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The effect of Sr-doped zinc oxide nanoadditives on the performance and emission parameters of a VCR engine powered by soybean biodiesel

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Abstract

In the present study, the effects of soybean biodiesel (SB)–diesel blends containing 1% strontium (Sr) doped zinc oxide (ZnO) nanoparticles (NPs) on the performance and emission parameters of a variable compression ratio (VCR) engine were investigated. To make the fuel blends, 25% soybean biodiesel (SB25) was added to the diesel. To improve the blend's stability, Sr/ZnO NP additions were blended with SB25 at 50 and 75 ppm utilizing an ultrasonication method and a surfactant at 2%. Various physicochemical techniques, such as X-ray diffraction, field-emission scanning electron microscopy, energy-dispersive X-ray spectroscopy, and ultraviolet spectroscopy, were used to characterize the produced NPs. These blends improved overall engine characteristics when used with a VCR. In comparison to the absence of nanoadditives, the brake thermal efficiency increased by 10.37% and the brake-specific fuel consumption decreased by 16.76% while using 50 ppm Sr/ZnO NPs additive in SB25 (SB25Sr/ZnO50).

Abbreviations: BD, biodiesel; BSFC, brake-specific fuel consumption; BTE, brake thermal efficiency; CO, carbon monoxide; CO_2, carbon dioxide; CR, compression ratio; EDX, energy-dispersive X-ray spectroscopy; FESEM, field-emission scanning electron microscopy; HC, hydrocarbon; nm, manometer; NOX, oxides of nitrogen; NPs, nanoparticles; PM, particulate matter; ppm, parts per million; SB, soybean; SBME, soybean biodiesel; SBME25 Sr/ZnO25, SBME 25 and 25 ppm Sr/ZnO NPs; SBME25 Sr/ZnO50, SBME 25 and 50 ppm Sr/ZnO NPs; SBME25 Sr/ZnO75, SBME 25 and 75 ppm Sr/ZnO NPs; Sr/ZnO, strontium-doped zinc oxide; UV-vis, ultraviolet–visible analysis; VCR, variable compression ratio; XRD, X-ray diffraction.

In addition, the presence of Sr/ZnO in SB25 results in lower harmful emissions such as hydrocarbon, CO, CO_2, and smoke, which are reduced by 11.20%, 13.81%, 41.43%, and 21.34%, respectively, when compared to SB25 fuel. The Sr/ZnO NPs in the blend are an excellent choice for improving engine emission and performance.

KEYWORDS
morphology, nanoadditives, soybean biodiesel, Sr/ZnO, VCR engine

1 | INTRODUCTION

In recent years, industrial units and transportation systems have relied heavily on traditional fossil fuels.[1] Diesel engines, in particular, are used as a key source of power generation in these industries due to their inherent benefits, such as high efficiency and power-to-weight ratios.[2–4] However, due of their limited resources, these sources fade away after a while. Furthermore, burning diesel in variable compression ratio (VCR) engines produces undesired exhaust pollutants like CO, NOx, smoke, and unburned hydrocarbons, all of which have negative effects on ambient climatic conditions and human health.[5–7] Another key issue that scientists must address completely is the research on lowering pollutants generated by diesel engines.[8,9] Emission rules for engines, in particular, are becoming more stringent every year.[10,11] As a result, researchers are compelled to research emission reduction technologies and to identify more clean, renewable, and environmentally friendly alternatives that do not require engine modification.[12,13]

Biodiesel (BD) is a good alternative fuel these days because of its advantages such as renewable nature, reduced greenhouse gas emissions, and long-term viability, and it has the potential to replace fossil fuels.[14,15] BD has emerged as a promising fuel for satisfying global energy demands, and vast quantities are readily available.[16,17] It improves not just usability but also thermophysical properties. BD enhances performance and reduces pollution when used to power diesel engines.[18–20] According to a review of the literature, pure BD has some drawbacks, including cold flow characteristics, high viscosity, poor fuel atomization, and piston ring sticking.[21,22] Blending a tiny amount of BD with diesel can overcome these problems. Some emissions, however, may suffer as a result of this, which can be remedied by adding nanoadditives. The addition of nanoadditives lowers emissions while boosting the VCR engine's performance.[23] Numerous publications on nanoadditives like as ZnO, Al_2O_3, carbon nanotube (CNT), SiO_2, and others have been published in this field.[15,24–26] Without requiring any adjustments, these additives improve the performance of biodiesel–diesel engines. Despite extensive work to improve engine performance by employing nanoadditives and other BD, the engine's performance remains poor, and further study is needed to find new ways to improve it. The current study focuses on the importance of additive-based fuel modification options for boosting engine performance and lowering emissions.

The purpose of this study is to investigate the effect of 1% Sr-doped ZnO nanoparticles (NPs) as fuel additives for a soybean BD fuel blend at varying loads in a VCR engine. The 1% Sr-doped

ZnO NPs were synthesized using zinc and strontium nitrates via a sonochemical method, and the NPs were characterized using various physicochemical techniques. These NPs were then ultrasonically blended with SB25 blends including Polysorbate 80 surfactant. Furthermore, the impact of NPs introduced into various fuel blends on the performance and emission parameters of a VCR engine was thoroughly investigated.

2 | MATERIAL AND METHODS

2.1 | Soybean oil extraction and BD manufacturing

SB are very well-suited to growing on soils comparable to those used for maize production. SBs are frequently cultivated in rotation with maize or wheat to interrupt pest, weed, and disease regimes. SB' s have lower nutritional needs than other crops, with significant nutritional needs of N_2, P, and K, and where most of the N_2 is obtained through a connection with microbes. SB oil is a prominent feedstock for biofuel manufacturing. The most popular technique of producing BD is to react vegetable oils or animal fats with CH_3 or C_2H_5OH in the presence of alkali (KOH or NaOH which acts as a catalyst). The BD is produced using the transesterification reaction. Several research studies conducted from 1980 to till date revealed that using plain soybean oil, causes carbon deposits and reduces engine life. However, the usage of SBME in diesel engines has no negative consequences.

The drying of grains was done initially during the soybean extraction process to ensure optimum oil quality throughout the oil extraction procedure. The beans were then dehulled and ground as part of the pretreatment process. Oil was extracted using a mechanical press with an electric heater. The extracted oil is then utilized in the transesterification process to make BD.

In a typical soybean BD synthesis, the extracted soybean oil is mixed with methanol and sodium methoxide for transesterification. This procedure is carried out at 60–70°C for 2 h with vigorous stirring. After ensuring that the reaction was complete, the heating was turned off and the mixture was transferred to a separating funnel for removal of BD and glycerol. To remove traces of glycerol, the obtained BD is thoroughly washed with water. The soybean biodiesel was then purified using the vacuum distillation method. Figure 1 depicts a schematic representation of the steps involved in the extraction of soybean oil and the manufacture of soybean biodiesel.[27]

2.2 | Fabrication of 1% Sr-doped ZnO NPs

The NPs are prepared by using sonochemical method.[28] In typical synthesis, zinc and strontium nitrates with sufficient molar ratios were dissolved in 40 ml water in a standard synthesis procedure for 1% Sr-doped ZnO NPs. 3.05 gm Malic acid was applied to this solution, which was then stirred for 20 min with a magnetic stirrer. The pH of the above mixture was then changed to 11 by adding ammonia to it. The collected white precipitate was subjected to a 2-h sonochemical treatment. For another 30 min, the resulting mixture was magnetically stirred. After that, the precipitate was centrifuged, washed several times with water, and dried at 60°C. The synthesized 1% Sr-doped ZnO NPs used further for physicochemical characterization.

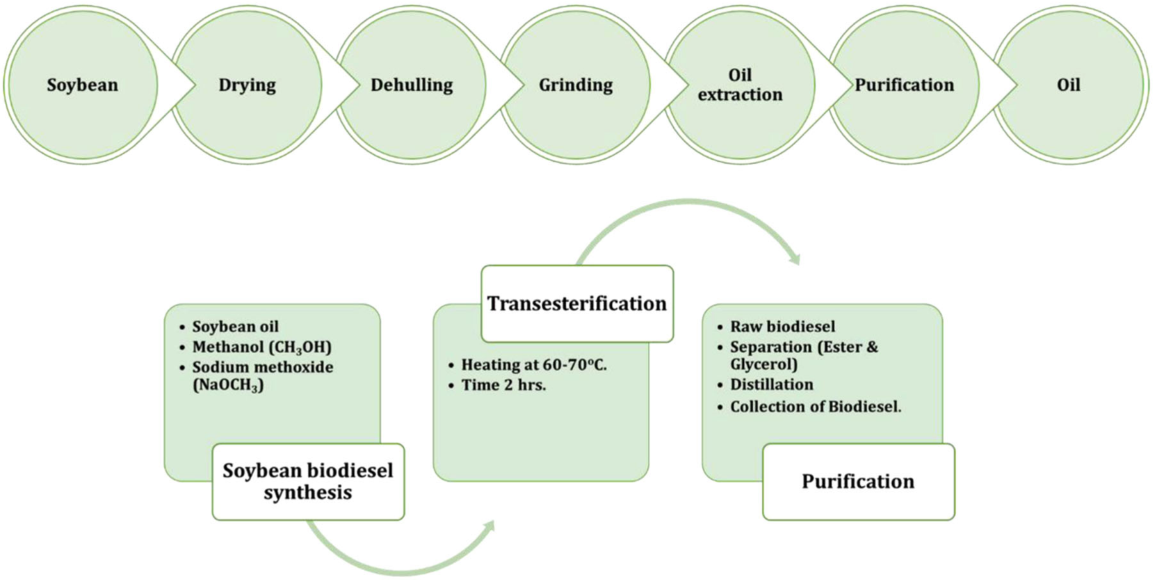


FIGURE 1 Schematic representation of soybean oil extraction and soybean biodiesel manufacturing.

2.3 | Preparation and physicochemical properties of nanofuel blends

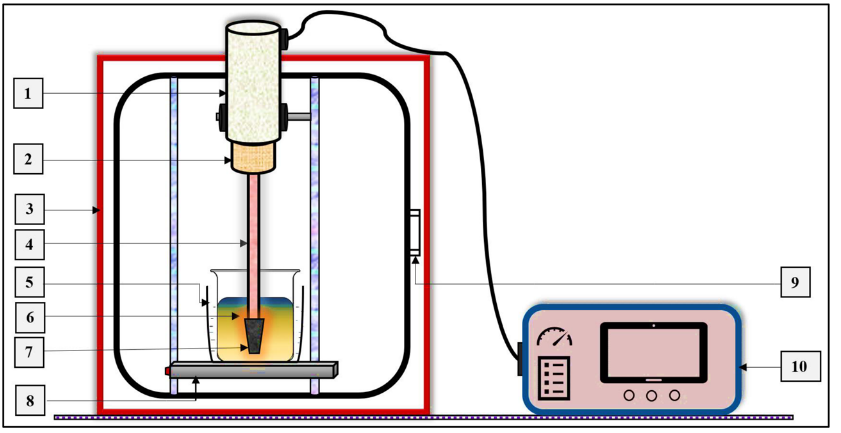
Under the magnetic stirrer, the diesel is mixed with 25% soybean biodiesel (SB25). To stabilize the SB25 blend, the highly dispersible and stable Polysorbate 80 surfactant was added. Then, using a 30 Hz probe sonicator, 1% Sr-doped ZnO NPs were disseminated in two concentration levels of 50 and 75 ppm, forming nano-fluids during ultrasonication for 60 min. The obtained blends were labeled as diesel (100% diesel), SB25 (25% soybean biodiesel + 75% diesel), SB25Sr/ZnO50 (25% soybean biodiesel + 75% diesel + 50 ppm Sr/ZnO), and SB25Sr/ZnO75 (25% soybean biodiesel + 75% diesel + 75 ppm Sr/ZnO), respectively. This method was previously used in the literature.[29] The ultrasonication equipment for the manufacture of nanofuel is shown schematically in Figure 2.[29] Table 1 lists the physicochemical features of several fuel mixtures.

2.4 | Uncertainty analysis

Uncertainty analysis is used to determine the likely errors obtained during experimentation, some of which are attributable to environmental variables and others owing to measuring tools. These errors involve human errors as well. The percentage of accuracy and uncertainty of various parameters are shown in Table 2.

The uncertainty for variables decided on the variables based on two or additional factors is accomplished out using Equation (1):

$$\frac{U_y}{y} = \sqrt{\left(\frac{u_{x_1}}{x_1}\right)^2 + \left(\frac{u_{x_2}}{x_2}\right)^2 + \cdots + \left(\frac{u_{x_n}}{x_n}\right)^n}, \tag{1}$$



1. Ultrasound Transducer + Mechanical rotor assembly	4. Sonotrode Assembly	7. Sonotrode	10. Ultrasound generator with power display
2. Ultrasound probe	5. Water Bath	8. Hot Plate + magnetic stirrer	
3. Reactor	6. Suspension (NPs + fuel)	9. Lock Assembly	

FIGURE 2 A probe sonicator is used to prepare fuel blends.[30]

TABLE 1 Physicochemical properties of soybean biodiesel + Sr/ZnO nanofluid.

Nanofluid	Density@25°C (kg/m^3)	Kinematic viscosity@40°C (mm^2/s)	Gross calorific value (MJ/kg)	Flash point (°C)	Pour point (°C)
Diesel	827	2.11	43.756	68	−3.7
Soybean	872	4.2	40.332	84.5	−5.3
SB25	841	3.44	42.112	77.6	−4.5
SB25Sr/ZnO50	833	3.25	42.414	74.2	−5.4
SB25Sr/ZnO75	837	3.33	42.102	76	−5.6

where U_y is uncertainty; y is testing value; $x_1, x_2, ...x_n$ is evaluated parameter, and the uncertainty of emissions is $U_y = \frac{\text{resolution}}{\text{range}}$.

The overall uncertainty of the engine characteristics is calculated using Equation (2):

$$\begin{aligned} &\text{Overall uncertainty} \\ &= \pm\sqrt{\text{Uncertainty \% of (BTR + BSFC + BP + CO + NOx + HC + smoke)}} \\ &= \sqrt{\text{Uncertainty \% of } (0.4 + 0.4 + 0.4 + 0.3 + 0.5 + 0.4 + 0.5)} = \pm 1.82. \end{aligned} \tag{2}$$

TABLE 2 Uncertainty and Accuracy levels of measurement 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
Smoke meter (HSU)	±1	±0.5

Abbreviations: BTE, brake thermal efficiency; BSFC, brake-specific fuel consumption.

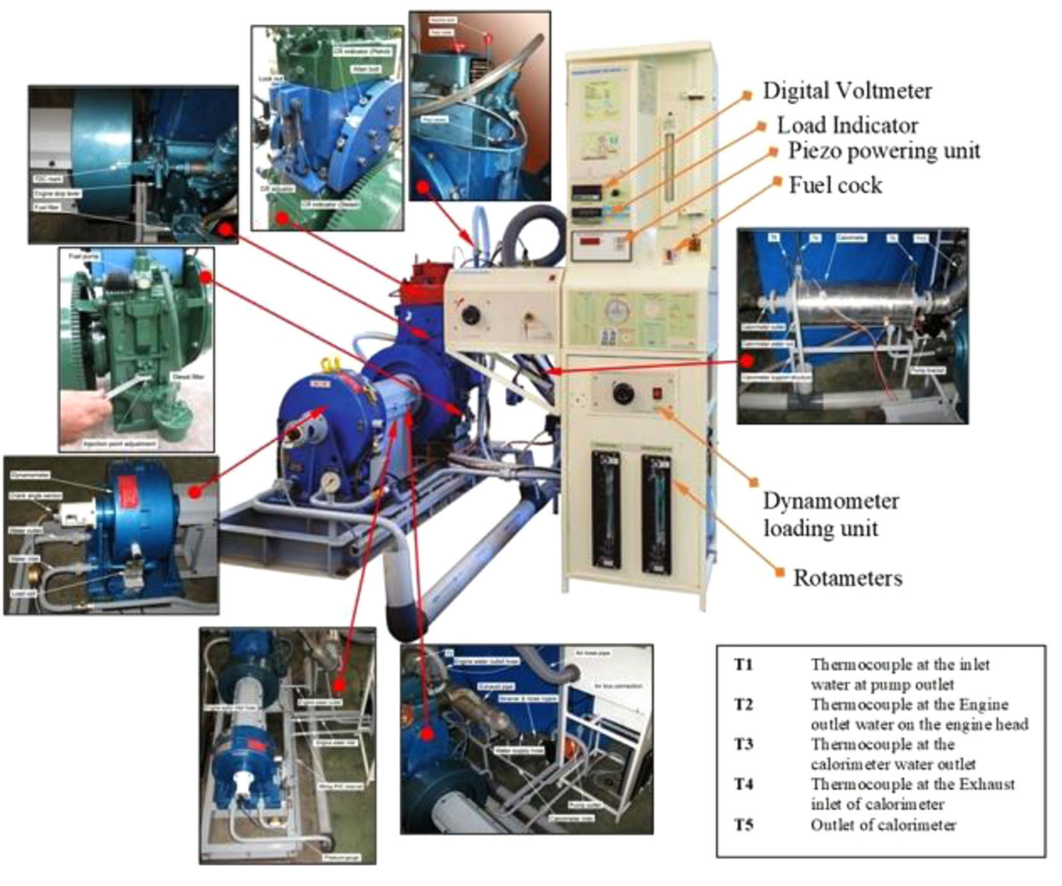


FIGURE 3 Kirloskar diesel engine with variable compression ratio (VCR).

TABLE 3 Engine specifications.

No. of strokes	4
Fuel type	Diesel, biodiesel, and nonfuel
Cylinder	Single, WC
Rated power	3.5 kW
Speed	1500 rpm
Cyl. dia.	87.5 mm
Load indicator	Digital, range 0–50 kg, supply 230 V AC
Fuel tank	Volume 15 L with glass fuel metering column
EGR	Water cooled, stainless steel, range 0%–15%
Piezo sensor	Range 5000 PSI, with low noise cable
T sensor	RTD, PT100, and TC, type K
Load sensor	Load cell, type strain gauge, range 0–50 kg
Rotameter	Engine cooling 40–400 LPH; Cal. 25–250 LPH
Dynamometer	Eddy current
Model	AG10
Make	Saj test plant rig
End flanges both sides	Cardon shaft model 1260 type
Air gap	0.77 mm
Torque	11.5 N m
Hot coil voltage	60 V
Continuous current (A)	5
Cold resistance (Ω)	9.8

2.5 | Test setup

Figure 3 shows a single-cylinder diesel engine from Kirloskar with a VCR.[31] This engine was used to evaluate the bends of nanofluids. Engine soft software was used to record the experimental outcomes. A tilting cylinder system was used to achieve a VCR (provided by manufacturer). Table 3 lists all of the engine specifications in detail.[31]

3 | RESULTS AND DISCUSSIONS

3.1 | Characterization of 1% Sr-doped ZnO NPs

The purity and phase identification of the 1% Sr-doped ZnO NPs were studied using X-ray diffraction analysis (XRD). The XRD spectra of as-synthesized 1% Sr/ZnO NPs are shown in Figure 4A. The powerful (hkl) peaks at 32.02, 35.64, 36.85, 48.57, 55.26, and 62.57, respectively, corresponding to the lattice planes (100), (002), (101), (102), and (110), respectively, as shown in

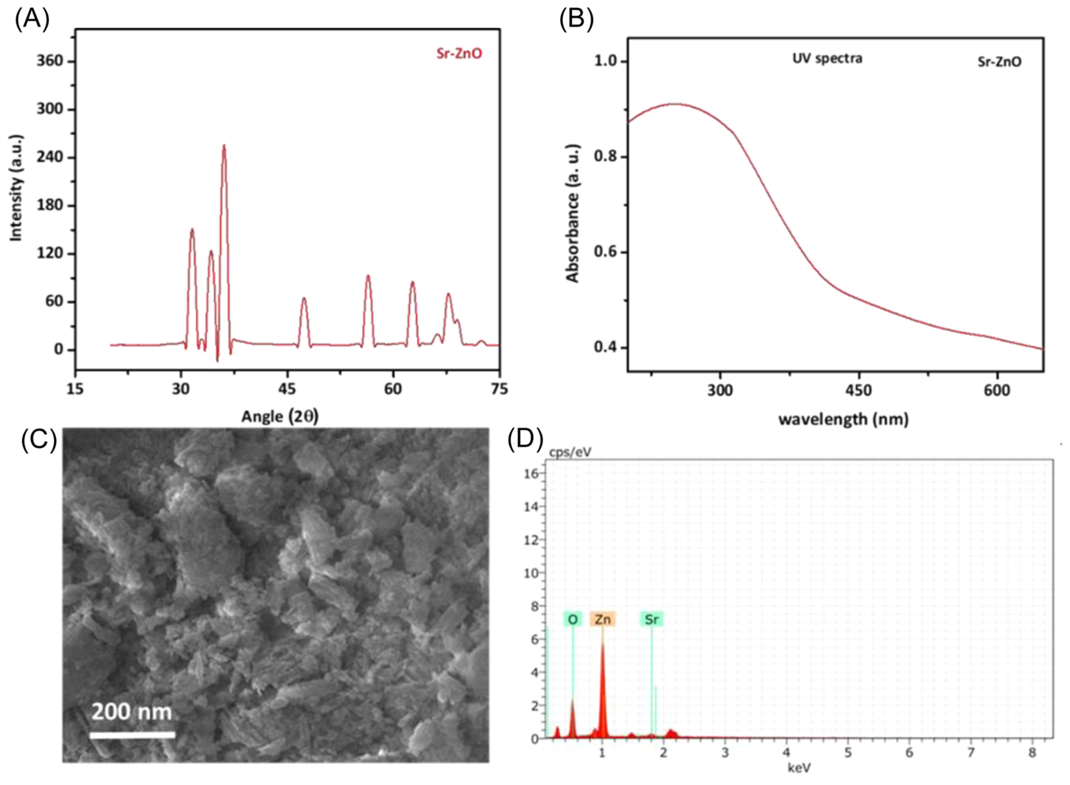


FIGURE 4 (A) X-ray diffraction; (B) ultraviolet; (C) field-emission scanning electron microscopy, and (D) energy-dispersive X-ray spectroscopy spectra of 1% Sr-doped ZnO.

the figure. The spectral data agrees well with JCPDS card no. 036-1451, indicating that the products are in the wurtzite process of pure hexagonal ZnO.[30,32–34] The absence of a strontium-related peak means that the strontium is incorporated into the ZnO lattice and that the ZnO crystal structure does not change as a result of doping. The average size of 1% Sr/ZnO NPs in crystallite was measured using the Debye Scherrer formula. One percent Sr/ZnO NPs nanostructures had an average crystallite size of 51.06 nm. This 1% decrease in Sr/ZnO NPs crystallite size is primarily due to the formation of Sr–O–Zn on the sample's surface, which may obstruct the growth of ZnO NPs to some extent.

The ultraviolet spectra of 1% Sr-doped ZnO as-synthesized are shown in Figure 4B. Lattice absorption may reveal information about the atomic vibrations involved. The optical absorption edge of ZnO was commonly estimated at 360 nm. With Sr doping (450 nm), the ZnO absorption edge clearly moves towards the blue shift.

Using field-emission scanning electron microscopy (FESEM), the surface morphology of as-synthesized 1% Sr/ZnO was investigated (FESEM). Figure 4C,D show the FESEM and energy-dispersive spectra (EDS) of 1% Sr–ZnO. Figure 4C shows that the irregularly shaped NPs of as-synthesized samples were formed through sonochemical treatment. These particles clump together, and the size of these NPs ranges from 20 to 80 nm. EDS was used to validate the formation of 1% Sr/ZnO NPs. The stoichiometric ratios of Sr, Zn, and O used in synthesis fit the

EDS results well. The absence of impurity peaks confirms the formation of extremely pure Sr-doped ZnO.

3.2 | The influence of 1% Sr-doped ZnO NPs and a soybean biodiesel blend on VCR diesel engine performance parameters

Brake thermal efficiency (BTE) is a critical performance metric that measures the ratio of output power to combustion heat produced by the fuel. The fluctuation of BTE under various loads and fuel mixtures is depicted in Figure 5A. Among all fuel blends, the SB25 had the lowest BTE performance characteristics. This serious engine behavior can be linked to poor spray characteristics caused by BD's lower volatile content and increased viscosity. Metal oxide NPs (Sr/ZnO) enhanced the complete combustion by decreasing the ID period; nevertheless, higher in-cylinder temperatures alos raised the BTE. The inclusion of Sr/ZnO nanoadditives improves the engine's BTE performance, possibly due to secondary atomization capabilities of

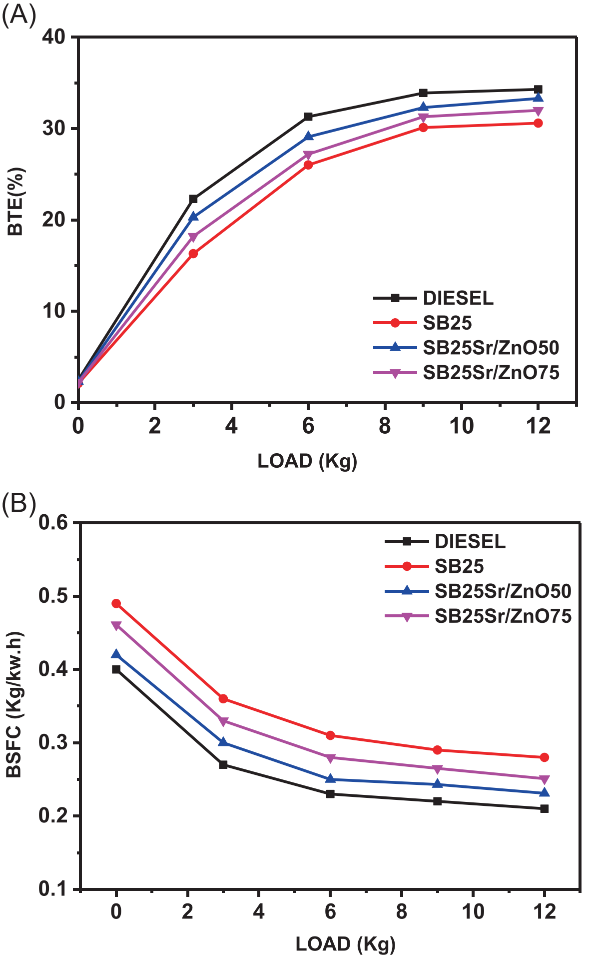


FIGURE 5 Effect of Sr/ZnO nanoadditives on (A) brake thermal efficiency (BTE) at varying load; (B) brake-specific fuel consumption (BSFC) at varying loads.

Sr/ZnO present in the SB25 fuel blend, which improves the SB25 fuel blend's combustion.[35–37] When compared to soybean biodiesel, the thermal efficiency of the fuel blend improves with each dose. The microexplosion phenomena is aided by the Sr/ZnO NPs in the fuel blends, which results in complete combustion of the fuel particles.[38] The fuel mix SB25Sr/ZnO50 had the greatest BTE value (10.37%), whereas SB25Sr/ZnO75 had a BTE value that was 5.45% higher than SB25 biodiesel.

The energy produced by the fuel to develop a unit engine power is described by brake-specific fuel consumption (BSFC), which is a significant parameter. For any fuel, the BSFC is intended to be the lowest.[39] At high loads, the BSFC value decreases due to lower heat losses and a lower quantity of fuel required to achieve specified BP. Figure 5B depicts the variance in BSFC with regard to different fuel blends and loads. The BSFC declines with increasing BD blending percentage for all load conditions of the engine, as seen in the graph. SB25Sr/ZnO50 and SB25Sr/ZnO75 had lower BSFC than SB25 by 16.76% and 8.67%, respectively, when compared to SB25. Heat loss is minimized at higher loads due to the presence of Sr/ZnO NPs. The Sr/ZnO NPs act as a potential catalyst during combustion due to their greater reactive surface area, resulting in decreased BSFC when compared to SB25.[39]

3.3 | The impact of 1% Sr-doped ZnO nanoadditives and a soybean-based fuel blend on engine emissions

Figure 6 shows the NOx emission characteristics of diesel, SB25, SB25Sr/ZnO50, and SB25Sr/ZnO75 blends at various loads. Due to efficient combustion, an increase in engine load increases the percentage of NOx emissions.[40] High temperature combustion of fuels occurs when the temperature rises high enough (above roughly 1300°C/2370°F) to oxidize part of the nitrogen in the air to NOx gases. The increase in the oxygen concentration in the combustion chamber also slightly increases the NOx emissions, the NOx emission generation can be prevented by using retard injection, fuel nozzle alteration, compression ratio (CR) change, water DI, water emulsification, EGR, and secondary methods such as SCR. In comparison to plain BD and diesel, the inclusion of Sr/ZnO nanoadditives resulted in greater NOx emissions.

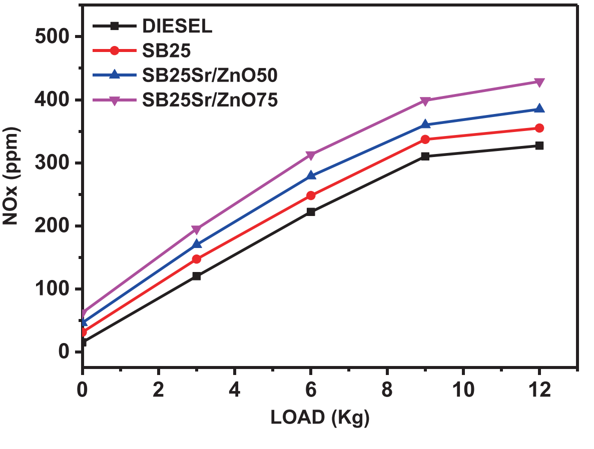


FIGURE 6 NOx variation with load for various fuel blends.

In comparison to SB25, NOx emissions increased 9.83% and 20% at maximum CR (21.5%) for SB25Sr/ZnO50 and SB25Sr/ZnO75, respectively. Increased NOx due to higher combustion chamber temperatures and extra oxygen atoms due to oxygen-donating Sr/ZnO NPs.[40]

For various fuel blends, Figure 7 shows how hydrocarbon (HC) emissions change with load. HC emissions are influenced by the CR, fuel density, fuel flow characteristics, fuel spray patterns, and engine operating condition. The combustion pressure and temperature grow as the CR rises, resulting in a drop in density. Regular fuel spray patterns and proper hydrocarbon burning are obtained due to the low density, decreasing HC emissions.[41,42] In the current study, SB25Sr/ZnO50 and SB25Sr/ZnO75 reduced HC emissions by 11.20% and 4.8%, respectively, when compared to SB25. The SB25 blend had the most hydrocarbons, which can be attributed to its high density and viscosity, which resulted in poor fuel atomization in the combustion chamber and, as a result, poor thermal efficiency.

In general, as the load on the engine grows, the volumetric efficiency drops, resulting in incomplete combustion of carbon molecules. As a result, CO is produced throughout the combustion process. According to the United States Environmental Protection Agency, vehicle exhaust accounts for approximately 95% of all CO emissions. CO is not totally transformed to CO_2 here. Nanoadditives that improved fuel combustion qualities resulted in 100% combustion of enriched nanofuel blends. As a result of proper combustion, maximum CO is transformed into CO_2, and CO emissions are reduced.[41,43]

Figure 8 illustrates the impact of nanoadditives on CO emissions. CO emissions are nearly constant until the load reaches 30%, beyond which they increase as the load increases. SB25Sr/ZnO50 had the least carbon monoxide emissions of all the evaluated nano-biofuels/BD blends due to the presence of additional oxygen and surface functional area (Sr/ZnO), that results in high in-cylinder pressure and temperature, leading in full combustion. SB25Sr/ZnO50 fuel blend emits less CO than other fuel blends, with the exception of diesel fuel, due to its superior combustion characteristics. When compared to SB25, CO emissions for SB25Sr/ZnO50 and SB25Sr/ZnO75 were reduced by 13.81% and 8.65%, respectively. Similar findings were observed by Paramashivaiah et al.[44]

Figure 9 depicts the fluctuation of CO_2 with load for various fuel mixtures. The carbon molecules in the fuel blend react with the O_2 to form CO_2. Soybean biodiesel raises CO_2

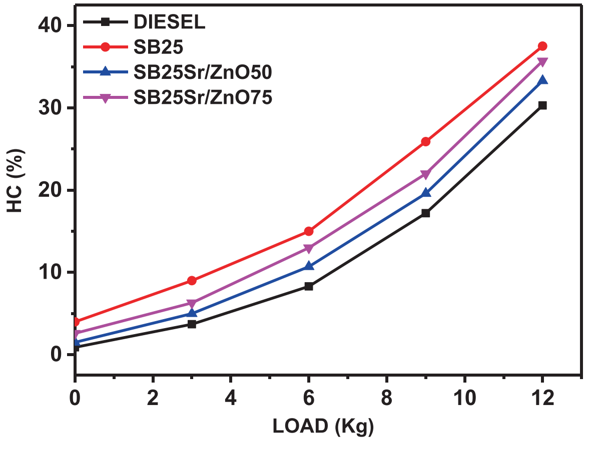


FIGURE 7 Hydrocarbon (HC) variation with load for various fuel blends.

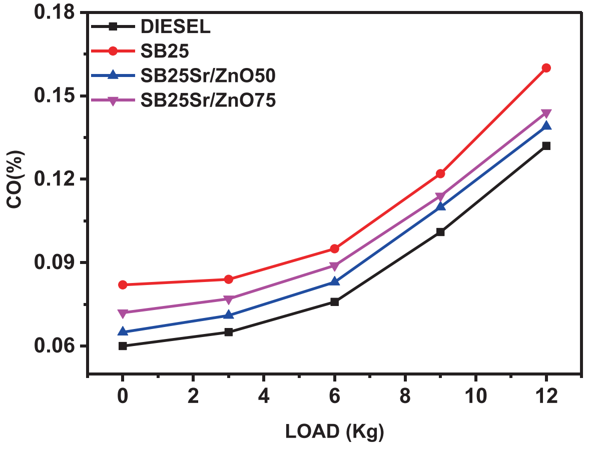


FIGURE 8 CO variation with load for various fuel blends.

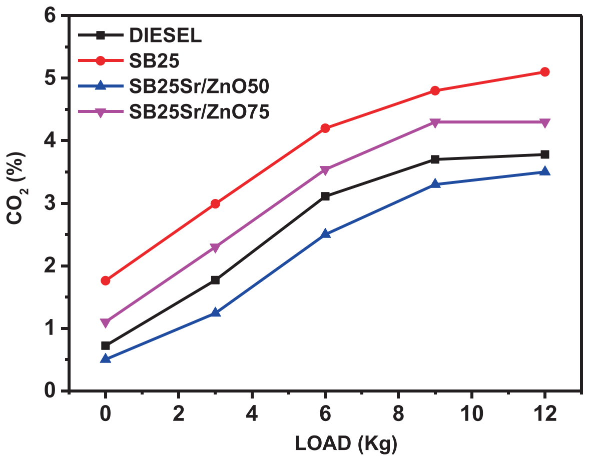


FIGURE 9 CO_2 variation with load for various fuel blends.

emissions marginally without requiring engine adjustments.[45] According to the literature, higher CRs result in increased CO_2 emissions. Volumetric efficiency diminishes as load increases. SB25 blends emit the most CO_2 when compared to other fuel blends because the high density of SB25 causes poor fuel atomization. When compared to the SB25 fuel mix, total CO_2 emissions were reduced by 41.43% and 17.55% for SB25Sr/ZnO50 and SB25Sr/ZnO75, respectively. At maximum load, SBMESr/ZnO50 emits less CO_2 than all other fuel blends. The presence of Sr/ZnO in fuel improves SB25 fuel combustion by acting as a reservoir for the extra oxygen necessary for SB25 combustion.[45]

The graph of smoke variation with engine load are shown in Figure 10. Smoke is found to be strongly dependent on load. The primary cause of smoke creation is poor air–fuel mixing; when the temperature in the combustion chamber is too high to decompose the fuel, there is a lack of oxygen available to burn the fuel.[14,46,47] Due to its low energy content and low heat

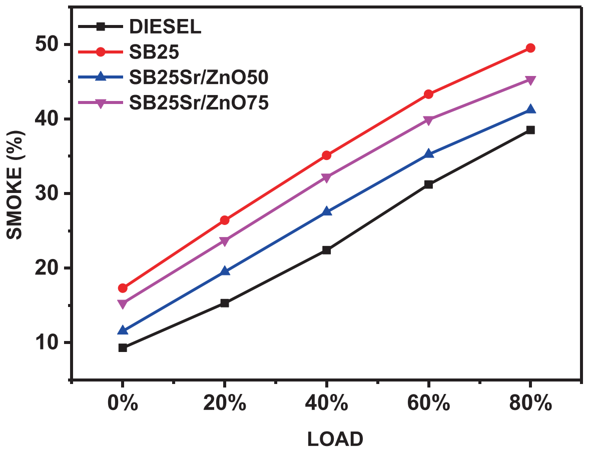


FIGURE 10 Smoke variation with load for various fuel blends.

release rate, the SB25 fuel blend produces increased smoke opacity. SB25 with Sr/ZnO fuel blends improves combustion phenomena by improving fuel particle microexplosion. Smoke emission for CR 21.5 for SB25Sr/ZnO50 and SB25Sr/ZnO75 was reduced by 21.34% and 8.85%, respectively, when compared to SB25, as shown in the figure. The combustion phenomenon is improved by the wide surface area of the SB25Sr/ZnO50 nanoadditives. As the CR rises, the combustion pressure rises, and the temperature rises, the smoke emission reduces.[14]

4 | CONCLUSION

The focus of this paper was on the emulsion of 1% Sr-doped ZnO NPs in soybean biodiesel. The ASTM standard was used to evaluate the physiochemical attributes of the fuel mixtures. In conclusion, the following observations are made in this experimental study:

1. The homogenous mixing of 1% Sr-doped ZnO with SB25 was done using ultrasonication technique. The physicochemical properties of SB25 fuel increased with the addition of Sr/ZnO NPs.
2. The addition of NPs improved the performance characteristics. SB25Sr/ZnO50 nanofuel combination boosts BTE by 10.37% and reduces BSFC by 16.76%.
3. CO, CO_2, HC, and smoke emissions were reduced by 13.81%, 41.43%, 11.20%, and 21.34%, respectively, with the SB25Sr/ZnO50 nanofuel blend. In comparison to SB25, NOx emissions increased by 9.83%.
4. The current study's cost analysis revealed that NPs in diesel and SBME marginally raise the fuel cost. The laboratory manufacture of Sr/ZnO NPs and SBME by precipitation and transesterification lowered the expense compared to purchase of commercially available NPs and BD. However, focusing on the development of NPs in biofuel combinations, on the other hand, outweighs economic concerns.

It is concluded that SB25 with 50 ppm Sr/ZnO blend improves performance parameters and reduces engine emissions.

5 | FUTURE RECOMMENDATIONS

1. The research on the impact of NPs on exhaust emissions has a lot more potential. It highlights concerns pertaining to environmental impact produced by NPs in biofuel fuels. Before releasing the concept to the marketplace, the effect of NPs utilized in fuel blends on human and animal wellbeing should be assessed. In addition to metal-based, nonmetal-based, and CNT NPs, the study on using organic nanomaterials as additives with BD fuels is trailing.
2. To validate the dependability of nanoadditives in a CI engine, a detailed examination of the surface reactivity NPs on engine wear and engine components as well as exhaust system corrosion is necessary.
3. Extensive research on the stabilization, thermal conductivity, endurance testing, innovative models, and storage stability of NPs in relation to petroleum products is necessary. Vehicles must be built and adjusted in terms of characteristics such as swirl ratios, pilot injections, and nozzle geometry adjustment (improves spray patterning and decreases the size of the droplets).

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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