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Implication of SiO_2 nanoparticles with novel water hyacinth biodiesel-diesel blends to improve the performance and emission parameters of a diesel engine

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Abstract

The current research explores experimentally the crude oil production from water hyacinth weed (potential renewable biomass), its biodiesel preparation and implication of SiO_2 nanoparticles (25 ppm, 50 ppm, 75 ppm, 100 ppm) with biodiesel (fixed 20%) and diesel (fixed 80%) blends on the performance and emission parameters of a 4-S single cylinder diesel engine. Crude water hyacinth oil is produced through the chemical Soxhlet extraction technique, and its biodiesel is prepared by transesterification. Metal oxide oxygenated SiO_2 nanoparticles are dispersed through ultrasonication in water hyacinth biodiesel blends to improve their combustion quality and make them more efficient. Prepared fuel blends' properties are examined as per the standards of the American Society for Testing and Materials. The experiment reveals that crude water hyacinth oil has 85.6% biodiesel yield. Dispersion of SiO_2 nanoparticles in WHB20 fuel decreases the brake specific fuel consumption by 12.61% and improves the brake thermal efficiency by 12.55% at a maximum load. HC and CO emissions are found to be decreased by 25.85% and 22.64%, respectively, whereas NO_x and CO_2 emissions are found to be increased by 45.85% and 10.87%, respectively, for WHB20SiO$_2$100ppm compared to fossil diesel at a maximum load. Overall, research concludes that WHB20SiO$_2$100ppm fuel is the best performer and suitable alternative for diesels without change in engine design.

Keywords: Transesterification; Water hyacinth biodiesel; Ultrasonication; Silicon dioxide nanoparticles; Performance and emission

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1. Introduction

Power generation in different sectors, increase in population, transportation, urbanisation, industrial developments and globalisation have enhanced the demand for fossil fuels (depleting rapidly) worldwide. Over the last two decades, energy has played an increasingly important role on both the social and economic fronts in emerging and industrialised nations. The world's energy requirements have been met mostly through fossil fuels, including gas, coal and mineral oils. Countries have emphasised utilising local and regional biomass feedstocks to meet the energy requirements and minimise the dependency on conventional fuels worldwide [1]. When the demand for fossil fuels begins to outstrip supply, prices will rise. Considering all that, the researchers' quest for a viable alternative feedstock for current unmodified diesel engines has been exacerbated by the rapid fossil fuel depletion and rising exhaust pollution.

India is currently 85% reliant on imports to satisfy its oil needs, which is extremely expensive. According to the Ministry of Petroleum & Natural Gas, Government of India, a mixture of

Nomenclature

Abbreviations and Acronyms

ASTM – American Society for Testing and Materials
BD – biodiesel
BSFC – brake specific fuel consumption
BTE – brake thermal efficiency
CO – carbon monoxide
CO_2 – carbon dioxide
EGT – exhaust gas temperature
HC – hydrocarbon
NO_x – nitrogen oxides
RPM – revolution per minutes
SiO_2 – silicon dioxide
WHB – water hyacinth biodiesel
WHB20– water hyacinth biodiesel 20%, diesel 80%
WHB20$SiO_2$25ppm – WHB20%, diesel 80%, SiO_2 25 ppm
WHB20$SiO_2$50ppm – WHB20%, diesel 80%, SiO_2 50 ppm
WHB20$SiO_2$75ppm – WHB20%, diesel 80%, SiO_2 75 ppm
WHB20$SiO_2$100ppm – WHB20%, diesel 80%, SiO_2 100 ppm
WHO – water hyacinth oil

5% biodiesel with the current diesel fuel is acceptable now to save thousands of crores per year. Usmani [2] discussed the potential use of agroforestry residues and biomass for biofuel and energy production. Rasid et al. [3] discussed recent pretreatment methods and their future utilisation for enhancing the biofuel production. The utilisation of highly potential metal oxides nano-catalysts for biofuel production strategies was presented by Manikandan et al. [4] and Hosseinzadeh-Bandbafha et al. [5].

Biodiesel is gaining popularity across the world; hence, many countries are producing biodiesel from different feedstocks to meet their energy demands. Nowadays, millions of litres of biodiesel are consumed in a number of countries globally (United States, European countries, Asian countries). In this regard, different biodiesels derived from different sources of biomass are presented subsequently.

The first-generation (corn, sugarcane and vegetable oil), second-generation (municipal waste and agricultural residues) and third-generation algal biomass renewable feedstocks for biofuel production were reviewed by Ho et al. [6]. The production of biodiesel from different feedstocks was reviewed by Zhang et al. [7], and revealed that microalgae, jatropha curcas, vegetable oil and waste cooking oil are the most widely utilised biodiesels.

Diesel engine performance parameters utilising corn oil biodiesel were examined by Saini et al. [8]. Extraction of microalgae oil, biodiesel production and its various blends with diesel were tested in a diesel engine [9]. The numerical model for lipid extraction from avocado seeds has been presented by Sathish et al. [10]. Oil extraction from mango seed and its utilisation with diesel-butanol blends were examined in Ahmad and Saini [11]. The production of biodiesel from soybean oil with higher conversion efficiency as an alternative fuel for diesel engines was discussed by Wang et al. [12]. The potential utilisation of synthesised lemongrass biodiesel with diesel blends for an unmodified diesel engine was discussed by Kumar et al. [13].

Bioethanol production from water hyacinth and its blends with diesel were utilised to investigate diesel engine characteristics by Choudhary et al. [14]. Different blends of water hyacinth biodiesel (WHB) with diesel were tested on a diesel engine by Venu et al. [15] and Alagu et al. [16]. Both studies reported that mixing of twenty percent water hyacinth biodiesel with eighty percent diesel was the best performer in terms of improved engine performance and reduced emissions parameters. In Indonesia, an experimental study recommended that the blending of up to 40% biodiesel in diesel without engine modifications is acceptable, Sukmono et al. [17]. Moreover, research is not limited to exploration of new renewable biomass sources for biodiesel generation. Worldwide, explorations of different metal oxide nanoparticles with biodiesel blends to improve performance and reduce emissions of unmodified diesels are an emerging research need.

The effect of nanoparticles as an additive in diesel and biodiesel blends on stability, engine performance and emission characteristics was reviewed by Soudagar et al. [18] and Alli and Kotha [19]. The studies suggested that metal oxide nanoparticles with biodiesel blends further improve the engine characteristics. Diesel engine running on biodiesels combined with nano-additives emits less carbon monoxide and unburned hydrocarbon with enhanced engine performance as reviewed by Damanik et al. [20], Manigandan et al. [21], and Tomar and Kumar [22]. Moreover, some studies of metal oxides nanoparticles as an oxygenated additive with various kinds of biodiesel to improve performance and reduce emissions of compression ignition (CI) engines have been reported in recent literature, such as: silver oxide nano-additive with neem oil biodiesel, Devarajan et al. [23]; aluminium oxide nanoparticles with palm oil biodiesel, Sundar et al. [24]; titanium dioxide nano-additive with mustered oil biodiesel, Yuvarajan et al. [25]; titanium dioxide nano-additive with azolla algae biodiesel, Narayanasamy and Jeyakumar [26]; silicon dioxide nano-additive with corn biodiesel, Saravankumar et al. [27]; cerium dioxide nano-additive with waste cooking oil biodiesel, Dinesha at al. [28]; titanium dioxide nano-additive with water emulsified soybean oil biodiesel, Vellaiyan et al. [29]; silicon dioxide nano-additive with mahua biodiesel, Nutakki et al. [30]; titanium dioxide nano-additive with polanga oil biodiesel, Praveen et al. [31]; silicon dioxide nano-additive with mahua biodiesel blends, Ramachander et al. [32]; titanium dioxide nano-additive with lemongrass biodiesel blends, Kumar et al. [33]; titanium dioxide nano-additive with eichhornia crassipes biodiesel, Jain et al. [34].

Although the above reviewed literature reported the biodiesel production from different renewable biomass, dispersion of nanoparticles with them and their utilisation in unmodified diesels, scarce research opportunity on water hyacinth biomass (abundantly available renewable feedstock worldwide) has attracted authors to explore for crude oil production from this biomass, biodiesel preparation, dispersion of silicon dioxide oxygenated nanoparticles with biodiesel blends and their applicability in diesels as sustainable alternate fuel.

In this paper, performance and emission parameters of a 4-S single cylinder diesel engine fuelled by binary blends of diesel (fixed 80%) and water hyacinth biodiesel (fixed 20%) with different SiO_2 nano-additive concentrations (25 ppm, 50 ppm, 75 ppm and 100 ppm) at various engine loads are investigated experimentally. These four concentrations are chosen based on standard incremental ranges reported in recent nanoparticle fuel studies, taking into account practical stability limits for stable dispersion, and economic feasibility for blending. Novelties of the current research may be considered twofold:

(i) Soxhlet chemical extraction of crude oil from potential renewable water hyacinth biomass and its biodiesel preparation through transesterification;

(ii) Dispersion of SiO_2 nanoparticles (oxygenated additives improve combustion quality) with WHB and diesel blends through the ultrasonication technique.

The prepared tested fuels are named as WHB20, WHB20$SiO_2$25ppm, WHB20$SiO_2$50ppm, WHB20$SiO_2$75ppm, and WHB20$SiO_2$100ppm, respectively. Important fuel properties of blends are determined as per the American Society for Testing and Materials (ASTM) standards. Eventually, experimental investigations are made to obtain performance characteristics: brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), exhaust gas temperature (EGT), and emission characteristics: hydrocarbon (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x). The characteristics of the prepared blends are obtained at different engine loads, and the results are compared with WHB20 and fossil diesel fuels.

2. Materials and methods

This section deals with the materials and methods used to extract crude water hyacinth oil, and prepare biodiesel and its different blending samples with SiO_2 oxygenated nanoparticles as an additive. In addition, the important property values of prepared samples are examined for utilisation in a 4-S single cylinder vertical diesel engine.

2.1. Water hyacinth plant collection and drying

Water hyacinth is an aquatic weed, which is available abundantly in the eastern region of India and is now prevalent across the country except in the dry western region. The plants may grow up to 1 m tall, with the average recorded height of 40 cm. Six to ten blooms, each about 4 to 7 cm in diameter, can be seen on the flowers. The stems and leaves feature air-filled tissue that allows it to float effortlessly, with a high growth rate of 60−100 tonnes per hectare per year.

In this research, water hyacinth plants were collected from the Ramgarh lake (covering an area of 723 hectares) located at Gorakhpur, Uttar Pradesh, India. Further, drying of green water hyacinth is done in sunlight, preceded by oven drying at 70℃. The ambient temperature varies between 21−26℃ in the months of December and January. It is found that 3.6 kg of green water hyacinth plants is converted into 1 kg after drying. After drying, the dried plants are chopped into small pieces and crushed into powder using a grinder. Figure 1 depicts the appearance and colour of water hyacinth (WH) from day one to day twenty eight.

2.2. Soxhlet oil extraction and biodiesel preparation

All the chemicals which are used in this research are of analytical grade and are purchased from a government authorised local

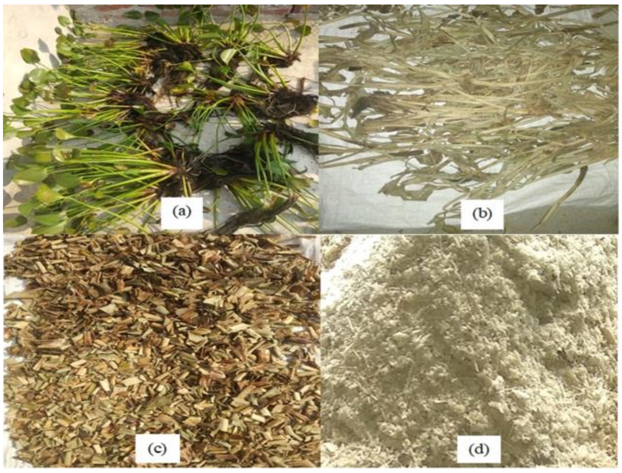

Fig. 1. Collection and drying of water hyacinth plant in sunlight: (a) day 1, (b) day 14, (c) day 21, (d) day 28 – powder form.

distributor (Lucknow, India), like NaOH, methanol and n-hexane. Figure 2 shows the crude water hyacinth oil extraction from waste biomass. The Soxhlet apparatus (effective technique for oil extraction) basically consists of four main parts: a condenser, Soxhlet flask and heating mantle, as shown in Fig. 2(a). To extract oil from water hyacinth, take 50 gm of dried powder form the water hyacinth sample in a thimble and keep it in the Soxhlet apparatus. A conical flask is filled three-fourth part with n-hexane and kept on the heating mantle. The condenser is connected with the top of the extractor, the outlet and inlet pipes of the condenser are joined with a pipe where cold water enters, and hot water exits, respectively. After these arrangements, the Soxhlet apparatus heating mantle is switched on and set to the temperature 69℃ (which is the boiling point of n-hexane). A few moments later, n-hexane starts boiling and is converted into vapour, which goes into the condenser via a vapour tube where it condenses into a liquid form. The liquid form is then passed through a thimble, after a fixed level it returns along with extracted water hyacinth oil into a conical flask via a syphon tube. Due to the high boiling point temperature of the extracted water hyacinth oil, it is not vaporised with n-hexane. The same procedure as discussed above is repeated 4–5 times for complete extraction of oil from water hyacinth biomass, and it takes approximately 2 hours for each thimble. The same process is done for all 20 thimbles (50 gm each) of samples. This results in a mixture of water hyacinth oil and n-hexane in a conical flask. After that, the separation of crude water hyacinth oil is done from the above extracted mixture by a horizontal condenser distillation setup as shown in Fig. 2(b). The flask mixture (water hyacinth oil and n-hexane) heating is done at a temperature of 69 ℃ (boiling point of n-hexane) and the flask is connected with the horizontal condenser, which has an inlet and outlet for cold water supply and hot water exit. This way, n-hexane starts boiling and is evaporated from the mixture, which condenses in the condenser, and is collected in another flask. Finally, crude water hyacinth oil remains in the heated flask as shown in Fig. 2(c). Each 50 gm of water hyacinth powder sample produces an average of 10.5 ml crude WHO.

After that, water hyacinth biodiesel was prepared from extracted crude WHO through the well-known transesterification

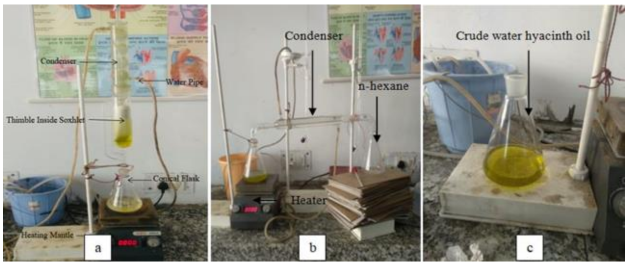

Fig. 2. Water hyacinth oil extraction: (a) Soxhlet apparatus, (b) distillation, (c) crude WHO.

technique. For the purpose of biodiesel preparation, NaOH of 1.4 gm is mixed with 25 ml of methanol by a magnetic stirrer until NaOH dissolves completely, and meanwhile, 100 ml of crude WHO is heated in a flask at 60℃ by a heating mantle to reduce its viscosity and remove moisture from oil. During the process, the temperature should not be higher than 60℃ (less than the boiling point of methanol), otherwise it may evaporate. After that, the prepared mixture of NaOH and methanol is mixed with heated WHO, and finally, the solution is stirred at 600 rpm for approximately120 minutes. During the process, heat may release: hence, a condenser is placed vertically over the flask and closed from the top as shown in Fig. 3(a). After that, the stirred solution is kept in a separating funnel for one day as shown in Fig. 3(b). In this way, glycerine and WHB were separated. The biodiesel yield can be calculated as the ratio of the total weight of water hyacinth methylesters and the total weight of oil in the sample. In this way, water hyacinth oil transesterification results in 85.6% yield of biodiesel.

Fig. 3. Biodiesel preparation: (a) magnetic stirring, (b) biodiesel and glycerine separation.

2.3. Tested fuel preparation

In this research, the SiO_2 nanoparticles of an average size of 25 nm with 99.9% purity are purchased from a government registered company in India. The SiO_2 nanoparticles (25 ppm, 50 ppm, 75 ppm and 100 ppm) are mixed individually with water hyacinth biodiesel and diesel through the well-known ultrasonication technique. Firstly, the mixing of nanoparticles (25 ppm, 50 ppm, 75 ppm and 100 ppm) is done by dispersing them in water hyacinth biodiesel (20 ml each) separately with the help of an ultrasonicator at a power and frequency of 120 W and 50 kHz, respectively, for half an hour shown in Fig. 4(a). SiO_2 nanoparticles are smaller than the size of the fuel injector nozzle diameter, hence not obstructing the fuel flow. Secondly, prepared blends of SiO_2 with water hyacinth biodiesel (25 ppm, 50 ppm, 75 ppm and 100 ppm) are mixed with diesel in a volume proportion 20% of biodiesel and 80% of diesel with the help of a magnetic stirrer for a time period of 30 minutes at 600 rpm, as shown in Fig. 4(b).

Finally, the prepared tested fuels were named as WHB20SiO$_2$25ppm (water hyacinth biodiesel 20%, diesel 80%, SiO_2 25 ppm), WHB20SiO$_2$50ppm (water hyacinth biodiesel 20%, diesel 80%, SiO_2 50 ppm), WHB20SiO$_2$75ppm (water hyacinth biodiesel 20%, diesel 80%, SiO_2 75 ppm) and WHB20SiO$_2$100ppm (water hyacinth biodiesel 20%, diesel 80%, SiO_2 100 ppm) respectively. These prepared fuels are shown in Fig. 5. The important examined fuel properties measured by various apparatuses are given in Table 1.

Fig. 4. Sample preparation: (a) ultrasonicator, (b) mixing of diesel and biodiesel.

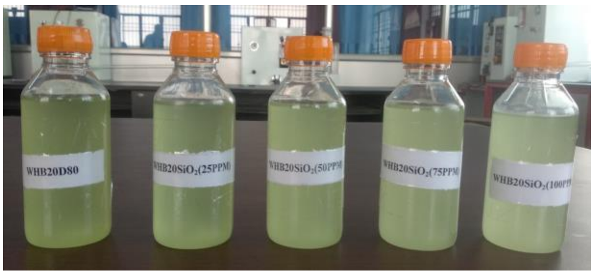

Fig. 5. Tested fuel samples.

Table 1. Important fuel properties.

Properties	Apparatus used	Diesel	WHB20	WHB20SiO$_2$25ppm	WHB20SiO$_2$50 ppm	WHB20SiO$_2$75 ppm	WHB20SiO$_2$100 ppm
Density, kg/m^3	Hydrometer	830	847	851	853	854	855
Flash point, ℃	Pensky-Martens apparatus	61	97	91	89	88	87
Kinematic viscosity, mm^2/sec	Viscometer	2.76	2.87	2.85	2.84	2.83	2.81
Calorific value, kJ/kg	Bomb calorimeter	42830	41910	42124	42262	42458	42620

3. Experimental procedure

To evaluate the performance, prepared samples are investigated on a 4-stroke, 1-cylinder water cooled vertical diesel engine. Table 2 shows the detailed specifications of the test engine setup. The engine loading is done through a rope brake, which is connected to the engine through a coupling. A multichannel digital temperature indicator measures the temperature of exhaust gasses and at various locations. The load on the test engine is gradually increased between 1−5 kW brake power, and the time it takes at each load to consume 10 ml of the prepared sample is recorded. Experiments on each fuel sample were carried out through the same way as stated above. All the tests were run three times, and the average value obtained is used to make calculations of performance parameters. Figure 6 shows the flow chart for the whole episode.

Table 2. Detailed engine specifications.

Particular	Description or value	Unit
Engine type	4-S single cylinder, water cooled, vertical CI engine	–
Cylinders number	1	–
Diameter of bore	120	mm
Length of stoke	139.7	mm
Cubic capacity	1580	cm^3
Compression ratio	17.5:1	–
Rated power	7.5	kW
Rated speed	1500	rpm
Number of nozzle holes	3	–
Injection pressure	202	bar
Fuel injection	Direct injection	–
Revolution of flywheel	Clockwise	–
Maximum HP	10	Horsepower

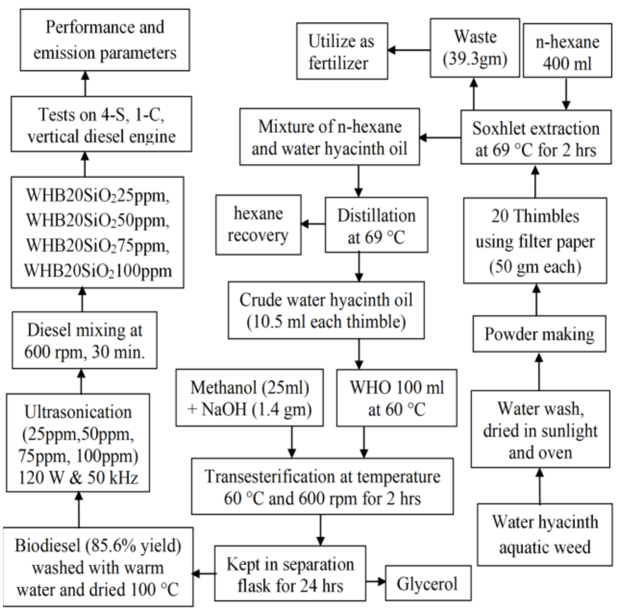

Fig. 6. Flow chart for the whole episode.

Blending samples performances are analysed in the diesel engine in terms of BSFC, BTE and EGT. BSFC (kg/kWh) and BTE (%) are determined, respectively, as:

$$BSFC = \frac{FCR}{BHP}, \quad (1)$$

$$BTE\ (\%) = \frac{BHP \times 3600}{FCR * CV} \cdot 100, \quad (2)$$

where BHP (kW) is the brake horsepower and CV (kJ/kg) is the calorific value of fuel.

3.1. Uncertainty percentage error

The instruments like tachometer, fuel meter, temperature indicator, bomb calorimeter, load indicator, Pensky-Marten's apparatus and exhaust gas analyser are used to record the speed, liquid column height, temperature, heating value, load, flash point and exhaust emissions, respectively.

Table 3 shows the instrumental uncertainty to identify the experimental percentage error.

Table 3. Instruments uncertainty.

Instruments	Parameter	Uncertainty (±)
Tachometer	Speed (rpm)	0.90%
Fuel meter	Heights of liquid column	0.5%
Temperature indicator	Temperature (°C)	0.30%
Bomb calorimeter	Heating value	1.4%
Load indicator	Load	0.3%
Pensky-Marten's apparatus	Flash point (°C)	0.45%
Exhaust gas analyser (ATS-206A):	HC	0.25%
	CO	0.75%
	NO_x	0.5%
	CO_2	0.5%

The instrumental uncertainty error (x) of this experimental research is identified as:

$$x = square\ root\ of\ uncertainity\ of\ [\text{temperature}^2 + \text{speed}^2 + \text{load}^2 + \text{fuel measuring}^2 + \text{heat value}^2 + \text{flash point}^2 + \text{HC}^2 + \text{CO}^2 + \text{NO}_x^2 + \text{CO}_2^2],$$

$$x = \sqrt{\begin{matrix} 0.3^2 + .90^2 + 0.3^2 + 0.5^2 + 1.4^2 + 0.45^2 \\ +0.25^2 + 0.75^2 + 0.5^2 + 0.5^2 \end{matrix}}.$$

In this way, the total uncertainty of experiments is identified as $x = \pm 2.127\%$.

4. Results and discussion

In this section, prepared tested blends performance and emission results with varying engine load are presented and compared with those of WHB20 fuel and fossil diesel. All experiments are performed thrice to ensure the accuracy and repeatability of results, and their average values are considered to make final calculations of performance parameters (BSFC, BTE and EGT). Further, important emission parameters (HC, CO, CO_2 and NO_x) of prepared test blends are recorded by an ATS-206A exhaust gas analyser model. In addition, these recorded emission parameters are compared with the WHB20 fuel and fossil diesel. Finally, the present study is compared with other available studies in the same field for validation purposes.

4.1. Brake specific fuel consumption

Figure 7 shows the implication of SiO_2 nanoparticles with WHB and diesel blends on BSFC for gradually increasing engine load.

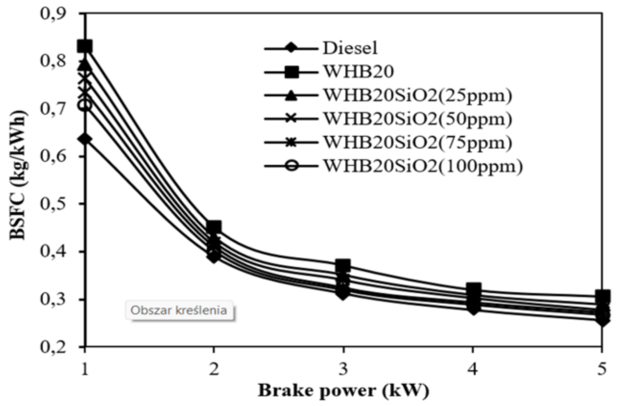

Fig. 7. Change of BSFC with load.

BSFC refers to the quantity of fuel required to produce unit power and should be lower for an efficient fuel. It depends on density, heating value and cetane number of individual fuels. Experimental results reveal that BSFC decreases with the increasing engine load for all tested blends. Additionally, increasing SiO_2 nanoparticles concentration in the blend increases their calorific values, resulting in a decrease in BSFC at all individual loads. BSFC (kg/kWh) for diesel, WHB20, WHB20$SiO_2$25ppm, WHB20$SiO_2$50ppm, WHB20$SiO_2$75ppm and WHB20SiO_2-100ppm was calculated as 0.2569, 0.3061, 0.2884, 0.2781, 0.273 and 0.2675 at the maximum load, respectively. It was observed to increase by 19.15%, 12.26%, 8.25%, 6.27% and 4.13% for WHB20, WHB20$SiO_2$25ppm, WHB20$SiO_2$50ppm, WHB20$SiO_2$75ppm and WHB20$SiO_2$100ppm, respectively, in comparison to fossil diesel. Whereas it was observed to decrease by 5.78%, 9.15%, 10.81% and 12.61% for WHB20$SiO_2$25ppm, WHB20$SiO_2$50ppm, WHB20$SiO_2$75ppm and WHB20SiO_2-100ppm, respectively, in comparison to WHB20 fuel. Overall, increasing SiO_2 nanoparticles concentration in WHB20 fuel may further reduce BSFC, approaching that of the fossil diesel fuel.

4.2. Brake thermal efficiency

Figure 8 shows the implication of SiO_2 nanoparticles with WHB and diesel blends on BTE for the gradually increasing engine load. BTE refers to the combustion of fuel within the combustion chamber and transformation of it into useful work. BTE depends on the calorific value and available oxygen content (proper burning) of the individual fuel. Experimental results reveal that BTE increases with the increasing engine load for all tested blends. Additionally, increasing SiO_2 nanoparticles concentration in the blend decreases BSFC, resulting in an increase in BTE at all individual loads. BTE (%) for diesel, WHB20, WHB20$SiO_2$25ppm, WHB20$SiO_2$50ppm, WHB20$SiO_2$75ppm and WHB20$SiO_2$100ppm was identified as 32.71%, 28.05%, 29.63%, 30.62%, 31.05% and 31.57% at the maximum load, respectively. It was observed to decrease by 14.26%, 9.42%, 6.39%, 5.07% and 3.49% for WHB20, WHB20$SiO_2$25ppm, WHB20$SiO_2$50ppm, WHB20$SiO_2$75ppm and WHB20SiO_2-100ppm, respectively, in comparison to fossil diesel. Whereas it was observed to increase by 5.63%, 9.16%, 10.70% and 12.55% for WHB20$SiO_2$25ppm, WHB20$SiO_2$50ppm, WHB20SiO_2-75ppm and WHB20$SiO_2$100ppm, respectively, in comparison to WHB20 fuel. Overall, increasing SiO_2 nanoparticles concentration in WHB20 fuel may further enhance the fuel quality, approaching that of the fossil diesel fuel.

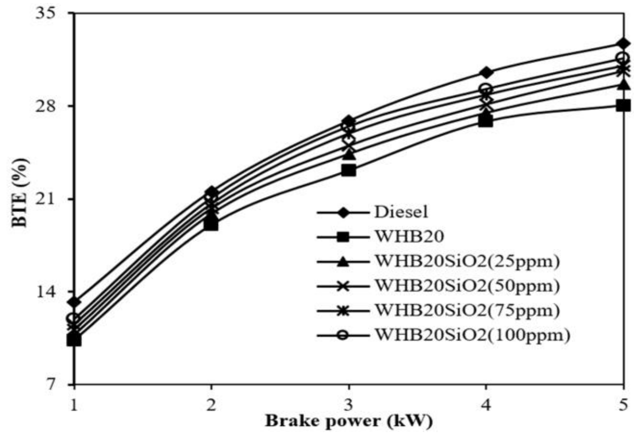

Fig. 8. Change of BTE with load.

4.3. Exhaust gas temperature

Figure 9 shows the variation in EGT for all tested samples with the gradually increasing engine load. EGT describes the quantity of heat discharge during combustion.

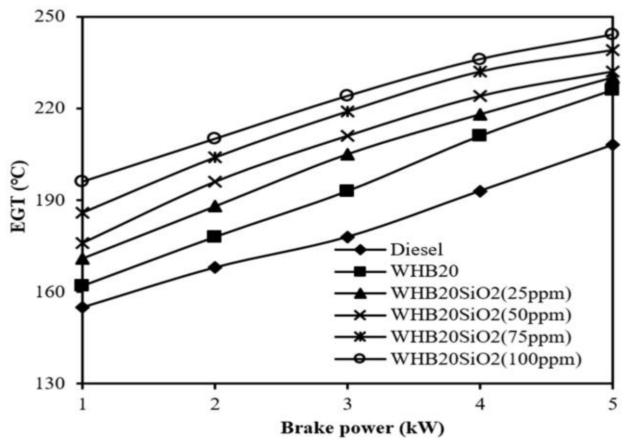

Fig. 9. Change of EGT with load.

The increase of EGT exhibits the presence of oxygen content in the fuel blends. Measurements reveal that EGT increases with the increasing engine load for all tested blends. As biodiesel has a higher content of oxygen than diesel, and further mixing of SiO_2 oxygenated nano-additive in biodiesel blends leads to proper combustion, due to which the inside cylinder temperature increases, resulting in an increased EGT. EGT was recorded for fossil diesel, WHB20, WHB20SiO$_2$25ppm, WHB20SiO$_2$-50ppm, WHB20SiO$_2$75ppm and WHBD20SiO$_2$100ppm as 208°C, 226°C, 230°C, 232°C, 239°C and 244°C, respectively, at the maximum load.

4.4. HC emission

Figure 10 shows the implication of SiO_2 nanoparticles with WHB and diesel blends on hydrocarbon emission for the gradually increasing engine load. HC emission shows the incomplete fuel/air combustion in the engine cylinder.

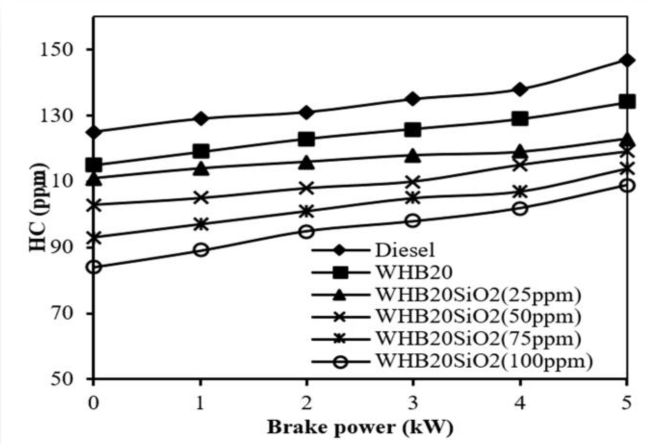

Fig. 10. Change of HC emission with load.

Recorded data reveal that the HC emission decreases with increasing SiO_2 nanoparticles concentration in the blends at a particular engine load. Additionally, it is always maximum for diesel fuel and minimum for WHBD20SiO$_2$100ppm fuel at all loads. The addition of metal oxide nanoparticles in the biodiesel blend accelerates fuel combustion further because they function as a catalyst (oxidising nature), which improves flame spread, thus lowers the carbon initiation temperature, resulting in reduced HC emissions. Hydrocarbon (ppm) emissions for diesel, WHB20, WHB20SiO$_2$25ppm, WHB20SiO$_2$50ppm, WHB-20SiO$_2$75ppm and WHBD20SiO$_2$100ppm are recorded as 147, 134, 123, 119, 114 and 109 at the maximum load, respectively. It was observed to decrease by 8.84%, 16.33%, 19.05%, 22.45% and 25.85% for WHB20, WHB20SiO$_2$25ppm, WHB20SiO$_2$-50ppm, WHB20SiO$_2$75ppm and WHB20SiO$_2$100ppm, respectively, in comparison to fossil diesel. Overall, dispersion of SiO_2 nanoparticles as additives in the WHB blends may reduce HC emission by 25%.

4.5. CO emission

Figure 11 shows the implication of SiO_2 nanoparticles with WHB and diesel blends on carbon monoxide emission for the gradually increasing engine load. Silicon dioxide (oxygenated nano-additive) dispersion in the WHB blends supports better quality of fuel, and enhances conversion of CO into CO_2, resulting in reduced CO emissions. Recorded data reveal that it is always maximum for diesel fuel and minimum for WHB-D20SiO$_2$100ppm fuel at all individual loads. CO emissions (% vol.) for diesel, WHB20, WHB20SiO$_2$25ppm, WHB20SiO$_2$-50ppm, WHB20SiO$_2$75ppm and WHBD20SiO$_2$100ppm are recorded as 0.53, 0.50, 0.48, 0.46, 0.43 and 0.41, respectively, at the maximum load. It was observed to decrease by 5.66%, 9.43%, 13.21%, 18.87% and 22.64% for WHB20, WHB-20SiO$_2$25ppm, WHB20SiO$_2$50ppm, WHB20SiO$_2$75ppm and WHB20SiO$_2$100ppm, respectively, in comparison to fossil diesel. Although an increased load increases the CO emission, the increasing concentration of SiO_2 nanoparticles in the blends reduces the CO emission.

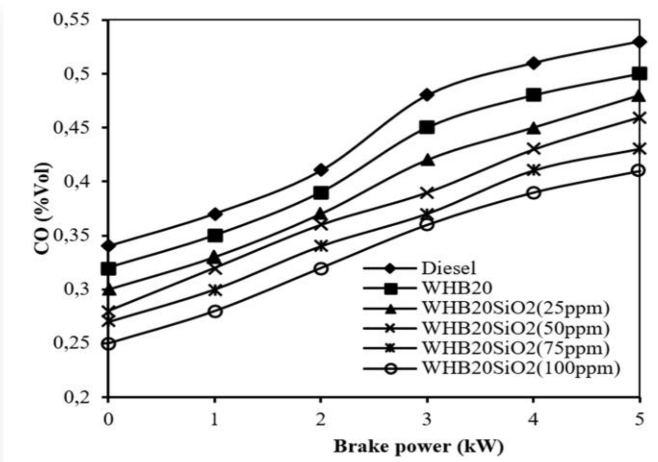

Fig. 11. Change of CO emission with load.

4.6. NO_x emission

Figure 12 shows the variation in NOx emissions for all tested samples with the gradually increasing engine load. Various factors may be responsible for the formation of NO_x, such as important fuel properties, operating conditions, reaction time, combustion temperature and engine design.

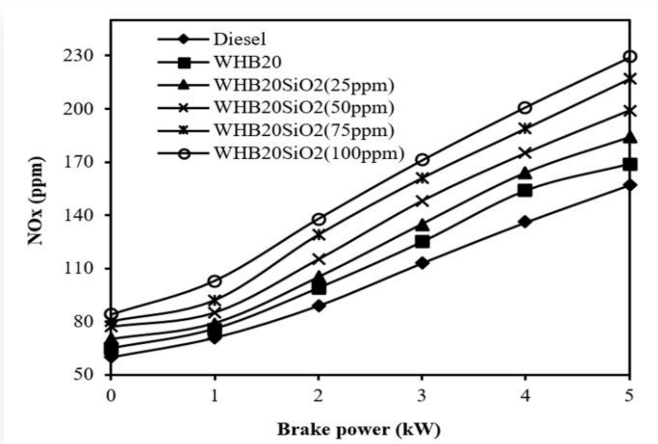

Fig. 12. Change of NO_x emission with load.

The increased oxygenated SiO_2 nanoparticles concentration (increases oxygen content in blends) leads to complete combustion, which in turn increases the cylinder temperature, resulting in higher NO_x emissions with the increasing engine load. NO_x emissions (ppm) for diesel, WHB20, WHB20SiO$_2$25ppm, WHB20SiO$_2$50ppm, WHB20SiO$_2$75ppm and WHBD20SiO$_2$-

100ppm are recorded as 157, 169, 184, 199, 217 and 229, respectively, at the maximum load. It was observed to increase by 7.64%, 17.19%, 26.75%, 38.21% and 45.85% for WHB20, WHB20SiO$_2$25ppm, WHB20SiO$_2$50ppm, WHB20SiO$_2$75ppm and WHB20SiO$_2$100ppm, respectively, in comparison to fossil diesel. Overall, NO_x emissions were found to be increased with the increasing load, but they can be controlled by the well-known exhaust gas recirculation technique and adjustments in combustion timing.

4.7. CO_2 emission

Figure 13 shows the variation in CO_2 emissions for all tested samples with the gradually increasing engine load. Increasing SiO_2 nanoparticles concentration increases CO_2 emissions at all individual engine loads due to enhanced quality of combustion. CO_2 emissions (% vol.) for diesel, WHB20, WHB20SiO$_2$25ppm, WHB20SiO$_2$50ppm, WHB20SiO$_2$75ppm and WHB20SiO$_2$100ppm are recorded as 2.30, 2.34, 2.40, 2.44, 2.50 and 2.55, respectively, at the maximum load. It was observed to increase by 1.74%, 4.35%, 6.09%, 8.70% and 10.87% for WHB20, WHB20SiO$_2$25ppm, WHB20SiO$_2$50ppm, WHB20SiO$_2$75ppm and WHB20SiO$_2$100ppm, respectively, in comparison to fossil diesel. Overall, dispersion of SiO_2 nanoparticles in blends increases CO_2 emissions with the increasing engine load.

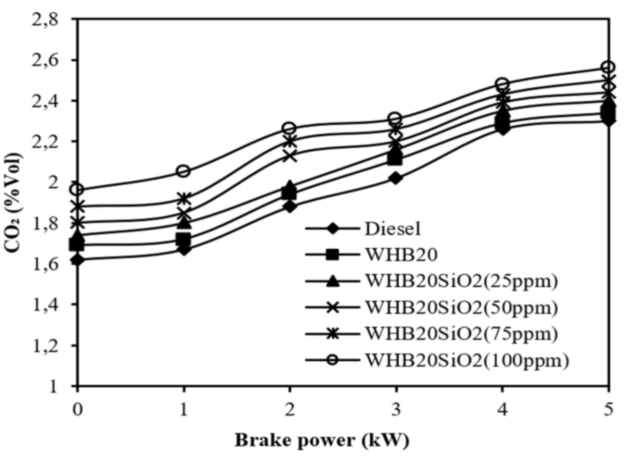

Fig. 13. Change of CO_2 emission with load.

4.8. Research validation

The present research is validated in terms of biodiesel yield, performance and emission characteristics with available recent literature data. In studies of Venu et al. [15] and Alagu et al. [16], WHB and fossil diesel blends in different volume proportions were tested on a single cylinder 4-stroke diesel engine, and revealed the WHB20D80 (water hyacinth biodiesel 20% + diesel 80%) fuel as the best performer compared to engine performance and emissions with neat diesel. A study of Rahman and Aziz [35] reported water hyacinth biodiesel yields of 87%, reduced HC and CO emissions by 48% and 21.9%, respectively, and increased NO_x emissions by 47.3% with induction of hydroxy compared to neat diesel, CO_2 not reported. Whereas the current research reported:

(i) Water hyacinth biodiesel yield of 85.6%;
(ii) Dispersion of SiO_2 nanoparticles in WHB20D80 fuel decreases BSFC by 12.61% and improves BTE by 12.55% at the maximum load;
(iii) Dispersion of SiO_2 nanoparticles reduced HC and CO emissions by 25.85% and 22.64%, respectively, and increased NO_x and CO_2 emissions by 45.85% and 10.87%, respectively, compared to neat diesel at the maximum load.

Additionally, aluminium oxide nanoparticles with biodiesel are frequently reported to improve atomisation/evaporation and increase BTE while reducing HC/CO, whereas NO_x effects vary but often increase due to improved combustion [24]. Cerium dioxide nano-additive with biodiesel is significant for oxygen storage/catalytic soot oxidation, reducing CO/HC/particulate matter, and may reduce or moderate NO_x emission in some formulations (because of catalytic soot oxidation and alternative reaction pathways), though results depend on the concentration and engine conditions [28]. Titanium dioxide nano-additive with biodiesel acts as an oxygen-bearing catalyst; many studies report smoke and CO/HC reductions and BTE improvement; CO_2 and NO_x may increase depending on the temperature rise, but smoke and particulate reductions are often more substantial. Moreover, the present study shows a reduced BSFC and improved BTE, and substantial HC/CO reductions, but a notable increase in nitrogen oxides. This pattern (better combustion, lower HC/CO, higher NO_x) is consistent with many oxide nanoparticle studies. The differences in magnitude depend on particle chemistry, oxygen content, catalytic surface and dispersion stability. Finally, WHB20SiO$_2$100ppm is recommended for future alternate fuel due to the favourable oil yield, enhanced performance and comparable emissions for the unmodified diesel engine.

5. Conclusions

This research dealt with crude oil extraction from water hyacinth waste biomass and its conversion into transesterified biodiesel as an alternate fuel for energy generation purposes. SiO_2 nanoparticles (25 ppm, 50 ppm, 75 ppm and 100 ppm) were dispersed through ultrasonication in WHB-diesel blends to make them more efficient. The prepared fuel blends' properties were examined as per ASTM standards. The prepared blends were tested on a 4-S single-cylinder, water cooled, vertical diesel engine to examine their performance and emissions characteristics, and compare them with those of WHB20 and diesel. The main research outcomes of this experimental work can be written as follows:

- One kilogram of water hyacinth powder (after drying 3.5 kg green WH plant) produces an average of 210 ml of crude oil, which has 85.6% transesterification biodiesel yield.
- Dispersion of SiO_2 nanoparticles in WHB20 fuel decreased BSFC by 12.61%, hence improved BTE, which approaches that of fossil diesel at the maximum load.
- HC emission decreased by 8.84%, 16.33%, 19.05%, 22.45% and 25.85% for WHB20, WHB20SiO$_2$25ppm, WHB20SiO$_2$50ppm, WHB20SiO$_2$75ppm and WHB20SiO$_2$100ppm, respectively, compared to fossil diesel.

- CO emission decreased by 5.66%, 9.43%, 13.21%, 18.87% and 22.64% for WHB20, WHB20$SiO_2$25ppm, WHB-20$SiO_2$50ppm, WHB20$SiO_2$75ppm and WHB20SiO_2-100ppm, respectively, compared to fossil diesel.
- Both NO_x and CO_2 emissions increased by 45.85% and 10.87%, respectively, for WHB20$SiO_2$100ppm fuel compared to fossil diesel at the maximum load. Higher NO_x emissions can be controlled by the well-known exhaust gas recirculation technique and adjustments in combustion timing.
- Overall, it can be concluded that the WHB20$SiO_2$100ppm fuel is the best performer and a suitable alternative for diesel without any change in engine design because its quality and performance are similar to those of fossil diesel, with comparable emissions.

The current study focused on the investigation of engine performance and emission parameters. Whereas an optimisation study across a wider range of nanoparticles (> 100 ppm), a cost-benefit assessment considering large-scale production, lifecycle aspects, and long-term durability study (injector wear, filter fouling and lubricant contamination) with periodic injector inspection, filter analysis and lubricant ferrous particle monitoring may be proposed as a future scope of work.

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