be either removed or esterified in the presence of an acidic catalyst; otherwise, it would impair the methanolysis by soap formation. After this processing, the resulting biodiesel has combustion properties very similar to those of petroleum diesel and can be substituted in most current uses. The first step in producing biodiesel is to determine the FFA value of the oil. In this work, the FFA value of the CH oil is determined as discussed below.

3.5.1 Determination of FFA value

The CH oil needs to be titrated over a 0.1N solution of NaOH to ascertain the FFA value. A 50mL of isopropyl alcohol and 10 grams of raw oil were taken in a clean 250mL flask and agitated well to make the solution mix to find out the FFA value of CH oil. The solution is heated to 65℃ to enhance the reaction of the solution. When the temperature reaches 65°C, the solution is removed from the heating plate and allowed to cool until it reaches room temperature. Few droplets (3 - 4) of phenolphthalein color indicator are added to the mixture for color changes. The mixed solution is then titrated on 0.1N NaOH solution until the color of the solution changes (usually to faint pink). Fig. 3.11(a) shows the oil sample, isopropyl alcohol, and the phenolphthalein solution ready for titration, and Fig. 3.11(b) shows the titrated and color changed solution at the end of the titration process.

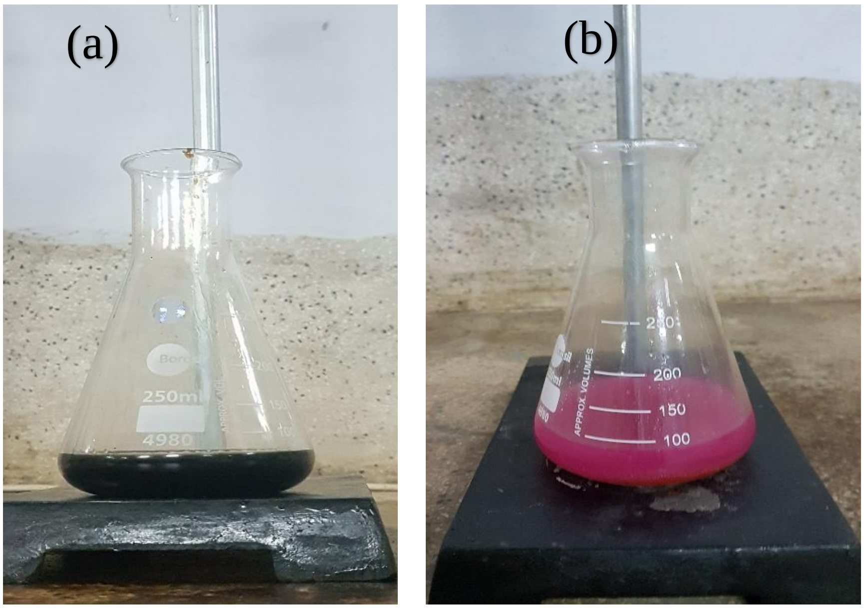


Fig. 3.11 Titration process (a) oil and isopropyl alcohol solution, (b) solution color changes after titration

The titration value is the point at which the color of the solution changes and the volume of the 0.1N solution consumed. The FFA value was calculated as per ASTM D5555-95, by equation (3.1) (Dwivedi and Sharma 2016; Rukunudin et al. 1998).

$$\%\text{FFA Content} = \frac{28.2 \times \text{ Normality of NaOH} \times \text{ titration volume (mL)}}{\text{Weight of oil (g)}} \tag{3.1}$$

The FFA value of coffee husk oil (CHO) is than 4% which indicates the produced CH oil contains a higher concentration of FFA and hence, a two-step transesterification process (acid esterification and base transesterification) is followed for the production of the biodiesel (Hamdan 2018; Kodate et al. 2021).

3.5.2 Acid esterification

At the beginning of this process, 1000 mL of oil is poured into a three-neck round bottom flask of volume 2000 mL. Then, the flask is placed on a magnetic stirrer with a heater. And then, the oil is heated to 60 °C to remove any residues of water molecules in the oil. After the oil temperature reached 64 °C, 150 mL of methanol is mixed with sulfuric acid (H_2SO_4) of 25% of FFA (i.e., FFA × 0.25 mL) and poured into the heated oil. Next, the mixture is heated to a constant temperature of 62 ± 2 °C and stirred continuously for a duration of two hours at 700 rpm, as depicted in Figure 3.12a. After that, the power is turned off, and the condenser is also disconnected. Later, the solution is transferred into a separating funnel with a capacity of 2000 mL. Then, the solution is kept in the separating funnel for a span of three hours. Later, two distinct layers, the acid layer and the diglyceride layer are formed. The acid layer formed on top as a black layer, and the diglyceride settled at the bottom of the funnel, as seen in Fig 3.12b. Finally, the diglyceride is removed, and the FFA value of the oil is checked for the second time. The FFA value is found to be 8.2 %; therefore, the acid esterification process is done for the second time. After the second esterification, the FFA value is found to be reduced to less than 4%.

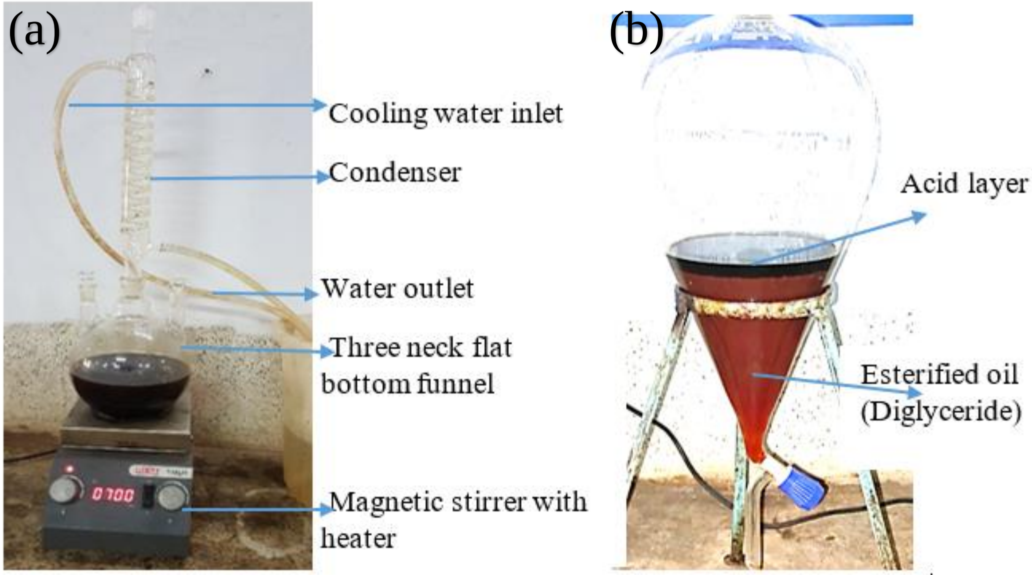
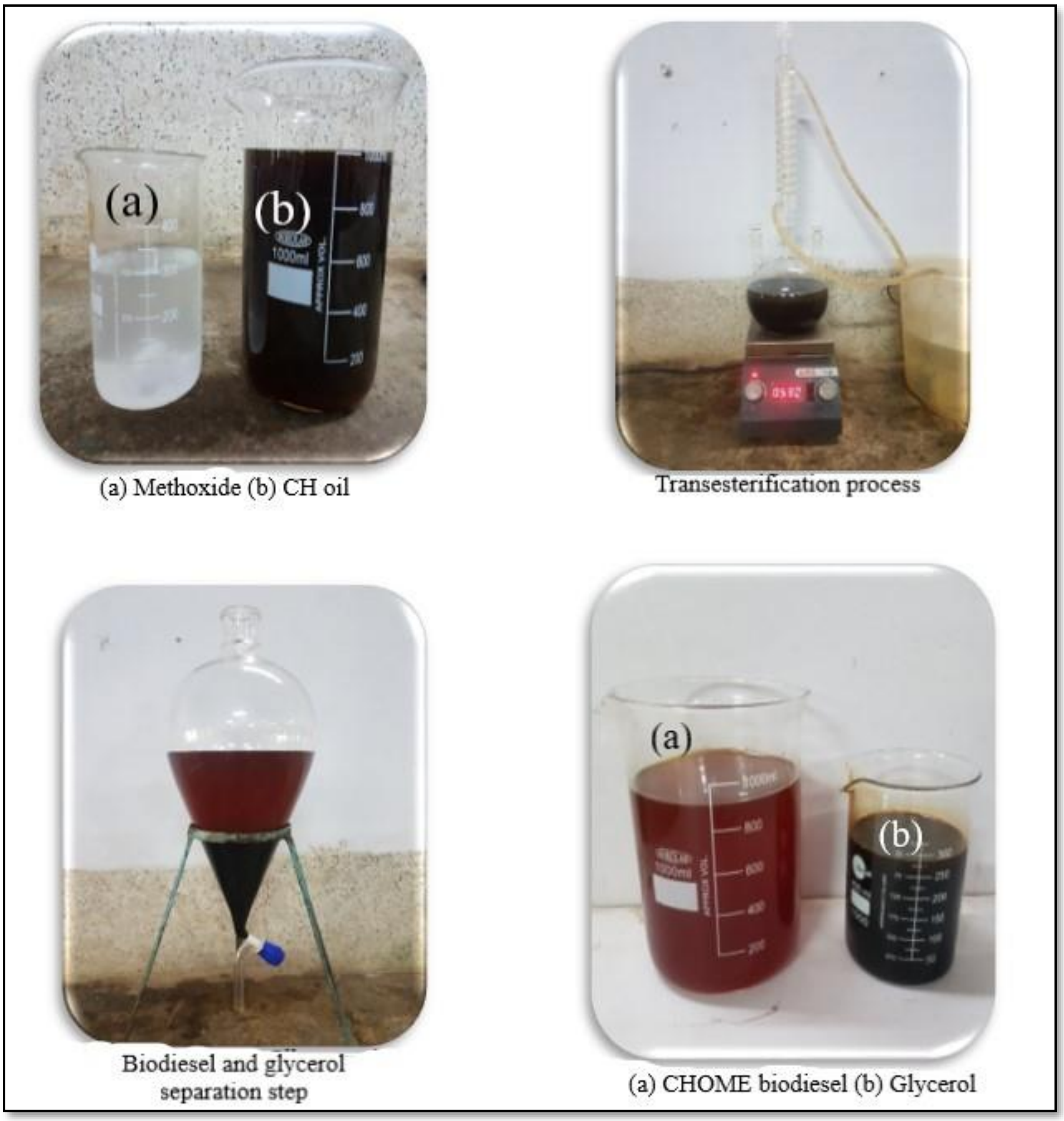


Fig. 3.12 Biodiesel production (acid esterification) (a) Transesterification setup (b) acid layer and diglyceride separation

As a result, the acid esterification process is repeated for the second time. The FFA value of the oil was dropped to less than 4% after the second esterification, and then the base transesterification process began at this stage.

3.5.3 Base transesterification

Diglyceride generated from one liter of CH oil is transferred to a 2000 mL 3-neck flat round-bottom flask reactor and heated to 64 °C. In the meantime, a methoxide mixture was prepared as per the new FFA value of the diglyceride. (3.5 + FFA) grams of sodium hydroxide (NaOH) pellet is dissolved in 300 mL of methanol to produce the methoxide solution. The methoxide solution is transferred to the heating oil as the oil temperature reached 64 °C. Then the temperature of the produced solution is kept at 64 °C, stirring continuously at 700 rpm for two hours to get a homogeneous mixture. After two hours of continuous heating and stirring, the mixture is poured into a separating funnel and kept there for another two hours. As shown in Fig. 3.13 (separation step), the glycerol is separated at the bottom of the flask as black, and the methyl ester biodiesel was separated at the top layer. 300 mL of glycerol is drained and kept separately. Finally, CH oil is changed to CH oil methyl ester (CHOME) biodiesel through transesterification process.



(a) Methoxide (b) CH oil

Transesterification process

Biodiesel and glycerol separation step

(a) CHOME biodiesel (b) Glycerol

Fig. 3.13 Biodiesel production process (base transesterification)

The CHOME biodiesel is poured into a washing funnel to remove residual glycerol impurities. Warm water 300 mL (30% of biodiesel) is poured slowly into the biodiesel in the washing funnel. The solution is allowed to settle for 15 minutes, during which soap water forms at the bottom and biodiesel forms at the top. The soap water is drained and kept in a separate container. The process is continued until the pH of the water reaches 7. After washing, the biodiesel is placed in a 1000 mL beaker and dried to remove any remaining moisture. Fig. 3.14 shows the final washing and drying process of biodiesel.

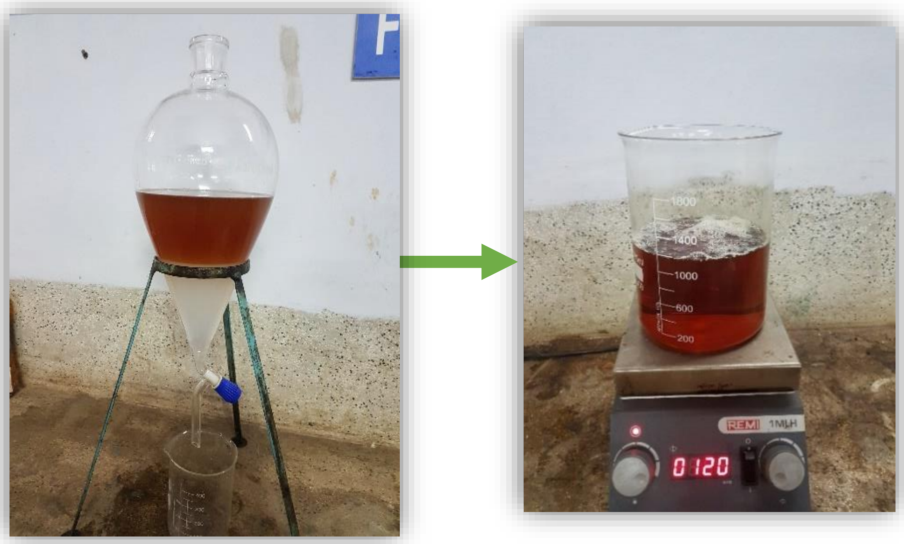


Fig. 3.14 Washing and drying of biodiesel

3.5.4 Characterization of the produced fuel

The fundamental physiochemical parameters of CHOME biodiesel and its blends with regular diesel are tested in the laboratory following ASTM standards. A hydrometer, redwood viscometer, bomb calorimeter, and Cleveland flash point testers are used to determine the density, viscosity, calorific value, flash point, and fire point of CHOME biodiesel and biodiesel-diesel blends, respectively.

The redwood viscometer consists of a vertical oil tube of 3 cm in diameter and 11 cm deep, with a 0.1765 cm orifice in the center of the bottom. Because timing uncertainty may affect the findings of the measured value throughout the experiment, ±5 seconds is used as a tolerance. A bomb calorimeter is used to measure the calorific value of the fuel following the ASTM D240 procedures stated for the instruments. Cleveland flash point tester is to assess flash and fire points of the biodiesel following ASTM D92 standard test method procedures. The instrument measures temperatures up to 400°C with a ±2-5°C tolerance. Table 3.3 illustrates the basic physicochemical properties of biodiesel-diesel blends using regular diesel as a baseline, along with the permissible values to be used as engine fuel.

The primary difference between using CHOME biodiesel and regular diesel is that CHOME biodiesel has a higher viscosity, which might affect engine components by generating a larger carbon deposit. Furthermore, owing to the presence of chemically bonded oxygen, the calorific value of CHOME biodiesel is lower than that of regular diesel. However, the volumetric energy content is not significantly lower than diesel due to higher density. CHOME biodiesel's higher flash and fire point helps to handle and store safely and prevents self-ignition if in contact with flame. In general, the higher flash point and the comparable calorific value of CHOME biodiesel at lower blends with regular diesel promote their usage in CI engines without significant engine modifications. As it is presented in Table 3.3 the produced biodiesel shows comparable physicochemical property with that of regular diesel.

Table 3.3 Physicochemical properties of CHOME biodiesel and regular diesel

Property	Unit	Measuring method	Limit	Regular Diesel	B10	B30	B50	B80	B100
Density @31 °C	kg m^{-3}	ASTM D4052	860- 900	812	818	823	832	836	863
Viscosity@31℃	cSt	ASTM D445	1.9–6.0	2.3	3.2	3.9	4.2	4.7	4.85
Flashpoint	°C	ASTM D92	≥130	68	80	82	82	98	151
Fire point	°C	ASTM D92	-	74	86	88	90	102	158
Calorific value	MJ kg^{-1}	ASTM D240	39 - 40	42.4	41.43	40.3	39.8	38.79	33.51

3.5.5 Fourier-transform infrared (FTIR) spectroscopy analysis

The chemical structure of CHOME biodiesel is examined using Bruker series FTIR, as indicated in Fig. 3.15. To compare the CHOME biodiesel results with those of regular diesel, the chemical structure of regular diesel was also examined as shown in Fig. 3.16. This method detects the chemical bonds present in a molecule by producing an infrared absorption spectrum for distinct functional groups of compounds. It comprises absorption bonds with different peaks in the range of 4000 - 400 cm^{-1}. Covalent bonding can stretch and flex during the interactions of infrared light and CHOME biodiesel due to over-excitation within a particular spectrum of wavelengths (Nandiyanto et al., 2019)

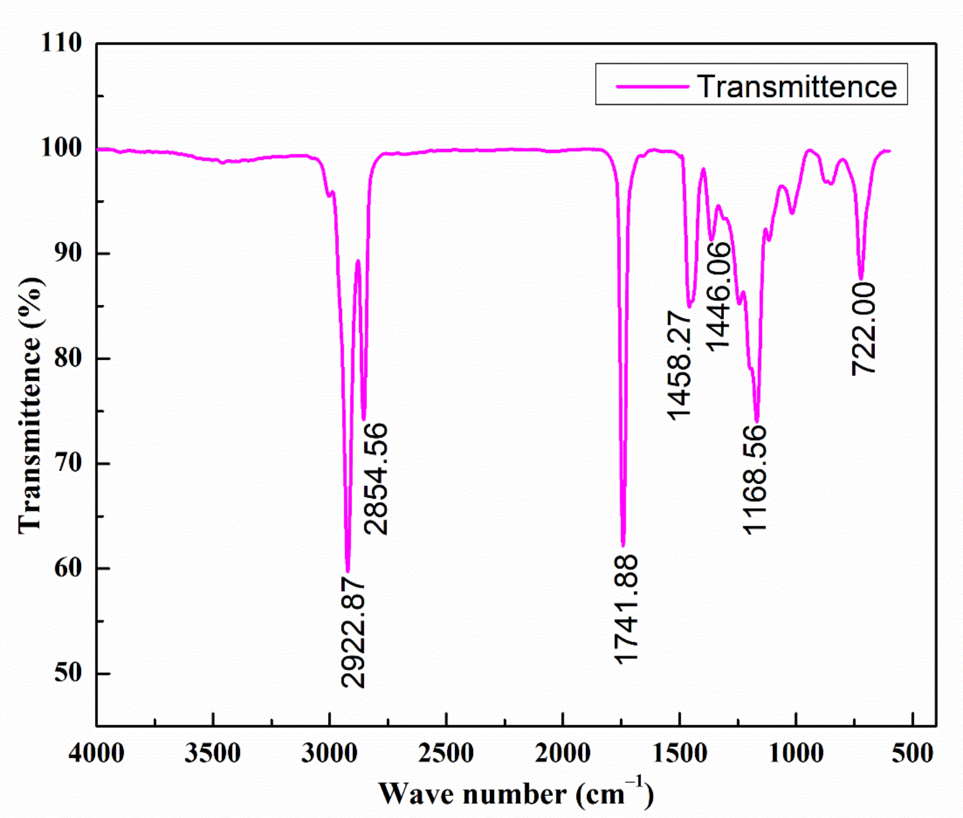


Fig. 3.15 Spectroscopy spectrum of CHOME biodiesel

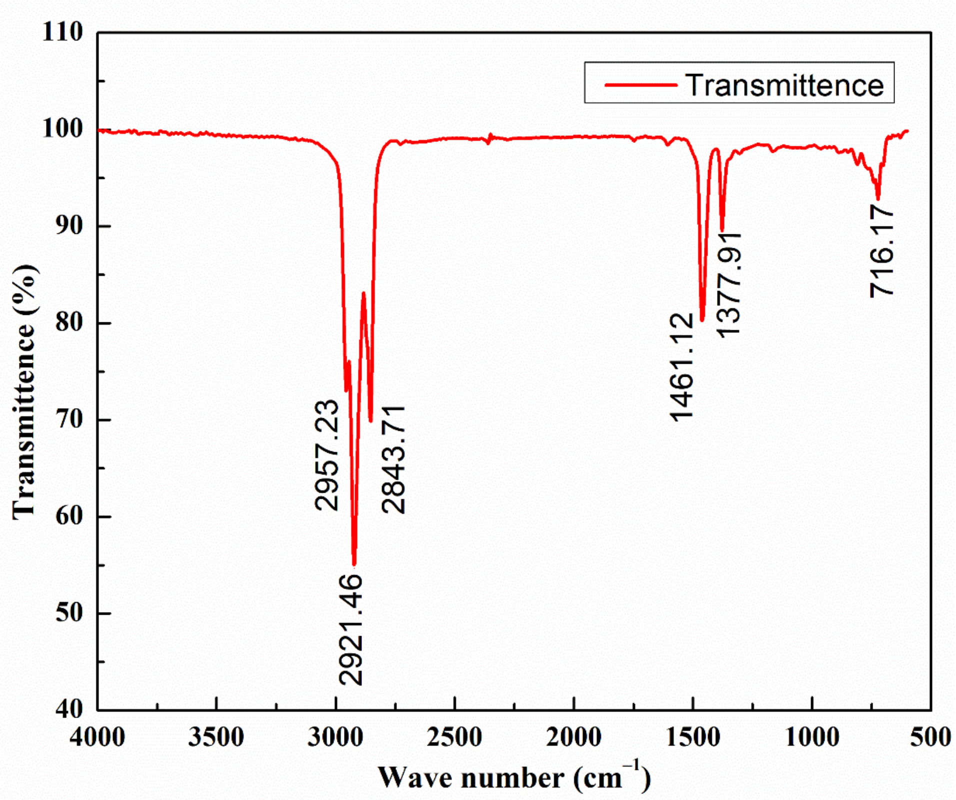


Fig. 3.16 Spectroscopy spectrum of regular diesel

The FTIR spectra of CHOME biodiesel, as shown in Fig. 3.15, reveal that the conversion of CH oil to CHOME biodiesel is successful. The CH stretches in the CH_2, and CH_3 groups of compounds are shown by peaks at 2922.87 cm^{-1} and 2854.56 cm^{-1}. Ester groups have a peak at 1741.88 cm^{-1} and 1168.56 cm^{-1}, the methyl (– CH_3) stretch peaks at 1458.27 cm^{-1}, and the alkene group (C-H) bend and $(CH_2)n$ overlaying rocking vibrations have peaks at 1446.06 and 722.00 cm^{-1}, respectively. The presence of two groups in biodiesel, i.e., methyl (CH_3) and ester (C–O), concluded that the addition of methanol caused the transesterification of CH oil and formed biodiesel. Table 3.4 shows the functional groups found in CHOME biodiesel.

Table 3.4 FTIR analysis of CHOME biodiesel

Functional group	**Assignment**	**Wavenumber (cm^{-1})**
Alkenes	C-H Stretch	2922.87
Alkenes	C-H Stretch	2854.56
Ester	C=O Stretch	1741.88
Methyl	– CH_3 Stretch	1458.27
Alkenes	C-H bend	1446.06
Ester	C-O Stretch	1168.56
Alkenes	-$(CH_2)n$ - Rocking	722.00

3.5.6 CHOME biodiesel stability tests

Several factors impact biodiesel durability, including storage setup, storage length, air exposure, sunshine, and heat. The quality of biodiesel degrades with the formation of oxidized compounds (Christensen and McCormick, 2014; Rashed et al., 2015; Yang et al., 2013). The storage stability of CHOME biodiesel was investigated in this experiment using the ASTM D6751 procedures. The produced CHOME biodiesel is blended with diesel, and stability is tested by storing blends for a month. As illustrated in Figs. 3.17 and 3.18, CHOME biodiesel and its blends did not gel, crystallize, separate, stabilize, or change color after 30 days, implying that the newly produced biodiesel has no stability issues.

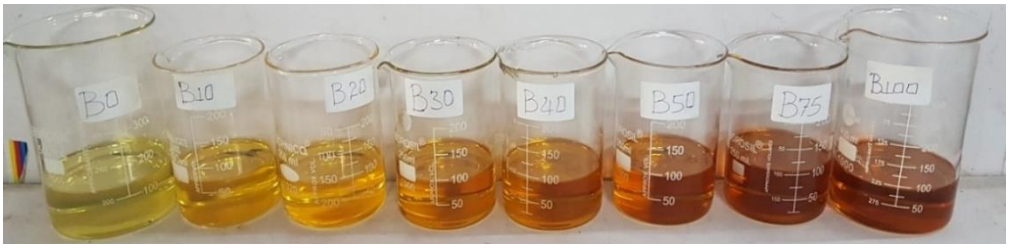


Fig. 3.17 Diesel and CHOME biodiesel blends at 0 hour

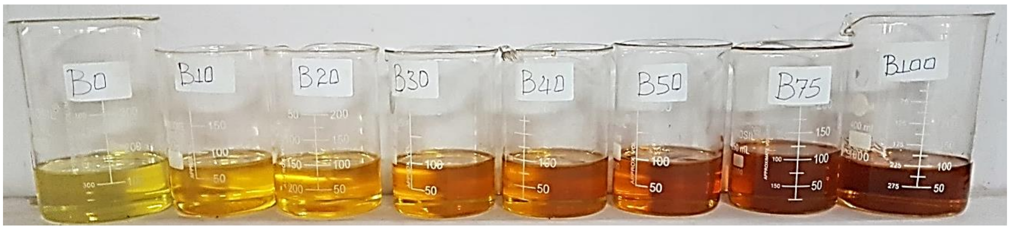


Fig. 3.18 Diesel and CHOME biodiesel blends after 30 days

3.6 Conclusions

In this chapter, the elemental composition and their distribution are analyzed for CH and SCG. CH is used to produce biodiesel that can be used as an alternate fuel in a CI engine, blending with regular diesel. The following findings were drawn based on the results of this investigation. The concentrations of carbon and oxygen in CH are 49.8% and 48%, whereas in SCG the concentrations are 67.7% and 26.2%, respectively.

- The concentrations of carbon and oxygen in CH are 49.8% and 48%, whereas in SCG the concentrations are 67.7% and 26.2%, respectively.
- The oxygen distribution of the CH was nearly equal to that of the carbon. Nevertheless, in the SCG, the oxygen distribution was less. It was mainly due to the roasting process since the SCG is a waste product of the coffee after the brewing process.
- The physicochemical properties of the produced CHOME biodiesel showed that it could be used as an alternate fuel in CI engines blending with regular diesel at different blending ratios.
- By blending the newly discovered CHOME biodiesel with regular diesel, at different blending ratios, the viscosity and fire point of the biodiesel is reduced, and the calorific value is also improved. This makes the CHOME biodiesel blends be used as an alternate fuel in CI engine without major modification.

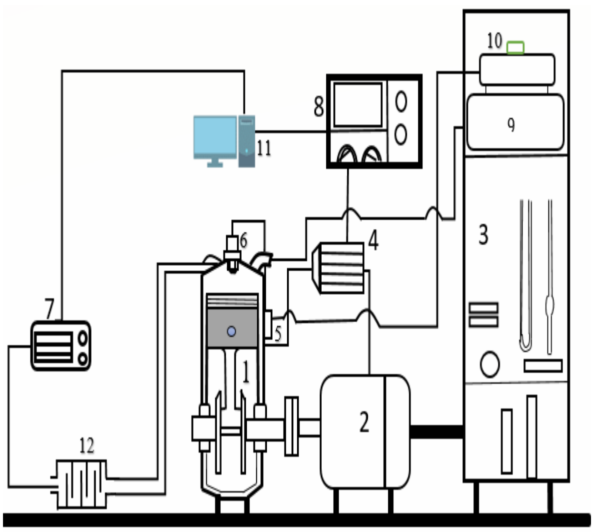
CHAPTER 4

EFFECT OF CHOME BIODIESEL–DIESEL BLENDS ON THE PERFORMANCE, COMBUSTION, AND EMISSION CHARACTERISTICS OF THE ENGINE

This chapter deals with the effect of CHOME biodiesel diesel blends (B10-B80) on the performance, combustion, and emissions of a single-cylinder direct-injection Kirloskar diesel engine. The main objective of this experiment is to evaluate the feasibility of the produced biodiesel to be used in CI engines. The biodiesel is blended with regular diesel starting from B10 (10% of biodiesel with 90% regular diesel). Blends are continued to 80%, and all measurements are recorded and compared with regular diesel.

4.1 Experimental setup and methodology

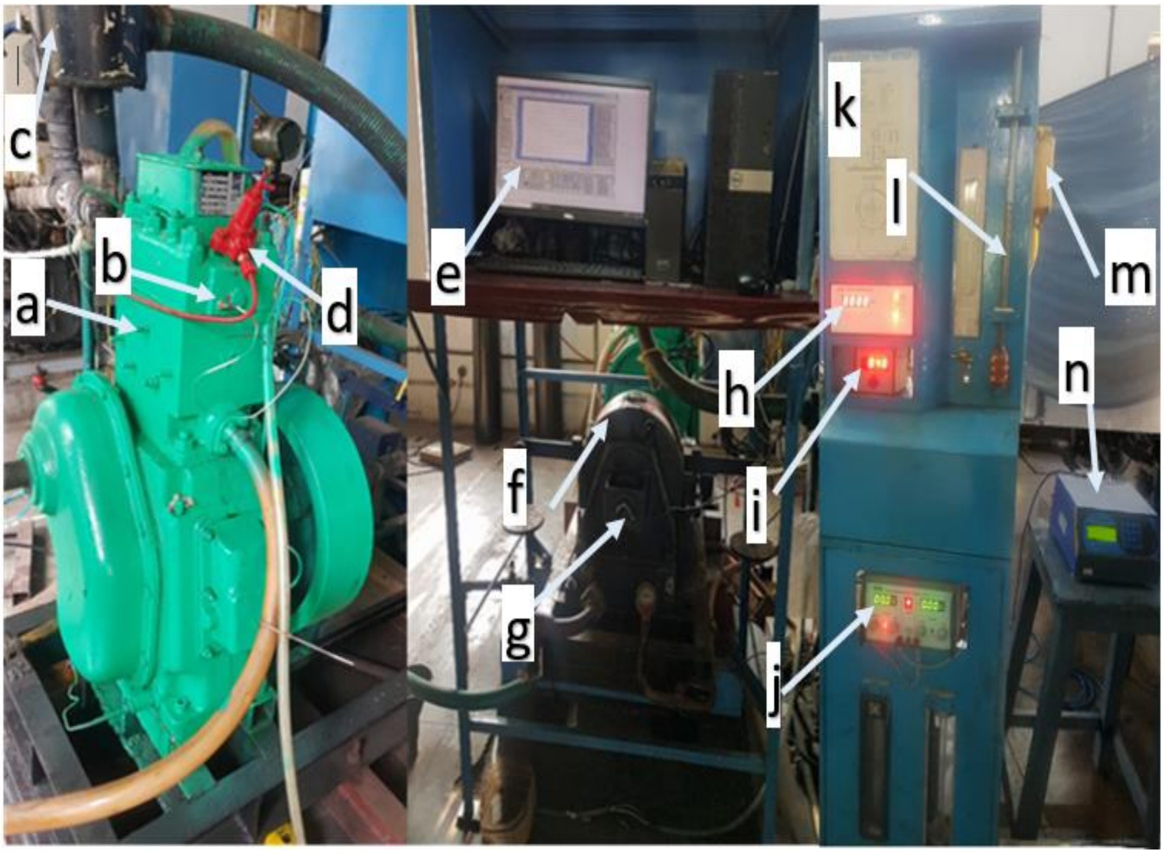
A single-cylinder, four-strokes, constant speed, naturally aspirated, water-cooled, direct injection Kirloskar TV1 diesel engine is used to conduct this experiment. This engine is connected to an eddy current dynamometer to vary the load on the engine. The schematic representation of the entire arrangement of the engine used in the experiment is shown in Fig. 4.1.



1. Kirloskar TV 1 Engine
2. Dynamometer
3. Control panel
4. Electronic control unit (ECU)
5. Injection pump
6. Fuel injector
7. INDUS 5 gas analizer
8. Data acquisition system
9. Air stabilizing tank
10. Fuel tank
11. Computer
12. Exhaust gas silencer

Fig. 4.1 Schematic representation of the experimental setup

A photographic view of the experimental setup is given in Fig. 4.2. The engine specifications are listed in Table 4.1. A data acquisition system (DAS) has been used to archive data throughout the experiments, and the data is recorded using "Engine Soft" software. The brake power loading percentage and engine fuel consumption are measured during the investigation. The measuring instruments used to measure the required parameters with their measuring techniques are listed in Table 4.2



a) Kirloskar TV1 engine, b) Pressure sensor, c) Air filter, d) Fuel injector, e) Computer display, f) Electrical operated dynamometer, g) Encoder, h) Engine speed indicator display, i) temperature control unit, j) Load controlling unit, k) Controlling display, l) Fuel consumption indicator, m) Fuel tank, n) INDUS 5 gas analyzer.

Fig. 4.2 Photographic view of the experimental setup

Table 4.1 Engine specification

Engine parameters	**Specification**
Model	Kirloskar TV1
Type	Single cylinder, 4-strokes, water-cooled, vertical, direct injection, compression ignition engine
Bore (mm)/Stroke(mm)	87.5/110
Rated power and Rated speed	5.2 kW at 1500 rpm
Compression ratio	17.5:1
Injection pressure	180 bar
Injection technique	Nozzle injection, mechanical pump
Dynamometer	Eddy current
Lubricating oil	SAE 20W40
TDC	At 360° crank angle
Fuel injection starts	At 27.5° CA BTDC

Table 4.2 Measuring instruments

Equipment	**Function**	**Measuring techniques**
Angle encoder	Measure crank angle	Magnetic pickup
Eddy dynamometer	Measure load on the engine	Load cell
pressure transducer	Measure cylinder pressure	Piezo-electric sensor
INDUS 5 Gas Analyzer	Parameters:	
	• Oxides of Nitrogen (NO_x),	Electrochemical sensor
	• Unburned hydrocarbons (HC),	Non-dispersive infrared
	• Carbon monoxide (CO),	Non-dispersive infrared
	• Carbon dioxide (CO_2), and	Non-dispersive infrared
	• Oxygen (O_2)	Electrochemical sensor

The exhaust gas emissions are measured by using INDUS 5 gas analyzer. The accuracy of the instruments for quantifying exhaust gas emissions is shown in Table 4.3. The most significant emissions measured are unburned hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), and oxides of nitrogen (NO_x).

Table 4.3 Exhaust gas analyzer specification

Emission	**Range**	**Data resolution**	**Accuracy**
HC	0 – 30000 ppm	1 ppm	± 12 ppm
CO	0 – 15%	0.001 %	± 0.06%
NO_x	0 – 5000 ppm	1 ppm	-
CO_2	0 – 20%	0.01 %	± 0.5%
O_2	0 – 25%	0.01%	± 0.1%

4.2 Measurement parameters and instruments

4.2.1 Fuel consumption measurement

A fuel flow measurement is carried out in order to acquire the performance characteristics of the engine. It is carried out on a volume basis with the help of a burette and a stopwatch. By using a stopwatch, the time required to consume 10cc of fuel was correctly recorded. While measuring the fuel levels between the calibrated marks on the fuel burette and starting and stopping the stopwatch, precautions were taken. To minimize the reading error fuel reading was taken five to 10 times for each experiment, and the average reading was taken for calculations.

4.2.2 Cylinder pressure and crank angle measurement

A pressure transducer (Make: PCB PIEZOTRONICS), model number S111A22, serial number 00017112, is used to measure the combustion variability pressure within the cylinder. Its measurement range (for ±5V output) 5000 psi (34475 kPa) and sensitivity of (±0.1mV/psi) 1.0 mV/psi (0.145 mV/kPa. The sensor was installed flush with the cylinder head surface in a hole bored into the engine cylinder head. A diaphragm exposes one end of the crystal to the pressure inside the cylinder. As the cylinder pressure increases, the crystal is compressed, generating an electric charge proportionate to the pressure. The pressure transducer measures the cylinder's internal pressure and turns it into electrical charge signals. The boosted signal is then transferred to a Windows-based digital computer running LABVIEW-based software capable of recording up to 100 consecutive combustion cycles.

The crank angle encoder is used to acquire the crank angle position for one complete cycle, which is then utilized to determine combustion parameters. In the present experiment engine crankshaft is fitted with a Kubeler-Germany crank angle encoder that measures the crank angle with a resolution of one °CA. Whenever the magnetically conductive mark carrier is moved in front of the sensor, a voltage is induced in the coil. The output voltage produced by inductive sensors is highly dependent on engine speed. An extra crank angle encoder with a permanent resolution is utilized for engine management on a test bench for engines. In order to minimize the effects of vibration, the encoder's position has been carefully centered.

Pressure and crank angle encoder signals were transferred into a computer-connected National Instruments (NI USB-6210, 16bit) data acquisition card. The data acquisition card acquires information at a rate of 250-kilo samples per second. The computer-stored information on in-cylinder pressure with crank angle was utilized to determine the NHRR and assess the combustion characteristics. The computer's "Enginesoft 9" program generates pressure-crank angle and pressure-volume diagrams. The pressure data from one hundred consecutive combustion cycles were averaged for each test to eliminate cycle-to-cycle variation. The averaged values were then evaluated to determine cylinder pressure and NHRR.

4.2.3 Data acquisition system

Labview-based "Enginesoft" software, a National Instruments (NI) USB-6210, 16-bit, 250kS/s in-vehicle data acquisition hardware system was used to acquire data from engine sensors for engine performance and combustion analysis. It contained one processor, three analog-to-digital converters, and a control area network (CAN) board.

4.2.4 Engine load measurement

The load measurement is done with an eddy current dynamometer (Make Sensotronics Sanmar Ltd., Model 60001, Type S beam, Universal, Capacity 0-50 kg) for this experiment. It comprises a stator with a number of electromagnets and a rotor disc, and it is attached to the engine's output shaft. When the rotor rotates, eddy currents are generated in the stator as a result of the magnetic flux created by the flow of field current through the electromagnets. These eddy currents counter the rotor's motion, exerting a load on the engine. These eddy currents are dissipated by producing heat, so this type of dynamometer needs a cooling arrangement.

4.2.5 Exhaust gas emission measurement

For emission measurement, INDUS 5 gas analyzer model number PEA205N is used. It measures CO, CO_2, HC, O_2, and NO in the automotive exhaust. An AVL 415S smoke meter, which measures the amount of soot in the exhaust from 0 to 100%, is used to measure the smoke opacity in the exhaust gas emission.

4.3 Theoretical background

The engine used in this experiment is a single-cylinder compression ignition diesel engine. This experiment aims to determine the effect of biodiesel on the engine's performance, combustion, and characteristics. The performance and combustion characteristics of the engine are calculated based on the following governing equations.

The average temperature of the gas in the cylinder and the rate at which heat is released are computed using the "Enginesoft/Labview" program, which employs the 0D model of a single combustion zone with a constant specific heat ratio to accomplish the calculations.

$$\frac{dQ_n}{d\theta} = \frac{dQ_{ch}}{d\theta} - \frac{dQ_{ht}}{d\theta} = \left(\frac{\gamma}{\gamma-1}\right) P \frac{dV}{d\theta} + \left(\frac{\gamma}{\gamma-1}\right) V \frac{dP}{d\theta} \quad (4.1)$$

Where,

$\frac{dQ_n}{d\theta}$ = Net heat release; θ = Crank angle; V = cylinder volume

γ = specific heat capacities ratio P = cylinder pressure

4.4 Uncertainty analysis

Several factors, including calibration, observation, instrument usage, incorrect readings, and the surrounding environment, can contribute to uncertainty. The uncertainty of each recorded parameter is approximated using the Gaussian distribution approach with a confidence limit of ±2σ (95.45%. Using this approach the measured data falls within the boundaries of ±2σ of the mean). Therefore, the uncertainty of every measured parameter is determined by:

$$w_i = \frac{2\sigma_i}{\bar{x}} 100 \quad (4.2)$$

Coordination of experiments is used to determine the mean ($\bar{x}$) and standard deviation (σ_i) of any measured parameter (x_i) for a number of readings. This is done for speed, load, and time for a specific air and fuel flow, etc.

Equation (4.2) is used to determine the uncertainty values for speed, load, temperature controller, pressure instruments, fuel flow rate, emissions of NO_x, HC, CO, CO_2, and smoke opacity.

Bedar and Kumar (2017) and Kline and McClintock (1953) have presented a method for assessing uncertainty in experimental outcomes. The method is based on carefully describing the amount of uncertainty in the different primary measurements. Consider a set of measurements in which the uncertainty associated with each measurement may be described using the same probabilities. These measurements are then utilized to calculate the required experimental outcomes. On the basis of the errors in the primary measurements, it is possible to estimate the uncertainty in the derived result.

If an estimated quantity R is influenced by "n" independent measured parameters x_1, x_2, x_3, x_4. . . x_n, then R is given by:

$$R = R(X_1, X_2, X_3 \ldots Xn) \quad (4.3)$$

Let U_R be the uncertainty total in the result and u_1, $u_2 \ldots u_n$ be the uncertainties in the independently measured parameters. U is the computed result function of the independently measured parameters x_1, x_2, $x_3 \ldots x_n$ in accordance with the relationship $x_1u_1 \pm x_2u_2 \pm x_nu_n$). If the uncertainties in the independent variables are all given with the same odds, then the uncertainty in the result having these odds.

$$U_R = ([\frac{\partial R}{\partial x_1} u_1]^2 + ([\frac{\partial R}{\partial x_2} u_2]^2 + \ldots . [\frac{\partial R}{\partial x_n} u_n]^2)^{1/2} \quad (4.4)$$

The uncertainties in computed quantities such as braking power, brake thermal efficiency, brake specific fuel consumption, and brake specific energy consumption are estimated using the equation (4.4) for a particular operating situation.

The uncertainty for the temperature sensor, burette reading, and time is computed by taking the readings 20 times and then calculating the average value of all readings. In the case of the exhaust gas analyzer, the accuracy of the reading is divided by the least accurate reading, and the result is recorded as an uncertainty value.

Lists of instruments used in this experiment and exhaust gas analyzer accuracy are presented in Tables 4.2 & 4.3 respectively in section 4.1. The total calculated measured uncertainty of all the instruments is found to be 2.75 %.

The overall total uncertainty of all instruments used to measure different parameters are listed in Table 4.4, and the overall uncertainty of the instruments is calculated using equation (4.2 and 4.4). For derived parameters such as BTE, BSFC, and BSEC, the uncertainty are calculated based on the variables on which the parameter depends.

$$\text{Uncertainty } (U_T)\ (\%) = \{\sqrt{(U_{engine\ speed})^2}+\sqrt{(U_{dynamometer})^2}+\sqrt{(U_{crankangle\ encoder})^2}+\sqrt{(U_{temperature\ controller})^2}+\sqrt{(U_{cylinder\ pressure})^2}+\sqrt{(U_{fuel\ flow})^2}+\sqrt{(U_{time})^2}+\sqrt{(U_{BP})^2}+\sqrt{(U_{BTE})^2}+\sqrt{(U_{BSEC})^2}+\sqrt{(U_{HC})^2}+\sqrt{(U_{CO})^2}+\sqrt{(U_{NOx})^2}+\sqrt{(U_{CO2})^2}+\sqrt{(U_{smoke\ opacity})^2}\} \quad (4.5)$$

$$U_T = \{\sqrt{(1)^2}+\sqrt{(0.2)^2}+\sqrt{(0.15)^2}+\sqrt{(0.5)^2}+\sqrt{(1.5)^2}+\sqrt{(0.9)^2}+\sqrt{(0.1)^2}+\sqrt{(0.8)^2}+\sqrt{(0.8)^2}+\sqrt{(0.8)^2}+\sqrt{(0.8)^2}+\sqrt{(0.12)^2}+\sqrt{(0.1)^2}+\sqrt{(0.1)^2}+\sqrt{(0.15)^2}+\sqrt{(1.1)^2}\}$$

$$= \underline{\underline{\pm 2.75}}$$

Table 4.4 List of uncertainty of measured and derived parameters

Instrument	% Uncertainty
Engine speed	±1.0
Dynamometer load cell	±0.2
Crank angle encoder	±0.2
Temperature controller	±0.15
Pressure instrument	±0.5
Burette for fuel measurement	±1.5
Time	±0.9
Brake power	±0.1
Brake thermal efficiency	±0.8
Brake specific fuel consumption	±0.8
Brake specific energy consumption	±0.8
Exhaust gas analyzer	
HC	±0.12
CO	±0.1
NO_x	±0.1
CO_2	±0.15
Smoke opacity	±1.1

4.5 Performance, combustion, and emission characteristics

The main factors affecting the appropriateness of fuel are its engine performance, combustion, and emission characteristics. The following sections discusses the fundamental engine performance, such as brake thermal efficiency (BTE) and brake specific energy consumption (BSEC). Fig. 4.3 shows the key parameters to be tested in this experimental work. For all derived and measured parameters, the error bars are included in the figures.

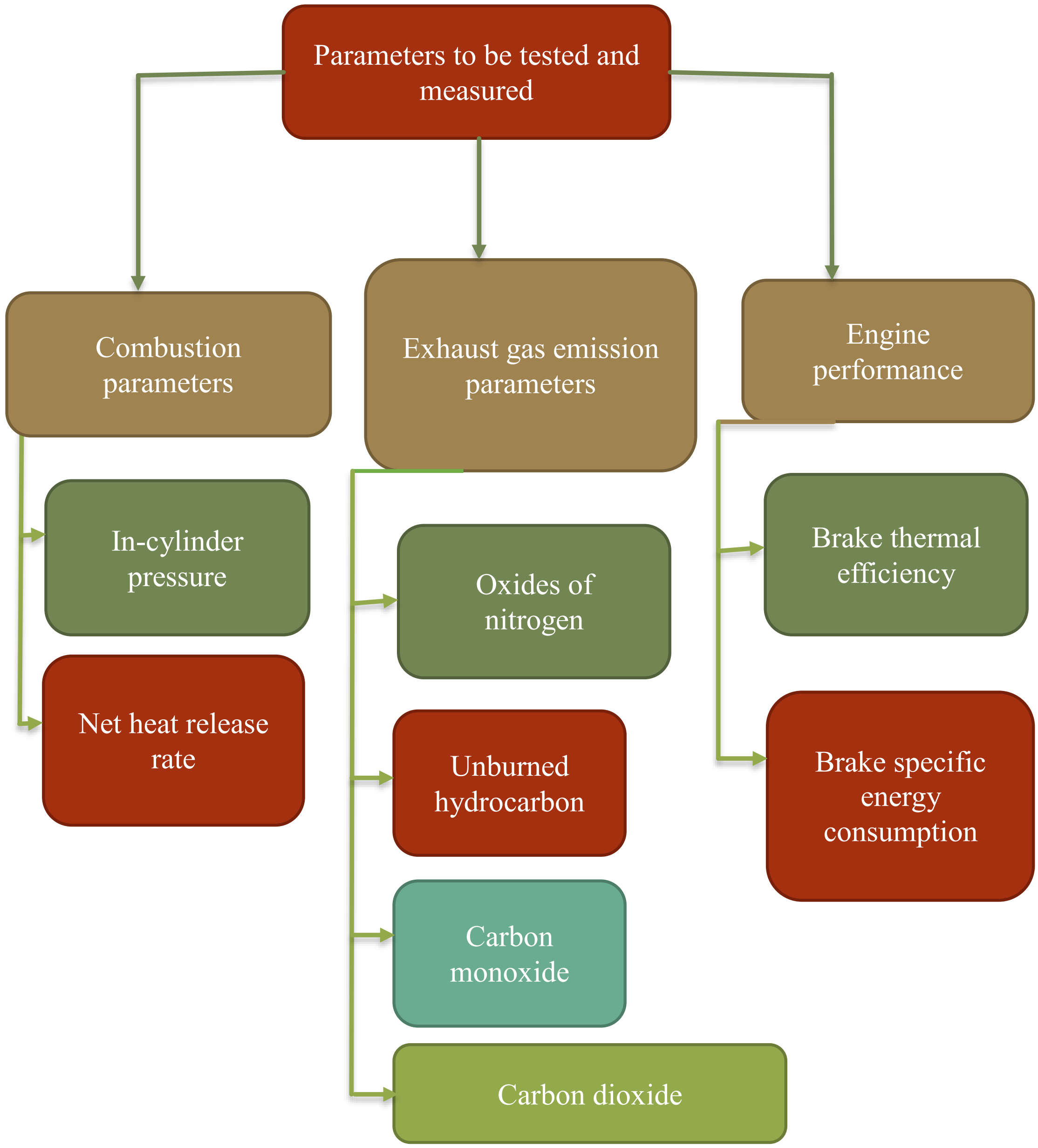


Fig. 4.3 Basic Engine parameters tested

4.6 Experimental methodology flow chart

Flow charts of the methodology and strategies followed to perform the experiments and engine set up are presented in Fig. 4.4.

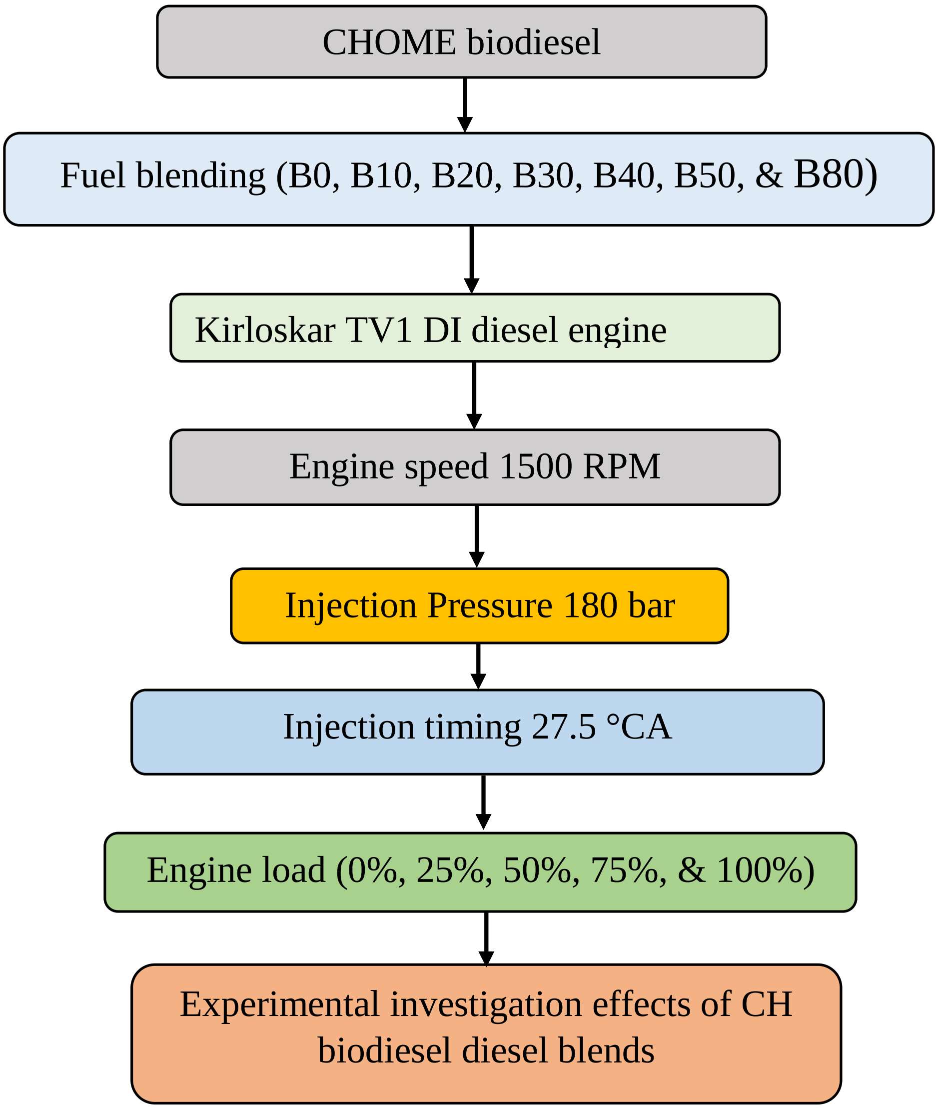


Fig. 4.4 Research strategy and setup

4.7 Engine performance test

This section discusses engine performance in terms of BTE and BSEC by using CHOME biodiesel as an alternate fuel and using regular diesel fuel as a baseline by varying the load on the engine.

4.7.1 Brake thermal efficiency (BTE)

The BTE is the performance parameter of the engine, which is a function of fuel consumption (mass flow of fuel) and brake power. It is an important parameter that plays a major role in evaluating the changing of the chemical energy of the fuel to mechanical energy. Fig. 4.5 depicts the BTE of regular diesel and CHOME biodiesel-diesel blends at various blending ratios (B0, B10, B20, B30, B40, B50, and B80) at different engine loads (0 – 100%). It is observed that the BTE of all tested fuels increases gradually with increasing load on an engine.

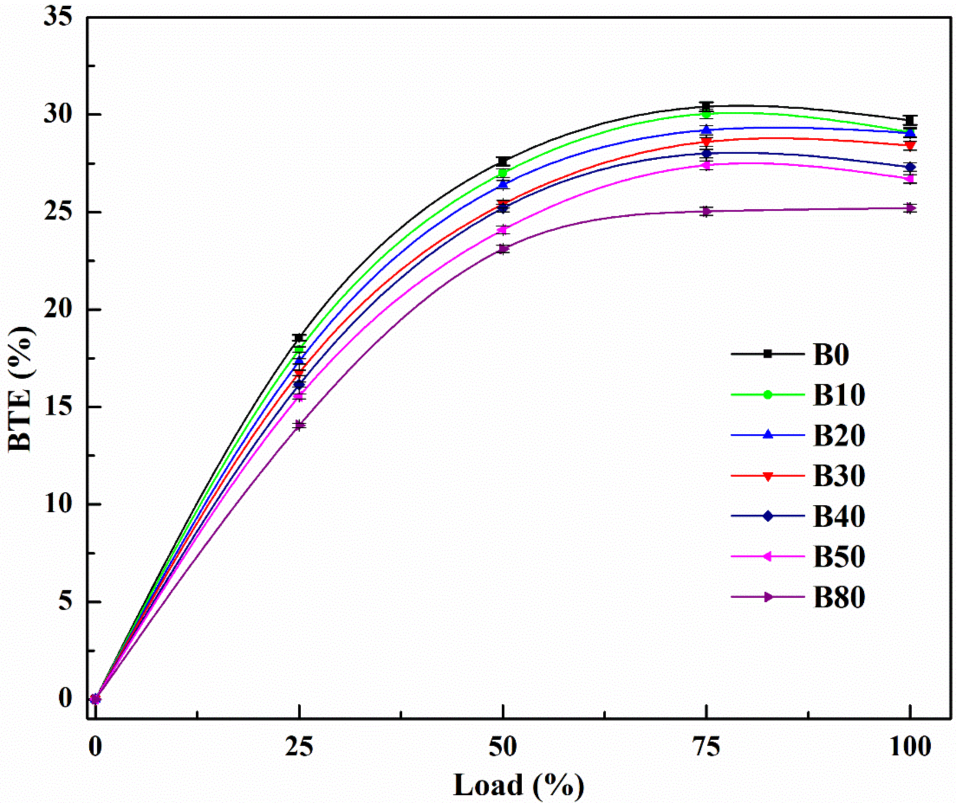


Fig. 4.5 BTE of CHOME biodiesel-diesel blends and regular diesel at different engine loads

This is because of higher fuel consumption and lower calorific value of biodiesel and their blends as compared to regular diesel (Chauhan et al. 2012a). BTE of B10, B20, and B30 show better results than higher blends, and the value is closer to that of B0. The BTE of B40, B50, and B80 is much lower than B0, B20, and B30. The BTE of CHOME biodiesel-diesel blends of B0, B10, B20, B30, B40, B50 and B80 at full load are 29.7%, 29.1%, 29%, 28.4%, 27.3%, 26.7% and 25.2% respectively.

The BTE of the newly developed biodiesel appears promising to be used as an alternative fuel in an IC engine without engine modification. As seen in the graph, the trends of all graphs follow regular patterns. Since BTE is the function of the mass flow of fuel consumed by the brake power, BTE drops as the percentage of the CHOME biodiesel in the blend increases.

4.7.2 Brake specific energy consumption (BSEC)

The BSEC is more reliable when comparing fuel blends with different calorific values; since, it takes care of both mass flow rate and heating value of the fuel. The BSEC is the amount of energy required per unit of power developed by the engine. BSEC often drops as energy consumption efficiency increases (Imtenan et al., 2015). Fig. 4.6 depicts the BSEC of regular diesel compared to CHOME biodiesel blended with diesel at various engine loading conditions.

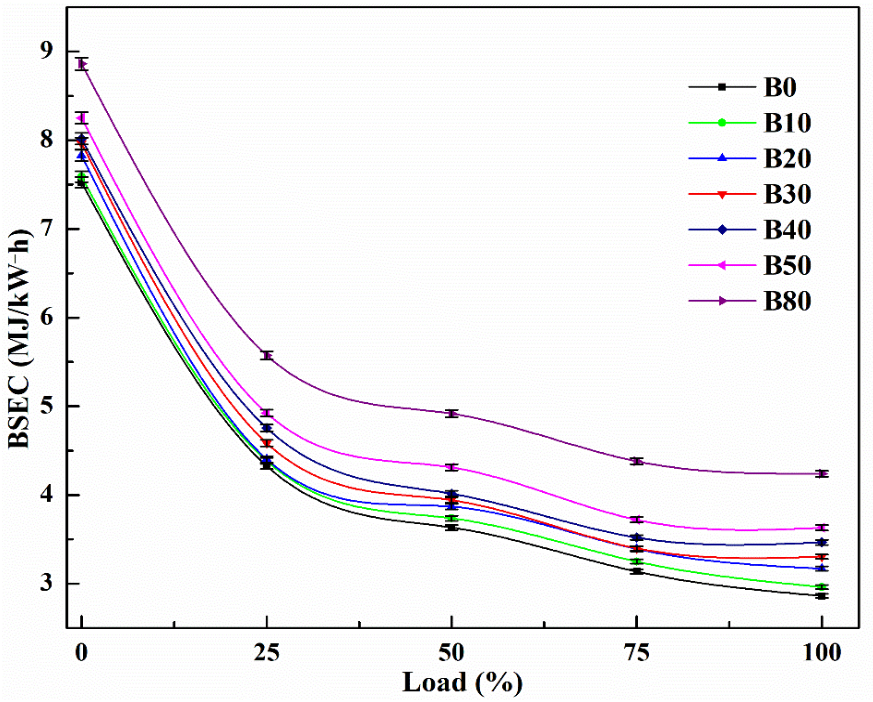


Fig. 4.6 BSEC of CHOME Biodiesel-diesel blends and regular diesel at different engine load

Because of the improved combustion process and increased combustion efficiency at higher loads, BSEC decreases as engine load increases. As BSEC is the function of mass flow of fuel and calorific value by brake power, it reduces as the load increases. For biodiesel, because of its lower heating rate and higher mass flow of fuel, BSEC increases with the increase in the share of CHOME biodiesel in the blend. BSEC of B10, B20, and B30 is lower than B40, B50, and much lower than B80 due to the characteristics of the biodiesel mentioned earlier. BSEC of B0, B10, B20, B30, B40, B50, and B80 is 2.86, 2.96, 3.169, 3.30, 3.46, 3.63, and 4.24 MJ/kWh respectively, at full load. Compared to regular diesel the BSEC of the biodiesel diesel blend at 100% load is increased by 3.5%, 9.7%, 13.4% 17.4% 21.2%, and 32.5% for B10, B20, B30, B40, B50, and B80 respectively. Similar results are discovered by Anandavelu et al. (2011) on engines fueled with eucalyptus oil and diesel blends and by Chauhan et al. (2012) on engine fueled with Jatropha biodiesel oil and its blends.

4.8 Combustion analysis

Combustion analysis is one of the tools to determine the quality of fuel. This section discusses the combustion characteristics of a single-cylinder TV-1 diesel engine running on regular diesel and CHOME biodiesel diesel blends at full load conditions, considering cylinder pressure and NHRR with different crank angles.

4.8.1 In-Cylinder pressure

Cylinder pressure is a crucial quantity to consider when investigating combustion quality and engine efficiency. As the quality of a fuel's combustion is determined by its characteristics, such as its calorific value, latent heat, cetane number, and viscosity, the blending ratio of the biodiesel in the regular diesel affects the in-cylinder combustion significantly (Santhosh and Kumar 2021). Fig. 4.7 describes the effect of CHOME biodiesel blends on peak cylinder pressure of CI engine at full load on the engine.

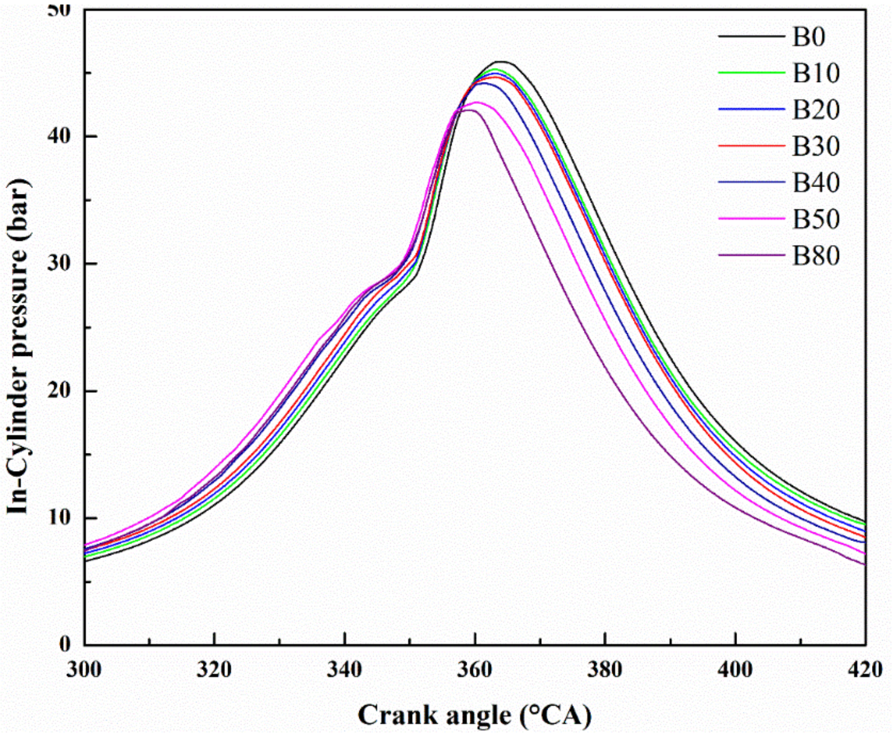


Fig. 4.7 Variation of in-cylinder pressure with the crank angle for different blends at full load

The biodiesel diesel blends graph trends follow a nearly similar curve to regular diesel. As the biodiesel concentration increases, the ignition delay decreases, and early combustion happens. Peak cylinder pressure appears to drop slightly when the blending ratio increases and the maximum cylinder pressure is achieved some degree before TDC compared to regular diesel. This may be due to the high viscosity and the low volatility of the biodiesel blends; poor atomization occurs in the combustion chamber, resulting in uncontrolled homogeneous mixture formation with air during the delay period. This is because biodiesel has a shorter ignition delay than diesel. Similar results are discovered by Viswanathan et al. (2020) on biodiesel from curry leaf and Kodate et al. (2021) on biodiesel from Dhupa seed oil.

4.8.2 Net heat release rate (NHRR)

Figure 4.8 shows the NHRR (heat produced by the combustion mixture at a particular crank angle) at the full load condition of the engine. The CHOME biodiesel blend with regular diesel at various blending ratios (B0, B10, B20, B30, B40, B50, and B80) is tested to investigate the NHRR of the fuel used. The heat release rate of all tested fuels follow the same trend as regular diesel. All biodiesel blends and regular diesel had a negative net heat release during the combustion delay period.

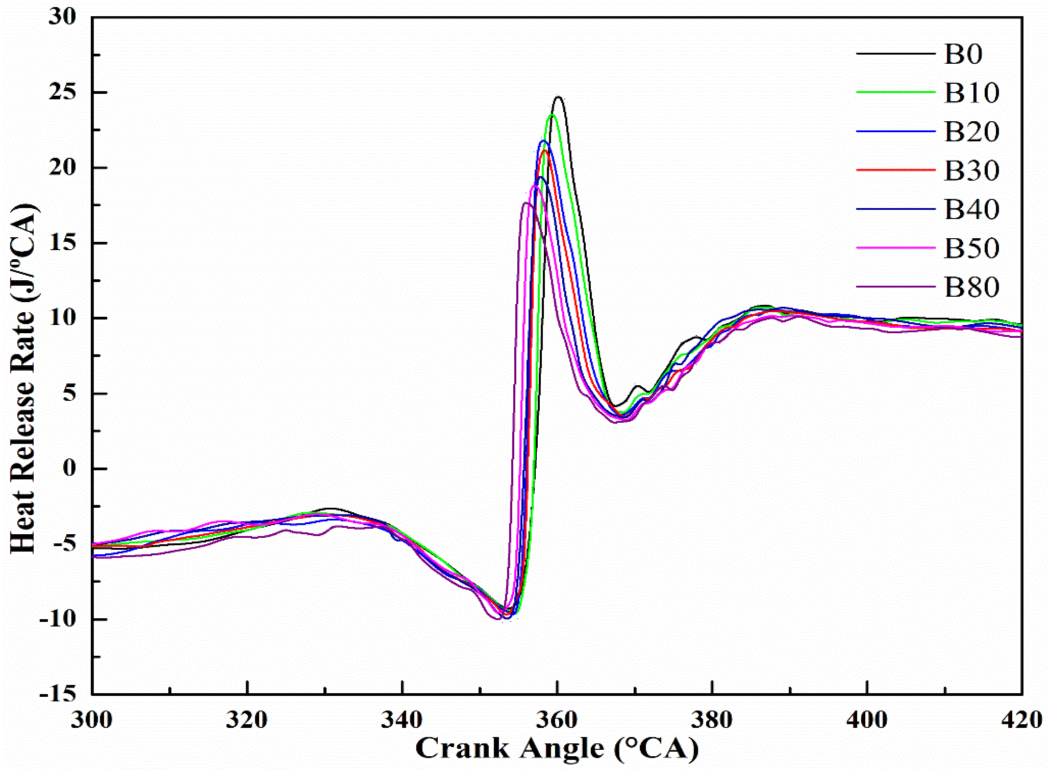


Fig. 4.8 Variation of the net heat release rate with crank angle

This is due to the injection of fuel into the cylinder during the injection delay time, which could absorb heat rather than generate it. The latent heat of biofuel is higher than regular diesel; hence the heat release rate of all biodiesel diesel blends is lower than that of regular diesel during the delay period of the injection.

Asokan et al. (2019) and Hosamani and Katti (2018) reported similar trends on juliflora biodiesel-diesel blends and a mixture of two biodiesel (Simarouba and Jatropha) blended with diesel, respectively. Due to its higher calorific value, lower viscosity, and lower latent heat of vaporization, regular diesel has a higher heat release rate than all biodiesel diesel blends. As the blending ratio of the CHOME biodiesel increases, the heat release rate drops, which could be due to the higher viscosity, density, and lower calorific value of the biodiesel (Jaichandar et al. 2016).

The maximum NHRR of B0, B10, B30, B50, and B80 are 24.87, 23.68, 21.41, 18.99, and 17.67 J/°CA, respectively. B10, B20, and B30 show a better heat release rate than other blends.

4.9 Exhaust gas emission characteristics

In this section, exhaust gas emission characteristics of the engine, such as oxides of nitrogen (NO_x), unburned hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide (CO_2).

4.9.1 Nitrogen oxides (NO_x)

NO_x is a compound of exhaust gas emission produced when oxygen reacts with nitrogen inside the combustion chamber of an engine cylinder at high temperatures.

The amount of NO_x emission produced is mainly the function of temperature specific stoichiometric of the mixture, reaction time, and oxygen in the mixture. Fig. 4.9 shows the NO_x gas emission characteristics of CHOME biodiesel-diesel blends and regular diesel at various engine loading conditions. As the load on the engine increases, the NO_x emission in the exhaust gas proportionally increases.

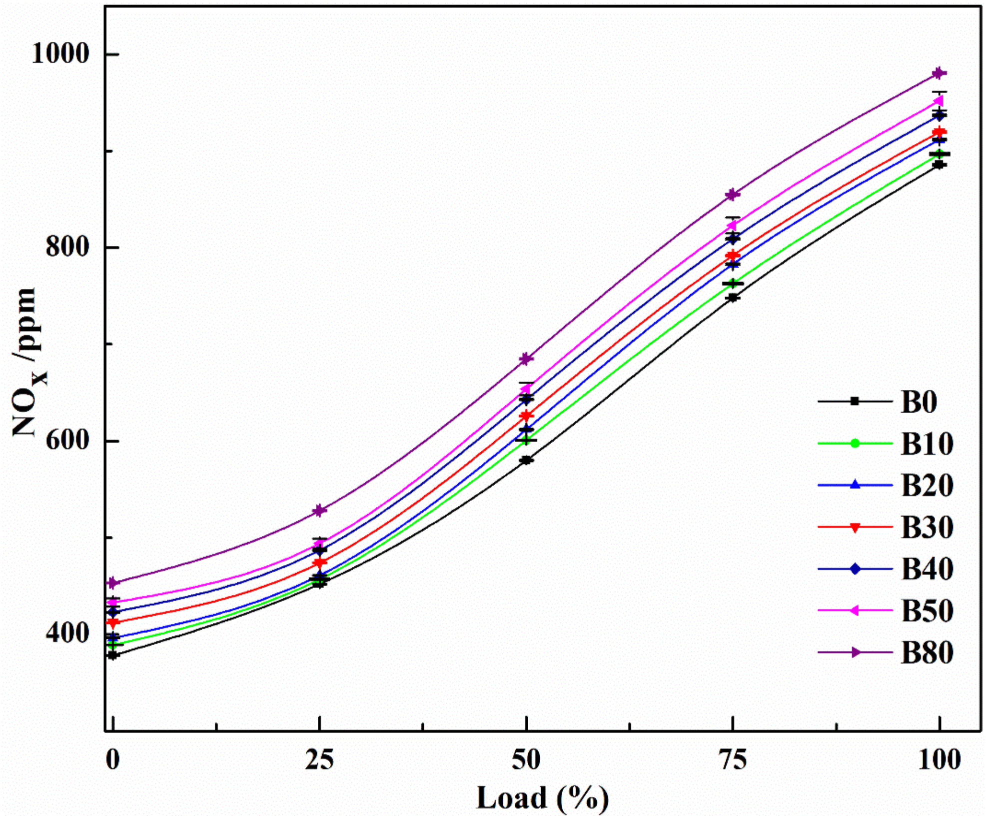


Fig. 4.9 Variation of NO_x emission with engine load

This is due to the higher temperature created inside the combustion chamber because of greater injection pressure due to a larger volume of fuel being delivered and a short reaction time. It is observed from the figure that in all circumstances, the NO_x emission from CHOME biodiesel is higher than regular diesel. This may be due to better ignition delay and increased injected fuel into the combustion cylinder due to higher density of the fuel, resulting in higher cylinder pressure and enhanced temperature inside the combustion chamber. As it is seen in the figure, the NO_x emission increases as the amount of CHOME biodiesel in the blend increases. This is because biodiesels have a short ignition delay, inherent oxygen content, increased volume of the injection of fuel into the combustion chamber due to the lower calorific value, and a relatively higher density. All these factors lead to an increase in the cylinder temperature, resulting in higher NO_x formation. The NO_x formation of CHOME biodiesel and its blend at full load (100%) is 1.2%, 2.9%, 3.8%, 5.7%, 6.8%, and 7.3 % for B10, B20, B30, B40, B50, and B80 respectively. Nearly similar results were also found by Anandhan et al. (2021) on diesel engine fueled with blends of jojoba biodiesel and by Xavier (2020) on diesel engine fueled with watermelon seed oil methyl ester.

4.9.2 Unburned hydrocarbon (HC) emission

HC is an indication of incomplete combustion of the fuel in the combustion chamber and low combustion chamber temperature due to a rich fuel-air mixture. Fig. 4.10 depicts the variation of HC emission concentration in an exhaust gas with different engine loading conditions for regular diesel and various CHOME biodiesel diesel blends.

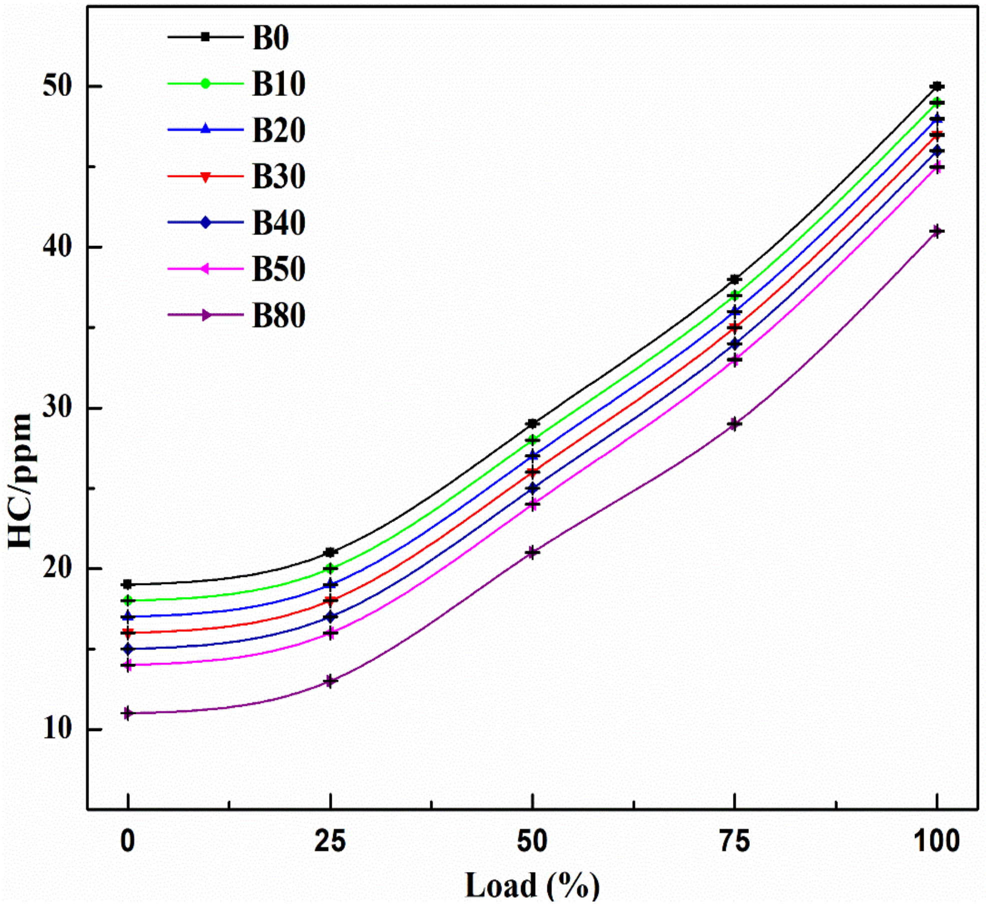


Fig. 4.10 Variation of HC emission with engine load

The HC of CHOME biodiesel diesel blends is lower than regular diesel under all engine loading conditions. This was mostly owing to the availability of molecular oxygen, which facilitates the combustion in CHOME biodiesel, and the high rate of generation of HC breakups compared to regular diesel. Similar trends are investigated by Kannan et al. (2020) on biodiesel from neem oil and by Gopidesi and Gangolu (2020) on biodiesel from Jatropha with tamarind seed oil. It is observed that the concentration of HC in exhaust emission for the tested fuels at no load and full loads is reduced by 42% and 18%, respectively, for B80 compared to B0.

4.9.3 Carbon monoxide (CO) emission

CO is a harmful gas that can be released into the air when incomplete combustion occurs. The CO emissions vary according to the physical and chemical qualities of the fuel, the parameters of the fuel spray, the time necessary for complete combustion, and the temperature inside the cylinder. CHOME biodiesel is tested for the concentration of CO in the exhaust gas. Fig. 4.11 shows CO emission versus the engine load at 1500 rpm.

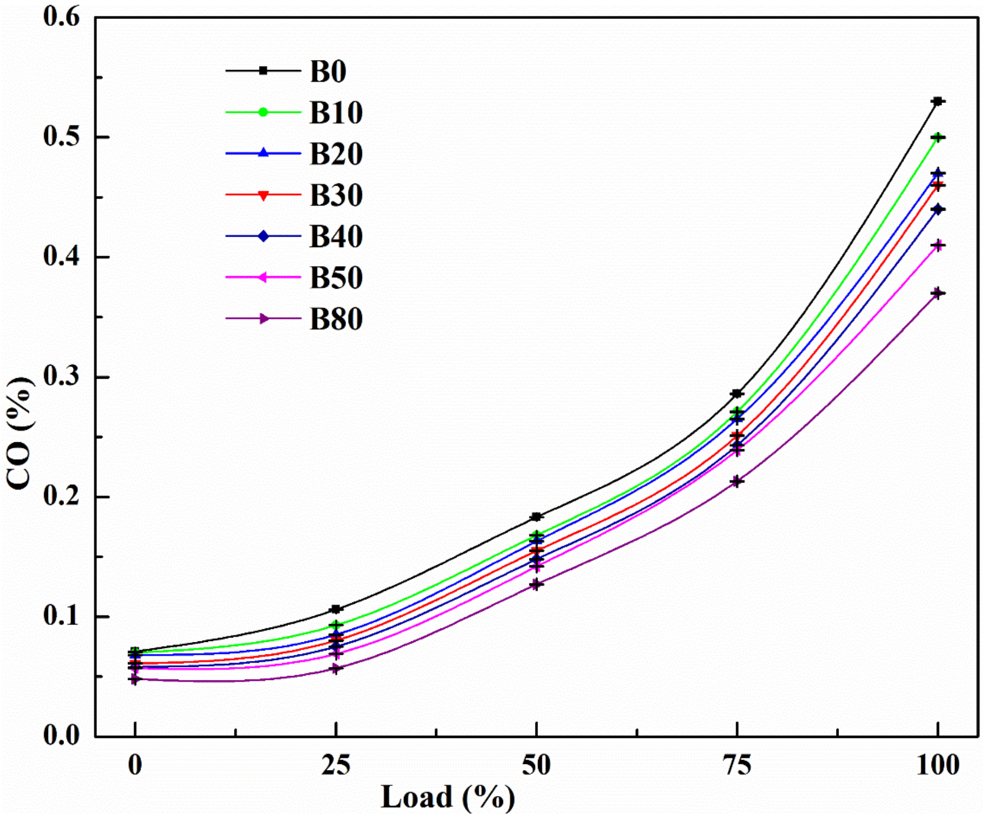


Fig. 4.11 CO emission versus engine load

As observed, the concentration of CO emission in the exhaust gas increases when the engine loading increases. This is due to the fact that increasing the load reduces the concentration of oxygen in the combustion chamber. Due to poor combustion of the mixture and a shortage of oxygen, fuel molecules could not be oxidized at high loads. For all engine loading conditions, CO decreases as the blending ratio of the CHOME biodiesel increases and is lower than that for conventional diesel. At full load CO emission in exhaust gas is reduced by 5.6%, 11.3%, 13.2%, 17%, 22.6%, and 30% for B10, B20, B30, B40, B50, and B80, respectively. This may be because CHOME biodiesel includes inherent oxygen; it promotes the successive oxidation of CO to CO_2

during the combustion process within the cylinder. Similar trends are reported by Prasada et al. (2022) on diesel engine fueled with a palmyra biodiesel blend by varying compression ratios and using exhaust gas recirculation. Elkelawy et al. (2021) also reported nearly similar results on DI-diesel engine fueled with algae biodiesel/diesel/n-pentane blends.

4.9.4 Carbon dioxide (CO_2)

CO_2 emissions are being used to determine the engine's combustion conditions. It is an indication of the complete combustion of fuel. CO_2 is an inevitable outcome of complete combustion, a source of greenhouse gas formation. Fig. 4.12 depicts the variations of CO_2 emissions with different engine loading conditions. The amount of CO_2 in exhaust emissions indicates that the fuel was correctly burned.

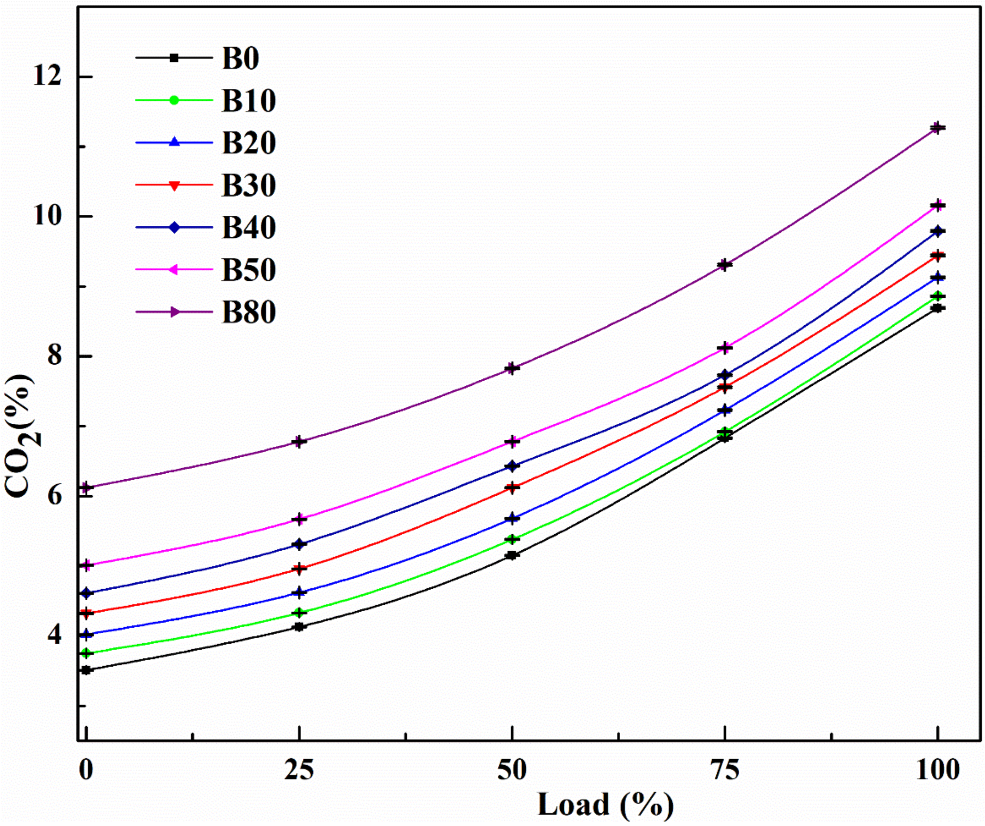


Fig. 4.12 Variations of CO_2 with engine load

Regular diesel CO_2 emissions are lesser than those of CHOME biodiesel diesel blends at all loading conditions. This is because biodiesel contains more oxygen than regular diesel. CO_2 emissions increase as the blending ratio and loading conditions on the engine increase. CO_2 emission is increased at full load by 0.27%, 0.84%, 1.15%, 1.52%, 1.97% and 3.58% for B10, B20, B30, B40, B50, and B80, respectively, as compared with regular diesel. This could be due to the fact that during combustion, as the concentration of the oxygen inside the combustion chamber increases, CO is oxidized to CO_2. In this experiment, CO is inversely proportional to CO_2 under all loading conditions and blending ratios.

4.9.5 Smoke opacity

Smoke opacity develops in the exhaust gas due to incomplete combustion, oxygen shortage, self-ignition, and fuel atomization (Chauhan et al., 2013). Fig. 4.13 compares the smoke opacity of CHOME biodiesel diesel blends to that of pure diesel. As the graphic plainly shows, the opacity of the smoke increases as the load on the engine increases.

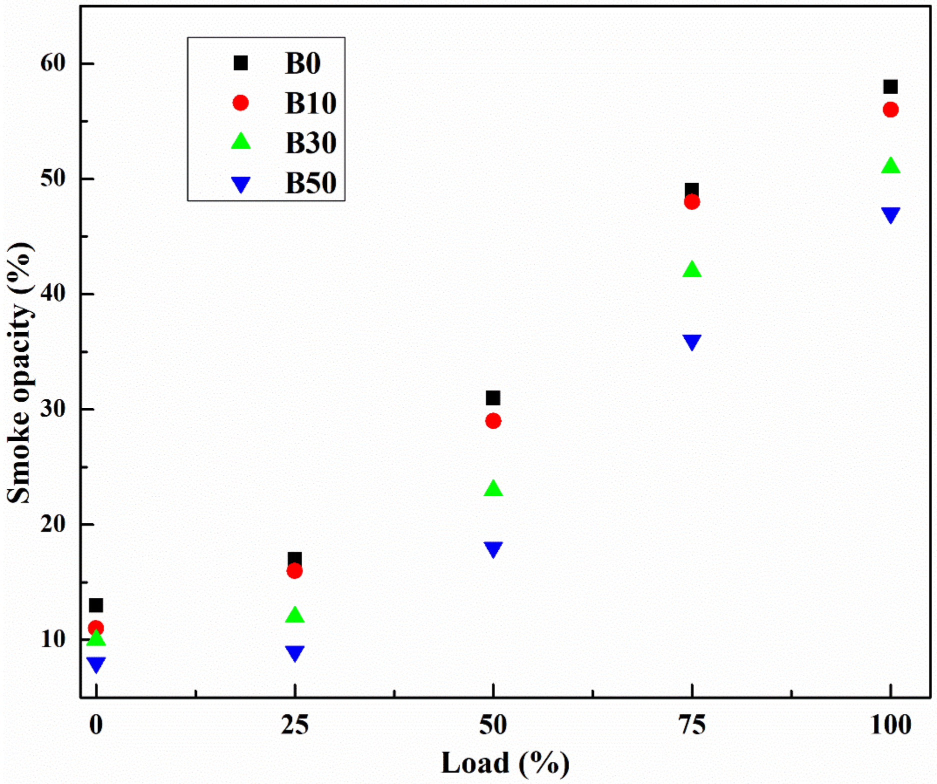


Fig. 4.13 Smoke opacity versus engine load

As the load increases, so does the amount of fuel injected for the same amount of air, resulting in a lesser oxidation process and, as a result, more smoke production occurs Çelik (2021). The emission of smoke opacity while fueling the engine with CHOME biodiesel-diesel blends are lower than regular diesel due to inherited oxygen. The CHOME biodiesel and its blends have excess oxygen, which accelerates burning and lowers smoke formation. Smoke opacity of B10, B30, and B50 are reduced by 3.45%, 12.07%, and 18.97%, respectively. Similar trends reported by Chintala et al. (2017) on a DI diesel engine with Jatropha biomass pyrolyzed oil.

4.10 Conclusions

In this chapter, the effect of CHOME biodiesel-diesel blends on the engine performance, combustion, and emission characteristics are investigated. Kirloskar TV-1 single-cylinder DI diesel engine with an eddy current dynamometer is used to accomplish the experiment. The following key details are observed throughout the investigation.

- BTE of all tested fuels shows acceptable results compared to regular diesel. BTE of B10, B20, B30, and B40 at 100% load is reduced by 0.6, 0.7, 1.3, and 2.4%, respectively, compared to B0.
- BSEC of B10, B20, B30, and B40 are increased by 3.49, 10.84, 15.38, and 20.97%, respectively, indicating that B10, B20, and B30 are better blending ratio to be used compared to other blends.
- Combustion analysis, such as in-cylinder pressure and NHRR of the CHOME biodiesel, shows better results for lower blends (B10 to B30).
- The tested biodiesel's exhaust emission characteristics show better results than regular diesel. Lower concentrations of HC and CO and higher concentrations of CO_2 and NO_x are noticed in the exhaust gas emission. At full load, the HC and CO of B30 are lowered by 9% and 13.21%, respectively.
- The smoke opacity in the exhaust gas is reduced by 3.45%, 12.07%, and 18.97% for B10, B30, and B50, respectively.

Overall, in this experimental study, it has been found that the newly produced CHOME biodiesel can be used in CI engines up to 30% blending with regular diesel without significant modification to the engine.

CHAPTER 5

EFFECT OF FUEL PREHEATING PRIOR TO INJECTION ON PERFORMANCE COMBUSTION AND EMISSION OF THE ENGINE FUELED WITH CHOME BIODIESEL

Due to lower calorific value and higher viscosity, biodiesel-fuelled engines have a lower brake thermal efficiency and a higher brake-specific fuel consumption than regular diesel-fuelled engines. In-cylinder pressure and NHRR, both directly related to engine performance, are also reduced significantly (Ashok et al., 2018). Carbon monoxide, unburned hydrocarbons, particulate matter, and sulfur dioxide emissions, on the other hand, are reduced with the marginal increase in NO_x emission (Reddy et al., 2020; Walle Mekonen and Sahoo, 2020).

In various studies preheating the fuel before delivering it into the combustion chamber is applied to lower the viscosity and density of biodiesel (Elumalai et al., 2021; Gopinath et al., 2019; Sivasubramanian and Sajin, 2021; Viswanathan and Wang 2021).

In this chapter, the effect of preheated CHOME biodiesel-diesel blend at different blending ratios (B10, B30, B50, and B100) is tested to investigate the engine performance, combustion, and emission characteristics by varying the load on the engine. Preheated and unheated regular diesel (B0) is also used as a baseline to validate the results. Preheating CHOME biodiesel is expected to enhance the performance and combustion characteristics of the engine significantly. Fig. 5.1 shows the methodology followed and the engine set up with the fuel blends used for this experimental work.

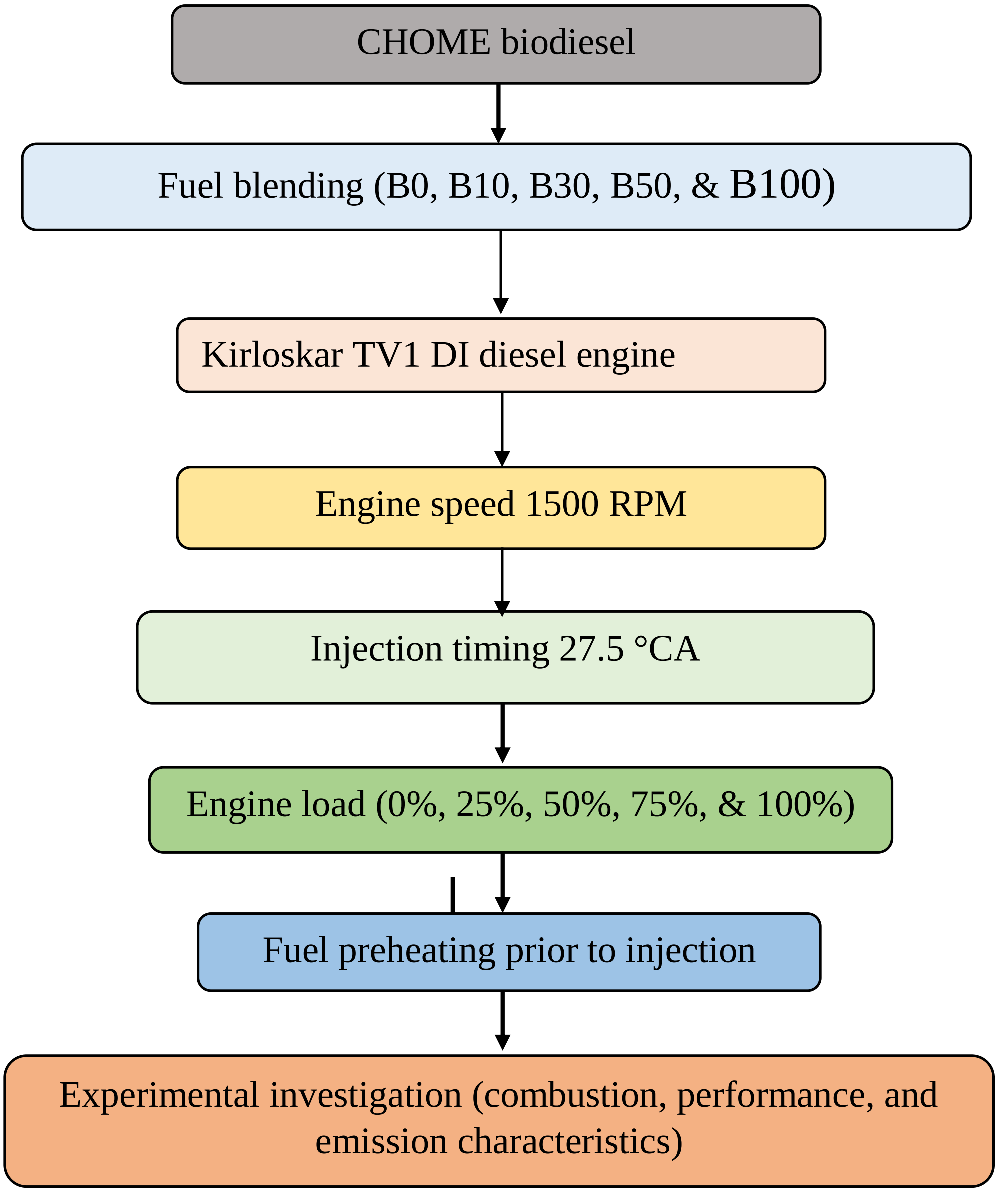


Fig. 5.1 Experimental procedure and strategy

5.1 Preheating the fuel

Preheating the fuel before injection reduces viscosity, increasing its atomization and vaporization. Wang et al. (2006) investigated that the main disadvantage of vegetable oils is higher density and viscosity compared to regular diesel. Recent diesel engines have a fuel injection mechanism that is sensitive to viscosity change. Higher viscosity of the fuel leads to poor atomization, incomplete combustion, clogging of the injector, and carbon deposit of piston head and valves. Some mechanisms to reduce these challenges and maintain the performance of the engine is to reduce the viscosity of vegetable oil through different mechanisms.

5.2 Preheating arrangement

Preheating the fuel before injecting it into the combustion chamber further reduces the viscosity of the fuel. In the present work fuel preheating is carried out by using a preheating setup arranged for the same. A heating cord rapped the fuel line from the injection pump to the fuel injector to heat the fuel flowing through the fuel line. Four thermocouples are connected with the fuel line from the inlet and outlet of the fuel line to measure the temperature. Rheostat and temperature regulators are used to regulate the temperature of the fuel. Fig. 5.2 shows the preheating arrangement setup used during experimental work.

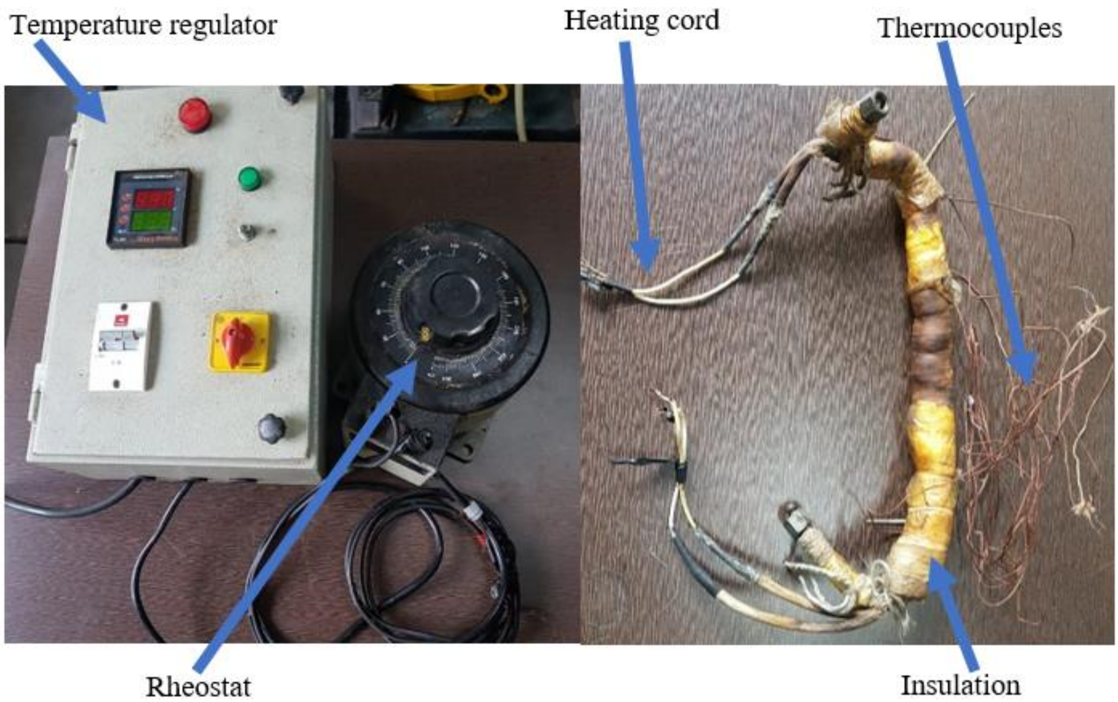


Fig. 5.2 Preheating setup

Proper insulation is done by covering the overall heating cord and fuel line with cotton thermal insulating material to reduce the heat loss to the surroundings, as shown in Fig. 5.2.

5.3 Effect of temperature on viscosity and density of CHOME biodiesel-diesel blends

CHOME biodiesel and its blend with regular diesel are preheated to 95 °C to decrease its viscosity before injection into the combustion chamber. Viscosity variation with a temperature change of tested fuels is presented in Fig. 5.3.

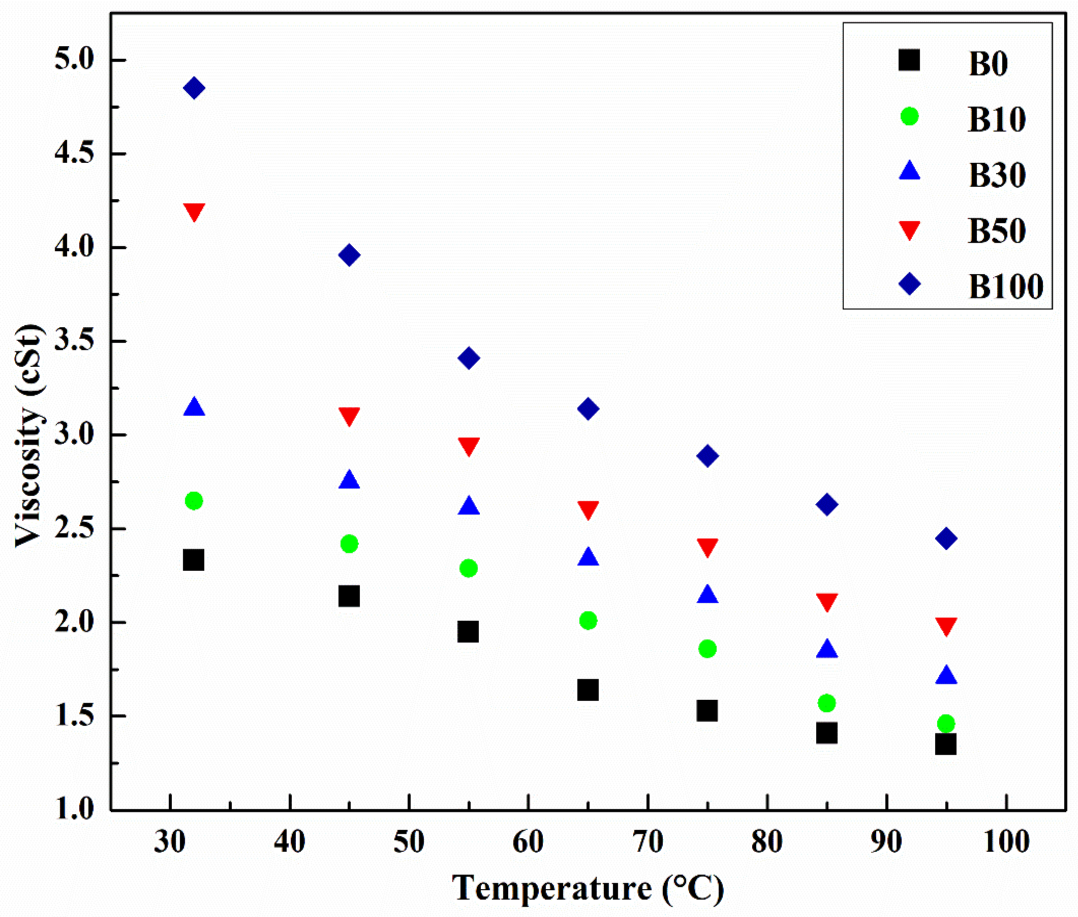


Fig. 5.3 The viscosity variation of test fuel with temperature

In the present work, neat CHOME biodiesel and its blend with regular diesel are preheated to 95 °C to decrease its viscosity before injection into the combustion chamber. Kinematic viscosity of preheated B100 is dropped by 49.5% compared to unheated. This will improve the engine combustion, performance, and emission characteristics.

Preheating setup is developed and connected with Kirloskar TV1 DI diesel engine injection system, as illustrated in Fig. 5.4, to heat the fuel prior to injecting it into the engine's combustion chamber

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1) Kirloskar TV 1 engine, 2) Fuel line with heater, 3) Fuel injector 4) Computer system, 5) Eddy current operated dynamometer, 6) Control panel, 7) Fuel consumption indicator, 8) Engine speed indicator display, 9) Temperature indicator, 10) Engine load controlling unit, 11) Gas analyzer, 12) AVL smoke analyzer

Fig. 5.4 Photographic view of the experimental setup with preheating arrangement

The engine's combustion, performance, and emission characteristics are tested by preheating the fuel at different engine loading conditions. This section determines performance matrices like brake thermal efficiency, brake specific fuel consumption, brake specific energy consumption, combustion characteristics such as in-cylinder pressure and NHRR, and exhaust gas emission characteristics are tested.

5.4 Engine performance test

The engine performance characteristics such as BTE, BSFC, and BSEC are computed by using preheated and unheated CHOME biodiesel-diesel blends (B0, B10, B30, B50, and B100) by varying the load on the engine. Neat regular diesel is used as a baseline to compare the results.

5.3.1 Brake thermal efficiency (BTE)

Figure 5.5 shows the BTE of regular diesel and CHOME biodiesel blends with regular diesel at various engine loads (0-100%). It can be seen from the figure that the BTE raises as the fuel preheated before injection for all blends.

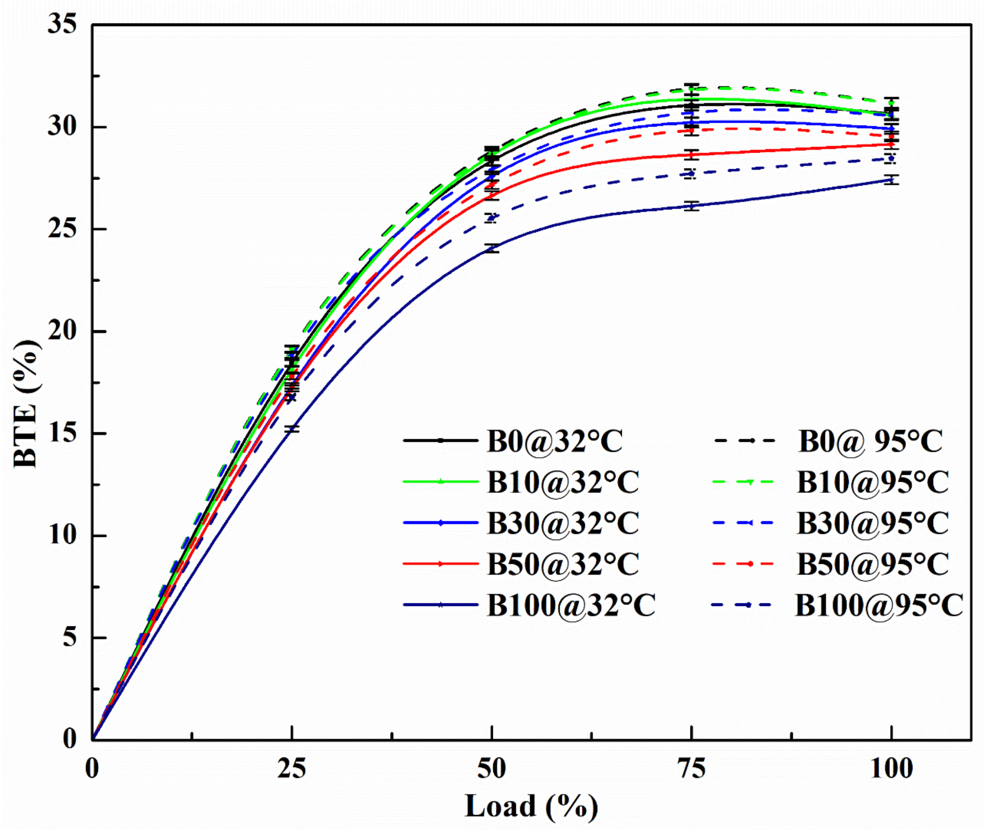

Fig. 5.5 BTE of preheated and unheated CHOME biodiesel-diesel blends versus engine load

The BTE of all blends at all loading conditions increased by preheating the fuel. This could be due to the reduced viscosity of the CHOME biodiesel fuel resulting in better atomization and combustion compared to unheated. BTE of preheated B10 is 0.5% higher than regular diesel, whereas B30 is closer to B0, indicating preheating the fuel improves the BTE of the engine. By preheating the testing fuel to 95°C, the BTE of B100 is increased by 5% compared to unheated.

5.3.2 Brake specific fuel consumption (BSFC)

The BSFC of the engine is determined for various fuel blends by changing the engine load, as presented in Fig. 5.6. BSFC of all tested fuels decreases as engine load increases. The probable reason for this is that the percentage of fuel in the fuel-air ratio increases as the load increases due to a smaller portion of heat loss at higher loads

(Godiganur et al., 2010). Increasing the portion of CHOME biodiesel in the blend increases BSFC proportionally. The probable reason for this could be the combined effect of higher density, viscosity, lower calorific value, and poor mixture formation of CHOME biodiesel compared to regular diesel (Augustine et al., 2012; Lapuerta et al., 2008; Pradhan et al., 2014).

Preheating the fuel before injection, BSFC of B100, B50, B30, B10, and B0 is reduced by 7.75%, 6.5%, 5.3%, 4.6%, and 4%, respectively compared to similar blends of unheated fuels.

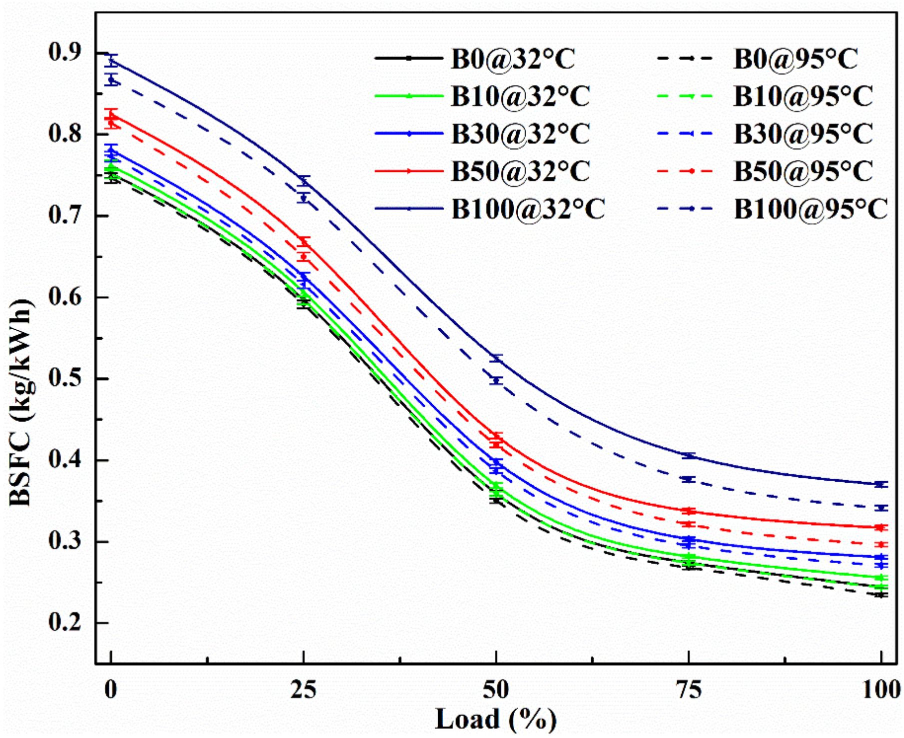

Fig. 5.6 BSFC of preheated and unheated CHOME biodiesel-diesel blends versus engine load

Preheated B10 has a lower BSFC than B0, while preheated B30 has significantly closer to B0. This is because preheating reduces viscosity and improves spray characteristics (Augustine et al., 2012). Similar trends are obtained by Vedharaj et al. (2015) on preheated cashew nut shell liquid biodiesel as an alternative fuel in diesel engine, Rajak et al. (2018) on spirulina microalgae biodiesel, Mekonen and Sahoo (2018) effect of fuel preheating on diesel engine operating parameters, and Walle Mekonen and Sahoo (2020) on the performance of preheated palm oil methyl ester used in a diesel engine.

5.3.3 Brake specific energy consumption (BSEC)

Fig. 5.7 depicts the BSEC comparisons of preheated and unheated regular diesel and blends of CHOME biodiesel at different blending ratios with various engine loading conditions.

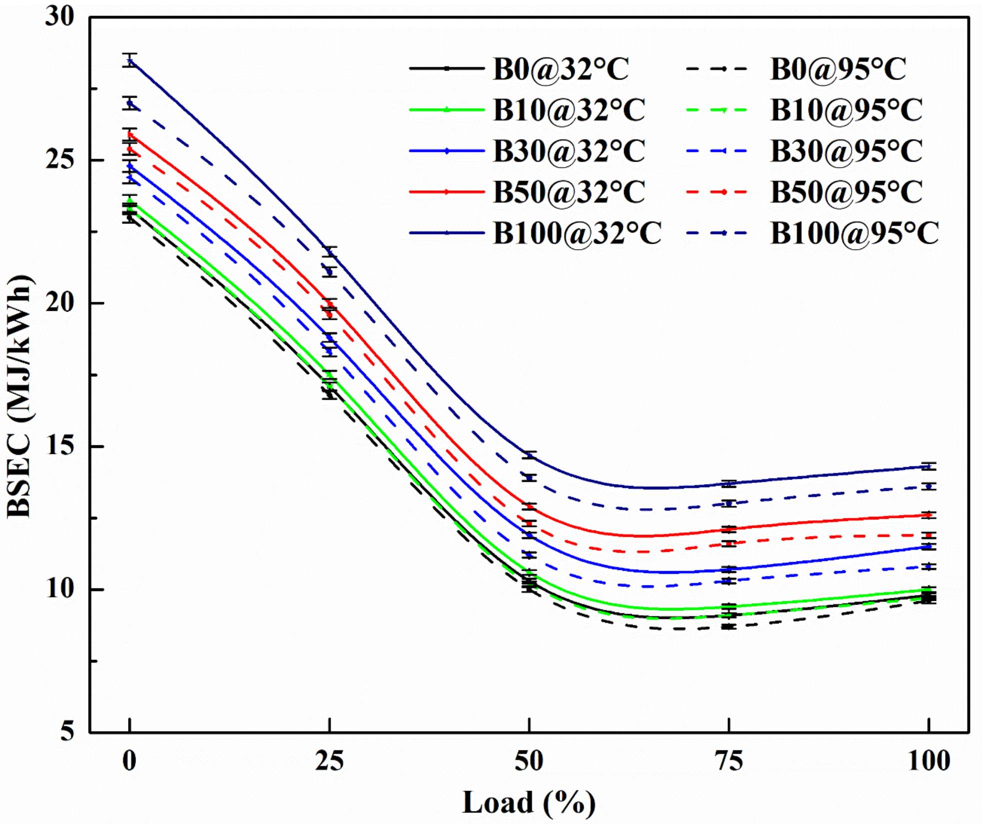

Fig. 5.7 BSEC of preheated and unheated CHOME biodiesel-diesel blends versus engine load

As it is shown from the figure the BSEC of fuel is lower than unheated fuel under all loading conditions. The BSEC is reduced by 2.04%, 2.6%, 3.21%, 4.29%, and 4.09% for B0, B10, B30, B50, and B100, respectively, by preheating. This is due to improved viscosity resulting in better atomization, vaporization, and mixing rate of the injected fuel (Chauhan et al. 2010). Similar trends were reported by Rao (2012) on engine fueled with preheated corn biodiesel, Shivaji et al. (2014) on preheated Pongamia oil, and Satyanarayana and Rao (2009) on Pongamia biodiesel in a DI diesel engine.

5.4 Combustion Characteristics

5.4.1 Cylinder pressure

Cylinder pressure is an important to consider when investigating combustion quality and engine efficiency. Fig. 5.8 depicts the cylinder pressure of all tested fuels (preheated and unheated) at 100% engine load with respect to crank angle. In-cylinder pressure of neat CHOME biodiesel and its blends follow the same trends as regular diesel. As shown in Fig. 5.8, the peak cylinder pressure of regular diesel is slightly greater than that of all biodiesel blends. This could be due to the higher viscosity, lower calorific value, and higher density of the biodiesel (Muralidharan et al., 2011; Subramani et al., 2018; Venu et al., 2021).

The maximum cylinder pressure of regular diesel and neat CHOME biodiesel (unheated) is 45.25 and 41.31 bar, respectively.

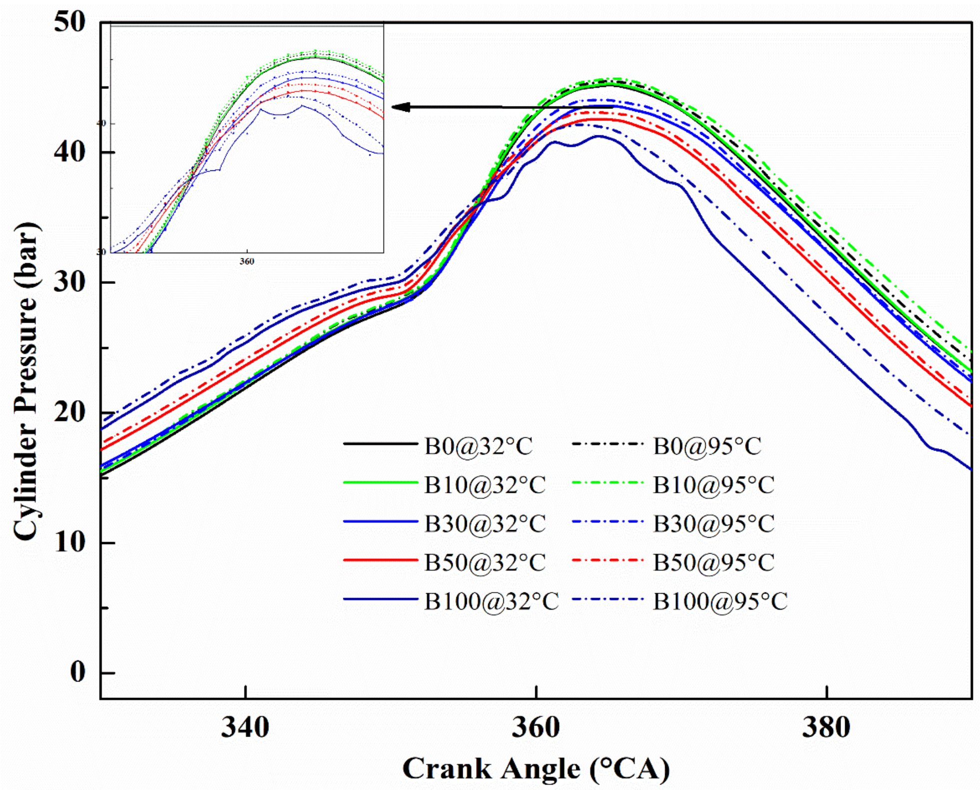

Fig. 5.8 Cylinder pressure versus crank angle

The rise in temperature decreases the viscosity of CHOME biodiesel to 2.45 cSt. Due to this, the atomization of the spray is improved, resulting in the combined effects of a better fuel-air mixture and better in-cylinder pressure compared to unheated fuels. By preheating test fuels to 95°C, the cylinder pressure of B0, B10, B30, B50, and B100 is improved by 2.81%, 2.97%, 3.11%, 3.4%, and 3.95%, respectively. Similar trends are reported by Kodate et al. (2021) on preheated Dhupa seed oil biodiesel.

5.4.2 Net heat release rate

The NHRR of an engine indicates the combustion phenomena of the fuel inside the combustion chamber. Fig. 5.9 depicts the NHRR of regular diesel and CHOME biodiesel at 100% engine load with respect to crank angle. The negative heat release rate is recorded during starting injection because of initiation of injection and ignition delay (Kathirvelu et al., 2017; Perumal and Ilangkumaran, 2017). Due to its higher viscosity and lower calorific value, it is observed that CHOME biodiesel blends release lower heat than regular diesel fuel. The maximum heat release rate of regular diesel, B10, B30, B50, and B100 is 20.14, 18.62, 16.87, 15, and 14.66 J °CA^{-1}, respectively.

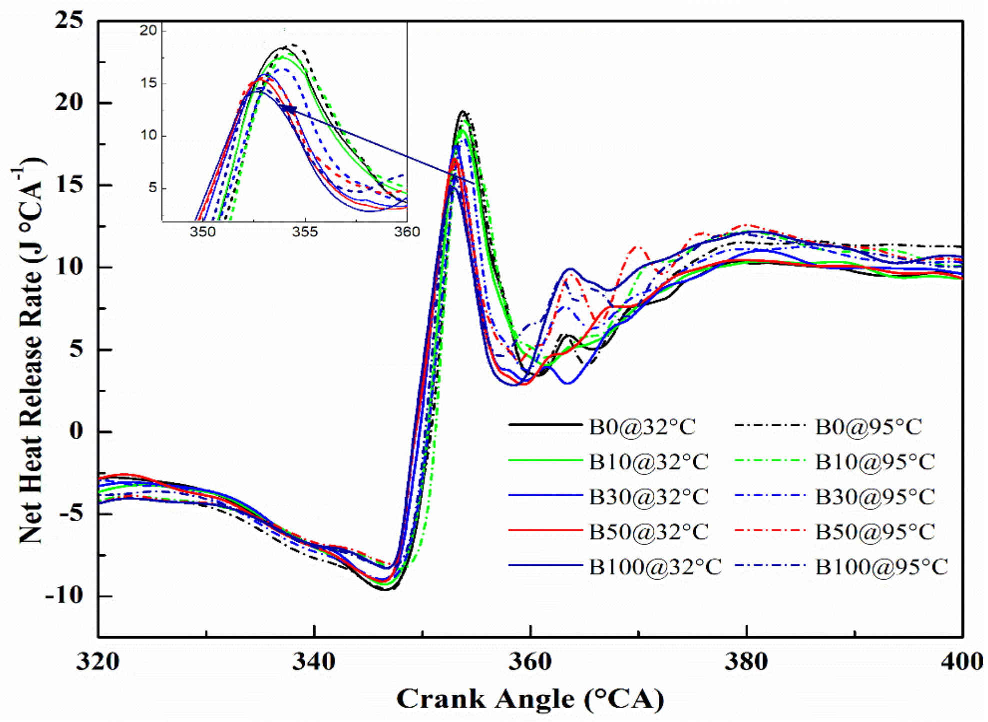

Fig. 5.9 Variation of NHRR with crank angle

Preheating the fuel prior to injection, the NHRR of regular diesel and neat CHOME biodiesel is increased from 20.35 to 20.56 J°CA^{-1} and 14.66 to 16.21 J°CA^{-1}, respectively. The enhanced NHRR could be attributed to better fuel atomization due to preheating (Gangwar et al. 2019). Similar trends are found by Viswanathan and Wang (2021) on preheated fish oil ethyl ester as a fuel in a diesel engine.

5.5 Engine emission analysis

Aside from engine performance and combustion, emission attributes such as nitrogen oxides (NOx), unburned hydrocarbons (HC), carbon dioxide (CO_2), oxygen (O_2), and smoke opacity are taken into account. The emission characteristics of the engine are evaluated for neat regular diesel and CHOME biodiesel with and without preheating by varying the load on the engine. After assessing the exhaust gas emissions of neat biodiesel and regular diesel, CHOME biodiesel is mixed with regular diesel at 10%, 30%, and 50%, and the emission characteristics of the blends are examined.

5.5.1 Oxides of nitrogen (NO_x)

The NO_x gas emission profiles of preheated and unheated CHOME biodiesel diesel-blends and regular diesel at different engine loading situations are depicted in Fig. 5.10.

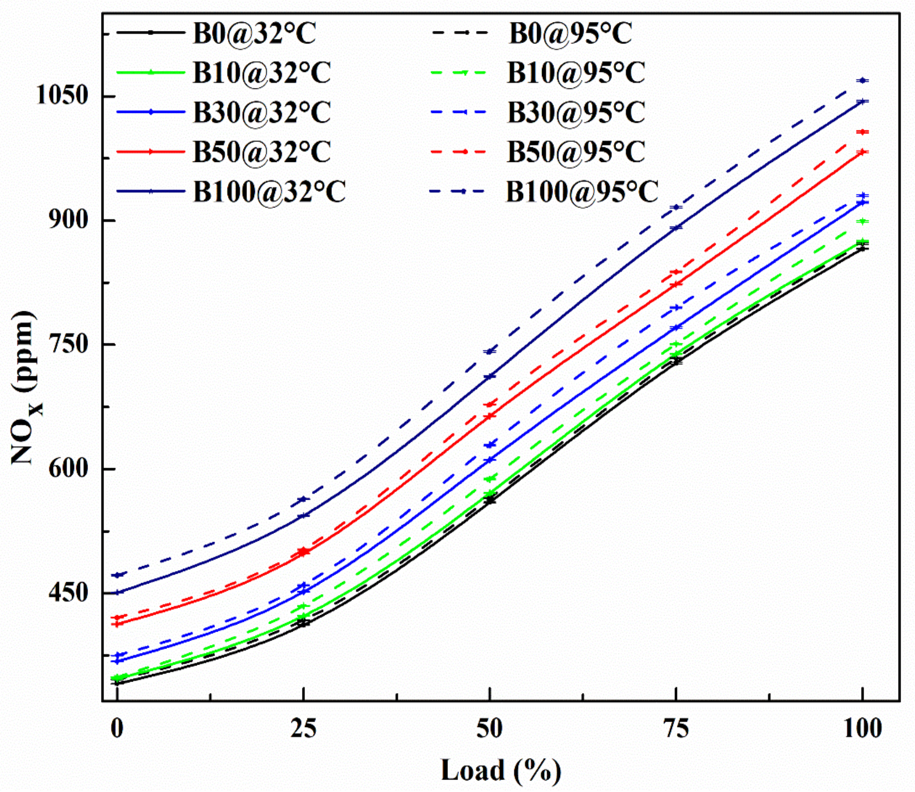

Fig. 5.10 Variations of NO_x emission with engine load

Preheating the test fuel also increases the NOx emission content of the exhaust emission marginally. For preheated B0, B10, B30, B50, and B100, NO_x emissions increase by 1.69%, 2.67%, 2.86%, 2.38%, and 2.34%, respectively. The increase in NOx emissions is caused by the combustion temperature being raised, the amount of oxygen being increased, and the time taken in the cylinder at temperatures that were enhanced.

Similar trends were observed by Kumar et al. (2021) on biofuel from Martynia annua seed in a diesel engine. Whereas in the experimental result by Reddy et al. (2020), it is shown that NO_x emission of canola oil methyl ester biodiesel is lower than regular diesel for both preheated and unheated.

5.5.2 Unburned hydrocarbon (HC) emission

The variation of HC in exhaust gas emission for unheated and preheated of all tested fuels is presented in Fig. 5.11.

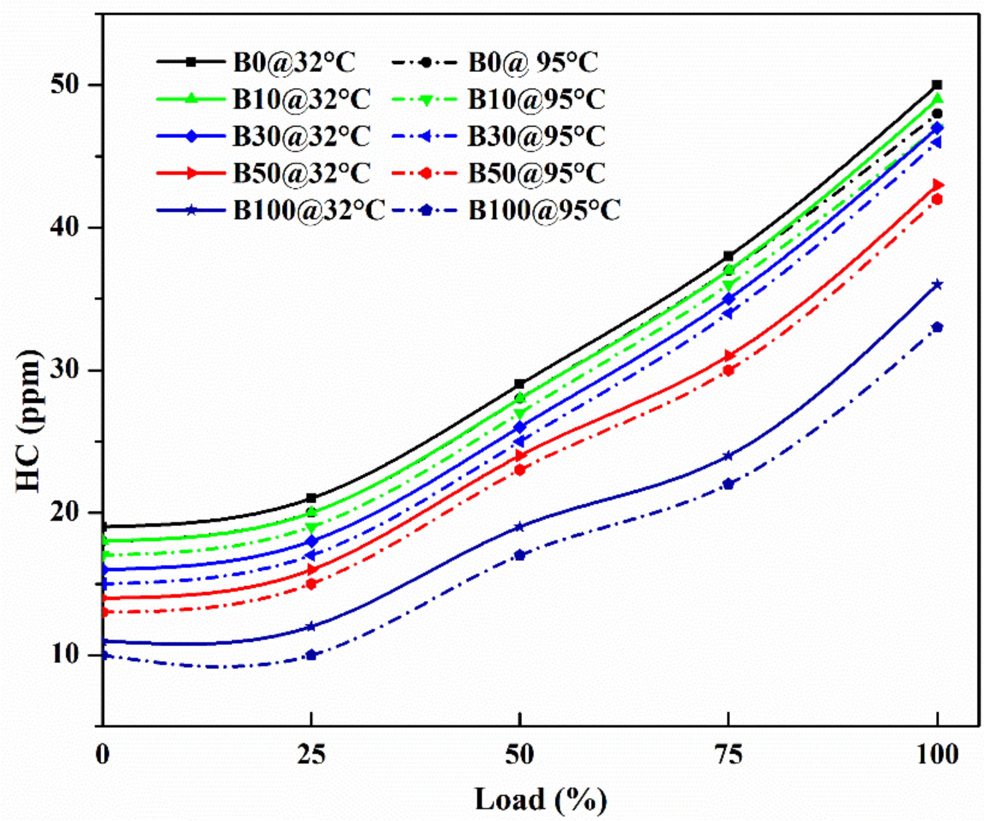

Fig. 5.11 Variation of HC for unheated and preheated CHOME biodiesel-diesel blends with load

Apart from increasing with loads, the figure clearly shows that HC emissions decrease preheated biodiesel-diesel blends. Preheating testing fuel improves the emission of HC in the exhaust gas. It is observed that HC emission of B0, B10, B30, B50, and B100 is reduced by 4%, 4.08%, 5.2%, 6.5%, and 8.33%, respectively. Preheated fuel has a lower viscosity than unheated fuel, which promotes atomization inside the combustion chamber and results in less HC. The finding is consistent with what was discovered by Sivasubramanian and Sajin (2021) by preheating neat biodiesel and Mekonen and Sahoo (2018a) by preheating both intake air and biodiesel blends.

5.5.3 Carbon monoxide (CO) emission

The variation of CO in exhaust emission for all tested fuels unheated and preheated all is shown in Fig. 5.12.

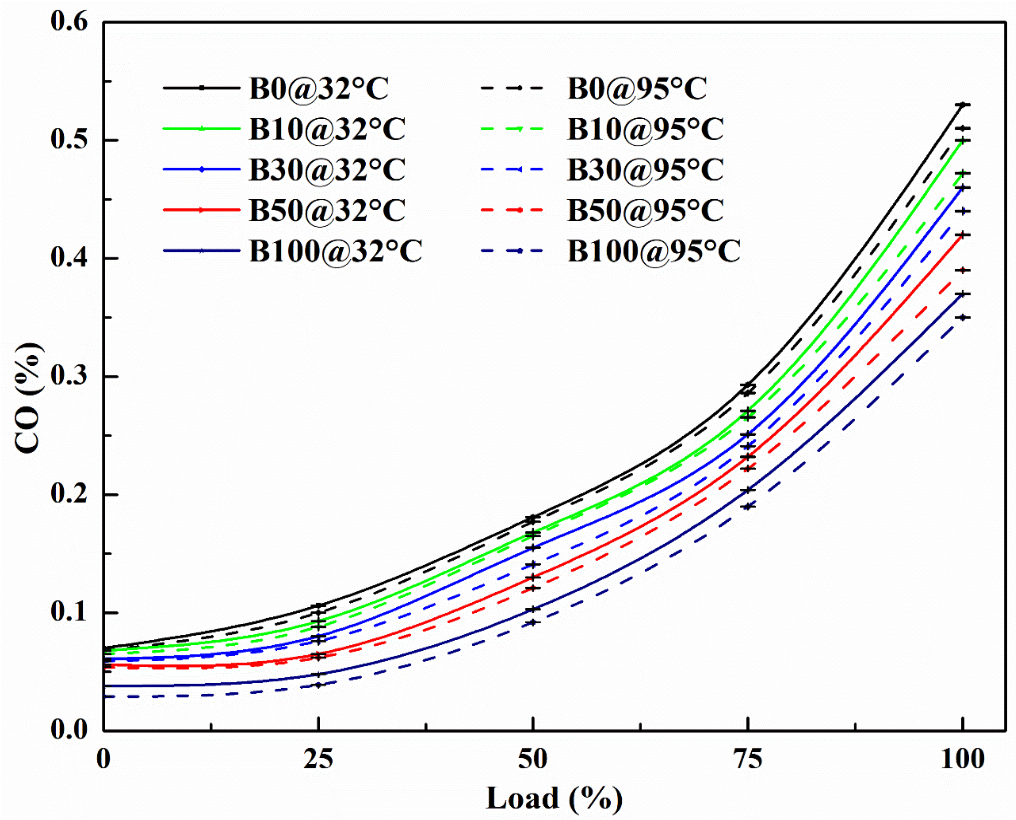

Fig. 5.12 Variation of CO for unheated and preheated CHOME-diesel blends with load

By preheating the CHOME biodiesel and its blend with regular diesel to 95°C, CO in the exhaust gas is reduced. This is due to the reduction of viscosity of the biodiesel resulting in good atomization of the fuel droplet, improved oxidation, and improved combustion. Preheating the testing fuel reduces CO emissions by 3.8%, 4.6%, 4.84%, 5.14%, and 6.4% for B0, B10, B30, B50, and B100, respectively. Similar results are presented by Chauhan et al. (2010) on preheated Jatropha oil in diesel engine, Hazar and Aydin (2010) on preheated raw rapeseed oil in diesel engine, and Ibrahim et al. (2020) on the effect of preheated Egyptian jatropha oil and biodiesel in a diesel engine.

5.5.4 Carbon dioxide CO_2) emission

Fig. 5.13 depicts CO_2 emissions for unheated and preheated CHOME biodiesel and its blend with regular diesel.

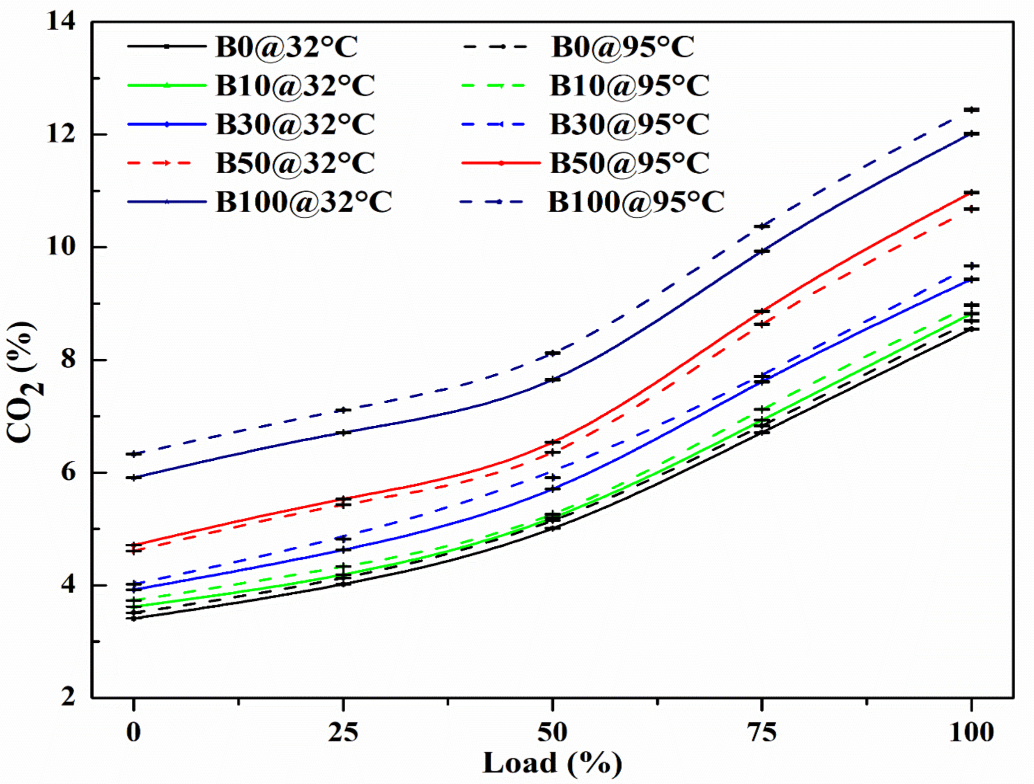

Fig. 5.13 Variation of CO_2 for unheated and preheated CHOME-diesel blends with load

By preheating the fuel, the concentration of CO_2 in the exhaust gas is considerably increased. The maximum concentration of CO_2 at full load for unheated B0, B100, and preheated B100 at 95°C was 8.55%, 12.02%, and 12.74%, respectively. CO_2 of preheated B0, B10, B30, B50, and B100 is improved by 1.6%, 1.67%, 2.48%, 2.64%, and 3.37%, respectively. This is because preheating the fuel before injection decreases the viscosity and density of the fuel which correspondingly improves the fuel atomization and better combustion compared to unheated fuel.

5.5.5 Smoke opacity

Fig. 5.14 depicts preheated and unheated regular diesel and CHOME biodiesel blend smoke opacity. As it is clearly seen from the figure, the smoke opacity decreases for all tested biodiesel diesel blends and B0 by preheating the fuel prior to injection.

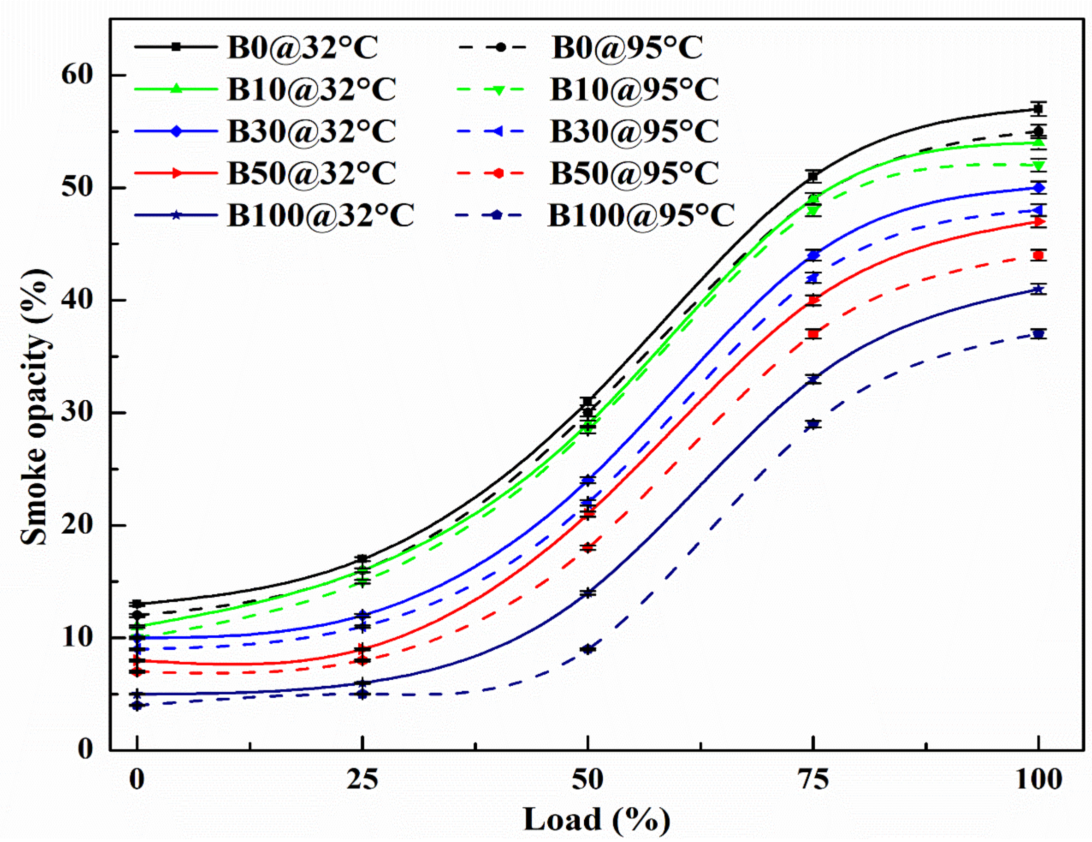

Fig. 5.14 Variation of smoke opacity for unheated and preheated CHOME biodiesel-diesel blends with engine load

Preheating the fuel to 95°C before injection reduces the smoke opacity in exhaust gas from 57% to 54% and 41% to 35% for B0 and B100, respectively. Compared to unheated fuel blends, the smoke opacity of B0, B10, B30, B50, and B100 are reduced by 5.5%, 5.9%, 6.4%, 14.6%, and 17.2%, respectively. This is because the fuel's viscosity and density are reduced, which improves fuel atomization during the injection time.

5.6 Change in performance and emissions of the engine

The change in performance and emission characteristics is measured using regular diesel as a baseline to evaluate the overall influence of preheated CHOME biodiesel blends on engine performance and emissions at full load. Fig. 5.15 shows the change in increase/decrease of performance and emission characteristics of the engine fueled with CHOME biodiesel blends using regular diesel as a baseline at full load and preheating the fuel to 95 °C before injection. Each observed performance and emission parameter's change is computed using equation (5.1 and 5.2).

$$\text{Change in performance}(\%) = \frac{\text{CHOME biodiesel performance} - \text{Regular diesel performance}}{\text{Regular diesel performance}} X100 \qquad (5.1)$$

$$\text{Change in emission}(\%) = \frac{\text{CHOME biodiesel emission} - \text{Regular diesel emission}}{\text{Regular diesel emission}} X\,100 \qquad (5.2)$$

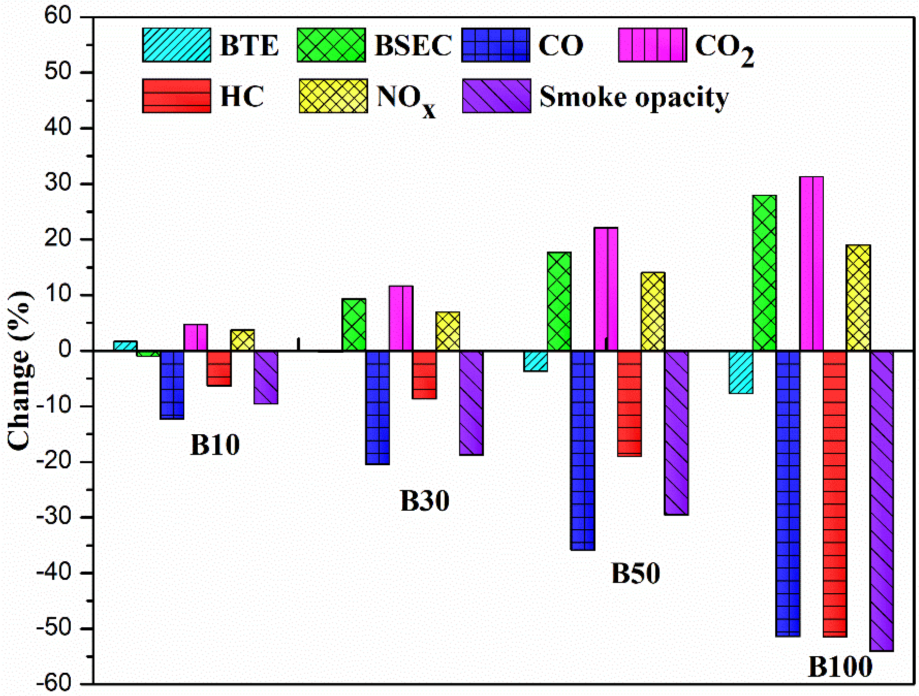

Fig. 5.15 Percentage change in performance and emission characteristics of preheated CHOME biodiesel-diesel blends at 100% load compared to unheated diesel

It is observed that the percentage change in BTE of the engine using neat CHOME biodiesel for B10, B30, B50, and B100 at 100% load is 1.6%, -0.24%, and -3.7%, and -7.7%, respectively. Preheated B10 has a higher BTE than unheated regular diesel, while preheated B30 has comparable performance to unheated B0. As the percentage of CHOME biodiesel increases, the rate of change in BSEC increases relatively.

The emission characteristics of preheated CHOME biodiesel show significant changes as the percentage in the blend increases. The rate of change in CO, CO_2, HC, and smoke opacity at full load is -51.43%, 31.27%, -51.52%, and -54.05%, respectively.

5.7 Conclusions

The study focuses on investigating the effect of unheated and preheated novel CHOME biodiesel on the engine's performance, combustion, and emission characteristics. The experiment is carried out with a Kirloskar TV-1 single-cylinder direct injection diesel engine, and an eddy current dynamometer is used for load variations on the engine. Preheating setup is arranged for the experimental purpose of heating the fuel before injection. The following significant conclusions are made based on the experimental investigation.

- Preheating the testing fuel up to 95 °C improves the viscosity of the B100 CHOME biodiesel by 49.5% leading to improved combustion, performance and emission characteristics.
- The BTE is improved by 1.63%, 1.83%, 2.17%, 1.32%, and 3.66% for B0, B10, B30, B50, and B100, respectively, by preheating before injection.
- Regular diesel exhibits lower BSFC and BSEC in all cases because of its higher calorific value and lower viscosity than all CHOME biodiesel blends, preheating the fuel before injection reduces the BSFC and BSEC compared to unheated blend under al loading conditions.
- Under normal temperature, the CHOME biodiesel's in-cylinder pressure and NHRR show lower values. By preheating the fuel before injection, in-cylinder pressure gets increased from 20.47 bar to 21.08 bar and from 23.86 bar to 24.42 bar for regular diesel and B100, respectively.
- For all the blends, preheating increases NO_x, CO_2, and lowers HC, CO, and smoke opacity in comparison to unheated fuels. Reductions in HC, CO, and smoke opacity are 8.3%, 6.4%, and 9.7% for B100 at 100% load, respectively.

CHAPTER 6

EFFECT OF INJECTION TIMING ON THE PERFORMANCE, COMBUSTION, AND EMISSION OF THE ENGINE FUELED WITH CHOME BIODIESEL

6.1 Introduction

It is known that injection timing substantially affects all engine properties. The reason for this is that injection timing has an effect on the air-fuel mixture's mixing quality and, consequently, on the entire combustion process (Agarwal et al., 2015; Anjaneya et al., 2018; Zhou et al., 2019).

In this chapter, altering injection timing techniques (25° CA bTDC – 29° CA bTDC) and load variation (0–100) are applied to evaluate the engine's performance, combustion, and emission characteristics by using B30. Neat regular diesel at standard injection timing is also tested and used as a baseline to compare the results. Fig. 6.1 shows the flow chart of the experimental work procedure.

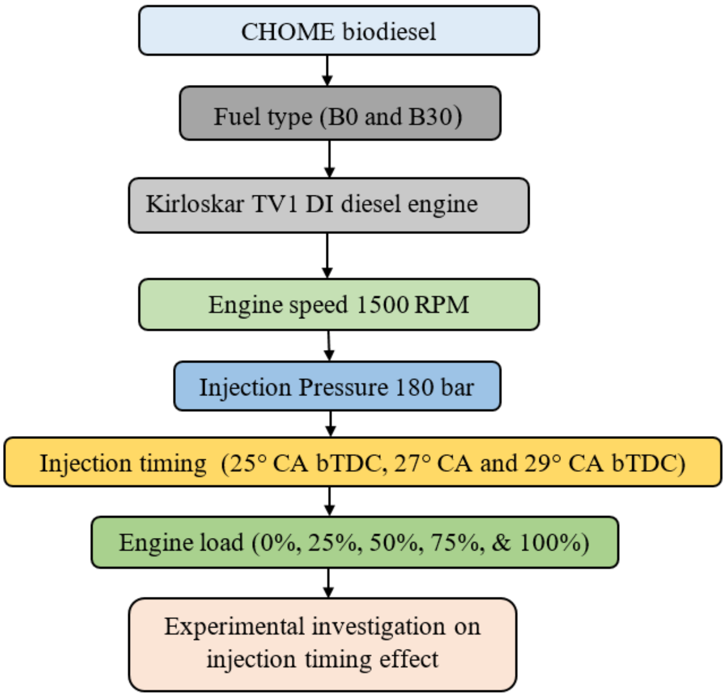

Fig. 6.1 Research strategy for an experiment on varying injection timing

6.2 Varying the injection timing

The injection timing of the engine is varied by changing the thickness of the shim between mounting flange of the injection pump and engine, as shown in Fig. 6.2. To vary the injection timing, a 0.3 mm thick shim is used.

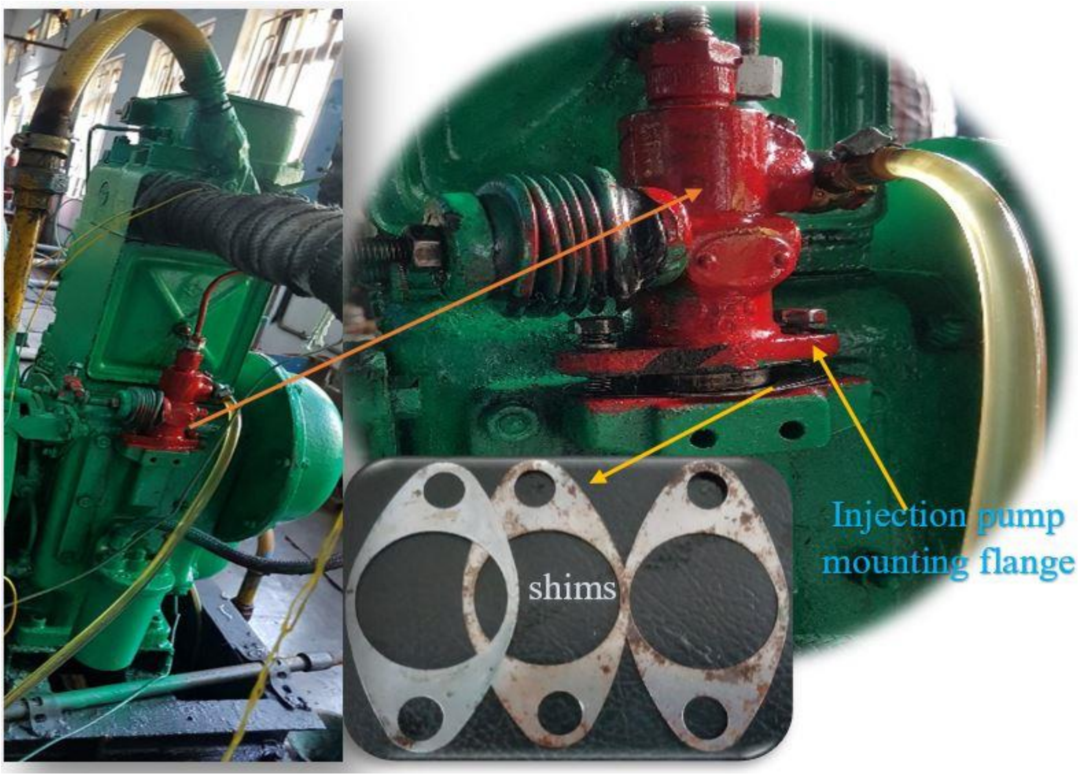

Fig. 6.2 Injection timing adjustment

The standard injection timing of the engine is 27° CA bTDC. Removing one shim under the mounting flange advances the injection timing by 2° CA (from 27° CA bTDC to 29° CA bTDC). Similarly, adding one 0.3 mm shim retards the engine injection timing by 2° CA (from 27° CA bTDC to 25° CA bTDC). In this experimental investigation, three injection timing positions and two fuels (regular diesel and B30) are tested by varying the injection timing. The three injection timings applied for the experiment are standard injection timing (27° CA bTDC), advanced injection timing by 2° CA bTDC (29° CA bTDC, removal of one shim), and retarded injection timing by 2° CA bTDC (25° CA bTDC, the addition of one shim). In the beginning, the experiment was started by running (idling state) the engine under standard injection timing for twenty minutes by using regular diesel to achieve steady-state conditions of the engine. After the engine reaches steady-state conditions, the engine is operated on regular diesel and B30 at various engine loading conditions (0, 25, 50, 75, and 100%) with a standard injection timing of 27° CA bTDC.

Then, the experiments are carried out for advanced and retarded injection timings for B30. For all the tests, 100 cycle reading is noted, and average values are used to analyze the result to minimize the error. All tests are repeated five to ten times to reduce the error of the reading equipment, and the average readings are used to make comparisons.

6.3 Engine performance test

Engine performance metrics such as BTE and BSEC are tested by altering injection timing by (29° CA bTDC, 27° CA bTDC, and 25° CA bTDC). Regular diesel is utilized as a baseline with original injection timing to compare the findings.

6.3.1 Brake thermal efficiency (BTE)

Fig. 6.3 illustrates the BTE of regular diesel and B30 at various loads (0–100%) and injection timings.

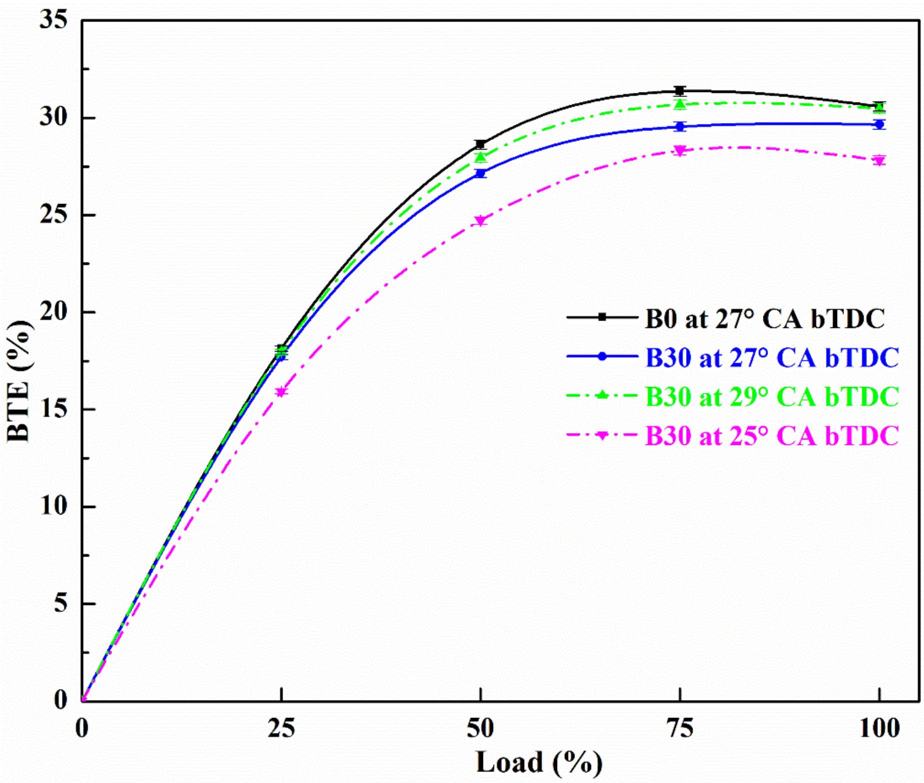

Fig. 6.3 BTE of regular diesel and B30 at various engine loads and injection timing

The BTE of B30 is enhanced by altering the injection timing to 29° CA bTDC, and the graph nearly coincides with B0 at 27° CA bTDC, as indicated in Fig. 6.3. BTE for regular diesel at standard injection timing and B30 at 27° CA bTDC, 25° CA bTDC, and 29° CA bTDC injection timings are 31.6%, 29.7%, 27.8%, and 30.9%, respectively, at full load. For B30, advancing the injection timing by 2° CA (f 27° CA bTDC - 29° CA bTDC) increases the BTE of the engine by 1.2%. This may be due to longer mixing time, reduced slow-burning, and early start of combustion caused by the advancement of the injection time, resulting in improved combustion (Jamuna Rani et al., 2020). However, retarding the injection timing shows lower BTE due to insufficient time available to achieve complete combustion.

6.3.2 Brake specific energy consumption (BSEC)

Fig. 6.4 displays the BSEC comparisons of B30 with regular diesel at various injection timing and engine loading conditions.

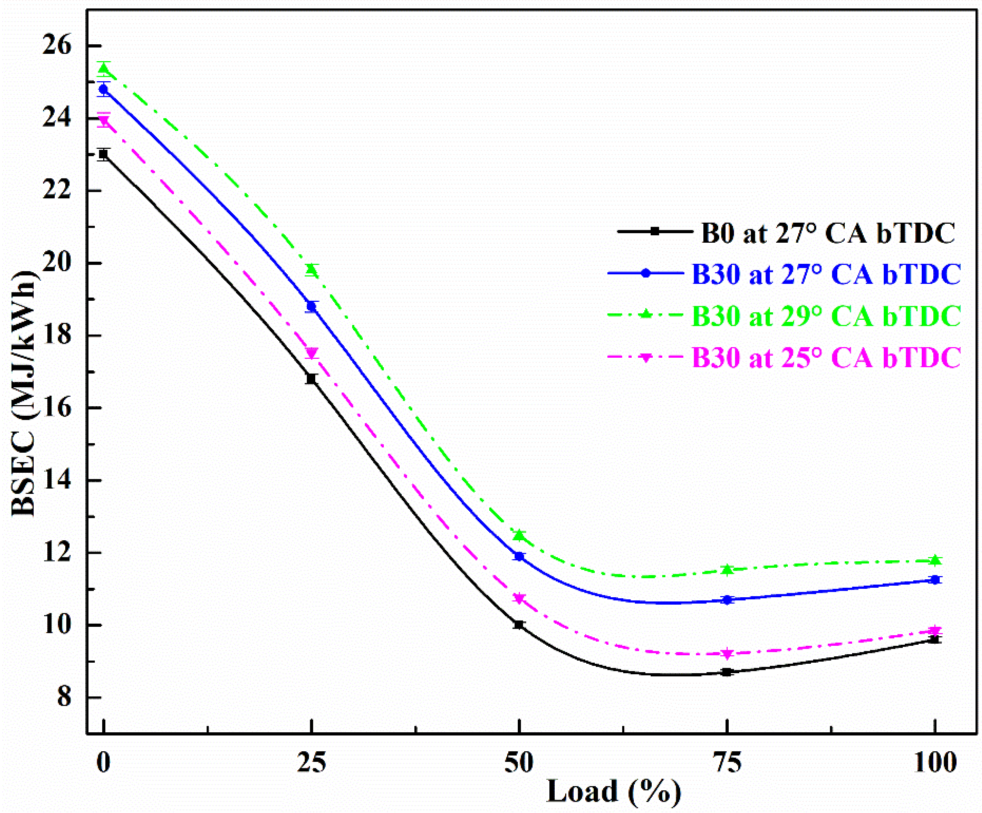

Fig. 6.4 BSEC of regular diesel and B30 at various injection timing and engine loads

Advancing the injection timing, the BSEC increases for the B30, whereas retarding injection timing causes a reduction in BSEC. The BSEC of the B30 increases by 0.53 kg/kW/h when the injection timing is advanced by 2° CA from the standard injection timing of 27° CA bTDC and decreases by 1.4 kg/kW/h when the injection timing is retarded by 2° CA bTDC (27° CA bTDC - 25° CA bTDC). This is because the B30 has a lower calorific value and a higher density than regular diesel, resulting in increased fuel consumption to provide the same power output level. Lower BSEC were obtained with retarded injection timing under all operating conditions for the same blend. This is because biodiesels have higher viscosity that needs a longer combustion duration compared to regular diesel, and less fuel is needed as the injection timing retarded. The majority of the fuel is used during the expansion stroke, while some fuel escapes through the exhaust without being burned. This may increase the amount of HC in the exhaust gas. At full load, the BSEC of regular diesel at standard injection timing and B30 operating at standard, 29° CA bTDC, and 25° CA bTDC are 9.6, 11.25, 11.78, and 9.85 MJ/KW/h, respectively. Similar results are reported by Harish et al. (2020) on diesel engine running with milk scum oil biodiesel at different injection timing.

6.4Combustion characteristics

6.4.1 Cylinder pressure

Fig. 6.5 compares the cylinder pressure of the B30 at different injection timing and loading conditions with regular diesel as a baseline at standard injection timing.

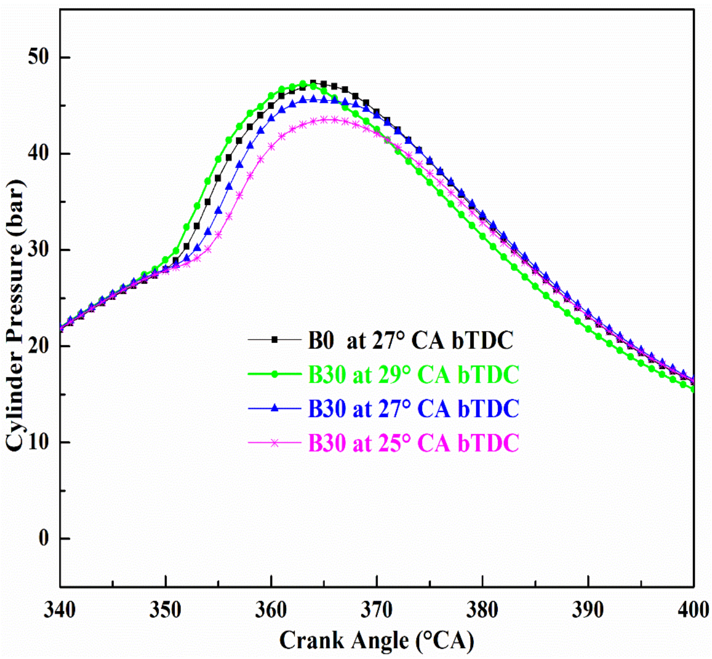

Fig. 6.5 Peak cylinder pressure at varied injection timing and load

Higher in-cylinder pressure is obtained for diesel compared to the B30 at standard injection timings. There have been rich fuel zones in the combustion chamber where a higher heat value, and lower kinematic viscosity of diesel, have made the fuel to burn more quickly before the piston reaches the top dead center Emma et al. (2022). The maximum cylinder pressure of B30 injecting at 27° CA bTDC is 45.64 bar which is 1.7 bar lower than regular diesel at same injection timing. Regular diesel and B30 at standard injection timing, B30 at advanced injection timing, and B30 at retarded injection time exhibit maximum cylinder pressures of 47.33 bar, 45.64 bar, 46.5 bar, and 43.54 bar, respectively. As the injection timing advances, the cylinder pressure of the B30 increased by 0.86 bar compared to standard injection timing. The increased cylinder pressure may be attributed to an increase in heat release; the accumulation of fuel in the combustion chamber as a result of the advanced injection timing leads to an increased rate of air/fuel ratio; because of which the air/fuel ratio approaches a stoichiometric state Nayak et al. (2022). In addition, because the fuel was introduced earlier, the combustion process was delayed, and accumulated heat released from the fuel resulted in high cylinder pressure in the cylinder. Similar results are reported by Sudarmanta et al. (2021) on engine fuelled with dual fuel by varying the injection timing.

6.4.2 Net heat release rate (NHRR)

Fig. 6.6 depicts the NHRR of regular diesel at standard injection timing and B30 at standard, advanced, and retarded injection timing. It is observed that, altering the injection timing varies the NHRR.

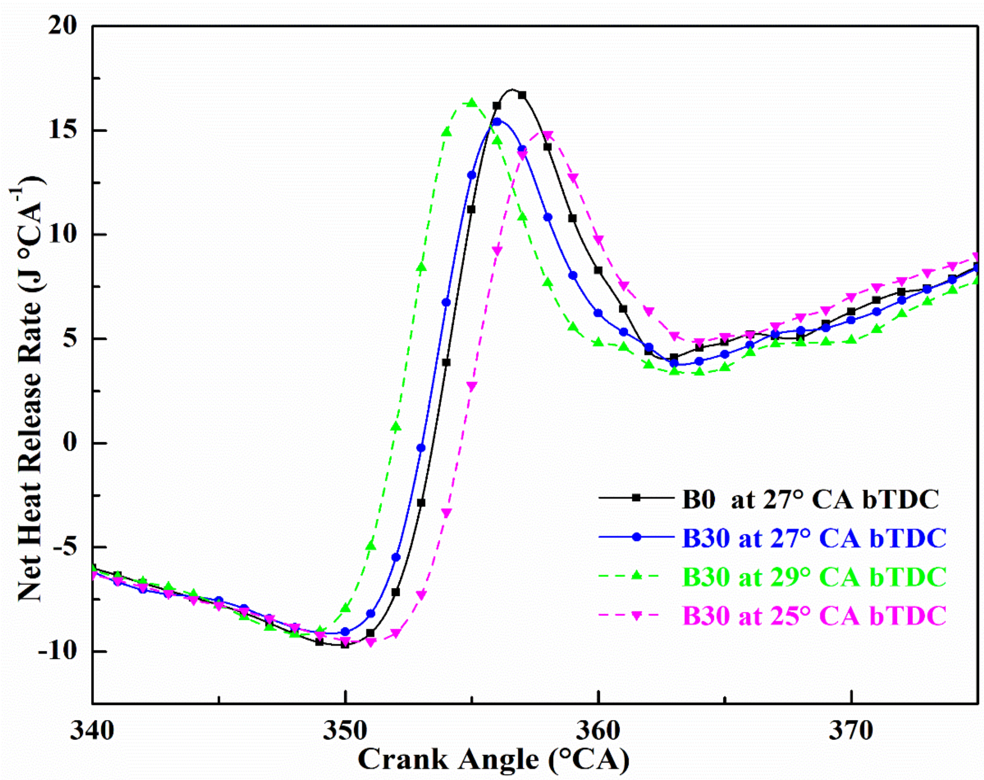

Fig. 6.6 Effect of injection timing on NHRR of B30 at various loads

As shown in Fig. 6.6, altering the injection timing by advancing or retarding against the standard injection timing changes the NHRR. The maximum NHRR of regular diesel at standard injection timing and B30 at standard, advanced and retarded injection timing are 16.89, 15.41, 16.19, and 14.82 J°CA^{-1}, respectively. Advanced injection timing encourages premixed air and fuel accumulation, longer ignition delay, and improved combustion processes resulting in a high NHRR (Rami Reddy et al., 2021). Due to this, injection timing at 29° CA bTDC produces higher NHRR compared to standard and retarded injection timing. At retarded injection timing, the NHRR is lower compared to standard and advanced injection timing; since, at retarded injection timing, the combustion and premixed time are shorter, resulting in incomplete combustion. Compared with both retarded and standard injection timing, the B30 shows a better NHRR with advanced injection timing. Jamuna Rani et al. (2020)

reported similar findings on diesel engine run with biodiesel blends by altering injection timing.

6.5 Effect of injection timing on emission

The engine exhaust gas emissions of B30, in comparison with regular diesel, by altering injection timing, are analyzed for unburned hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), smoke opacity, and carbon dioxide (CO_2).

6.5.1 HC emission

Fig. 6.7 depicts the HC of regular diesel, B30 at standard, advanced, and retarded injection timing. It is observed that altering injection timing varies the HC emission in the exhaust gas.

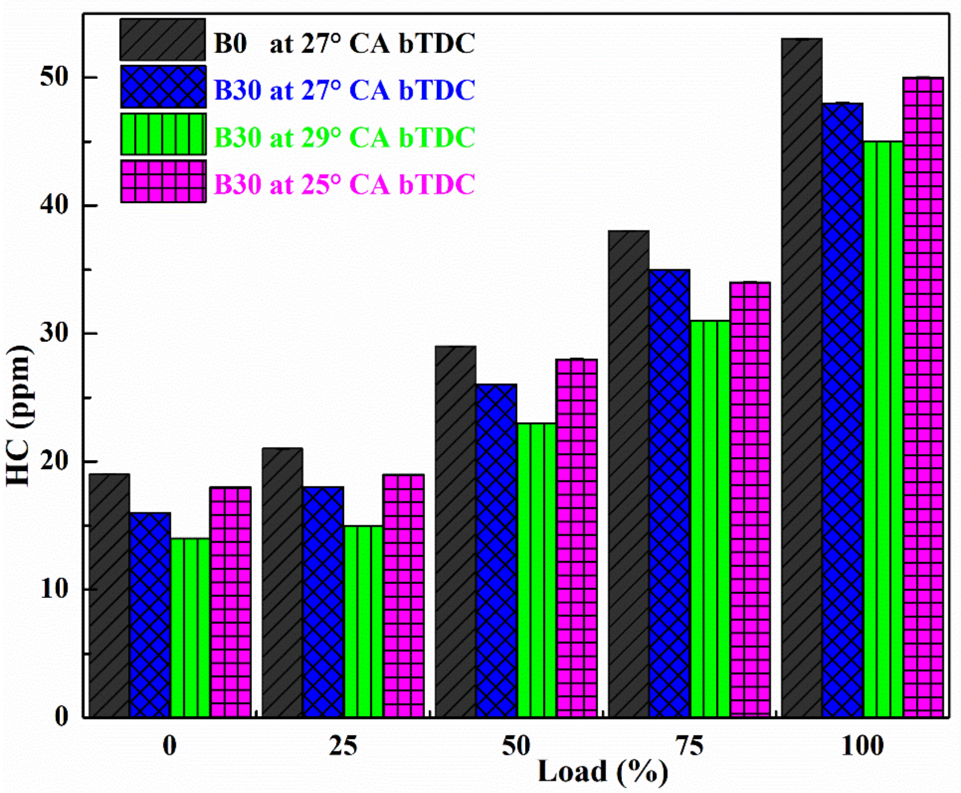

Fig. 6.7 Variations of HC with injection timing and loads

At 100% load, the concentration of HC of B30 at standard, advanced and retarded injection timings is reduced by 10.4%, 17.8%, and 6%, respectively, compared to regular diesel at standard injection timing. When injection timing is retarded, HC emissions increase, but when injection timing is advanced, HC emissions decrease. In advanced injection timing, the availability of a longer combustion time encourages the fuel in the combustion chamber to burn more thoroughly, which lowers the concentration of HC emissions from the engine. Reddy et al. (2021) reported HC results similar to this on diesel engine fuelled by waste mango seed biodiesel at different injection timings and EGR rates.

6.5.2 CO emissions

Fig. 6.8 shows the variations of CO emission of B30 at various load and injection timing using regular diesel as a baseline. It is observed that the CO formed during the combustion with B30 is lower than regular diesel at standard injection timing for all loading conditions.

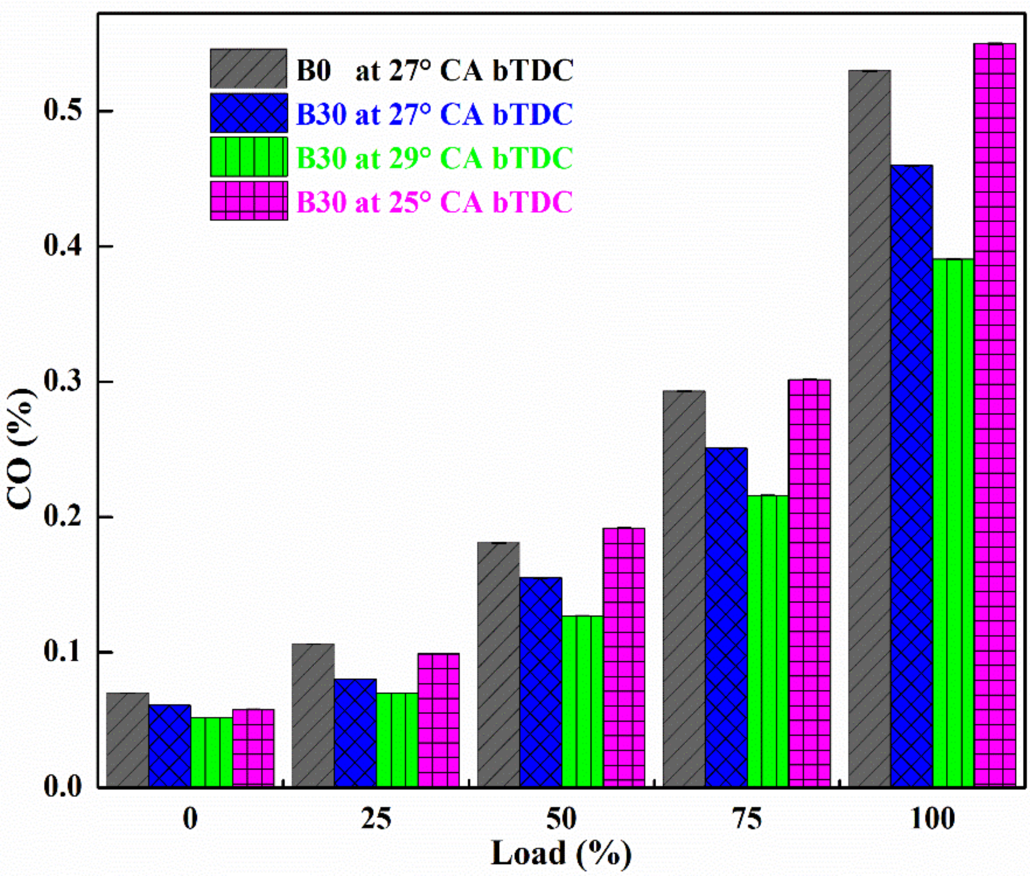

Fig. 6.8 Variation of CO emission with engine load and injection timing

Advancing the injection timing reduces the concentration of CO in the exhaust gas at all engine loading conditions. At full load conditions, the CO of B30 at advanced injection timing is 36% and 15.2% lower than regular diesel and B30 at standard injection timing. CO reductions are primarily due to better oxidation reactions during the premixed stage because of an early start of combustion, longer combustion time, and better afterburner performance because of higher in-cylinder temperatures (Appavu et al., 2018; Anjaneya et al., 2018). Conversely retarding the injection timing increases the CO emission of the B30.

6.5.3 CO_2 emission

The variation of CO_2 emissions with engine loads and varied injection timings is presented in Fig. 6.9. It is found that CO_2 emission is changing with an altering injection timing.

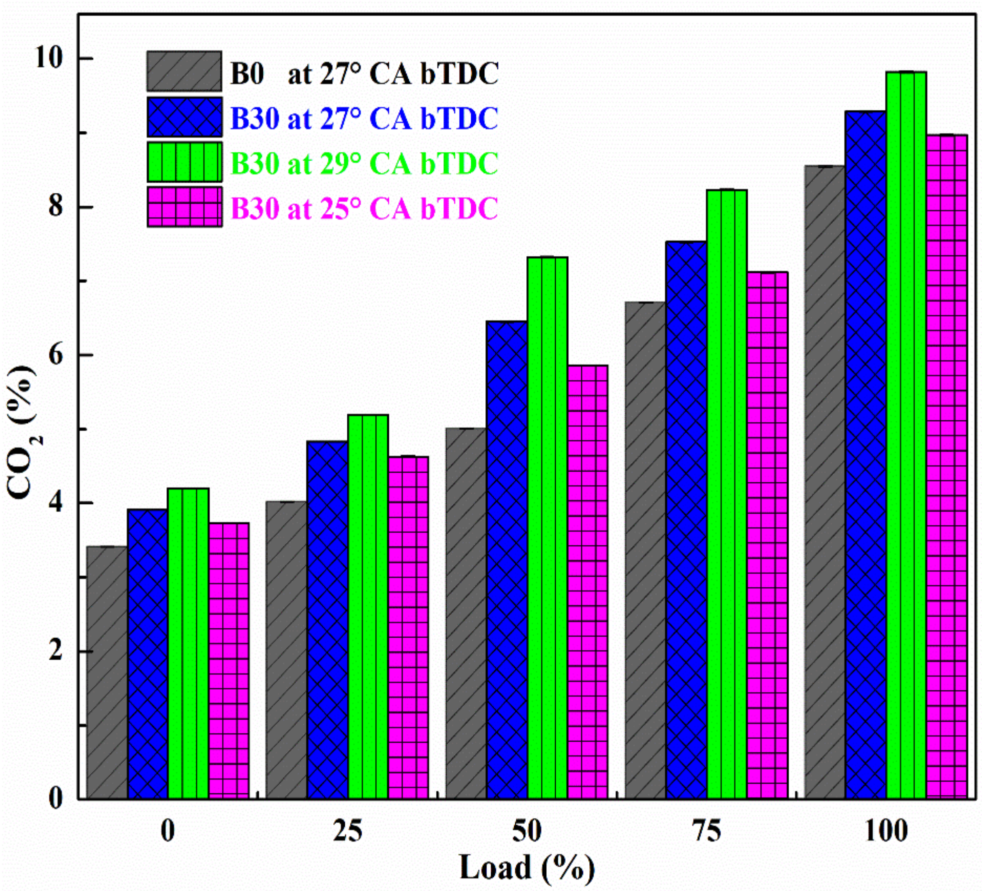

Fig. 6.9 Variation of CO_2 with engine load and injection timing

As shown in Fig. 6.9, advancing the injection timing also increases the production of CO_2 in the exhaust gas. This may be due to the combined effect of increased fuel consumption and longer combustion time. Similar trends are also reported by Sayin and Uslu (2008) on diesel engine fuelled with ethanol-blended diesel and Öztürk et al. (2020) on diesel engine fuelled with canola biodiesel by varying injection timing.

6.5.4 NO_x emission

The variation of NOx emission in the exhaust gas of B30 at standard, advanced and retarded injection timings and regular diesel at standard injection timing is depicted in Fig. 6.10.

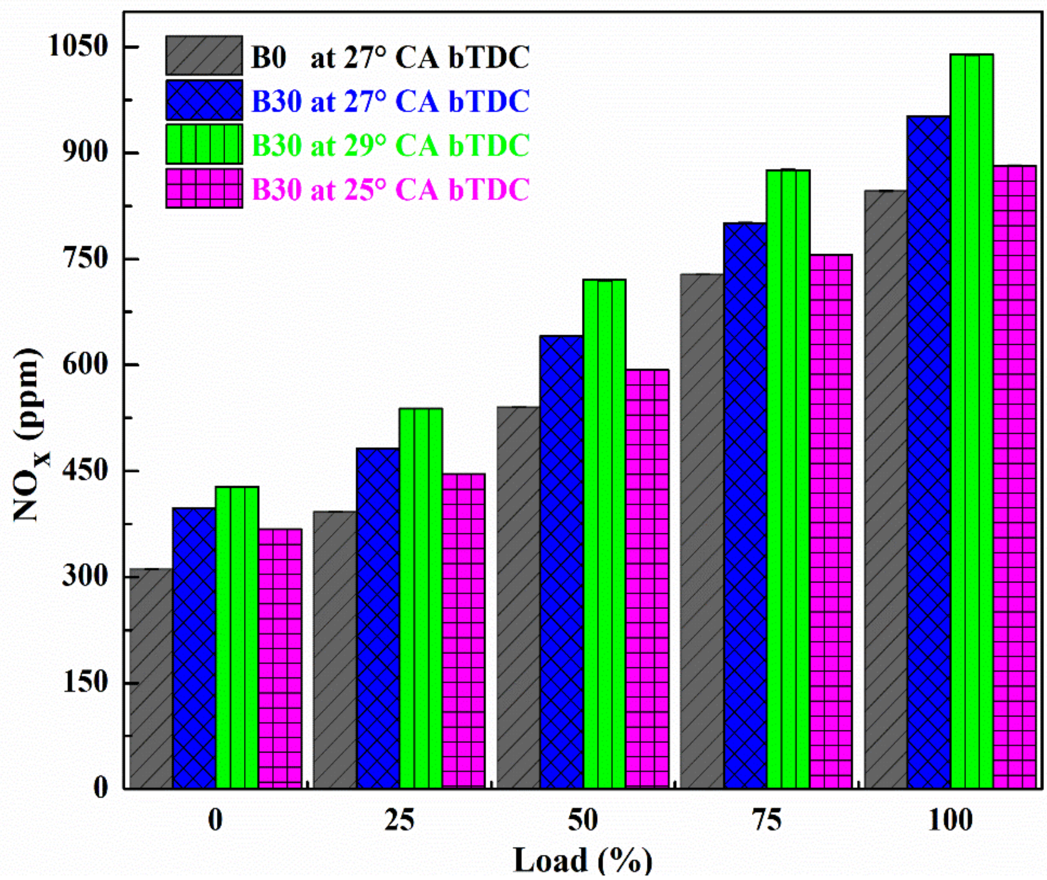

Fig. 6.10 Variation of NO_x emission with injection timing and load

Advancing the injection timing increases the NO_x emission in the exhaust gas. At full load, the NO_x emission in the exhaust gas is increased by 9.6% compared to standard injection timing. This could be due to higher cylinder temperature and a higher heat release rate at advanced injection timing, resulting in more fuel burns as the combustion starts earlier than standard injection timing. Retarding the injection timing reduces the NO_x emission in the exhaust gas by 7.4% compared to standard injection timing. This is because at retarded injection timing, the maximum cylinder pressure decreases as more fuel burns after TDC. Similar results are reported by Jindal (2011) on CI engine running with Karanja methyl ester by changing injection timing and Reddy et al. (2021) on diesel engine powered with waste mango seed biodiesel at different injection timings and EGR rates.

6.5.5 Smoke opacity

Fig. 6.11 depicts the smoke opacity of regular diesel at standard injection timing and B30 at standard, advanced, and retarded injection timing with the load.

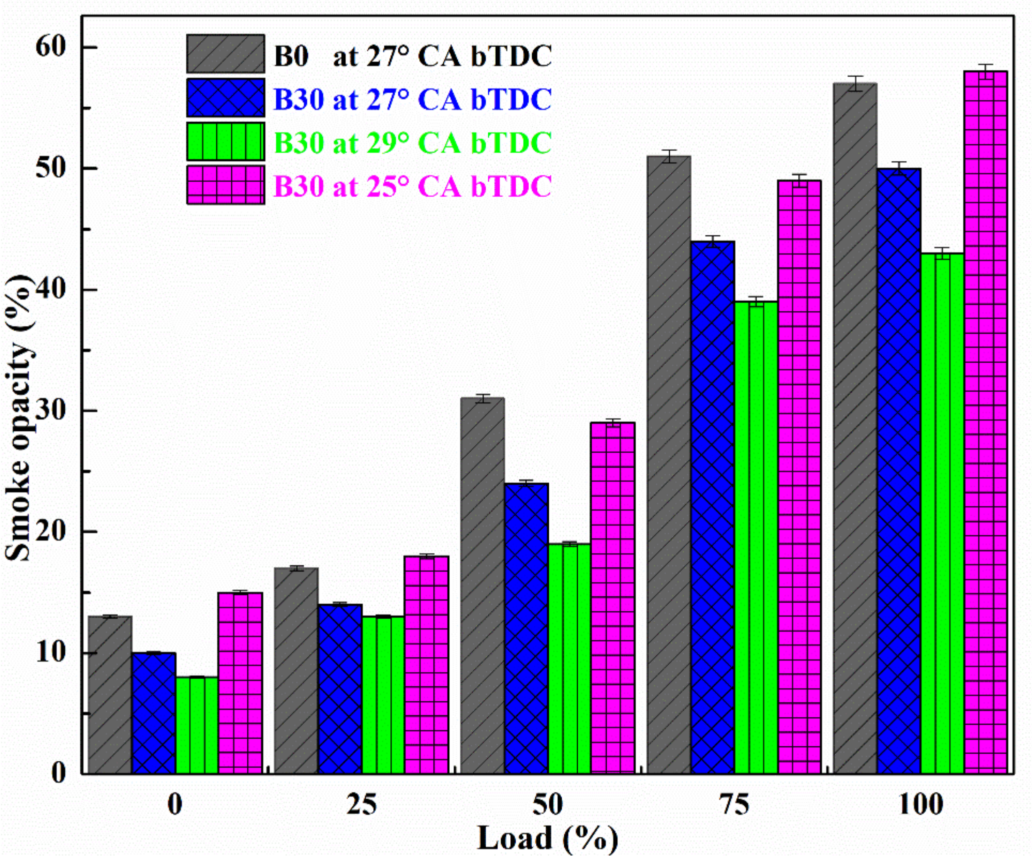

Fig. 6.11 Variation of smoke opacity with injection timing and load

It is observed that as the injection timing is advanced by 2° CA, the smoke opacity in the exhaust gas reduced. At full load, the smoke opacity of B30 is found to be 50% and 43%, respectively, while using standard and advanced injection timing. Lower smoke opacity is determined at advanced injection timing due to the complete combustions of hydrocarbons due to prolonged ignition delay and extra oxygen contributed by the B30. The result is nearly similar to the IC engine working on quaternary blends by Nayak et al. (2022) by changing injection timing.

6.6 Changes in the performance and emission of the engine

The change in performance and emission characteristics is measured using regular diesel at standard injection timing as a baseline to evaluate the overall influence of B30 at advanced and retarded injection timing on engine performance and emissions at full load. Fig. 6.13 depicts the change in performance and emission characteristics using B30 at full load by changing the engine's injection timing. The formula used to calculate the change in performance and emission is shown in equations (6.1 and 6.2).

$$\text{Change in performance}(\%) = \frac{\text{performance of B30 at } 29° \, CA \, bTDC - \text{Performance of regular diesel at } 27° \text{ CA bTDC}}{\text{Performance of regular diesel at } 27° \text{ CA bTDC}} \text{X } 100 \qquad (6.1)$$

$$\text{Change in emission}(\%) = \frac{\text{Emission of B30 at } 29° \, CA \, bTDC - \text{Emission of regular diesel at } 27° \text{ CA bTDC}}{\text{Emission of regular diesel at } 27° \text{ CA bTDC}} \text{X } 100 \qquad (6.2)$$

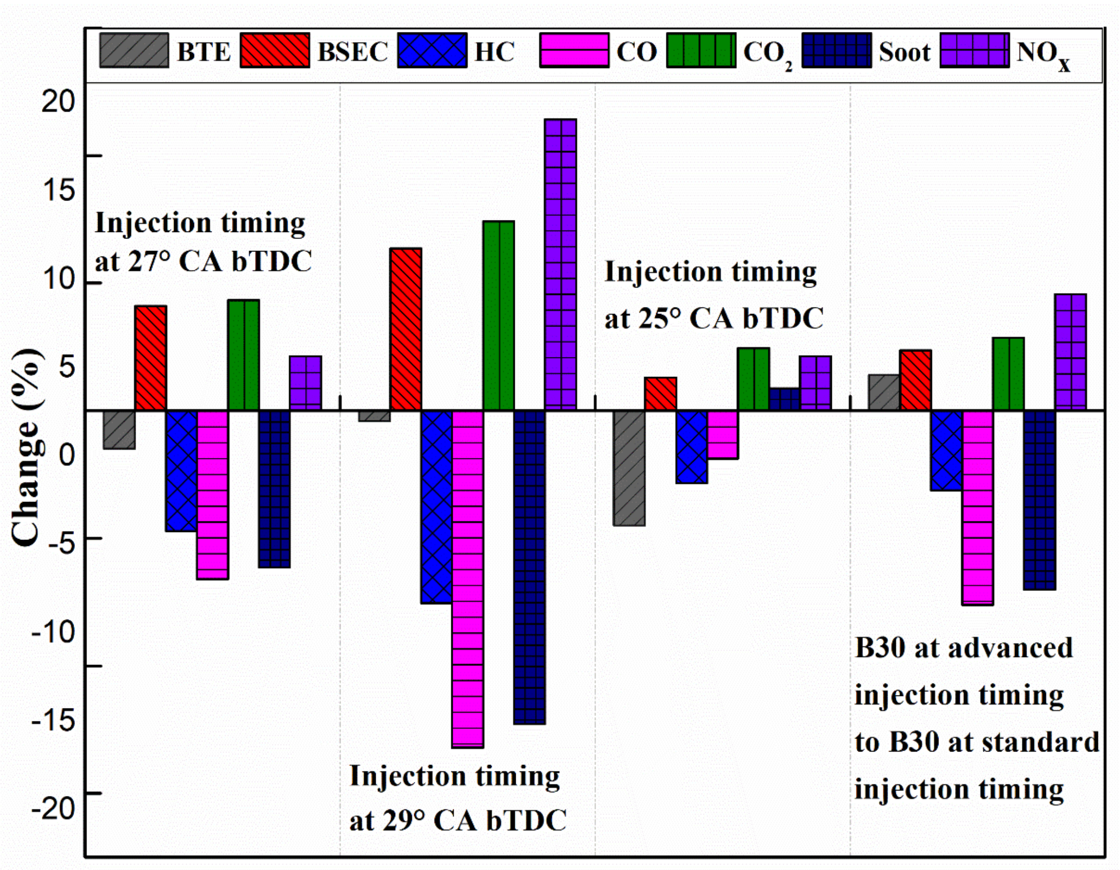

Fig. 6.12 Percentage change in performance and emission characteristics of B30 at 100% load, varying injection timing

It is observed that compared to regular diesel fuel, the B30 shows lower BTE at all injection timings in the present study. Compared to regular diesel at standard injection timing, the BTE of B30 is reduced for standard, advanced and retarded injection timing, as indicated in Fig. 6.13. When comparing the B30 at standard and advanced injection timings, the BTE gets improved, and the BSEC of the engine gets increased while advancing the injection timing.

Altering the injection timing of the engine, the exhaust gas emission characteristics gets affected significantly. At advanced injection timing, HC, CO, and smoke opacity (soot) get reduced, and NO_x gets slightly increased, as shown in Fig. 6.12.

6.7 Conclusions

The influence of injection timing on the performance, combustion, and emission characteristics of a DI diesel engine is investigated in this study. The main parameters varied in this investigation were injection timing, load on the engine, and type of fuel. The key experimental findings of this study are listed below.

- BTE of the engine using B30 is increased by 1.2% by advancing the injection timing statically by 2° CA at 100% load compared to standard injection timing at full load conditions. Retarding the injection timing reduces the BTE of the engine under all loading conditions.
- Advancing the injection timing increases the BSEC of the engine under all loading conditions, whereas retarding reduces the BSEC of the engine.
- The peak cylinder pressure of the engine using B30 at advanced injection timing is higher than standard and retarded injection timings. At maximum load, the peak cylinder pressure of regular diesel and B30 at standard injection timing and B30 at advanced and standard injection timing is 47.3 bar, 45.64 bar, 47.2 bar, and 43.5 bar, respectively.
- Similar to cylinder pressure, the NHRR of the engine is increased, and the maximum NHRR is shifted to the left of TDC as the injection timing advanced, and retarding the injection timing by the same CA reduces the NHRR, and the maximum NHRR is shifted to the right of TDC.

- HC emission of the B30 was reduced by 6.3% at advanced injection timing compared to B30 at standard injection timing. At retarded injection timing, the HC emission increases by 4.2% compared to advanced injection timings.
- At full load by standard and advanced injection timings, the CO emission in the exhaust gas by using B30 is reduced by 15.2% and 36%. By retarding the injection timing, the CO emission is increased by 3.6%.
- CO_2 exhaust gas emission for B30, is increased by 5.7% by advancing the injection timing compared to standard injection timing.
- Increasing the load on the engine increases the smoke opacity of the exhaust gas emission. Advancing the injection timing, the smoke opacity of the engine fuelled by B30 is reduced by 14% compared to regular diesel at standard injection timing and by 7% compared to B30 at standard injection timing.
- Using B30, while advancing the injection timing, NO_x emission is increased by 9% compared to standard injection timing and reduced by 7% by retarding the injection timing.

Based on these experimental results, it is possible to conclude that B30 can be used in a DI diesel engine with improved performance, combustion, and emissions by advancing the injection timing without requiring major engine modifications. However, there are certain aspects that may be investigated in the future, such as how to minimize NO_x emissions and decrease fuel viscosity to discover the optimal features based on various engine parameters.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Conclusions

In this experimental investigation of coffee husk biodiesel as a renewable fuel in CI engines, coffee waste is used as the substrate material for biodiesel production. For the experiment, coffee waste was collected from local coffee processing industries and coffee brewing shops. Produced biodiesel is characterized and compared with regular diesel. Kirloskar TV1 single cylinder DI engine is used to test the produced fuel at different loads, injection timing, and preheating the fuel before injection. The following conclusions are drawn from the experimental investigation in this study.

7.1.1 Analysis of CH and SCG biomasses, extraction, and characterization of coffee husk biodiesel

In this section, coffee waste is used as a base material for biodiesel production. The Field Emission Gun Scanning Electron Microscope (FEG-SEM) was used to examine the chemical composition of the CH and SCG samples. The result indicated that the coffee husk was composed of 49.84% carbon and 48.06% oxygen by weight. SCG contained 67.72% carbon and 26.18% oxygen by weight. 250gram of oil was produced from 1000 grams of coffee husk powder using a screw-type expeller machine. The oil was converted to biodiesel by the transesterification process, yielding 700 mL of biodiesel from 1000 mL of oil. The crude biodiesel was characterized and checked for the feasibility of being used as an alternate fuel in IC engines. Results of the characterization reveal that the newly produced biodiesel physicochemical property meets the standards to be used as biodiesel.

7.1.2 Performance, combustion, and emission characteristics of the engine using CHOME biodiesel

In this section, CHOME biodiesel is used as an alternate fuel in Kirloskar TV1 direct injection diesel engine by varying the load on the engine. The engine was equipped with an eddy current dynamometer to change the load. Different blends are tested (B10 – B80) to study the effect of CHOME biodiesel on the engine's performance, combustion, and emission characteristic under different engine load (0-100%) conditions.

The result of this work reveals that at full load, a slight reduction of BTE and increment in BSEC is noticed compared to regular diesel. Comparing the blends B10 to B30 shows better performance under all conditions leading to the conclusion that CHOME biodiesel up to 30% can be possibly used in IC engines without significant engine modifications. Increasing the blending ratio reduces the BTE of the engine. Regarding emission characteristics, the CO, HC, and smoke opacity are reduced considerably, and CO_2 is increased. Because of the extra oxygen in the biodiesel, the NO_x emission rises a little more than with regular diesel at a higher load, and the higher the blend of biodiesel, the more it rises.

7.1.3 Performance, combustion, and emission analysis of preheated CHOME biodiesel at different engine load

Considering the physicochemical property of the CHOME biodiesel, preheating the fuel prior to injection is proposed to improve the engine's performance, combustion, and emission characteristics by using the same biodiesel. Preheating the fuel before injection reduces the viscosity of the fuel by 49.5%, which improves the combustion and performance, and emission properties of the engine. The engine's cylinder pressure and heat release rate were improved while preheating the fuel before injection. BTE of B100 was enhanced by 5% compared to unheated B100, and B10 produces 0.5% BTE more than regular diesel fuel at 100% load. In contrast, BSFC and BEC are increased considerably by preheating the fuel. Under all loading conditions and blending ratios, the BTE of preheated biodiesel diesel blend considerably improves the BTE of the engine. Fuel consumption of preheated fuel is lower than unheated fuels used for the experiment. Since preheating the fuel before injection increases the overall temperature of the combustion chamber, NOx emission increased to some extent. Other emissions such as HC, CO, and smoke opacity significantly reduced, and CO_2 increased considerably.

7.1.4 Performance, combustion, and emission analysis of CHOME biodiesel at different injection timing and load

In this section, an experimental investigation was done to study the influence of injection timing on engine performance, combustion, and emission characteristics by using the B30. Considering the previous experimental results, B30 was selected to run the engine under different loads by varying the injection timing. The B30 has lower BTE and higher BSEC than regular diesel at standard injection timing. It was observed that advancing the injection timing enhanced the engine's BTE and increased the BSEC under all load conditions. Retarding the injection timing reduces the BTE and improves the BSEC.

The exhaust gas emissions such as HC, CO, and smoke opacity are reduced compared to standard injection timing with the same blends. Retarding the injection timing increases the HC, CO, and smoke opacity considerably. NO_x emission increases under all loading conditions by advancing the injection timing and reducing while retarding the injection timing. Overall advancing the injection timing improves the performance and emission characteristics of the engine.

7.2 Scope for the future study

In this experimental investigation, CHOME biodiesel is used as an alternative fuel to study the performance, combustion, and emission characteristics of the DI diesel engine. Collecting, analyzing, extraction characterization, and utilization of the biodiesel from coffee husk oil is performed. Furthermore, preheating and varying injection timing techniques are also applied to study the effect of preheating before injection and the injection timing on engine characteristics. Based on that few areas which need further studies are mentioned as follows;

- Further investigation can be conducted by varying the injection pressure using different injectors and changing the engine's compression ratio to obtain additional results.

- Further research work is required to improve the properties of the produced biofuel. This can be done by blending additives or nanoparticles into the biodiesel diesel blends to enhance the property of the biodiesel to get better combustion performance and emission characteristics.
- Investigating and implementing a mechanism to use exhaust gas for preheating the fuel before injection can be studied.

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LIST OF PUBLICATIONS BASED ON RESEARCH WORK

S1. No.	Title of the paper	Authors (in the same order as in the paper. Underline the Research Scholar's name)	Name of the Journal/ Conference/ Symposium, Vol., No., Pages	Month & Year of Publications	Category *
1	Extraction and characterization of coffee husk biodiesel and investigation of its effect on performance, combustion, and emission characteristics in a diesel engine.	Frinjo Emma, Addisu Sathyabhama, A. Kumar Yadav, Ajay	Energy Conversion and Management:X 100214.DOI https://doi.org/10.1016/j.ecmx.2022.100214	March 2022	1
2	Extraction and characterization of biodiesel derived from the coffee husk, and its effect on diesel engine performance and emission characteristics	Addisu Frinjo Emma, A. Sathyabhama and Ajay Kumar Yadav	*International Journal of Energy for a Clean Environment*	Revision submitted	1
3	Experimental investigation on performance, combustion, and emission characteristics of a CI engine fuelled with preheated coffee husk biodiesel.	Addisu Frinjo Emma, A. Sathyabhama and Ajay Kumar Yadav	*Arabian Journal for Science and Engineering*	Under review	1
4	Effect of injection timing on performance, combustion, and emission characteristics of an engine fuelled with coffee husk biodiesel	Addisu Frinjo Emma, A. Sathyabhama and Ajay Kumar Yadav	International Journal of Ambient Energy	Under review	1

5	Coffee Husk Biofuel as an Alternate Fuel for an Internal Combustion Engine - Review	Addisu Frinjo Emma, A. Sathyabhama and Ajay Kumar Yadav	International Conference - RARE 2020 BLUE ROSE PUBLISHERS ISBN: 978-1-64826-759-8. Page 87-92.	February2 020	3
6	Extraction and characterization of biodiesel derived from the coffee husk, and its effect on diesel engine performance and emission characteristics	Addisu Frinjo Emma, A. Sathyabhama and Ajay Kumar Yadav	International Conference on Thermo-Fluids and System Design organized by the Department of Mechanical Engineering, Birla Institute of Technology Mesra Ranchi	March 2022	3

*Category 1: Journal paper, the full paper reviewed

2: Journal paper, Abstract reviewed

3: Conference/Symposium paper, full paper eviewed

4: Conference/Symposium paper, abstract reviewed

5: others (including papers in Workshops, NITK Research Bulletins, Short notes, etc.)

(If the paper has been accepted for publication but yet to be published, the supporting documents must be attached.)

Addisu Frinjo Emma	Dr. Sathyabhama A	Dr. Ajay Kumar Yadav
Research Scholar	Research Guide	Research Guide
Name & Signature, with Date	Name & Signature, with Date	Name & Signature, with Date

BIO-DATA

Name: Addisu Frinjo Emma

Date of birth: **24-11-1982**

Current Address:

National Institute of Technology Karnataka, Surathkal

Srinivasnagar Mangalore 575025 Karnataka – INDIA

Permanent Address: Dilla University, Southern Nations Nationalities and Peoples of Ethiopia, Gedeo Zone, P.O Box 419, Dilla, Ethiopia

Phone Number: +91 – 7625050883, +251-913457473, *+251-972-68-4229*

E-mail ID: mahdrmma@gmail.com, addisu187me002@nitk.edu.in

https://orcid.org/0000-0001-6435-1078

https://scholar.google.com/citations?user=LbhwEBwAAAAJ&hl=en

Qualification			
Qualification	Specialization	Institution	Year of completion
M.Sc.	Automotive Technology	Adama Science and Technology University	July, 2014
B.Ed.	Automotive Technology	Adama Science and Technology University	July, 2006
Work experience			
Designation	Organization	from	to
Lecturer	Dilla University Ethiopia	1st September 2014	20th June 2018
Instructor	Dilla Polytechnique College Ethiopia	7th September 2007	7th August 2013

Other responsibilities:

- **Director**: General Maintenance and operation, Dilla University, Ethiopia (October 2016 to April 2018)
- **HoD:** Department of Automotive Engineering, Dilla University, Ethiopia (October 2014 to October 2015)
- **HoD:** Department of Automotive Technology, Dilla polytechnique college, Dilla, Ethiopia (January 2008 to September 2011)

Projects:

M.Sc. Thesis: Designing and Developing Solar Energy Operated Water Pump for Small Scale Irrigation

B.Ed. Project: A study on charging system of trailed truck at Bekelcha Transport enterprise, Adama