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Hydrothermal Liquefaction of Terrestrial Biomass Waste for Sustainable Biodiesel Production in CI Engines

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Globally, there is a growing demand for alternative fuels and biodiesel has been recognized as a viable substitute for petroleum-based diesel. This research produces biofuels through hydrothermal liquefaction (HTL) of terrestrial biomass. In the HTL reactor, biomass (sugarcane wastes) serves as the feedstock and after processing, bio-oil is generated. Subsequently, bio-oil-diesel blends (B5, B10, B15 and B20) are prepared, tested across various engine load configurations and their performance and emissions are recorded and compared. The experiments are carried out using a single-cylinder, water-cooled compression ignition engine equipped with an eddy current dynamometer. Among all the blends, B15 performs best in terms of both performance and emission characteristics. Therefore, biofuel derived from biomass waste (such as sugarcane waste) can serve as a substitute for diminishing fossil fuels in existing compression ignition engines. It also helps reduce harmful gases emitted by conventional fossil fuels, thus protecting the environment.

KEYWORDS

Bio-oil, Hydrothermal liquefaction, Biodiesel, Performance, Emission

1. INTRODUCTION

Fossil fuels are energy sources formed millions of years ago from the remains of extinct plants and animals. These non-renewable resources include coal, oil and natural gas. These fuels are widely used to produce electricity, power transportation and heat buildings. Coal is a sedimentary rock, that forms from the remains of plants that lived millions of years ago. It is mainly used to generate electricity and is a major source of carbon dioxide emissions. Oil and natural gas are created from the remains of marine organisms that died millions of years ago. They are extracted from underground reservoirs, processed and used for transportation, heating, electricity generation and more. These fuels also contribute to greenhouse gas emissions and air pollution. Despite the environmental impacts associated with fossil fuels, they remain the dominant energy source worldwide due to their reliability and affordability [1]. However, efforts are underway to shift to cleaner and more sustainable energy sources to combat climate change and reduce environmental harm.

Fossil fuels form through a natural process takes millions of years [2]. The decomposing bodies of plants and animals that accumulate on Earth's surface are the starting point of this process. These organic materials are exposed to extreme heat and pressure from the weight of surrounding rock as they become buried beneath sediment layers over time [3]. During this process, known as diagenesis, organic matter undergoes a series of chemical reactions that eventually turn it into fossil fuels. The type of fossil fuel that forms depends on the composition of the organic matter and the burial environment [4]. For example, oil and gas originate from the remains of marine organisms that settle in sediments on the ocean floor, while coal forms from terrestrial plant remains buried in bogs and swamps. Fossil fuels are considered non-renewable resources due to their complex and slow formation process, which

Figure 1. *Carbon nanotube powder and titanium dioxide*

also has significant negative environmental impacts during extraction and use [5].

India's primary energy consumption is expected to double by 2040, leading to increased use of alternative fuels, like biodiesel. Since biodiesel produces a 95% carbon-free final product, it also helps reduce environmental impact [6]. Biofuel, produced through hydrothermal liquefaction of biomass, offers a renewable alternative to fossil fuels and it tends to be less corrosive and generate less pollution [7,8]. Therefore, objective of this study is to produce bio-oil from biomass waste by hydrothermal liquefaction and prepare biodiesel by blending the bio-oil with diesel in various proportions by volume. The investigations are carried out on a single-cylinder compression ignition engine to analyze the performance and emission characteristics of various bio-oil-diesel blends.

2. MATERIAL AND METHOD

The steps involved in this study include collecting biomass, preparing catalysts, hydrothermal liquefaction of biomass, collecting bio-oil, preparing bio-oil-diesel blends and testing engines with the blends.

2.1 Collection of biomass

The local sugarcane juice stores around Anna Nagar, Chennai, supplied the feedstock for this work. The collected sugarcane waste is reduced to small pieces and mixed with water to form a slurry, which is then processed in the hydrothermal liquefaction reactor.

2.2 Carbon nanotubes

One type of nanomaterial is carbon nanotube powder, which consists of tiny, cylindrical carbon atom tubes. Some nanotubes are extremely small, reaching lengths of several millimeters and thicknesses as thin as a few nanometers. Because carbon nanotubes possess unique mechanical, electrical and thermal properties, they can be applied in various ways. They are ideal for use with materials that require high strength and low weight since they are lightweight, flexible and stronger than steel. It is important to carefully control the powder's properties because they influence the final product's characteristics [9]. The titanium dioxide and carbon nanotube powder used in this investigation are shown in figure 1.

2.3 Titanium dioxide

Titanium dioxide (TiO_2), a naturally occurring form of titanium oxide, is one of the most widely used materials worldwide [10]. It is an odourless, tasteless white powder extensively used in various industries due to its special properties. Titanium dioxide can reflect and scatter light, making it versatile in paints, coatings and plastics. It is also used as a UV blocker in sunscreens and as a preservative in food and cosmetics. Titanium dioxide can be produced through several methods, including sulphate, chloride and hydrothermal processes [11]. The Kraft process is the most common, where ilmenite (a titanium-containing mineral) reacts with sulphuric acid to produce titanium dioxide. Besides its optical properties, titanium dioxide is known for its chemical stability, which makes it resistant to corrosion and degradation. This stability makes it suitable for many industrial applications, such as catalysts, ceramics and electronics manufacturing. Overall, titanium dioxide is a versatile material with unique properties that enable its use in a wide range of applications.

2.4 Titanium carbon nanotubes

One type of hybrid material that combines the unique qualities of titanium with carbon nanotubes is titanium carbon nanotubes. A carbon nanotube is known for its high strength, flexibility and electrical conductivity, which are some of its key mechanical, electrical and thermal properties. However, these nanotubes are often limited by their poor chemical stability, which can lead to deterioration and reduced performance over time. In contrast, titanium is a metal widely used in various applications, such as aerospace and biomedical implants, due to its strength, biocompatibility and low toxicity [12]. It is also highly valued for its excellent chemical stability and resistance to corrosion. By combining these two materials, researchers aim to develop a new class of materials that leverage the best properties of both.

2.5 Catalyst preparation with carbon nanotubes and titanium dioxide

Titanium-carbon nanotube catalysts are prepared in six

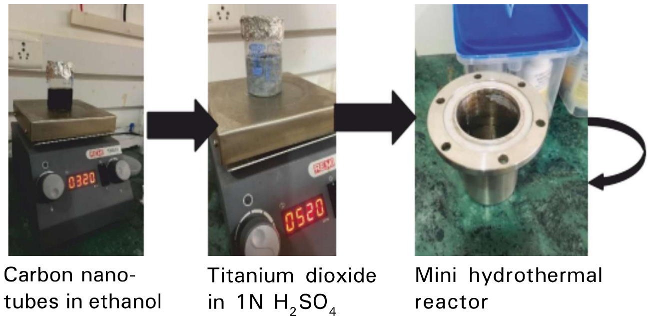

Figure 2. *Carbon nanotubes alongwith various feedstock preparation*

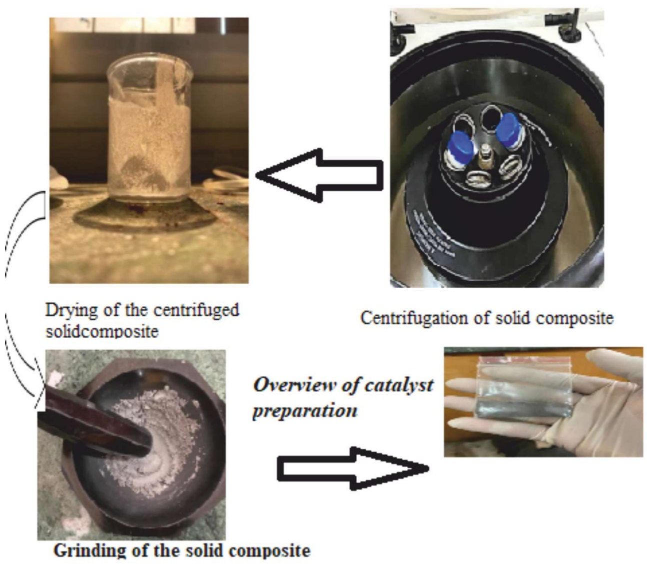

Figure 3. *Overview of the catalyst preparation*

different ratios while keeping the carbon nanotubes constant and varying the amount of titanium dioxide. Titanium dioxide is fully dissolved in 1N H_2SO_4 solution. The 1N H_2SO_4 solution is prepared by dissolving 9.2 mL of concentrated H_2SO_4 in 100 mL of distilled water. The required amount of titanium dioxide is mixed with 35 mL of 1N H_2SO_4 solution and stirred thoroughly using a magnetic stirrer. Meanwhile, 50 mg of carbon nanotubes is dissolved in 35 mL of ethanol and stirred well with a magnetic stirrer. Both solutions are then combined and mixed thoroughly with magnetic stirrer. The resulting solution is transferred into a small hydrothermal liquefaction (HTL) reactor and heated in a hot air oven at 150°C for 6 hr, then cooled overnight. Figures 2 and 3 illustrate the feedstock preparation and catalyst preparation processes. The next morning, a solid composite forms inside the reactor, which is collected and centrifuged three times with distilled water and once with ethanol. The solid composite is then dried

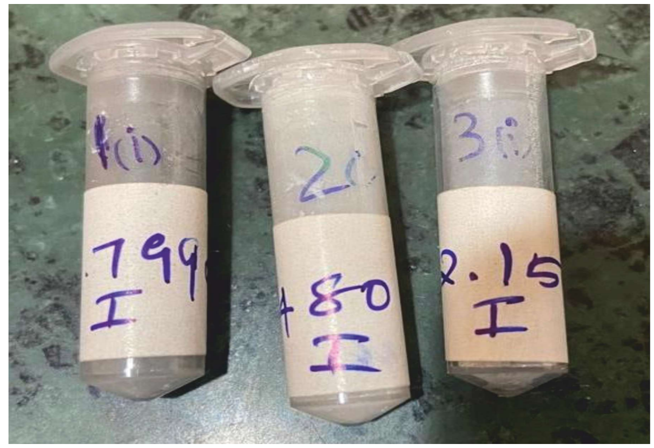

Figure 4. *Titanium carbon nanotubes catalyst*

Table 1. *Quantity of carbon nanotubes and titanium dioxide*

Amount of carbon nanotubes mixed with ethanol (mg)	Amount of titanium dioxide mixed with 1N H_2SO_4 solution (g)
50	0.72
50	1.42
50	2.15
100	0.72
100	1.42
100	2.14

in an oven, crushed into a fine powder and stored in an airtight container. Figure 4 displays produced titanium carbon nanotubes and table 1 lists the quantities of carbon nanotubes and TiO_2 used in catalyst preparation.

2.6 Hydrothermal liquefaction process

Hydrothermal liquefaction (HTL) is a process that involves converting biomass into liquid biofuel through the application of high pressure and heat in a confined space [13]. This process offers several advantages over other biomass conversion methods, such as pyrolysis and gasification, as it operates at lower temperatures, reduces energy requirements and produces liquid products suitable for mass production. The HTL process involves four main stages: pre-treatment, liquefaction, product separation and product recovery. The type of biomass feedstock used, particle size, reaction temperature, reaction time, pressure and catalysts can influence the efficiency, yield and quality of final product [14].

2.7 Preparation of fuel blends

Bio-oil is a renewable fuel that can be used in diesel

Table 2. *Engine specification*

Engine model	Kirloskar TV1
Number of cylinders	1
Number of strokes	4
Cubic capacity	0.661 L
Rated speed	1500 rpm
Power	5.20 KW
Power rating	7 HP
Cylinder bore	87.50 mm
Stroke length	110.00 mm
Connecting rod length	234 mm
Compression ratio	17.5
Pump type	Monobloc
Cooling type	Water cooled
Overall dimensions (LxWxH)	2500 mm x 2000 mm x 1500 mm
Dynamometer	Eddy current type water-cooled
Software	Engine Soft

engines. It is produced from biomass using HTL, a process that heats organic material without oxygen to create a liquid oil [15]. The properties of bio-oil, like its viscosity and density, can vary depending on feedstock and process. Therefore, testing the bio-oil is essential to ensure it is compatible with the engine and meets fuel specifications [16]. Using bio-oil in diesel engines offers benefits, such as lower greenhouse gas emissions and reduced dependence on fossil fuels. However, using biofuel directly for generators can pose challenges, including engine damage and chemical contamination. Hence, special caution is necessary when using bio-oil as a direct fuel in diesel engines. The engine and its operation must be carefully evaluated for safe and effective biofuel use. The kinematic viscosity of bio-oil is 6.31 mm^2/s and its density is 868 kg/m^3. These properties inform us about bio-oil's flow behaviour and physical characteristics. A lower kinematic viscosity indicates less resistance to flow, meaning it may flow more easily. Its density of 868 kg/m^3 suggests the bio-oil is relatively lightweight with lower viscosity. Based on this, bio-oil-diesel blends are prepared volumetrically, creating B5, B10, B15 and B20 blends for experimentation.

2.8 Experimentation

The study uses a single-cylinder, four-stroke water-cooled compression ignition engine equipped with an eddy current dynamometer for loading. Table 2 presents the engine specifications and figure 5a shows diesel engine test setup. The engine test rig includes a single-cylinder four-stroke diesel engine connected to an eddy current dynamometer for engine loading, alongwith a panel box that contains a fuel tank, fuel measuring unit and digital speed indicator. Figure 5b displays the gas analyzer and smoke meter used to measure exhaust emissions and smoke, respectively. The smoke meter assesses engine exhaust gases to determine particulate matter emissions, while the gas analyzer measures concentrations of various gases in the engine exhaust, such as carbon monoxide, nitrogen oxides, and hydrocarbons.

3. RESULT AND DISCUSSION

The ratio of power produced to energy generated through fuel injection is called brake thermal efficiency (BTE). It is calculated by multiplying the lower heating value by the total mass flow rate of the injected fuel. Figure 6a shows how brake thermal efficiency varies with load. An increase in BTE indicates an improvement

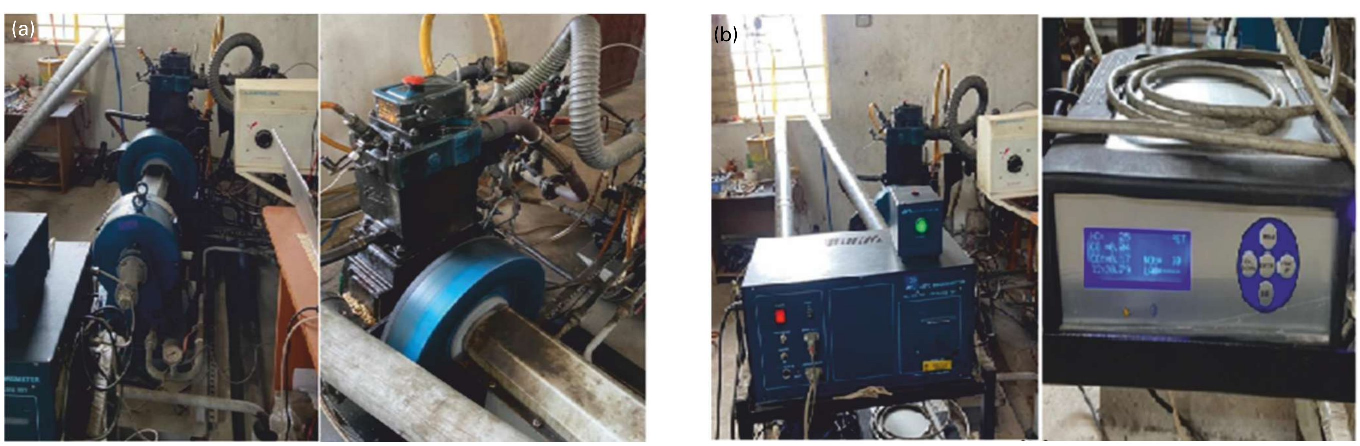

Figure 5. *(a) Engine test setup, (b) gas analyzer and smoke meter*

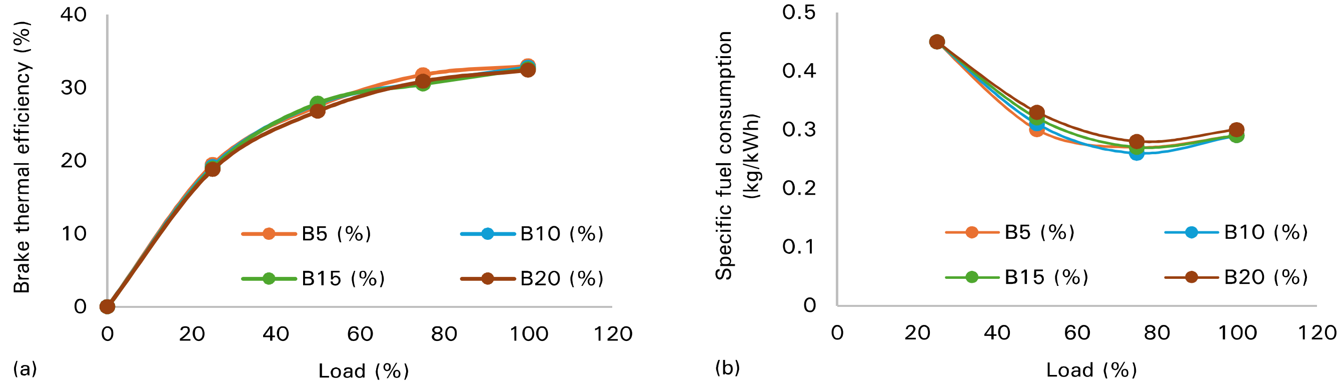

Figure 6. *Graphical representation of: (a) brake thermal efficiency and (b) specific fuel consumption for various blends studied*

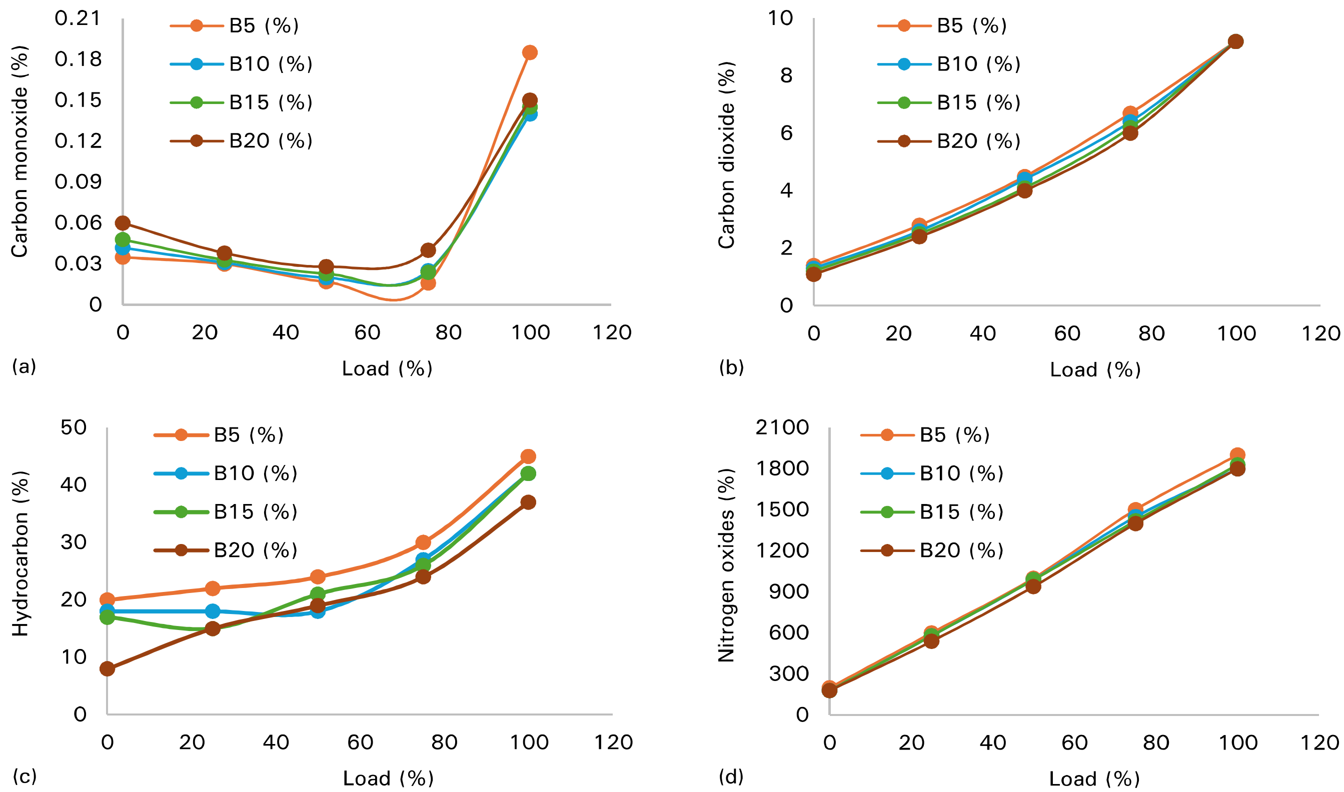

Figure 7. *(a) CO emission, (b) CO_2 emission, (c) HC emission and (d) NOx emission for different blends*

in engine efficiency, which leads to better fuel economy and lower emissions. These results show that the B5 blend has the highest brake thermal efficiency among the blends, followed by the B15 blend. Even a small amount of diesel improves engine performance in the mixture. This is due to decreased viscosity, which enhances vapourization, atomization and combustion. Several studies have examined the effect of various fuel properties on BTE and found that increasing the cetane number of diesel fuel can improve BTE in a diesel engine [17]. An important factor in evaluating the fuel economy of internal combustion engines is specific fuel consumption (SFC). Figure 6b shows the percentage change in fuel consumption with load and the engine's fuel consumption rate at a specific power output. This is a key measure for engine design and optimization. The experimental results demonstrate that the B20 blend has the highest SFC among the blends. The B20 biodiesel blend has higher viscosity and density and a reduced heating value, which could be reasons for its greater SFC compared to other blends. Conversely, the SFC in the B5 blend is lower than in the B20 and other mixtures. The main factor causing the SFC to increase as fuel blends rise is the test engine's increased use of

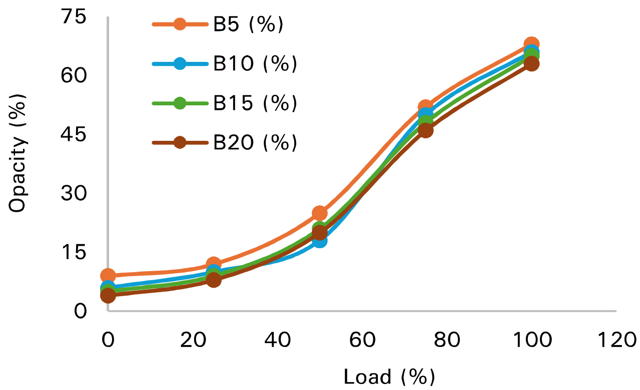

Figure 8. *Smoke opacity for different blends*

biodiesel fuel to maintain steady power output. A higher SFC indicates that the engine consumes more gasoline per unit of time for each unit of power output. This means the engine is less fuel-efficient and will use more fuel to produce the same amount of power as engine with a lower SFC. A high SFC increases fuel costs, raises emissions and reduces overall fuel efficiency. Conversely, a low SFC points to a more fuel-efficient engine that uses less fuel to generate the same power, leading to lower fuel expenses, fewer emissions and better fuel economy.

The carbon monoxide emissions from bio-oil are influenced by several factors, including the bio-oil content, engine type, operating conditions and combustion efficiency. Figure 7a shows CO emissions as percentage at different load levels. The results indicate that bio-oil emits less CO than standard diesel. In this study, for the B5 sample, CO emissions are 0.03% lower than for the B20 sample, while B15 blends produce 0.14% higher emissions. Combustion in chamber continues until the air-fuel mixture reaches the stoichiometric ratio at B5. Compared to other blends, like B15, CO emissions have increased. Biofuels generally contain more oxygen and less energy than fossil fuels. This results in incomplete combustion and higher CO_2 emissions. Figure 7b shows carbon dioxide emission as a percentage with load. The results indicate that the lowest CO_2 emissions are achieved with B15 and B20 blends compared to B5 and B10. Conversely, B5 blend produces highest range of CO_2 emissions during engine operation. Figure 7c displays hydrocarbon (HC) emissions. In this case, sample B20 releases 32% of HC emissions, which is the lowest among the blends. Similarly, the B5 blend emits more hydrocarbons than other blends because the mixing ratio increases HC emissions from biodiesel.

Bio-oil synthesis produces nitrogen oxide (NOx) emissions, which contribute to air pollution and adversely affect human health and the environment. Therefore, studying NOx emissions from biofuels and developing strategies to reduce them is essential. Figure 7d shows nitrogen oxide emissions as percentage with load. The internal temperature of the combustion chamber influences NOx formation. The B15 blend exhibits better NOx emissions compared to other blend mixtures. The other blends have higher NOx emissions due to lower-than-expected octane levels in the fuel, which may partly explain increased nitrogen oxide production. Figure 8 shows the smoke opacity as a percentage vs load. It was observed that the maximum emissions are lowest for B20 blend compared to other types of blends. It is possible that B5 has a higher viscosity, which results in higher fuel pressure and increased fuel penetration to the combustion chamber wall in the diesel engine. At full load, the B20 blend exhibits approximately a 50% reduction in smoke emissions. Diffusive combustion, where most smoke forms, is helped by oxygenated fuel blends in the B20 mixture.

4. CONCLUSION

The biomass (sugarcane waste) is collected and processed in a hydrothermal reactor to produce bio-oil. The properties of resulting bio-oil are examined. The bio-oil is then tested in a diesel engine. The addition of TiO_2 nanoparticles improved performance during hydrothermal liquefaction. Compared to diesel, bio-oil reduced specific fuel consumption and increased thermal efficiency by 2.73%. In all cases where nano additives are used, the specific fuel consumption (SFC) is lower than that of pure bio-oil and even lower than pure diesel. Adding TiO_2 nanoparticles increased density, ignition temperature and viscosity of the fuel. The calorific value of fuel with TiO_2 nanoparticles is slightly higher than that of diesel. Bio-oil is an excellent substitute for diesel because it significantly reduces CO, HC and smoke emissions. However, NOx emissions show an opposite trend. The use of nanoparticles further decreases CO, HC and smoke emissions. TiO_2 reduces CO by 12.7%, HC by 7.01% and smoke by 25.7% more effectively than diesel. Unlike diesel, the addition of nanoparticles does not decrease NOx emissions.

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