Science and Technology for Energy Transition **78**, 4 (2023)

https://doi.org/10.2516/stet/2022021

Available online at:
stet-review.org

REGULAR ARTICLE OPEN ACCESS

Performance and emission characteristics of salviniaceae filiculoides aquatic fern oil and SiO_2 nano additive biodiesel in CI engine

Kannan Thurairaj Rajeswari* and Sheeju Selva Roji Selvadas

Department of Mechanical Engineering, University College of Engineering Nagercoil, Nagercoil 629004, Tamil Nadu, India

Received: 16 January 2022 / Accepted: 15 November 2022

Abstract. This present study deals the engine performance and emission of adding SiO_2 nano additives in novel salviniaceae filiculoides aquatic fern biomass derived biodiesel. The primary aim of this present study was to investigate the effect of adding SiO_2 nano additives into the Azolla Oil Methyl Ester (AZOME) as a sustainable biodiesel in the Compression Ignition (CI) engine and studying the engine performance and emission effects. The Azolla Oil Methyl Ester was prepared via transesterification process and blended with as-present diesel with various percentages. The SiO_2 nano particles are mixed with AZOME using sonication. The test was conducted using a single cylinder Compression Ignition engine with different blends of AZOME biodiesel. The fuel was injected into the engine at different spill timings as 20°, 23°, and 26° Crank Angle (CA) before (b) Top Dead Centre (TDC). According to the results the break thermal efficiency of AZOME and its SiO_2 blends were improved with spill timings. On compare with the conventional diesel the Injection Time (IT) of 23° b TDC and the average Brake Thermal Efficiency (BTE) of AZ20 fuel at the retarded spill timing of 20° was raised by 3.38%, while the AZ100 fuel at 20° b TDC is decreased by 0.9%. However the emission of AZ100 fuel found to be lesser due to the presence of SiO_2 nano additives. Thus the addition of SiO_2 nano additives along with aquatic biomass Azolla Oil Methyl Ester reduced the emission without affecting the engine performance.

Keywords: Biofuel, Aquatic fern, SiO_2, Transestrification, BTE, Emission.

1 Introduction

As a green energy, biodiesel could be a viable replacement for fossil fuels. It can help to prevent air pollution by lowering CO_2, SO_2, CO, and HC emissions [1]. Because plants absorb more CO_2 than is released by the biodiesel combustion process, the carbon cycle of biodiesel from sustainable resources is a zero budget in terms of photosynthetic process and combustion emission as a whole [2]. When compared to the usage of fossil fuel, biodiesel can more efficiently reduce CO_2 emissions, safeguard the natural environment, and maintain ecological equilibrium [3]. Because of its low sulphur content, biodiesel emits far less SO_2 during the combustion process than regular diesel oil [4]. As a result, using biodiesel instead of regular diesel oil will effectively reduce acid rain, which poses a serious threat to the environment and human infrastructure, including acidification of soil, surface, and groundwater, forest and vegetation damage, and corrosion of buildings and historical monuments made of calcium-containing stones [5]. Furthermore, because biodiesel's ester components contain oxygen, the emissions of CO, HC, and particulate matter will be reduced [6]. When biodiesel is used in a standard diesel engine, hydrocarbons, aromatic hydrocarbons, carbon monoxide, alkenes, aldehydes, ketones, and particulate matter are significantly reduced [7]. In this line up the edible vegetable oils such as canola, soybean, peanut, sunflower, palm, and coconut oil, non-edible vegetable oils such as *jatropha curcas*, *pongamia pinnata*, *polanga calophyllum inophyllum*, *azadirachta indica*, *hevea brasiliensis*, *madhuca indica*, animal fats, and waste cooking oil from food processing units, restaurants, and domestic kitchens are among the raw materials for making biodiesels [8]. Kumar *et al.* [9] have done a research study on energy and economic analysis of different vegetable oil plants for biodiesel production in India. Authors stated that the lower energy intensity was obtained for palm and neem biomass. Moreover authors confirmed that the total production cost was low for palm (76.120 R kg^{-1}) and neem (78.139 R kg^{-1}). However the higher value of average productivity (0.0122 kg R^{-1}) and gross return (168.70 R kg^{-1}) were obtained for neem. Similarly, Ishola *et al.* [10] studied the potentiality in biodiesel production from palm olein in Nigeria. The transesterification of RBD palm olein with methanol in the

* Corresponding author: kannan.tr@yahoo.com

presence of a potassium hydroxide (KOH) catalyst produced biodiesel with a yield of 62.5%, indicating that it is feasible for mass production. However the study by ShenavaeiZare *et al.* [11] demonstrated the production of biodiesel through nanocatalytic transesterification of extracted oils from halophytic safflower and salicornia plants in the presence of deep eutectic solvents. In this study a new CaO/Na-ZSM5 nanocatalyst was synthesized to achieve a 97% of conversion to biodiesel from waste biomass. Finally Khan *et al.* [12] researched the sustainable biodiesel production from waste cooking oil utilizing waste ostrich (*Struthio camelus*) bones derived heterogeneous catalyst. In this case, authors did valorization of waste ostrich bones biomass to synthesize novel catalyst. Since the method yields more production this approach was recommended for the utilization of indigenous waste to produce biodiesel. Thus it is clear that the biomass conversion to biofuel attains its maximum reach due to its potential gain in the circular economy.

However in the emission point of view still the biodiesel have considerable amount of emissions like CO, No_x, HC and particulate matters to the environment, which is highly toxic for the ecosystem. Thus researchers start researching the reduction methodologies in the fuel burning characteristics in engine. Recent research says that adding metallic or ceramic additives along with biofuel or conventional fuel could reduce the emission rate. Gavhane *et al.* [13] researched the effect of adding SiO_2 additives on performance and emission characteristics of soybean biodiesel fuelled diesel engine. According to the authors the addition of SiO_2 increased the oxidation thus the emissions are reduced. Adzmi *et al.* [14] assessed at how adding 50 and 100 ppm of alumina and silica nano additives to a palm biodiesel blend affected the performance and emissions of a diesel engine. After adding SiO_2, they had seen a 43% increase in BP, a 25% reduction in CO emissions, and a 4.48% reduction in NO_x emissions. Similarly, performance and emissions investigation of SiO_2 nano additives in rapeseed methyl ester at dosages of 25 and 50 ppm on diesel engine was done by Özgür *et al.* [15]. They reported a maximum increase of 4.8% of BP and 4.3% of brake torque for 25 and 50 ppm blends with a maximum CO reduction of 10.4% was obtained for the 25 ppm silica nano additives. Thus it is clear that the addition of nano additives along with biodiesel improves the engine performance and reduces the engine emissions.

Nevertheless the collection and conversion of solid wastes, animal manure and plant residues costing more and the total economy builds in the conversion of waste as biofuel is worsen in the collection of raw material feed stock. Some aquatic species, such as salviniaceae filiculoides (Azolla), have been advocated as agents of bioremediation of waste waters in recent years due to their significant nature of controlling oxygen balance by substantially accumulating nutrients and heavy metals. Salviniaceae filiculoides (Azolla) is an aquatic species that can be exploited as a cheap and reliable source of biodiesel feedstock [16]. It is a fern that lives in water and is heterosporous. Azolla, a Salviniaceae family member, is found in moderate temperate and freshwater regions. It grows quickly and works well as a biofertilizer. The extracellular cavity measures around 0.3 mm in length and has a small outlet to the outside. The chemical process involved in the conversion of this Azolla is transesterfication process. It is simple and yields output at higher rate than other methods [17]. Singh *et al.* [18] have done a comparison study using optimization techniques such as RSM and ANN for the salviniaceae filiculoides oil blended biodiesel using ultrasonic energy assisted transesterification process. Authors concluded that the transesterification process was the effective process in order to yield higher outcomes from the biomass. Moreover the aquatic fern salviniaceae filiculoides was the cheap and high outcome yield feedstock for diesel production. Similarly, Arefin *et al.* [19] had done a review on biofuel production from floating aquatic plants as an emerging source of biorenewable energy. The authors compared biofuel production processes such as transesterification, pyrolysis, hydrolysis, and torrefaction to five different water ferns, including water hyacinth, Azolla, water fern, duckweed and water lettuce. According to the findings, the aquatic Azolla water fern gives high-quality diesel biofuels than other aquatic plants in terms of calorific value and viscosity. Thus it is clear that the biofuel production from waste salviniaceae filiculoides could be a noteworthy process in order to get high ratio of fuel production. Moreover in any engines the fuel spill timing is the most important factor, which affects a diesel engine's combustion performance and emission characteristics [20]. As the spill time changes, the amount of air and fuel pumped into the fuel injector changes, and thus the ignition delay occurs. Because of the low beginning air temperature and pressure, if spill timing is delayed, the ignition delay will raise thus higher amount of exhaust emissions, particularly CO, HC and NO_x are possible [21].

Thus based on the previous literatures it is set righted that there was a decent testimonial for the salviniaceae filiculoides biomass as fertilizers, feedstock and biofuel deployment. However experiments based on the addition of nano additives such as SiO_2 into the biodiesel and its combustion performance and emission parameters of a CI engine running on salviniaceae filiculoides biodiesel at various spill timings have not been documented. Since the research on Compression Ignition engine with bio derived aquatic fern and nano additives have lot of scope in terms of cleaner fuel, less pollutant and cleaner environment. Hence considering this gap as potential research interest the objectives of this preset study were fixed. The major goal of this research was to see how the addition of nano additive SiO_2 along with biofuel in combustion and emission performance of CI engine that runs on salviniaceae filiculoides biodiesel.

2 Experiment

2.1 Preparation Azolla oil

To prepare oil from salviniaceae filiculoides (Azolla) there are two steps. Firstly, the Azolla was collected from the wetlands of India's southwest coasts. The collected Azolla was then cleaned twice with fresh water to remove the sand particles. Secondly the oil extraction from the feedstock

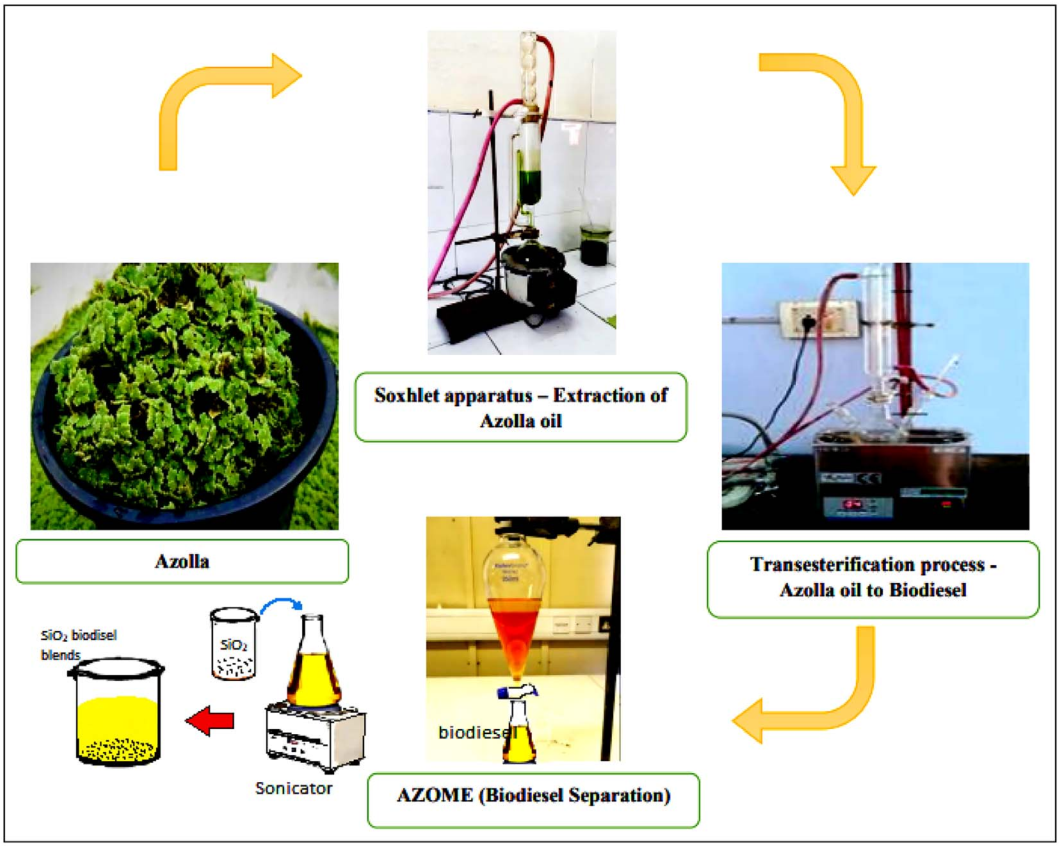

Figure 1. Biodiesel preparation from Azolla biomass.

begins. Using Soxhlet process [22] the Azolla oil was prepared and the oil yield was calculated gravimetrically using equation (1). The extracted Azolla oil was then subjected to physiochemical parameter evaluations such as saponification value, acid value, and molecular weight. According to the results it is noted that the Azolla oil gives density of 898.3 kg/m^3 at 15 °C, flash point of 145 °C, kinematic viscosity of 11.39 Cst at 40 °C, saponification value of 190.2, acid value of 14.84 mgKOH and molecular weight of 959.73 g/mol.

$$\text{Yield of Azolla oil} = \frac{\text{Weight of the extracted Azolla oil}\,(g)}{\text{Weight of Azolla}\,(g)} \times 100. \quad (1)$$

2.2 Biodiesel preparation from Azolla oil and SiO_2

To prepare nano additive biodiesel from the Azolla oil two subsequent steps were followed. In the first step the transesterification of Azolla oil was employed. This process was done based on the experimental work of Thiruvenkatachari *et al.* [23]. Secondly the transesterification process completed salviniaceae filiculoides oil methyl ester was blended with SiO_2 nano additives of size 20 nm supplied by *Sigma Aldrich*, USA in various ratios such as 15, 30, 45, 60 and 75 ppm using ultra sonication for about 20 min. Thus homogenous biodiesel blends of SiO_2 and AZOME were prepared. Figure 1 shows the graphical illustration of biodiesel preparation using Azolla oil and SiO_2. Similarly, the physiochemical parameters and the emission of prepared biodiesel and its bio blends were analyzed in accordance to ASTM D6751 standards. Table 1 shows the various bio blends used in this present investigation. Similarly, Table 2 shows the composition of fuel properties of biodiesel and its blends.

Table 1. Designations of biodiesel blends prepared.

Designation	ASTM D975 diesel	ASTM D6751 biodiesel	SiO_2 (ppm)
AZ00	100	0	0
AZ20	80	20	15
AZ40	60	40	30
AZ60	40	60	45
AZ80	20	80	60
AZ100	0	100	75

2.3 Engine performance test

Figure 2 and Table 3 show the test engine layout and specifications maintained during the test. The test engine was loaded with an electrical dynamometer.

Table 2. Fuel properties of biodiesel and its blends.

Property	ASTM D975 diesel	ASTM D6751 biodiesel	AZOME and its diesel-based mixtures				
			AZ20	AZ40	AZ60	AZ80	AZ100
Density (kg/m^3 @ 15 °C)	834	860–900	833.4	843.6	855.1	866.3	876.4
Specific gravity @ 15 °C	0.852	0.882	0.832	0.845	0.857	0.868	0.876
Kinematic viscosity (Cst @ 40 °C)	1.9–4.1	1.9–6.0	3.40	3.66	3.95	4.28	4.73
Flash point (°C)	60–80	100–170	64	73	85	127	164
Fire point (°C)			72	82	92	135	175
Cloud point (°C)			Below 2 °C	4	7	9	10
Pour point (°C)			Below- 6 °C	Below- 4 °C	Below- 2 °C	−1	+4
Calorific value (KJ/kg)	43,000	46,160	44,240	43,701	43,342	42,974	42,567

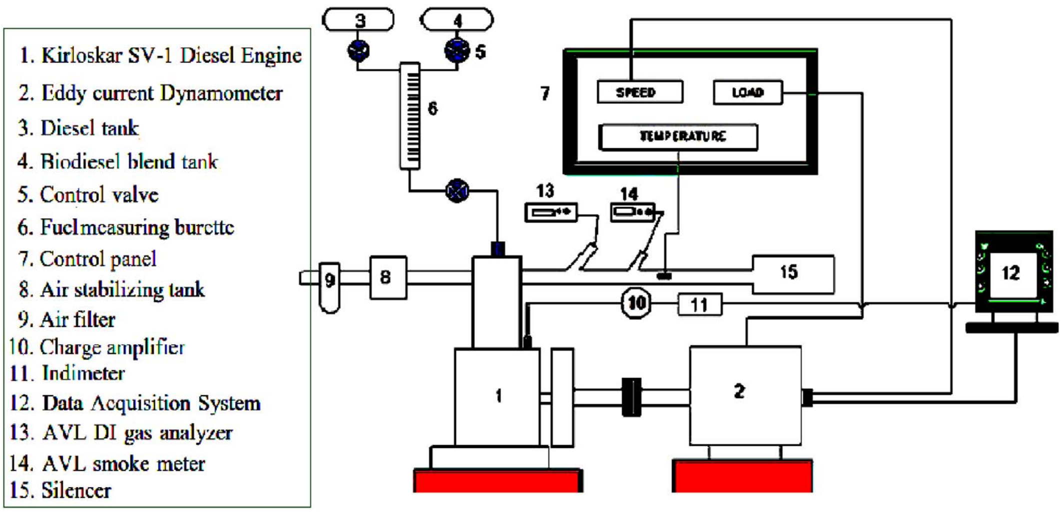

Figure 2. Schematic diagram of the experimental setup.

Table 3. Test engine specification.

Make and model	Kirloskar SV1
General details	Direct injection, single-cylinder, four stroke, water cooled
Rated speed (rpm)	1800
Loading type	Eddy current (Back EMF)
Rated power (Kw)	5.9
Compression ratio	17.5:1
Smoke measurement	AVL 437 smoke meter (HSU)
Bore × stroke (mm)	87.5 × 110
CO, HC and NO_x measurement	AVL di-gas analyzer
Injection timing	23° b TDC

An exhaust gas analyzer and a smoke meter are also the part of the experimental setup to find the emission of the setup and oil. The test run was begun with a preliminary examination of the engine using a diesel fuel at 1800 rpm. The engine was permitted to run from no load to full load, with increasing the load by 20%. All basic performance characteristics such as BTE, SFC, SEC were noted during the run. Subsequently the AZOME diesel blends were used as fuel and the experiment was continued with three different spill timings such as 20°, 23°, and 26° CA b TDC with

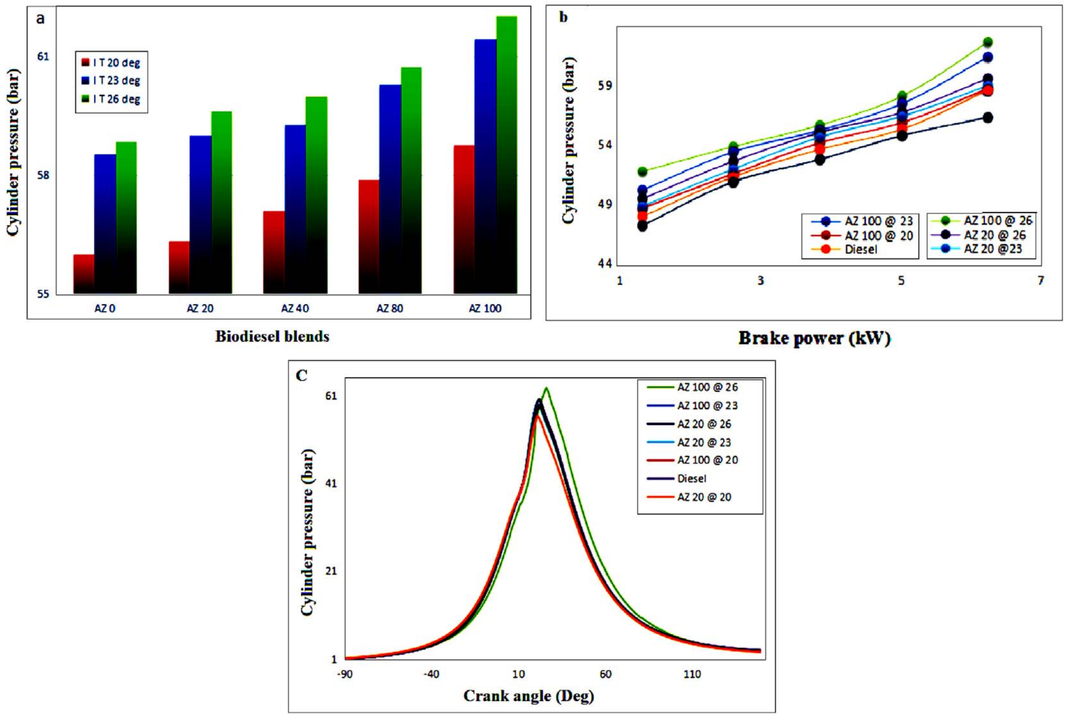

Figure 3. Cylinder pressure *vs.* bio blend, brake power and Crank Angle.

220 bar operating pressure. Moreover the spill timing was retarded and advanced by 3° CA than the standard spill timing by adding an extra shim.

3 Results and discussion

3.1 Performance analysis

3.1.1 Rate of pressure rise

Figures 3a–3c show the cylinder pressure *vs.* biodiesel blends, break power and Crank Angle. It is noted that the biodiesel blends into the cylinder improved the cylinder pressure. This improvement is the reason for high denser biodiesel into the cylinder within the controlled volume [24]. Thus the increased volume in the same area simultaneously increased the cylinder pressure. Moreover, the spill timing of 26° greatly increased the cylinder pressure. With a movement away from TDC, the rate of pressure rise drops slightly when the spill timing is delayed. This is due to the fact that delaying the spill timing results in a larger volume of fuel being injected, as injection begins earlier and ends later [25]. However, because of the ignition delay and longer when the injection is advanced, the cylinder pressure rises compared to the retarded spill timing. When compared to normal peak pressure, spill timing 20° b TDC delivers the lowest cylinder pressure at maximum load. The pressure drop and gain in the retarding and advancing position of piston is 4.37%, 4.45%, 3.61%, 3.90%, 4.28% and 0.421%, 1.02%, 1.19%, 0.78%, 2.1% for diesel, AZ20, AZ40, AZ80 and AZ100, respectively. Moreover, the bio blend AZ100 at 26° gives highest cylinder pressure than other blends. This highest value is the reason for increased volume of spilled fuel due to high denser Azolla and presence of more SiO_2 nano additives. However at lower break power the cylinder pressure is less. On comparing to the pure diesel the Azolla blended biodiesel is seen giving almost equal performance. Moreover, the peak pressure is obtained for the blend AZ100 at advanced spill timing of 26° b TDC. The Crank Angle is slightly shifted from the base line (diesel) in the AZ100 bio blend, which is possibly due to the lower calorific value of biodiesel based on Azolla and SiO_2 [26].

3.1.2 Heat release rate

Figure 4 shows the graphs of heat release rate *vs.* bio blend, brake power and Crank Angle. It is noted that at 26° spill timing the AZ100 gives higher values than other combinations. The highest heat release rate of 164 kJ/m^3 deg was observed for AZ100 designation. This high heat release rate is the reason of increased calorific value of biodiesel and the addition of nano additives. The presence of nano additives donates large oxygen and promotes higher combustion. Moreover the presence of oxygen rich additives reduced the ignition delay thus complete combustion with lesser emissions are spelled out [27]. Similar improvements were noted as the improvement in the blended ratio with AZOME content. Moreover it is noted that the heat release rate was increased with increasing in brake horse power. The high energy produced higher heat release in the blend designation AZ100, which consists of biodiesel with nano additives and improved combustion. However other designation gives decrement in heat release rate when the piston moves towards TDC. The spill timing of 26° scored higher value in the heat release rate in all time. This is because of

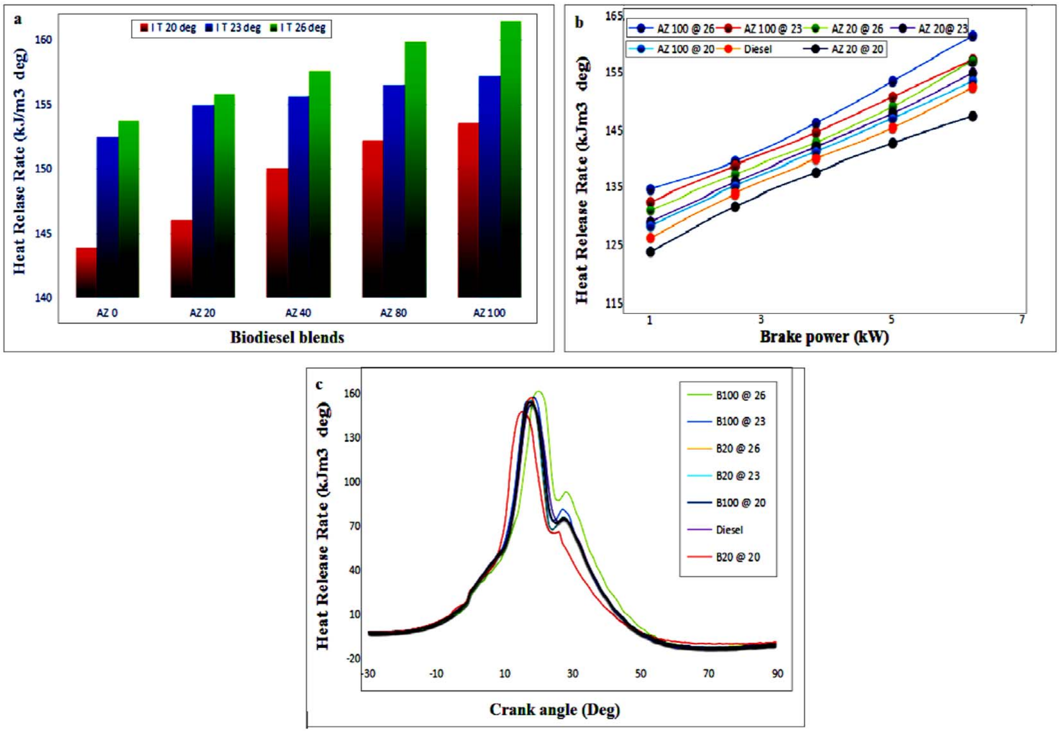

Figure 4. Heat release rate *vs.* bio blend, brake power and Crank Angle.

large fuel burning at the compression stroke end and the movement of piston towards down from the TDC. Similarly, the Crank Angle of about 14° offered higher heat release rate of 160 kJ/m^3 deg with AZ100 diesel designation. This higher value is the reason for high energy dissipation from the bio blends. It is also noted that the Crank Angle reaches little larger degree of about 1.3% than the diesel fuel. This increment is the reason for large energy production by the supplying of high calorific content Azolla fuel and SiO_2 additives [28]. Hence in the increase of bio diesel content and the nano additives in the as-received diesel the heat release rate is increased with higher brake power and Crank Angle.

3.1.3 Brake Thermal Efficiency (BTE)

Figure 5 shows the Brake Thermal Efficiency of engine with various diesel blends. It is observed that the BTE decreases when the biodiesel content in the test fuel is increased for all spill timings. The retarded spill timing of 20° b TDC gives the highest BTE (%) compared to the other spill timings of all biodiesel blend ratio considered. As compared with standard IT of 23° b the TDC at maximum load, BTE for IT 20° b TDC is increased by 5.01%, 6.47%, 5.54%, 6.42% and 8.30% for fuel designations diesel, AZ20 AZ40, AZ80, and AZ100, respectively. This increase in BTE may be due to the early start of injection resulting in more amounts of fuel being injected and injection starts early in the cycle leading to earlier pressure rise before the piston reaches the TDC position. Due to the large amount of nano additives the ignition was advanced thereby large fuel was consumed. However at the lowest percentage blends the biodiesel with nano SiO_2 gives significant improvement in combustion and efficiency [29]. The BTE of the AZ20 blend at 20° b TDC varies from 16.16% at low load to 33.07% at full load, whereas the BTE of the AZ100 mix at 20° b TDC varies from 15.17% at low load to 31.11% at full load. Similarly, the BTE for diesel fuel varies from 15.44% at low load to 31.46% at full load under conventional spill timing. Moreover at a retarded spill time of 20° b TDC, AZ20 fuel had a maximum thermal efficiency of 33.78%. When compared to diesel fuel at regular spill timing, the average BTE of AZ20 fuel at retarded spill timing of 20° b TDC is raised by 3.77%, while the average BTE of AZ100 fuel at retarded spill timing of 20° b TDC is lowered by 4.78%. From the observations it is clear that the delay in the spill timing by 3° b TDC improves the Brake Thermal Efficiency.

3.1.4 Brake Specific Fuel Consumption (BSFC)

Figure 6 shows the values of Brake Specific Fuel Consumption *vs.* various bio blends and the brake power. It is noted that the addition of Azolla ester and nano additives to the significant volume (up to 40% of biodiesel and 30 ppm of nano SiO_2) maintains almost same fuel consumption as like as conventional fuel. But the addition of large volume beyond 40% of biodiesel and 30 ppm of SiO_2 requires high fuel consumption than the ordinary diesel. This reduction is the reason for early ignition of large Azolla molecules and the high oxygen supply of nano additives [30].

However the difference in the fuel consumption between various spill timings is very less. The spill time of 26° found consuming more fuel of 0.33 MJ/kW/h to produce peak power. Similar findings were noted in the Figure 6b also.

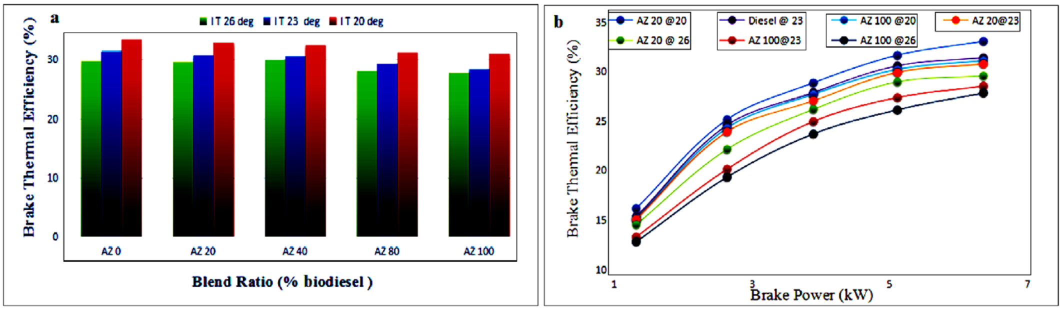

Figure 5. Brake Thermal Efficiency *vs.* bio blends and brake power.

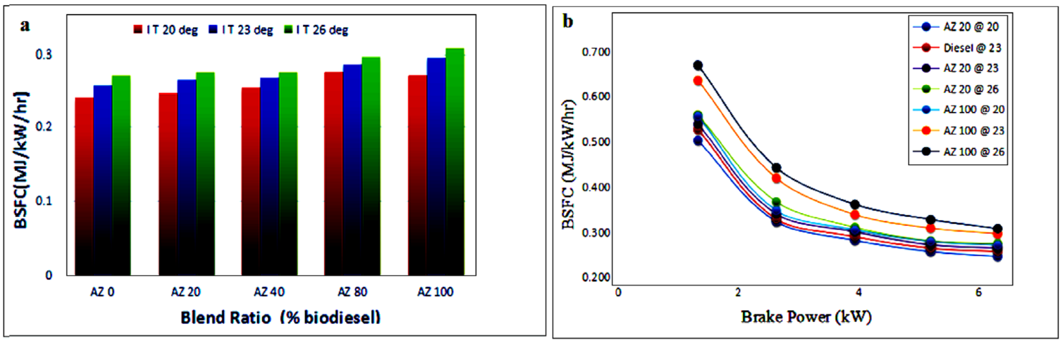

Figure 6. Brake Specific Fuel Consumption *vs.* bio blends and brake power.

The specific fuel consumption is gradually reduced at the increment of brake power. On comparing to the diesel fuel the bio blend shows slightly higher fuel consumption at the lower to higher brake power values. This is because of large waste of heat energy at the lower brake power and advanced ignition of highly loaded biodiesel [31]. It is noted that the diesel gave maximum reduction % of BSFC and was very close to that of AZ20. Therefore for 20° b TDC, diesel, and AZ20 give better results in BSFC as compared with all blends. Similarly, for diesel at usual spill timing the Brake Specific Fuel Consumption varies from 0.525 MJ/kW/h at lesser load to 0.255 MJ/kW/h at full load condition. The highest Brake Specific Fuel Consumption of 0.306 MJ/kW/h was obtained for AZ100 fuel at an advanced spill timing of 26° b TDC whereas minimum Brake Specific Fuel Consumption of 0.245 MJ/kW/h was observed for AZ20 fuel at retarded spill timing of 20° b TDC at full load condition. The average BSFC of AZ20 fuel at retarded spill timing of 20° b TDC is decreased by 3.31% and for AZ100 at 20° b TDC it is increased by 5.2% when compared with diesel fuel at standard spill timing. Thus overall the bio blends performed well at the engine combustion almost equal to diesel.

3.1.5 Exhaust Gas Temperature (EGT)

Figures 7a and 7b show the values of Exhaust Gas Temperature *vs.* biodiesel blend ratios and the brake power. The graphs show forward trend for the Exhaust Gas Temperature for both the diesel blends and brake power.

The AZ100 biodiesel blend gave the highest exhaust temperature at the 26° spill timing. This higher exhaust temperature is the reason for higher burning octane from the fuel and complete burning due to the presence of SiO_2 additives in it. Moreover the Exhaust Gas Temperature increased with the incremental in the spill timing. This increment is the reason for supplying of large fuel to the cylinder and the fine combustion of bio blends [32]. There is no loss of heat due to the improper combustion found. In comparison to other IT's and all blends, diesel has the lowest EGT for all spill timings at maximum load situation. IT 20° b TDC has the lowest EGT in case of blends diesel, AZ20, AZ40, AZ80, and AZ100. EGT for diesel, AZ20, AZ40, AZ80, and AZ100 is lowered by 3.63%, 5.14%, 5.05%, 4.4%, and 3.9%, respectively, when compared to conventional IT of 23° b TDC. Similar improvements were noted in the brake power. The increase of brake power increased the Exhaust Gas Temperature. It is obvious that the increment in the brake power increased the fuel consumption thereby the released gases and their temperature is high [33]. The increased temperature is the source of fine combustion of blends and zero burning. The Exhaust Gas Temperature for the mix AZ20 at retarded spill timing 20° b TDC varies from 194 °C at no load to 428 °C at full load, while the Exhaust Gas Temperature for the blend AZ100 varies from 189 °C at no load to 455 °C at full load. The lower Exhaust Gas Temperature associated with AZOME's delayed spill timing is attributable to less heat loss, as seen by the high Brake Thermal Efficiency. When the spill time is advanced, combustion

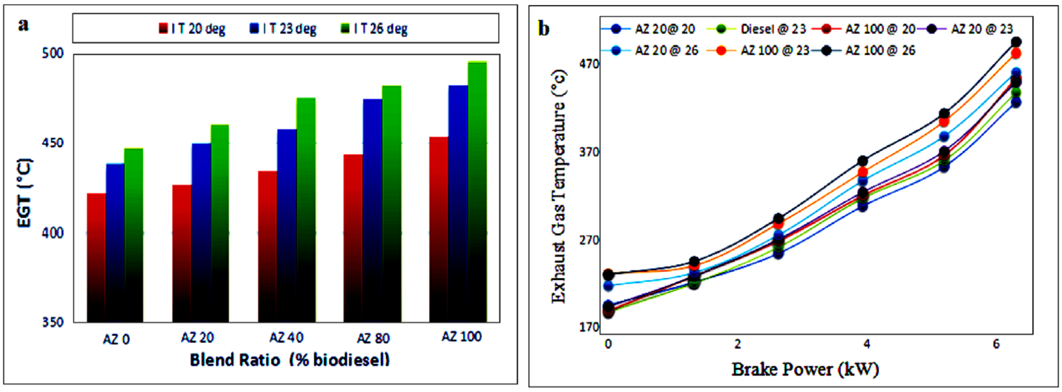

Figure 7. Graphs of Exhaust Gas Temperature *vs.* blend ratio and brake power.

Table 4. Emissions at full load.

Types of emission	AZOME and its diesel-based mixtures																	
	20°						23°						26°					
	AZ0	AZ20	AZ40	AZ60	AZ80	AZ100	AZ0	AZ20	AZ40	AZ60	AZ80	AZ100	AZ0	AZ20	AZ40	AZ60	AZ80	AZ100
Carbon monoxide (%)	0.15	0.12	0.10	0.08	0.075	0.06	0.11	0.10	0.096	0.082	0.065	0.058	0.10	0.086	0.071	0.065	0.057	0.052
Carbon di oxide (%)	11	10.6	10.1	9.8	9.4	9.2	9.5	9.2	8.9	8.6	8.1	7.9	8.2	8.0	7.8	7.6	7.4	7.2
Hydro carbon (ppm)	35	31	26	21	17	14	40	32	26	20	15	12	43	35	30	27	23	17
Smoke opacity (m^{-1})	85	70	62	54	50	46	76	71	65	59	54	42	68	61	54	48	45	38
Oxides of nitrogen (ppm)	550	472	416	382	348	322	480	436	405	376	348	312	380	362	328	311	302	294

begins earlier, compressing the cylinder charge as the piston approaches TDC, resulting in increased EGT.

3.2 Smoke analysis

Table 4 shows the various emissions developed from the CI engine during combustion at full load. It is noted that at 20° fuel spilling angle the emissions such as CO, CO_2, HC, SO and NO_x for conventional diesel is 0.15%, 11%, 35 ppm, 85 m^{-1} and 550 ppm. However the blending of AZOME and nano SiO_2 additives the emissions are reduced. The amount of AZOME and SiO_2 additives gradually decreases the emission %. It is further noted that the diesel blend AZ100 gives emission values of 0.06%, 9.2%, 14 ppm, 46 m^{-1} and 322 ppm at full load. This is about 100%, 17.02%, 105.8%, 70% and 70.8% on comparing with the base diesel fuel. This improvement is the reason for complete combustion of fuel molecules due to the excess supply of oxygen via the addition of nano additives [34]. The delay in combustion literally reduced due to the oxygenated nano additive fuel, which is made up of SiO_2 nano particles. Thus the high calorific value of AZOME and the adequate supply of oxygen in the fuel enhanced the complete burning process during combustion thus the amount of emissions from the burnt fuel is less. Similarly the smoke emission after the combustion was significantly less due to the complete burning of biodiesel fuel. A lowest smoke emission was found in AZ100 biodiesel blend. This lesser smoke emission was the reason for oxygen rich burning inside the cylinder when the piston moves towards the TDC.

It is noted that the 20° Crank Angle fuel spilling at full load gives higher emission than the 26° Crank Angle. This is because of effective combustion of fuel at larger clearance volume within the cylinder wall and piston head. Moreover the addition of nano additives (SiO_2 particle) into the fuel boost up the combustion thus at larger Crank Angle complete combustion takes place [35]. Thus the addition of oxygen rich nano additive SiO_2 particle with high Crank Angle firing greatly improved the combustion properties thereby reduced the emission of toxic elements to the atmosphere.

4 Conclusion

The effect of spill timing on the engine performance and characteristics of a diesel engine was explored experimentally using AZOME blends with SiO_2 nano additives and diesel in this study. The following conclusions were drawn based on the study.

- Delaying the spill timing by 3° b TDC had a substantial impact on AZOME and its SiO_2 nano additive blend's combustion, performance and emissions.
- For IT 20° b TDC with diesel fuel, a drop in in-cylinder peak pressure was detected for the blend AZ20 and a minor rise in in-cylinder peak pressure was noted for the blend AZ100 at all loads. The blend AZ100 achieves maximum peak pressure at advanced spill timing of 26° b TDC, whereas the blend AZ20 achieves minimum peak pressure at delayed spill timing of 20° b TDC, and the differential in-cylinder pressure for the two blends is about 6.65 bar.
- The rate of heat release followed a similar pattern. When compared to diesel fuel, the average heat release for the blend AZ20 at retarded spill timing 20° b TDC is 1.96% lower, while the average heat release for the mix AZ100 at retarded spill timing is 1.37 % higher.
- When the spill timing was delayed, the Brake Thermal Efficiency of AZOME and its SiO_2 additive blends improved. At a retarded spill time of 20° b TDC, the maximum BTE for AZ20 fuel was 33.08%, whereas the maximum BTE for AZ100 was 31.13%.
- When compared to diesel fuel at regular spill timing, the average BTE of AZ20 fuel at retarded spill timing of 20° b TDC is raised by 3.78%, while the average BTE of AZ100 fuel at retarded spill timing of 20° b TDC is lowered by 4.79%. When compared to diesel fuel, the drop in BTE for AZ100 at retarded spill timing was just 0.89% at full load, which is not so significant.
- The amount of emission released from the combustion was less for SiO_2 additive added AZOME diesel blends on comparing with base diesel fuel. The CO, CO_2, HC, SO and NO_x were marginally reduced in the AZ100 biodiesel blend.
- As a result of the findings, it is obvious that biodiesel made from Azolla biomass could be a viable alternative to traditional fossil fuels with a high circular economy and the addition of SiO_2 nano additives played a significant role in engine performance and emission control.

Conflict of interest

No conflict of interests to this article.

Funding

No funding for this work.

Availability of data and material

Data sharing not applicable.

Code availability

Custom code.

Ethics approval and consent to participate

Authors approved to publish in this journal.

Consent for publication

Authors are agreed to proceed with the journal.

Authors' information

All the authors are aware of submitting the manuscript.

Authors' contributions

All the authors have contributed equally to the manuscript.

Acknowledgments. The submitted manuscript is original research work, has not been published before nor be submitted parallel to any other journal.

References

1 Kularathne I.W., Gunathilake C.A., Rathneweera A.C., Kalpage C.S., Rajapakse S. (2019) The effect of use of biofuels on environmental pollution – a review, *Int. J. Renewable Energy Res.* **9**, 3, 1355–1367.

2 Alsultan A.G., Asikin Mijan N., Mansir N., Razali S.Z., Yunus R., Taufiq-Yap Y.H. (2020) Combustion and emission performance of $CO/NO_x/SO_x$ for green diesel blends in a swirl burner, *ACS Omega* **6**, 1, 408–415.

3 Zhao J., Wei Q., Wang S., Ren X. (2021) Progress of ship exhaust gas control technology, *Sci. Total Environ.* **799**, 149437.

4 Dhahad H.A., Chaichan M.T. (2020) The impact of adding nano-Al_2O_3 and nano-ZnO to Iraqi diesel fuel in terms of compression ignition engines' performance and emitted pollutants, *Therm. Sci. Eng. Prog.* **18**, 100535.

5 Anwar M.N., Fayyaz A., Sohail N.F., Khokhar M.F., Baqar M., Khan W.D., Rasool K., Rehan M., Nizami A.S. (2018) CO_2 capture and storage: a way forward for sustainable environment, *J. Environ. Manage.* **226**, 131–144.

6 Yusop A.F., Mamat R., Yusaf T., Najafi G., Mat Yasin M. H., Khathri A.M. (2018) Analysis of particulate matter (PM) emissions in diesel engines using palm oil biodiesel blended with diesel fuel, *Energies* **11**, 5, 1039.

7 Hong W., Yuan C., Xie F., Yan S., Chen J. (2018) Particulate matter and particle-bound PAHs emissions from gasoline direct injection (GDI) engine with methanol–gasoline blended fuel during start, *Int. J. Automot. Technol.* **19**, 4, 717–726.

8 Islam A.K.M.A., Yaakob S.R.P.P.Z. (2018) Non-edible vegetable oils as renewable resources for biodiesel production: south-east Asia perspective, in: Nageswara-Rao M., Soneji J. R. (eds.), *Advances in Biofuels and Bioenergy.* IntechOpen. https://doi.org/10.5772/intechopen.73304.

9 Kumar A., Tirkey J.V., Shukla S.K. (2021) Comparative energy and economic analysis of different vegetable oil

plants for biodiesel production in India, *Renew. Energy* **169**, 266–282.

10 Ishola F., Adelekan D., Mamudu A., Abodunrin T., Aworinde A., Olatunji O., Akinlabi S. (2020) Biodiesel production from palm olein: a sustainable bioresource for Nigeria, *Heliyon* **6**, 4, e03725.

11 ShenavaeiZare T., Khoshsima A., ZareNezhad B. (2021) Production of biodiesel through nanocatalytic transesterification of extracted oils from halophytic safflower and salicornia plants in the presence of deep eutectic solvents, *Fuel* **302**, 121171.

12 Khan H.M., Iqbal T., Ali C.H., Javaid A., Cheema I.I. (2020) Sustainable biodiesel production from waste cooking oil utilizing waste ostrich (*Struthio camelus*) bones derived heterogeneous catalyst, *Fuel* **277**, 118091.

13 Gavhane R.S., Kate A.M., Soudagar M.E.M., Wakchaure V. D., Balgude S., Rizwanul Fattah I.M., Nik-Ghazali N.-N., et al. (2021) Influence of silica nano- additives on performance and emission characteristics of Soybean biodiesel fuelled diesel engine, *Energies* **14**, 5, 1489.

14 Adzmi M.A., Abdullah A., Abdullah Z., Mrwan A.G. (2019) Effect of Al_2O_3 and SiO_2 metal oxide nanoparticles blended with POME on combustion, performance and emissions characteristics of a diesel engine, *Int. J. Automot. Mech. Eng.* **16**, 3, 6859–6873.

15 Özgür T., Özcanli M., Aydin K. (2015) Investigation of nanoparticle additives to biodiesel for improvement of the performance and exhaust emissions in a compression ignition engine, *Int. J. Green Energy* **12**, 1, 51–56.

16 Rajeswari G., Jacob S., Banerjee R. (2019) Perspective of liquid and gaseous fuel production from aquatic energy crops, in: *Sustainable Biofuel and Biomass*, Apple Academic Press, pp. 167–182.

17 Liu K., Devarajan Y., Nithyanantham V., Nalla B.T., Krishnamurthy V. (2021) An experimental study on transesterification process and emission analysis of diesel engine propelled with *Capparis spinosa* biodiesel, *Biomass Convers. Biorefin.* 1–8.

18 Singh A.A.M.M., Franco P.A., Jinu G.R., Radhakrishnan A. (2021) Comparison of RSM and ANN optimization techniques and modeling of ultrasonic energy assisted transesterification of salviniaceae filiculoides oil blended to biodiesel, *Bonfring Int. J. Ind. Eng. Manage. Sci.* **11**1, 08–19.

19 Arefin M.A., Rashid F., Islam A. (2021) A review of biofuel production from floating aquatic plants: an emerging source of bio-renewable energy, *Biofuels Bioprod. Biorefin.* **15**, 2, 574–591.

20 Golzary A., Hosseini A., Saber M. (2021) Azolla filiculoides as a feedstock for biofuel production: cultivation condition optimization, *Int. J. Energy Water Resources* **5**, 1, 85–94.

21 Dabi M., Sahoo B.B., Saha U.K. (2021) Increase of efficiency and reduction of CO and NO_x emissions in a stationary compression ignition engine run on Mesua ferrea Linn oil-diesel and diethyl ether, *Therm. Sci. Eng. Prog.*, **25**, 100980.

22 de Avila S.G., Silva L.C.C., Matos J.R. (2016) Optimisation of SBA-15 properties using Soxhlet solvent extraction for template removal, *Microporous Mesoporous Mater.* **234**, 277–286.

23 Thiruvenkatachari S., Saravanan C.G., Edwin Geo V., Vikneswaran M., Udayakumar R., Aloui F. (2021) Experimental investigations on the production and testing of azolla methyl esters from *Azolla microphylla* in a compression ignition engine, *Fuel* **287**, 119448.

24 Raman L.A., Deepanraj B., Rajakumar S., Sivasubramanian V. (2019) Experimental investigation on performance, combustion and emission analysis of a direct injection diesel engine fuelled with rapeseed oil biodiesel, *Fuel* **246**, 69–74.

25 Elkelawy M., Bastawissi H.A.E., Esmaeil K.K., Radwan A.M., Panchal H., Sadasivuni K.K., Ponnamma D., Walvekar R. (2019) Experimental studies on the biodiesel production parameters optimization of sunflower and soybean oil mixture and DI engine combustion, performance, and emission analysis fueled with diesel/biodiesel blends, *Fuel* **255**, 115791.

26 Ağbulut Ü., Karagöz M., Sarıdemir S., Öztürk A. (2020) Impact of various metal-oxide based nanoparticles and biodiesel blends on the combustion, performance, emission, vibration and noise characteristics of a CI engine, *Fuel* **270**, 117521.

27 El-Seesy A.I., Abdel-Rahman A.K., Bady M., Ookawara S.J. E.C. (2017) Performance, combustion, and emission characteristics of a diesel engine fueled by biodiesel- diesel mixtures with multi-walled carbon nanotubes additives, *Energy Convers. Manag.* **135**, 373–393.

28 Narayanasamy B., Jeyakumar N. (2019) Performance and emission analysis of methyl ester of Azolla algae with TiO_2 Nano additive for diesel engine, *Energy Sources A: Recovery, Util. Environ. Eff.* **41**, 12, 1434–1445.

29 Abed K.A., Gad M.S., El Morsi A.K., Sayed M.M., Abu Elyazeed S. (2019) Effect of biodiesel fuels on diesel engine emissions, *Egypt. J. Petrol.* **28**, 2, 183–188.

30 Atmanli A., Yilmaz N. (2020) An experimental assessment on semi-low temperature combustion using waste oil biodiesel/C3–C5 alcohol blends in a diesel engine, *Fuel* **260**, 116357.

31 El-Seesy A.I., Xuan T., He Z., Hassan H. (2020) Enhancement the combustion aspects of a CI engine working with Jatropha biodiesel/decanol/propanol ternary combinations, *Energy Convers. Manag.* **226**, 113524.

32 Sathish T., Singaravelu D.K. (2020) *Combustion analysis using third generation biofuels in diesel engine*, NISCAIR-CSIR, India.

33 Sathish T. (2019) Profit maximization in reverse logistics based on disassembly scheduling using hybrid bee colony and bat optimization, *Trans. Can. Soc. Mech. Eng.* **43**, 4, 551–559.

34 Karthickeyan V. (2019) Effect of combustion chamber bowl geometry modification on engine performance, combustion and emission characteristics of biodiesel fuelled diesel engine with its energy and exergy analysis, *Energy* **176**, 830–852.

35 Karthikeyan S., Prathima A. (2016) Emission analysis of the effect of doped nano- additives on biofuel in a diesel engine, *Energy Sources A: Recovery Util. Environ. Eff.* **38**, 24, 3702–3708.