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Influence of silica nano-additives on performance and emission characteristics of Soybean biodiesel fuelled diesel engine

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Abstract

The present study examines the effect of SiO_2 nano-additives on the performance and emission characteristics of a diesel engine fuelled with soybean biodiesel. Soybean biofuel was prepared using the transesterification process. Nano-additives characterisations were done using different tests such as FESEM, XRD, EDS, etc., to study the morphology of nano-additives. For proper blending of nano-additives with biodiesel, the ultrasonication process was used. Surfactant was used for the stabilisation of nano-additives. After making all the combinations of nano fuel blends, physicochemical properties were measured as per ASTM standards. Performance and emissions readings were taken at different load conditions. It was found that with the addition of SiO_2 nano-additives, brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) was increased by 3.48-6.39% and 5.81-9.88%, respectively. Significant reduction of CO, CO_2, NOx, and smoke emissions were also observed compared to baseline fule due to better combustion efficiency with the use of SiO_2 nano-additive.

Keywords: Soybean biodiesel; Engine performance; Engine emission; Nano-additives.

1. Introduction

The current scenario of increasing fuel prices and depletion of fossil fuels has increased biofuels' demand in the industry and heavy-duty diesel engines. Biodiesel is one of the potential sources for clean and green energy for today's world's sustainable development [1]. Biodiesel is a clean-burning fuel which helps to decrease the emission of unburnt hydrocarbon (HC), carbon monoxide (CO) and smoke emissions [2]. On the contrary, due to lower heating value than petroleum-based fuels, lower brake power (BP) and higher brake specific fuel consumption (BSFC) is observed [3]. Biodiesel is also reported to increase nitrogen oxides (NOx) emissions [4,5]. It was found that soybean biodiesel has properties similar to pure diesel fuel and different blends of soybean biodiesel can be used in a diesel engine without significant alteration. However, some adverse effects are observed associated with biodiesel use. For example, Özener et al. reported that the blends of soybean biodiesel showed a 1–4% decrease in the brake torque and a 2–9% increase in BSFC [6]. They also reported a 6.95–17.62% increase in NOx emission. Another recent study by Seraç et al. [7] studied the performance, combustion and exhaust emission characteristics of 5% and 20% by volume soybean biodiesel blend with ULSD. Tests were carried out at constant power output. They reported a maximum increase in BSFC of 8% for 20% biodiesel

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blend compared to that of ULSD. They also reported the lowest HC emission and highest NOx emission for 20% biodiesel blend compared to that of ULSD.

Addition of fuel additives to improve fuel properties, thereby the combustion characteristics have become a recent trend in research due to obvious benefits [8-10]. Of particular interest, it has been reported that nano-additives effectively reduce the agglomeration during blending with fuel and improve engine characteristics due to the large surface air-to-volume ratio, favourable thermophysical properties, and high thermal conductivity [11,12]. The combined effect of these properties assists in decreasing BSFC as well as engine emissions [10,13,14]. A previous review by Soudagar et al. [15] pointed out that there is an extensive literature gap in the investigations to the addition of various types of nano-additives in various biodiesel feedstocks. Najafi [12] studied the combustion characteristics of CNT, and Ag nano-additives treated diesel-biodiesel blend. The author showed that addition of nano-additives to diesel-biodiesel blends resulted in an increase in the in-cylinder peak pressure and the peak pressure rise rate compared to that of neat diesel fuel. He attributed this to the shorter ignition delay resulting in earlier and higher maximum cylinder pressure. An earlier study by the same group studied the performance and emission characteristics of nano-additive added blends. They showed that these blends reduced BSFC by 7.08%, CO emissions decreased by 25.17% and NOx emissions increased by 25% to 32% on average compared to diesel fuel [16]. Research on enhancing the performance and emission characteristics using silica nano-additives to biodiesel is still minimal.

Adzmi et al. [17] studied the effect of adding silica (SiO_2) nano-additives (50 and 100 ppm) to palm biodiesel blend on the performance and emission of a diesel engine. Tests were carried out in a single-cylinder diesel engine at various operating load and constant engine speed condition. They reported an increased brake power, reduced CO and NOx emission with the addition of silica nano-additives. They reported up to 43% increase in brake power, 25% reduction in CO emission and 4.48% reduction in NOx emission at various load conditions and amount of silica nano-additives. Saravankumar et al. [18] used silica nano-additives as an additive (at 50, 75 and 100 ppm) to the 20% corn oil methyl ester blends with diesel in the form of emulsions. Test results showed that the addition of nano-additives was conducive to decreasing the HC emission due to promoting complete combustion via acting as an oxygen buffer that supplies enough oxygen at higher loads. They also reported lower smoke emission for nano-additives blended fuels as the presence of nano-additives leads to better evaporation rate and enhanced oxidation property of the fuel, which facilitates complete combustion of the fuel. However, they reported an increase in NOx emission due to addition of silica nano-additives, which they attributed to the higher oxygen content in fuel as well as the temperature inside the combustion chamber. Özgür et al. [19] studied the effect of SiO_2 nano-additives addition at the dosage of 25 and 50 ppm to pure rapeseed methyl ester on diesel engine performance and emission. They reported a maximum increase of 4.2% - 4.8% of brake power and 3.6% - 4.3% of brake torque for 25 and 50 ppm blends respectively. A maximum average CO reduction of 10.4% was obtained for 25 ppm silica nano-additives blend. The maximum NOx emission reduction of 7.2% and 9.4% were observed for 25 and 50 ppm nanopricle blends, respectively. Thus, it can be seen that the variation in the effect on diesel engine performance and emission depend on a lot of factors and are generally not conclusive. Thus, this study focuses on studying the effects of silica nano-additives on soybean biodiesel blends with diesel on the diesel engine's performance and emission characteristics.

2. Materials and methodology

2.1. Materials

In this study, soybean was collected from the local market to extract oil. The extracted oil was further used to produce biodiesel using transesterification process. SiO_2 nano-additives (spherical, amorphous) was purchased from Sigma Aldrich, USA. The size, molecular weight, surface area and density of the nano-additives were 5-20 nm, 60.08 and 590-690 m^2/g and 2.2-2.6 g/mL at 25 °C, respectively.

2.2. Preparation of Soybean biodiesel by transesterification process

Drying of grains was carried out first to ensure good quality of oil during oil extraction method. After that, pre-treatment on beans such as dehulling and grinding was carried out. A mechanical press with an electrical heater was employed for oil extraction. After extracting the raw soybean oil transesterification process was employed to produce biodiesel. In this process, crude soybean oil was reacted with methanol (17% v/v oil) and 1% (w/w oil) sodium methoxide and maintained at 60 °C for two h. The stirring of the mixture was carried out at 1000 rpm to achieve a greater reaction. The produced biodiesel was poured into a separation funnel for 12 h to separate the glycerin from the biodiesel. Then the lower layer, which contained impurities and glycerin, was drawn off after the completion of settling down. The produced methyl ester was washed with distilled water to remove the impurities and glycerin. In this process, 50% (v/v) distilled water at 60 °C was sprayed over the esters and shaken gently, and lower layer containing water and impurities was taken out. Then methyl ester was subjected to vacuum distillation at 65 °C for one hour using a rotary evaporator to remove excess water and remaining methanol. The whole process is shown in Fig. 1.

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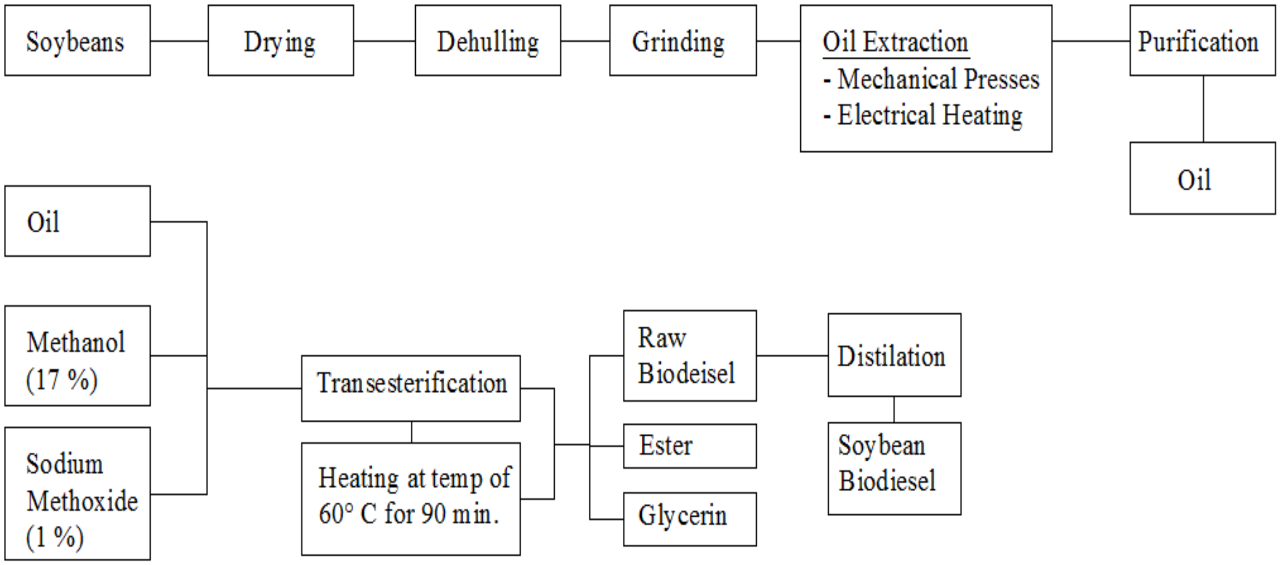

Fig. 1. Production of soybean biodiesel from beans through transesterification process

2.3. Characterisation of silica nano-additive

The morphology of SiO_2 nano-additives was analysed using X-ray diffraction (XRD) shown in **Fig. 2**. The XRD analysis was performed to analyse the crystalline nature of nano-additives using Xpert MPD, Philips, Holland, with a range of (2θ) from 3° to 136°, copper X-ray tube. The structure of the XRD reveals a broad, amorphous peak corresponding Bragg angle at 2θ=22° typical for the amorphous phase of SiO_2 nano-additives with no diffraction peaks was observed. The minute size and partial internal structure of the nano-additives will trigger this broad XRD peak. This indicates that a high proportion of certain particles are amorphous [20]. This illustrates the presence of pure SiO_2 nano-additives with no other significant impurities. The results are in accordance with the JCPDS card [21,22]. **Figure 3** illustrates the EDS analysis of the SiO_2 nano-additives. The EDS, also known as energy dispersive X-ray analysis, was performed to determine the elemental and chemical analysis of the SiO_2 nano-additives. The EDS analysis showed a higher quantity of silicon (65.68%) with an adequate amount of oxygen molecules (30.4). Also, some

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impurities were observed due to the previous stains of carbon and sodium in the canister [23]. The SEM analysis was carried out using XL 30 ESEM, EDAX Inc, USA, with an accelerating voltage of 200kV with the secondary and back detectors of the scattered electron. The SEM of SiO_2 nano-additives at 6000x magnification is shown in **Fig. 4**.

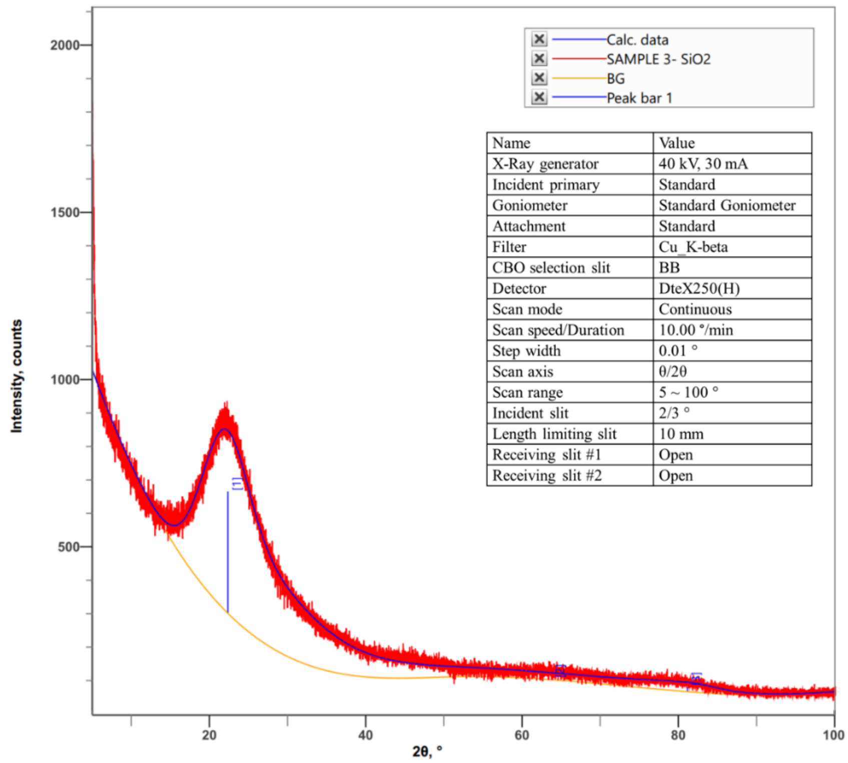

Fig. 2. X-Ray Diffraction (XRD) analysis including measurement conditions

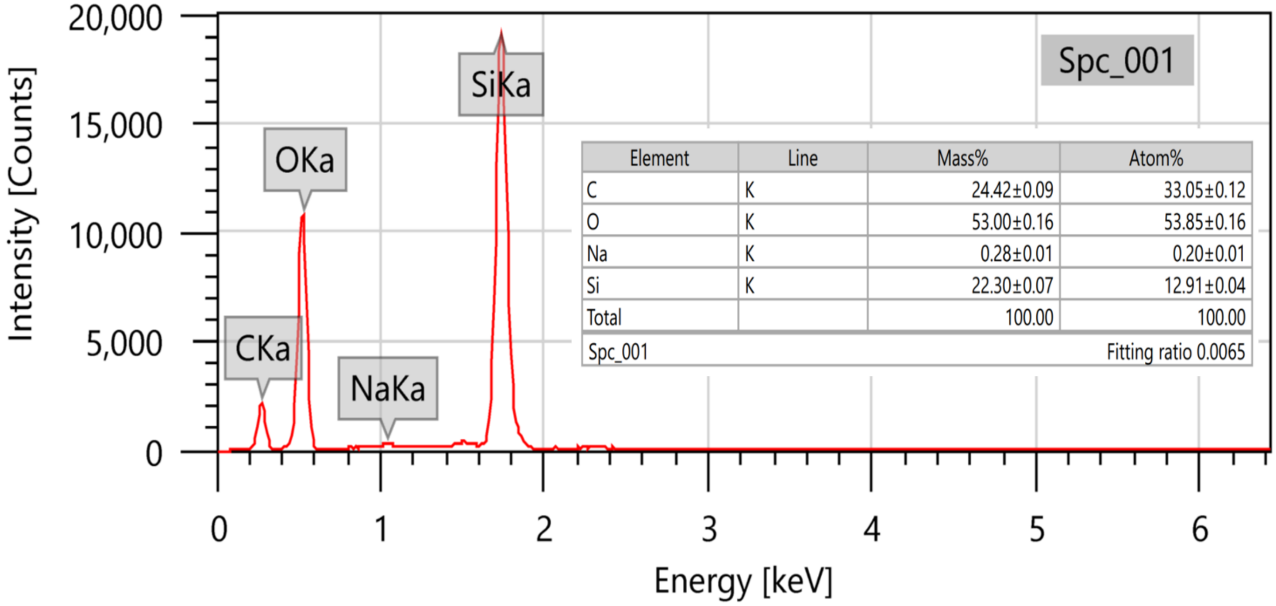

Fig. 3. Elemental composition of SiO_2 nano-additives

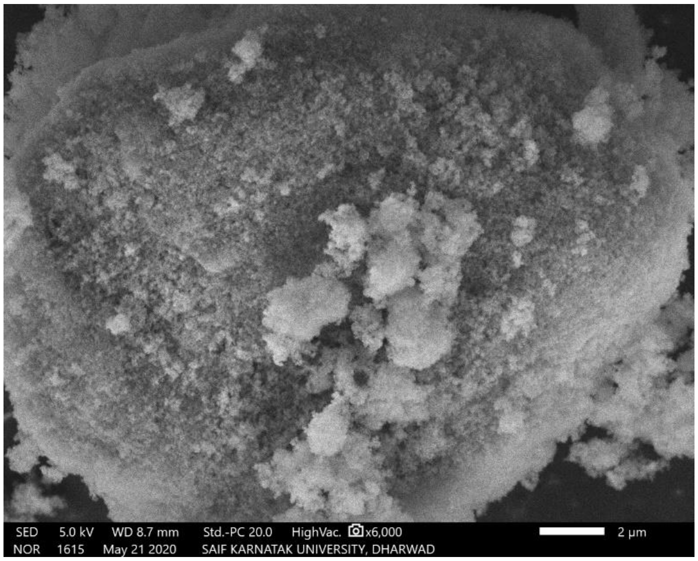

Fig. 4. SEM at 6000x magnification

2.4. Preparation and physicochemical properties of nano fuel blends

In the current study, ultrasonicator was used for making a well-mixed nano solution. To stabilise the blend sodium dodecyl sulphate (SDS) surfactant was used, for the ultrasonication process. Initially, 25 vol.% soybean biodiesel were blended with diesel in the ultrasonication bath

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for 60 min. An ultrasonication probe at 15–30 Hz was used for 20 min to mix the blend further. After that, SiO_2 nano-additives along with SDS surfactant were transferred to the biodiesel blend and steadily mixed using a magnetic stirrer at 60 °C for 30 min to remove traces of water molecules. Then, the same ultrasonication processes were carried out for a steady dispersion of SiO_2 nano-additives in SBME25 biodiesel–diesel fuel blend. This process was adopted in the previous literature [11]. **Fig. 5** illustrates the schematic of the ultrasonication unit for preparation of nano fuel. The physicochemical properties of fuel blends are shown in **Table 1**.

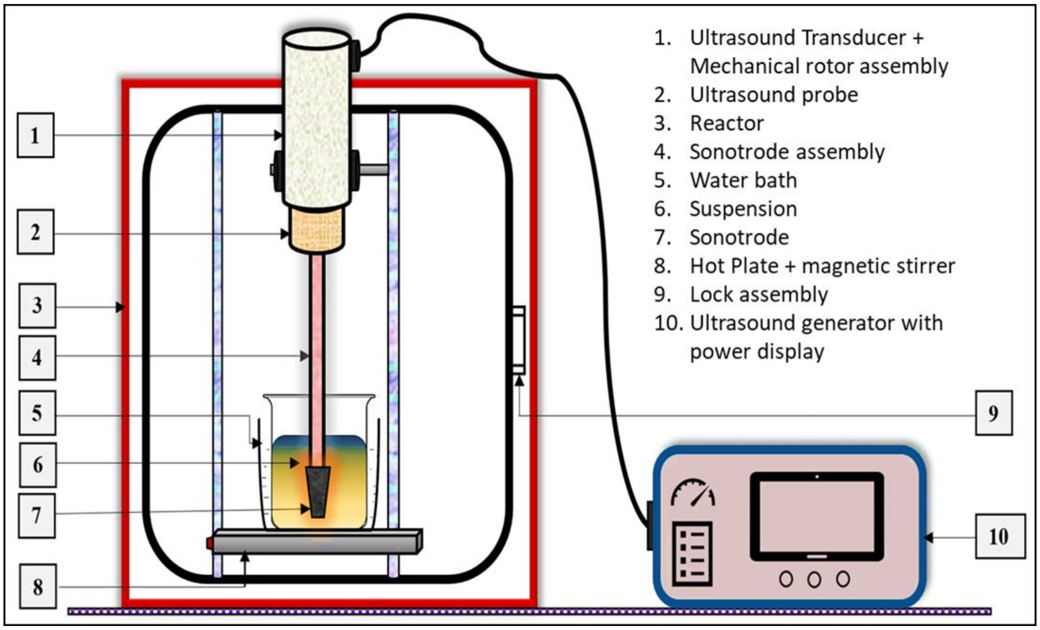

Fig. 5. Schematic representation of ultrasound-assisted preparation unit

Table 1. Physicochemical properties of fuel blends.

Property	Units	ASTM Standard	Diesel	SBME25	SBME25 Si25	SBME25 Si75
Density @25°C	kg/m^3	ASTM D 287	830	876	844	842
Specific Gravity	-	ASTM D 287	0.830	0.876	0.844	0.842
Gross Calorific Value	kJ/kg	ASTM D 4809	43994	40884	42459	42489
Flash Point	°C	ASTM D 93-58T	70	86	79	78
Fire Point	°C	ASTM D 93-58T	76	98	85	83
Cloud Point	°C	ASTM D 97	-6	-2	-3	-3
Pour Point	°C	ASTM D 97	-10	-5	-7	-8
Kinematic Viscosity@40°C	CSt	ASTM D 445	2.8	4.72	5.3	5.3

2.5. Test setup

The measured value is entered into the Enginesoft software, and by clicking the start button, the effective compression ratio will be reflected on the screen. The test rig consists of different fuel tanks and three ways stop cock assisted for the different fuel blends. In the case of petrol mode fuel injector is replaced by a spark plug and the fuel supply system is replaced by a carburettor; hence the same engine can be used for different fuels. Figure 6 shows the schematic of the testbed. The experiment was conducted under varying load condition of from no load to 1kg load condition with an increment of 3 kg at the rated speed of 1800 rpm. The engine was run with diesel as baseline fuel. After running a few times, it was switched to biodiesel and its blends and run at the same operating conditions. After completing all the tests, the engine was switched back to diesel fuel and continued running for 15 minutes until the biodiesel blends were removed from the injector and fuel line. The engine satisfactorily ran throughout the test at the same operating

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conditions. Every test for different fuel samples was triplicated, and the average values were obtained to obtain the uncertainty of the study.

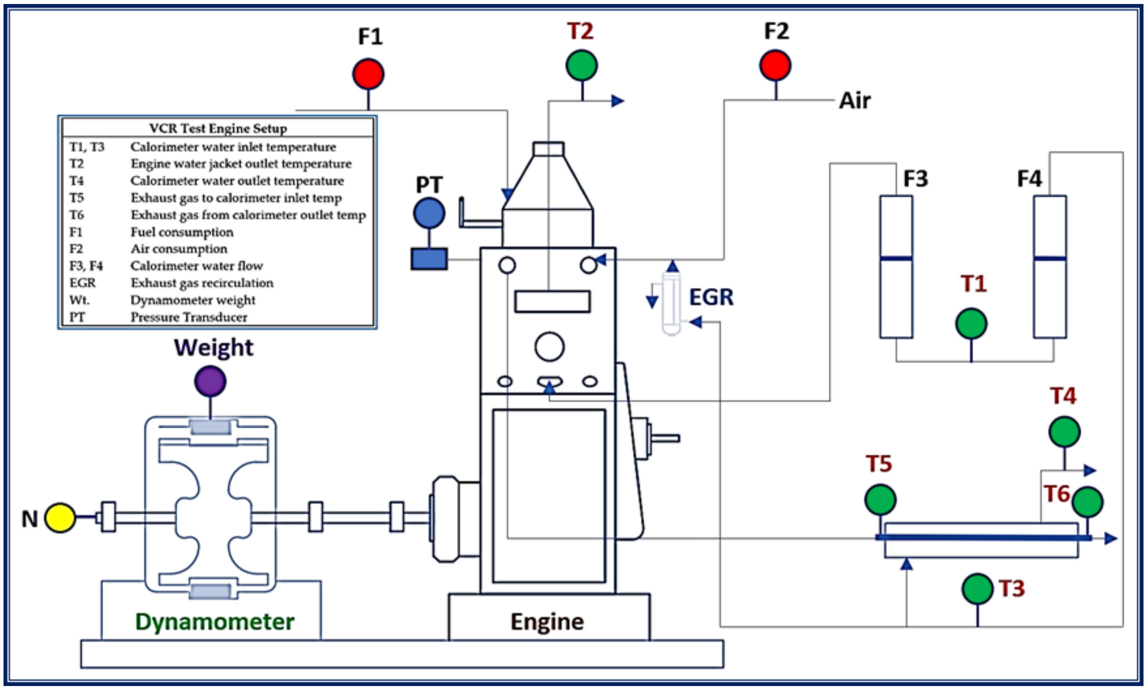

Fig. 6. Engine test rig set up

Table 2. Engine specifications

Parameter	**Specification**
Rated Power	5 HP @ 1800 rpm
Bore	87.5 mm
Stroke	110 mm
Connecting Rod Length	232 mm
Compression Ratio	5 to 11 for SI mode and 12 to 21.5 for CI mode
Type	4 Stroke, Single Cylinder
Fuel tank	15 L with glass fuel metering column
Piezo sensor	Range 5000 psi, with low noise cable
Temperature sensor	RTD, PT100 and thermocouple type K

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Rotameter	Eureka, Engine cooling 40–400 LPH; Calorimeter 25–250 LPH
Temperature sensor	Radix, Type RTD, PT100 and Thermocouple, Type K
Load sensor	Load cell, strain gauge type, range: 0–50 kg
Dynamometer	Type eddy current, water-cooled with loading unit
Crank angle sensor	Kübler Germany, Resolution 1 Deg, Speed 5500 RPM with top dead centre (TDC) pulse
Piezo pressure transducer	Make: Kistler

2.6. Uncertainty analysis

Uncertainty analysis is used to determine the probable errors obtained during the experimentation due to environmental conditions, and some are due to instruments used for the measurement [24-26]. Human errors are also included in these errors. Table 3 shows the % uncertainty and accuracy of various parameters.

Table 3. Uncertainty and accuracy levels of performance and emission parameters.

Parameters	**Accuracy (±)**	**Uncertainty (%)**
BP (kW)	-	± 0.4
BTE (%)	-	± 0.4
BSFC (%)	-	± 0.4
CO emission (%)	± 0.01%	± 0.3
NOx emission (ppm)	± 8 ppm	± 0.5
HC emission (ppm)	± 8 ppm	± 0.4

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Smoke meter (HSU)	± 1	± 0.5

3. Results and discussion

3.1. Effect of nano-additive on the performance parameters

3.1.1. Effect on BTE at varying load condition

Figure 7 indicates the change in BTE at different loads. The readings were taken for different blends of biodiesel with the addition of nano-additives at various combinations. At every combination, thermal efficiency always increases up to 9 kg of load. After that, it either stabilises or decreases. Generally, biodiesel's addition reduces the ignition delay, which causes faster combustion resulting in higher peak pressure [24,25]. However, due to the lower heating value of biodiesel owing to its fuel bound oxygen and higher density, the BTE reduction is significant. It has been reported that combustion efficiency is enhanced with the addition of nano-additives as they have the ability to donate oxygen from their lattice structure, thereby catalysing the combustion reaction [12]. They also help in reducing the ignition delay. It was observed that because of the addition of SiO_2 nano-additives, enhanced combustion of fuel particles takes place. Hence, blends with nano-additive dosage showed an increase in BTE compared to that of soybean biodiesel blend. At maximum load, the average value of BTE increased by 6.39 % (SBME25Si50) and 3.48% (SBME25Si75) compared to the SBME25 fuel blend.

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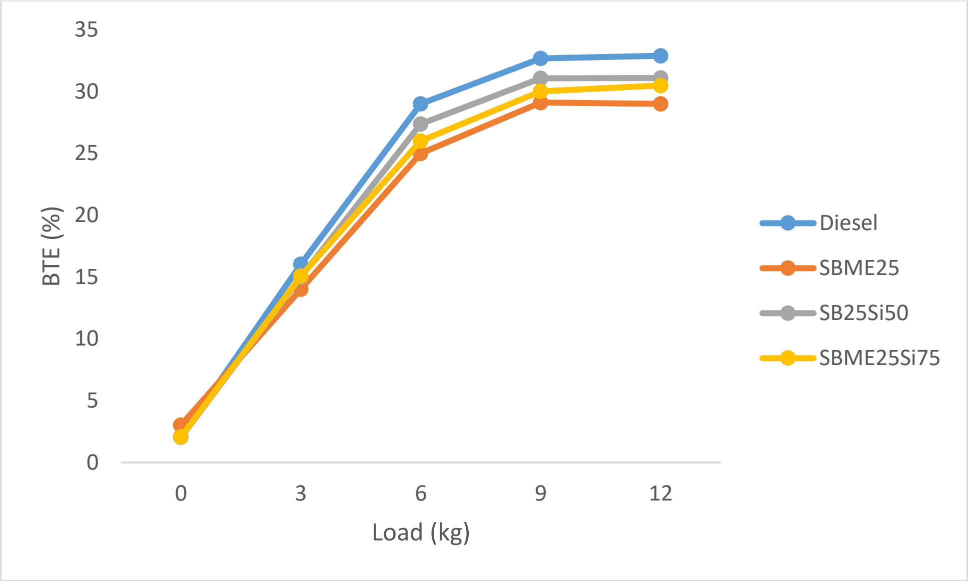

Fig. 7. Effect of SiO_2 nano-additives on BTE at varying load

3.1.2. Effect on BSFC at varying load condition

Figure 8 indicates the variation of BSFC at concerning load and all combinations of nano-fuel. SBME25 biodiesel blend had the highest BSFC, and diesel fuel showed the lowest BSFC at all load. However, the addition of 50 and 75 ppm of SiO_2 nano-additive results in lower BSFC compared to that of SBME25 biodiesel. As the load increases, the cylinder temperature increases resulting in a reduction in the ignition delay period, which results in a reduction in BSFC [26,27]. In addition, at a higher load, lower heat loss is observed. The SiO_2 nano-additives acts as a catalyst because of their higher reactive surface area during combustion [12,26]. This enhances the combustion after a droplet injected inside the combustion chamber, which results in lower BSFC as compared to SBME25. Hence, a reduction in BSFC of about 9.88%, 5.81% for SBME25Si50 and SBME25Si75 were observed compared to SBME25, respectively.

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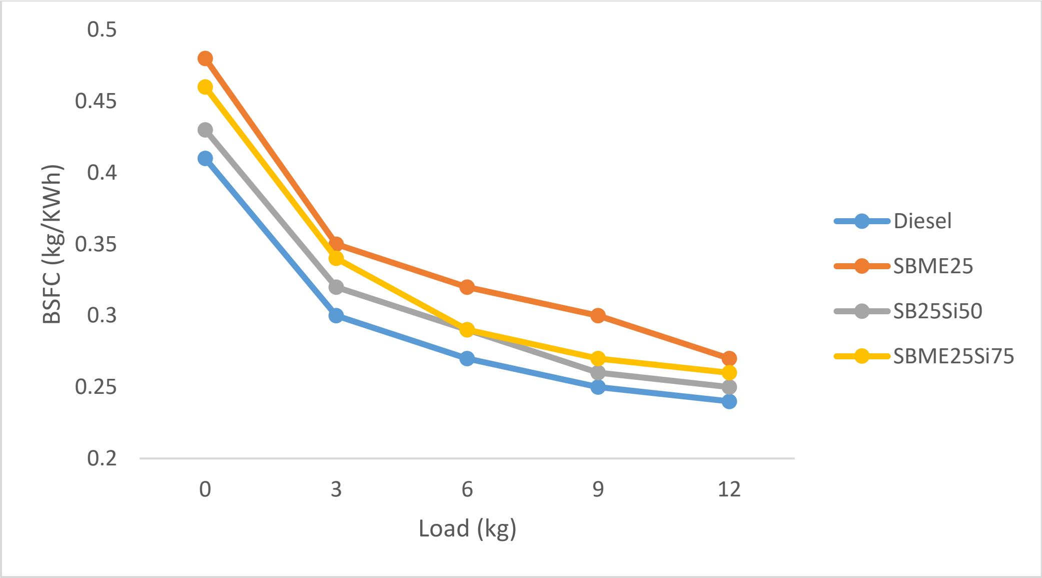

Fig. 8. Effect of SiO_2 nano-additives on BSFC at varying loads

3.2. *Effect of nano-additive on the engine emission parameters*

3.2.1. Effect on CO emission at varying load condition

CO is formed during combustion whenever the air-fuel mixture is burned with an insufficient air supply with low flame temperature [28]. It can be observed from **Fig. 8** that with the increase in load, the CO emission was increased. With the increase in load gradually, the volumetric efficiency increases. However, due to insufficient time for combustion, incomplete combustion occurs resulting in the formation of CO. As mentioned previously, the addition of biodiesel results in higher cylinder temperature and higher combustion pressure improving the combustion efficiency. Hence, CO emissions were found to be lower for biodiesel blends. As mentioned previously, oxygenated nano-additives provide oxygen molecules in a chain reaction causing complete combustion to reduce CO compared to baseline fuel (SBME25) [12]. SBME25Si75 fuel gives the lowest CO emission compared to all other blends. The CO emissions

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were decreased by 6.36% and 4.54% for SBME25Si50 and SBME25Si75, respectively compared to SBME25.

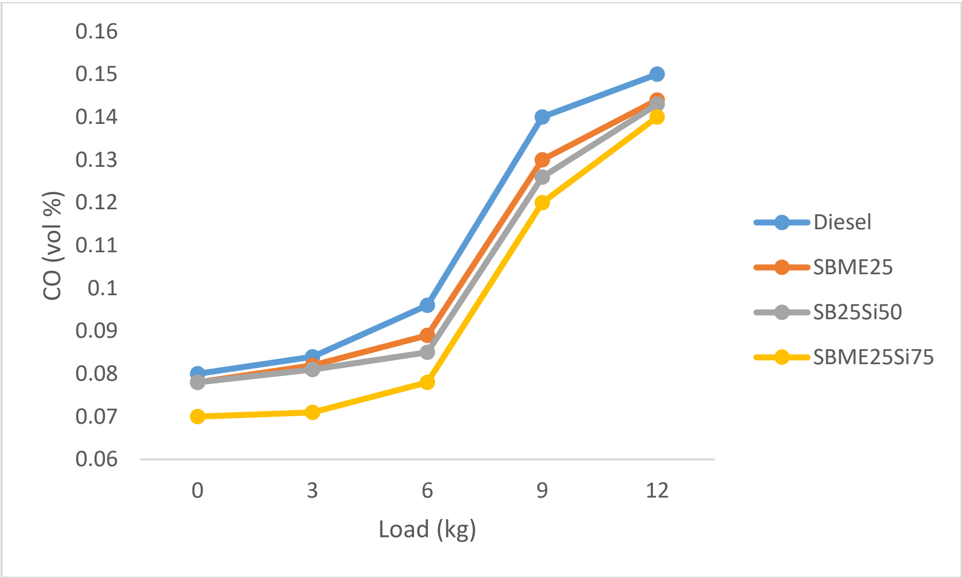

Fig. 9. Effect of SiO_2 nano-additives on CO emission at varying loads

3.2.2. Effect on HC emission at varying load condition

HC emissions rely on fuel density, fuel flow properties, fuel spray patterns, and engine operating conditions [29-31]. As mentioned previously, the addition of biodiesel results in higher cylinder temperature and higher combustion pressure improving the combustion efficiency. This results in a reduction in HC emission compared to baseline diesel fuel. HC emissions were reduced by 18% and 9% for SBME25Si50 and SBME25Si75 respectively compared to that of SBME25. SBME25 blend shows the highest HC emissions in the biodiesel blends with or without additives. This can be attributed to its high density as well as viscosity which in turn results in poor fuel atomisation.

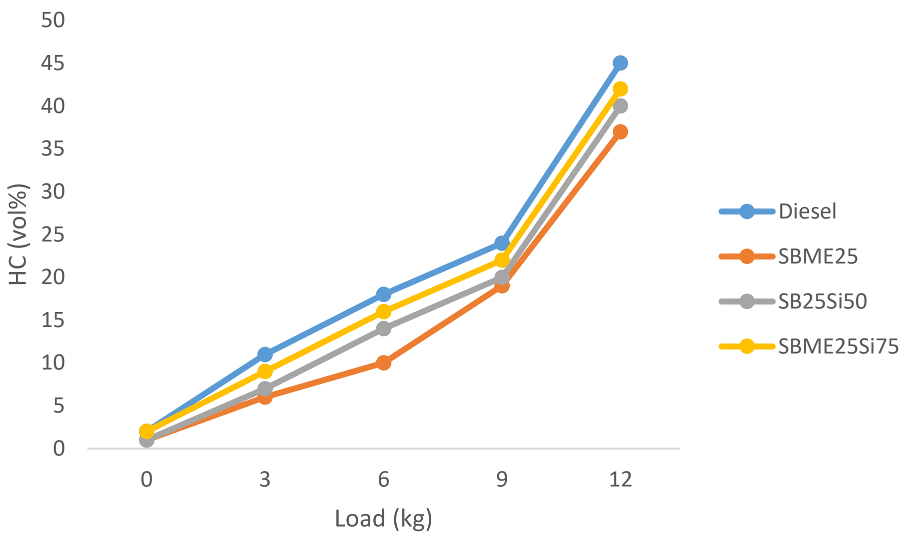

Fig. 10. Effect of SiO_2 nano-additives on HC at varying load

3.2.3. Effect on NOx emission at varying load condition

Figure 11 explains the NOx emissions for various biofuel blends. It was observed from the plots that NOx emission increases with an increase in load. NOx emissions are generated at a very high temperature and pressure [32]. Addition of oxygenated fuel such as biodiesel enhances the combustion, thereby increasing the NOx emission. With the addition of nano-additives, a faster premixed-combustion occurs, which produces higher combustion temperature inside the chamber and the subsequent higher NOx emission than baseline fuel [12]. All nano fuel blends show an increase in NOx emissions in comparison with only biodiesel blend owing to this elevated in-cylinder temperature and pressure. The NOx emissions were increased by 9.18%, and 15.55% for SBME25Si50 and SBME25Si7 respectively in comparison with SBME25 as shown in **Fig. 11**.

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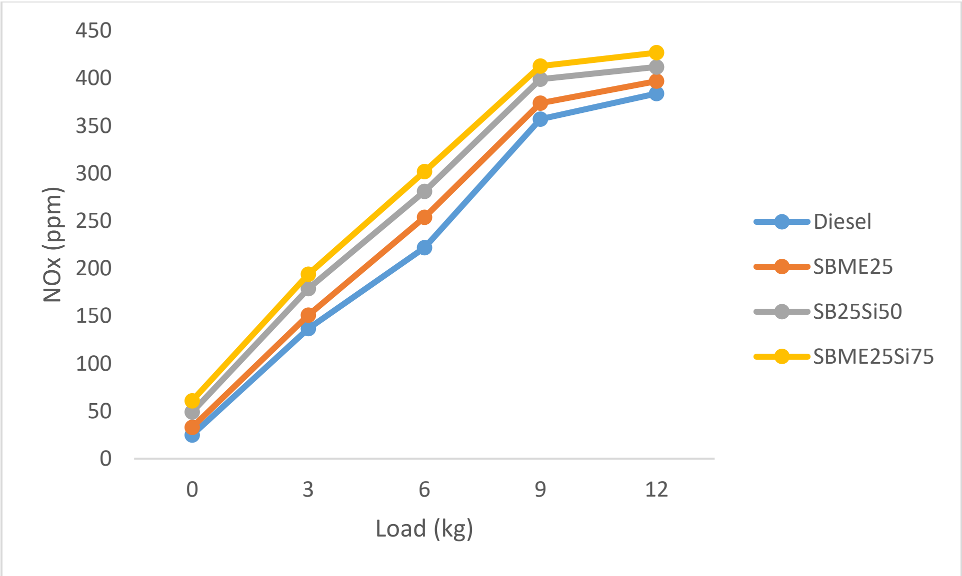

Fig. 11. Effect of SiO_2 nano-additives on NOx at varying loads

3.2.4. Effect on smoke emission at varying load condition

Figure 12 shows the production of smoke with the variation in engine load. It was observed that smoke is highly dependent on the engine load. Smoke opacity increases with an increase in the engine loads. Other input parameters have less affecting on smoke. The diesel fuel combustion produced the maximum smoke opacity. The addition of biodiesel results in enhanced combustion, thereby higher combustion temperature inside the chamber. The higher temperature enhances the combustion resulting in less smoke emission compared to diesel fuel. On the contrary, the addition of silica nano-additives with SBME25 produces better micro-explosion of blend leading to less smoke opacity. The smoke emission for SBME25Si50 and SBME25Si75 was reduced by 23.54% and 10.16% respectively compared to that of SBME25. The maximum surface area of the SBME25Si50 nano-additives improves the combustion phenomenon hence fuel combustion.

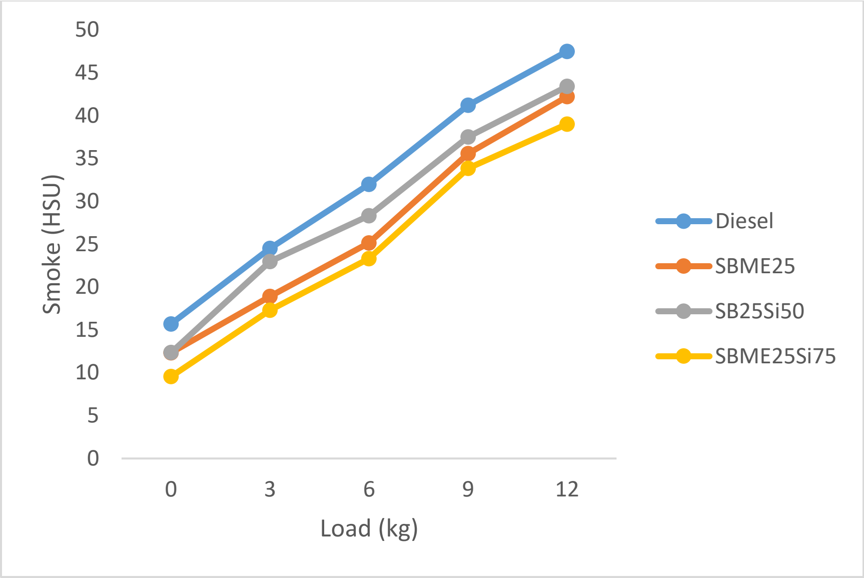

Fig. 12. Effect of SiO_2 nano-additive on smoke at varying loads

4. Conclusion

The present study is focused on the effect of SiO_2 nano-additives on performance and emission characteristics of soybean biodiesel fuelled diesel engine. The addition of SiO_2 nano-additives in soybean biodiesel blend improves performance parameters like brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) was increased by 3.48-6.39% and 5.81-9.88%, respectively. All the emissions except NOx decreased by the addition of nano-additives. The CO, HC, and smoke emissions decreased by 6.36%, 18%, and 23.54% respectively, while NOx emission increased for all fuel blends by the nano-additives addition.

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