ENGINE PERFORMANCE AND EMISSION CHARACTERISTICS OF MICROWAVE-PRODUCED BIODIESEL BLENDS

by

Fakher HAMDI [a]***, Ilham YAHYA*** [a]***, Mehrez GASSOUMI*** [a]***, Aliya FAZAL*** [b]***,***
Ridha ENNETTA [a*]***, and Hakan Serhad SOYHAN*** [c]

[a] Mechanical Modelling, Energy and Materials, National School of Engineers, Gabes University, Gabes, Tunisia
[b] Department of Chemistry, Fatima Jinnah Women University, Rawalpindi, Pakistan
[c] Engineering Faculty, Mechanical Engineering Department, Sakarya University, Sakarya, Turkey

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The main objective of this research is to investigate, experimentally, the effects of biodiesel blends on the performance and emissions of a Diesel engine. Measurements were carried out on a single-cylinder, four-stroke, and air-cooled compression-ignition engine, under half and full load conditions. Engine speed was varied from 1000-3000 rpm. Biodiesel was produced by transesterification process of sunflower oil with ethanol, using microwave-assisted heating reactor. Three biodiesel-diesel mixtures: containing 5%, 10%, and 20% by volume of biodiesel, respectively, have been tested and compared to pure diesel fuel. The effects of these biodiesel blends on the engine operating characteristics such as brake specific fuel consumption, brake power, brake thermal efficiency, brake mean effective pressure, and on carbon CO, CO_2, and NO_x emissions, have been investigated. It was noticed that, at full load, the specific fuel consumptions of biodiesel blends were higher compared to the pure diesel fuel, but no change was observed under ½ load. An improvement in the brake thermal efficiency, under ½ load, was obtained, but at full load, for medium and high speed, the thermal efficiencies of all biodiesel blends showed a decrease compared to pure diesel fuel. Concerning pollutants emissions, a decrease in CO emissions of all biodiesel blends was noticed. The best result in CO emissions was achieved by the mixture containing 10% by volume of biodiesel with an average reduction value close to 40%. In addition, a significant reduction in NO_x emissions was observed for the three biodiesel blends.

Key words: *microwave, biodiesel, blends, Diesel engine, performance, emissions*

Introduction

Nowadays, the internal combustion engines (ICE) are facing many challenges, mainly related to fossil fuels. Indeed, the rely on fossil fuels is declining due to their environmental issues, depletion and price fluctuations. This situation pushes governments to tighten standards that are increasingly restrictive, with the objective to switch to more green and sustainable energy resources. The last historic decision of the European Parliament [1] to adopt a regulation proposal for banning ICE new sales starting from 2035, is forcing the scientific community and engineers to rethink the fate of ICE. Obviously, the Europen Parlament decision will promote the use of battery electric vehicles (BEV) instead of internal combustion engine vehicles (ICEV).

* Corresponding author, e-mail: ridha.ennetta@issig.rnu.tn

Despite of a booming development, especially in light-duty application [2], BEV are not able to compete with ICEV, at least in the near future, and this is for several reasons such as the undeveloped charging infrastructures worldwide, the electricity origin which still relies on fossil fuels, the unresolved technical issues of batteries in terms of autonomy, manufacturing materials supply, sensitivity of their performance to environmental condition variations*, etc.* [3]. Compression ignition (CI) engine are considered as the keystone of the global economy throughout the maritime, railway and heavy-duty transportations. However, they are viewed as the principal source of air pollution causing irrevocable damages to nature and humans [4]. Many scientists assume that the problems of ICE are not due to the engine itself but mainly to the HC used to feed the engine [5]. Focusing on alternative fuels, with low CO_2 emissions, could be the best answer to fix the fossil fuels problems, especially during this transitional period. These alternatives can, initially, substitute partially fossil fuels, and then entirely replace them.

Biodiesel obtained from renewable oleic vegetable sources are the most promising substitute to HC diesel fuel [6] paired with the harmful environmental effects of fossil fuels, has triggered the search for alternative, RES. Biofuels are arguably a potential RES in the transportation industry as they can be used within current infrastructures and require less technological advances than other renewable alternatives, such as electric vehicles and nuclear power. The literature suggests biofuels can negatively impact food security and production, however, this is dependent on the type of feedstock used in biofuel pro-duction. Advanced biofuels, derived from inedible biomass, are heavily favoured but require further research and development to reach their full commercial potential. Replacing fossil fuels by biofuels can substantially reduce PM, [7]. Over the past few years (two decades), biodiesel production and application have been comprehensively studied by many researchers [8-12]. These researches aimed either to develop new solutions to improve biodiesel production processes, or to assess their effects on the performance of combustion systems, experimentally and numerically [13]. The scientific literature on biodiesel application in ICE is very extensive. Nevertheless, in the following, we will review recent publications, mostly from the last three years, that have addressed the effects of biodiesel blending on diesel engines performance and emissions characteristics.

Accordingly, Emma *et al.* [14] conducted a research on the transesterification of coffee husk oil, which leads to coffee husk oil methyl ester, that have been mixed with pure diesel fuel and used to power a Diesel engine under different loads. Their experimental results showed that the brake thermal efficiency (BTE) of the mixtures, B10, B20, B30, and B50 suffered a slight drop which did not exceed 3%, compared to pure diesel. Exhaust gas emissions are reduced for all biodiesel blends. At full load, a reduction in CO, HC, and smoke opacity was reported for B30, by a percentage of 13.2%, 4%, and 12%, respectively. On the other hand, CO_2 and NO_x emissions increased for B30 by 8.63% and 3.8%, respectively.

Tayari *et al.* [15] used microalgae to produce biodiesel, which was mixed with pure diesel fuel for two percentages (10% and 20%). Their engine tests revealed that the use of biodiesel resulted in a slight increase in break specific fuel consumption (BSFC) and a slight decrease in engine brake power (BP) and torque. This behavior was accompanied by a significant decrease in CO and HC emissions and a modest reduction in CO_2 emissions, while there was a slight increase in NO_x emissions.

In another study, Jagtap *et al.* [16] investigated the blending effect of 4%, 10%, and 20% of esterified jatropha biodiesel with pure diesel fuel. Experimental results showed an increase in BSFC, with increasing the biodiesel blends. This was explained by the low calorific value and slightly higher density of biodiesel blends compared to pure diesel fuel. Therefore, the loss of energy will be compensated by better fuel consumption. In addition, a reduction of CO and HC emissions was obtained.

Sivakrishna *et al.* [17] conducted a study devoted to the evaluation of the performance and emissions of automotive Diesel engines, affected by the use of palm biodiesel. They found that emissions of CO, HC, and particles have decreased considerably with the increase of the biodiesel blends. The reduction in particulate emissions was very clear at 10% blend (B10), while the sharp reduction in HC emissions started at 20% blend (B20). Palm oil biodiesel blends generated more torque and power than petro-diesel. They explained these results by the highest value of cetane number (CN) and the lower viscosity of biodiesel used than that of petro diesel.

A different experimental study, on sunflower oil (SFO) methyl ester, was conducted by Temizera *et al.* [18]. This work aimed to analyze and study the combustion characteristics such as the in-cylinder pressure and the heat release rates. The engine, fueled with 10%, 20%, and 30% of biodiesel, operated at 2000 rpm under full load.

Yesilyurt *et al.* [19] investigated two types of fuels, binary blend of diesel-SFO biodiesel and ternary blends of diesel-biodiesel-pentanol. For the two fuels, the maximum BTE underwent an increase until medium load then a decrease for high loads and this was explained by the fact that the larger quantity of fuel injected at the higher engine load led to accumulate fuel in the cylinder and the possibility of incomplete combustion. Moreover, B20 gave a decrease in CO and HC compared to pure diesel under all loads, this decrease becomes more important as the percentage of pentanol increase. Totally opposite behavior was noticed for CO_2 emissions, thanks to the more complete combustion due to the excess of oxygen content.

Venkatesana and Nallusamyb [20] conducted in-depth experimental work on the performance, combustion, and emission characteristics of an agricultural tractor engine using the combination of methyl esters of soapnut oil and pine oil at different proportions. Their results showed that specific fuel consumption (SFC) of all biodiesel blends was higher than pure diesel at low load, and an enhancement was observed in fuel economy beyond 50% load. This reduction reached 18%, at full load condition, comparatively to pure diesel fuel. Also, an increase in BTE, varying from 8% to 13%, was observed for three biodiesel blends. Concerning emissions, it has been shown that the majority of bi-mixtures have smoke emission less than pure diesel up to 75% load and almost the same as that of pure diesel at full load. They also noticed a significant reduction of unburned HC emission for two biodiesel blends at full load. However, an increase in NO_x emission for all biodiesel blends, under different loads, was obtained.

Tomić *el al*. [21] have carried out an experimental research on a tractor engine using a blend of pure diesel and 40% of biodiesel produced by transesterification of SFO. Their work showed a bit decrease of maximum engine power with the B40, compared to pure diesel fuel, under low load and this difference become more evident and reached 3.21% at medium load. On the other hand, SFC of the biodiesel blend was higher, at low load, but the difference between the two fuels consumption decreased with the increase of load. At high load, about 6.54% less CO was emitted using B40 fuel compared to pure diesel fuel. But at low load and speed CO emissions were similar for both fuels. A rising by 3.2% of CO_2 concentration, and by 2.4% of NO_x concentration with biodiesel compared to pure diesel was observed at high load which is related to a higher fuel consumption or more complete combustion.

Results from biodiesel research studies vary widely, however common conclusions can be drawn. The CI engines fueled with biodiesel show slight decrease in mechanical operating characteristics and emit more NO_x emission, comparatively to ordinary Diesel engines

[22]. To overcome the drawbacks of biodiesel, there are several solutions such as the addition of metal oxides nanoparticles [23-26] the injection of gaseous fuels (natural gas, hydrogen*, etc.*) [27, 28] or the addition of oxygenated fuels, mainly alcohols, which is gaining more and more attention [29-34]. The last solution is the subject of the present research work. Indeed, the main objective of this research is to experimentally study the effect of adding a small amount of alcohol (ethanol) on the mechanical operating characteristics and pollutant emissions of an engine powered by a mixture of diesel and biodiesel fuels. To achieve this objective, the work was divided into three-stages. First, the effect of adding ethanol to pure diesel fuel have been previously studied [35]. The current step is to evaluate the blending effect of biodiesel on the Diesel engine. The last step aims to study the addition of ethanol on biodiesel-diesel fuel blends.

The positive impacts, in terms of fuel consumption reduction and pollutants emissions mitigation, are highly affected by the biodiesel properties, which strongly depend on its production process. Microwave-assisted transesterification is one of the new methods to produce high quality biodiesel. As a chemical process for biodiesel production, this technique has been widely studied [36]. However, in the scientific literature, only few studies have addressed the effects of biodiesel obtained by microwave-assisted technique on engines performance and emissions [37]. Therefore, the aim of this study is to evaluate the impacts of using microwave-produced biodiesel on the performance and emissions characteristics of a Diesel engine. Three biodiesel-diesel mixtures (B5, B10, and B20) have been investigated comparatively to pure diesel fuel (B0). The effects of these biodiesel blends on the engine operating characteristics such as SFC, BP, and BTE and on CO, CO_2, and NO_x emissions have been carried out using a one-cylinder Diesel engine.

Materials and methods

Biodiesel production and fuels preparation

Biodiesel was produced by microwave-assisted transesterification process of commercial SFO using ethanol and NaOH as a catalyst. Microwave heating was used in the transesterification process to overcome the minimum mass transition of the two immiscible reactants, oil and alcohol. By improving the mixing phase at lower temperature, lower amounts of alcohol and catalysts are needed [38]. Microwave-assisted transesterification increases the biodiesel production yields and reduces the energy consumption by reducing the reaction time compared to traditional methods [39].

Figure 1 presents the microwave reactor used for the biodiesel production transesterification process. The experimental set-up consists of a modified microwave oven with a built-in stirring, raw materials supply and temperature measurement systems [40].

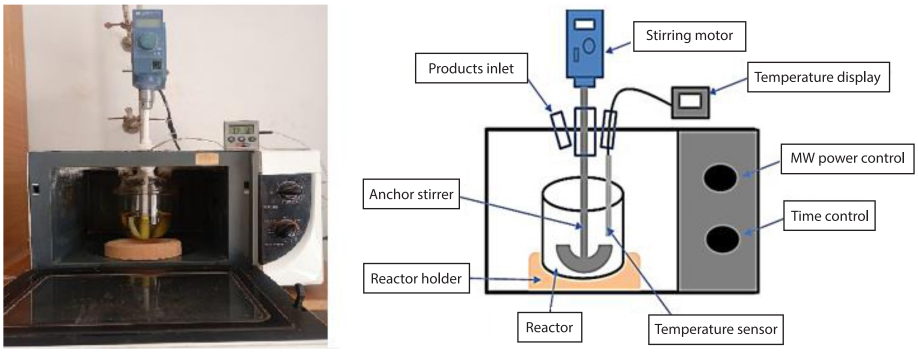

Figure 1. Microwave-assisted biodiesel production reactor

Figure 2 illustrates the different steps of the biodiesel production. Yahya [40] optimized this process and a yield of 98.4% has been obtained in just 85 seconds using an oil-to-alcohol molar ratio of 1:6, a 2% (by oil mass) as the catalyst amount and a reaction temperature of 70 °C. Table 1 gives the main properties of neat biodiesel and diesel fuel.

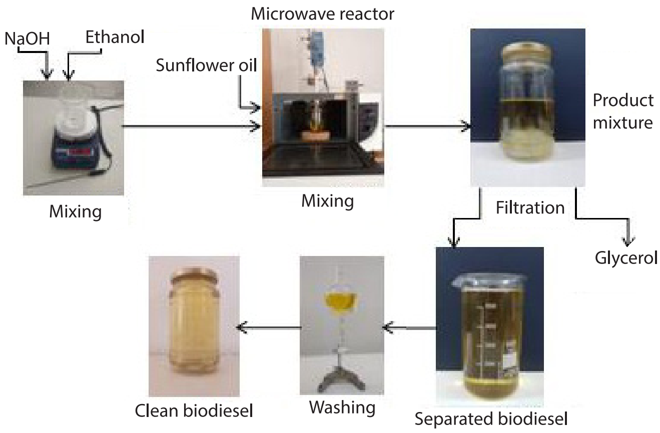

Figure 2. Biodiesel production steps

Table 1. Fuel properties

Properties	SFO biodiesel (B100) [40]	Diesel fuel (B0) [41]
Density [kgm^{-3}] at 15 °C	882.9	853.36
Kinematic viscosity [mm^{2}s^{-1}] at 40 °C	4.5	3.55
Lower heating value (LHV) [MJkg^{-1}]	37.70	42.67
CN	53.76	49

The LHV and CN of biodiesel were calculated using prediction models selected based on a comprehensive critical review of Bukkarapu and Krishnasamy [42]. They stated that the following models based on the biodiesel density, ρ, gives good results [41, 43]:

$$LHV = -0.167\rho + 184.95$$

$$CN = 538.7 - 0.55\rho$$

The obtained biodiesel was mixed with pure diesel fuel at three different blends 5%, 10%, and 20% by volume and then compared to pure diesel fuel (B0). Exceeding 20% the atomization of biodiesel becomes more difficult because of its high viscosity and density [44].

Engine performance measurement set-up

Figure 3 presents the experimental set-up diagram. It consists of a Lombardini type, single-cylinder, four-stroke air-cooled Diesel engine. The engine characteristics are presented in tab. 2. This engine is coupled to a swinging field DC dynamometer which is used, initially, to start the engine, then as an electric generator which converts mechanical energy into electric energy. This energy is then dissipated in an external variable rheostat which converts electricity into heat.

The engine loading operation is realized by varying the electric resistance of the rheostat, this allowing the creation of a braking torque in the dynamometer shaft. The mechanical engine torque was measured directly by means of a graduation in the dynamometer outer case

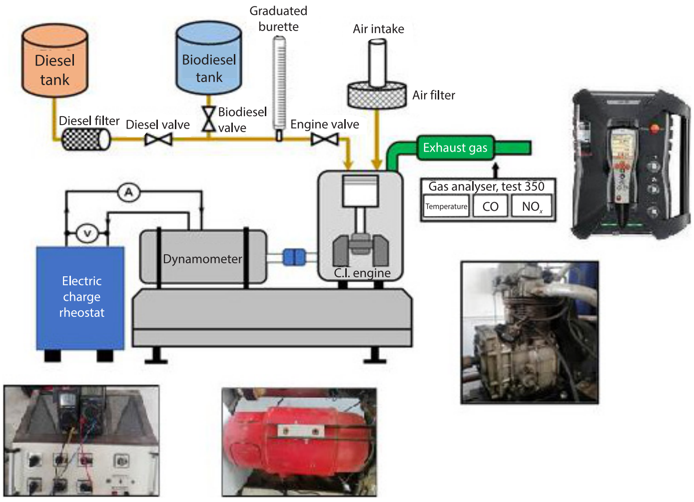

Figure 3. Experimental set-up

Table 2. Engine characteristics

Type	Lombardini 6LD325N
Cylinder	1
Stroke	4
Displacement [cc]	325
Compression ratio	18:1
Power [kW]	5
Maximum torque [Nm] at [rpm]	14 at 2100
Maximum speed [rpm]	3500

that tends to rotate due to the magnetic drag. The engine rotation speed is determined by an optical tachometer type VT-8204. A Pitot tube anemometer model VPT-100 is used to measure the intake air-flow and temperature. The fuel consumption is measured by a graduated burette connected to a fuel tank supply. Quantitative exhaust gas composition (CO, CO_2, and NO_x) are determined by a Testo 350 gas analyzer. Measurements were carried out at the speed range {800-3200 rpm} under 1/2 load and full load. Before taking measurements, the engine was running at the idle speed and under no load for at least 15 minutes to reach its stabilization state. For each test, all measurements are repeated three times then the average value is calculated.

Table 3. Uncertainties of measurement instruments

Instrument	Uncertainty
Speed sensor	±0.3
Fuel measuring	±1.0
Dynamometer	±1.0
CO sensor	±3.4
CO_2 sensor	±0.34
NO_x sensor	±0.1

Uncertainties analysis

Based on the instrument's specifications, tab. 3, the standard deviation method was used to analyze the uncertainty and to evaluate the reliability of the measurements.

According to Holman [45], the overall uncertainty is calculated using the formula:

$$\left[\sum_{i=1}^{n}\left(Ux_i\right)^2\right]^{1/2} \quad (1)$$

where Ux_i is the uncertainty associated with each measured value using the corresponding instrument given in tab. 3.

Overall uncertainty [%] = square root of $[(0.3)^2 + (1.0)^2 + (1.0)^2 + (3.4)^2 + (0.34)^2 + (0.1)^2]$

The overall percentage of uncertainty is 3.71% which is acceptable for experimental work.

Results and discussion

The effects of biodiesel blends (B5, B10, and B20) on the CI engine operation and emissions characteristics were carried out under ½ and full loads. In the following sections, we will present and discuss the obtained results of SFC, BP, and BTE under each load. In addition, emissions of CO, CO_2, and NO_x will be presented.

Engine performance

Specific fuel consumption

Figure 4 shows the variation of SFC, for pure diesel B0 and for all biodiesel blends B5, B10, and B20 under ½ load, fig. 4(a) and full load, fig. 4 (b).

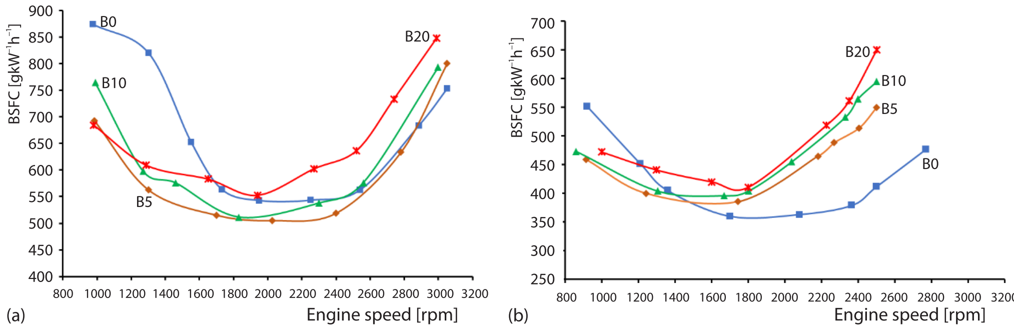

Figure 4. Effect of biodiesel blending on specific fuel consumption under half and full loads; (a) ½ load (b) full load

At low engine speed, high SFC is observed due to the low combustion efficiency caused by the walls heat losses. The same phenomena is observed at high engine speeds, but in this case, the combustion efficiency reduction is induced by the friction heat losses.

Under both loads, SFC increases with increasing biodiesel blends for all the speed range. When the engine is running under ½ load, SFC increases with increasing the percentage of biodiesel for all the speed range, but it remains weaker than that of pure diesel for a speed below 2000 rpm and become almost equal for B0, B5, and B10 when the speed increases further. Except for B20, starting from 2000 rpm, SFC exceeds that of B0 with an average of 13%. At full load, an overall reduction ranging from 10% to 35% in SFC was observed for all fuel mixtures comparatively to ½ load. By comparison pure diesel B0, one cannotice that at low speed, the SFC of biodiesel blends are lower than B0. However, at medium and high speeds (>1600 rpm), the engine behavior, in terms of SFC, is different for ½ load from that for full load. Indeed, under ½ load, the SFC of B0 is comparable to that of B5 and B10 but, under full load, the SFC of B0 is lower than that of biodiesel blends. For example, under full load, the biodiesel blends SFC increase is about 22%, comparatively to B0. At 2400 rpm it reaches about 40%. This is due to the lower LHV and greater density of biodiesel as explained by Yasar and Altun [46]. Similar results were obtained by Carraretto *et al*. [47], Oyedepo *et al*. [48], Sharon *et al*. [49], and recently by Jagtap *et al*. [16].

Brake power

In general, most biodiesel are characterized by higher oxygen content, viscosity, lubricity and LHV compared to pure diesel fuel. According to Allami *et al.* [37], the engine power is directly related to the fuel heating value and inversely proportional to its viscosity and lubricity. Figure 5 shows clearly that adding biodiesel to pure diesel slightly increases the engine power output, this difference becomes somewhat clear and in the order of 4% at high speed and under ½ load. A same behavior was found by Allami *et al.* [50] and Jagtap *et al.* [16]. The authors attributed this increase to the high oxygen content and flammability of biodiesel.

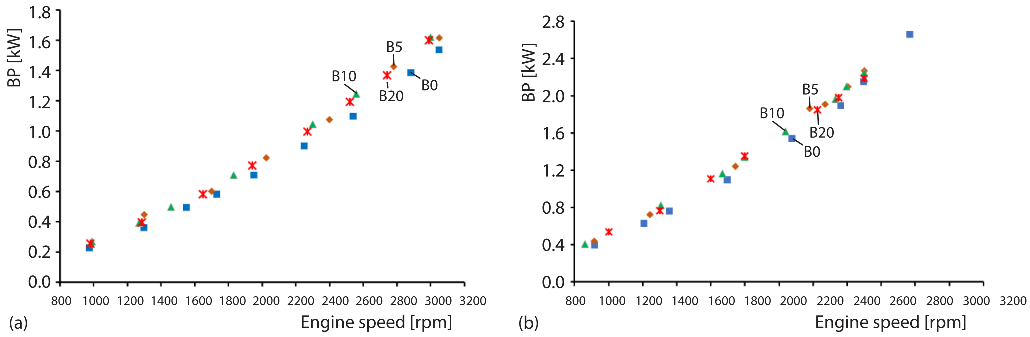

Figure 5. Effect of biodiesel blending on BP under (a) ½ load and (b) full loads

Contrary results have been found by Oyedepo *et al.* [48] giving a slight decrease in the power delivery by biodiesel and it has been attributed to the lower CN of the tested biodiesel which increases the fuel ignition delay, thereby reducing the engine power. Also, Boubahri *et al.* [10] when investigated waste cooking oil (WCO) biodiesel blends, they observed a 5% decrease in engine power and torque for each 10% of biodiesel blend added, comparatively to neat diesel fuel.

As stated by Ennetta *et al.* [51], the performances of the engine are affected by the quality of the fuel which changes strongly depending on the process and the raw materials used for its production.

At ½ load and for all engine speeds, B10 gives the best results in terms of BP compared to other mixtures. Under full load conditions, comparable results are given by B10 and B20 at low and medium speeds. But at high speed, B5 gives the best results. This behavior can be attributed to the dual competition between biodiesel high CN and oxygen content, on the one hand, and its low LHV and high viscosity, on the other hand.

Brake thermal efficiency

Thw BTE is the ratio between the mechanical power delivered by the engine crankshaft output and the amount of energy generated by the fuels during the combustion process. Many factors affect the engine BTE such as the fuel properties, the air-fuel ratio, the engine compression ratio and the combustion process [19, 52].

Figure 6 presents the effect of biodiesel blends on BTE for various engine speeds under ½ and full loads. As expected, the BTE results are the inverse image of those of the SFC since BTE is inversely proportional to the SFC.

A higher engine speed increases friction losses and combustion frequency, lowering the generated torque and tending to decrease engine efficiency [53].

These results show that BTE is improved with increasing engine load for all tested fuels. The reason behind this may be the higher in-cylinder temperature, which increases with increasing injected fuel quantity. One more probable reason is that at high loads, increasing injected fuel quantity leads to greater charge cooling, resulting in slightly higher volumetric efficiency [54].

Regardless of load, the engine BTE decreases with increasing biodiesel blends which can be attributed to the low LHV and high viscosity of biodiesel blends. Under ½ load conditions, the maximum values of BTE for the three biodiesel blends B5, B10, and B20 are ranging from 16.7%-15.6% and are obtained at the vicinity of 1900 rpm. For the full load case, the maximum BTE values, ranging from 22-20.5% are obtained at a lower speed of 1600 rpm. Considering the pure diesel fuel B0, its maximum BTE, under ½ load, is similar to that of B20 but under full load conditions B0 gives the highest BTE value among all tested mixtures, 23.5% at the vicinity of 1800 rpm.

Referring to the fig. 6, it is clear that, under ½ load, biodiesel blends have better thermal efficiency than that of pure diesel fuel. This can be attributed to the high CN and oxygen content of the biodiesel fuels which help improving the combustion process compared with pure diesel fuel [55]. Similar results were also shown by Raheman and Phadatare [56]. As for ½ load, a same result is obtained under full load at low engine speed (<1400 rpm). However, at medium and high speeds (>1600 rpm), the pure diesel fuel gives the best BTE values followed by B5, B10, and B20. This behavior is mainly due to the low LHV and high viscosity of biodiesel blends which play the major role in reducing the fuel mixing process and combustion efficiencies, at elevated engine speeds.

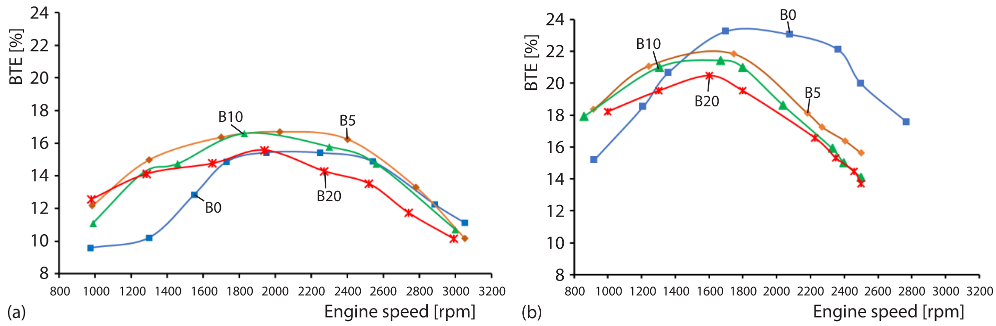

Figure 6. Effect of biodiesel blending on BTE under (a) ½ load and (b) full loads

Several experimental results have been reported by Masimalai and Subramaniyan [57]. Considering the scientific literature, data is very contradictory: some researchers reported that biodiesel has a higher BTE than pure diesel fuel which was explained by the improvement of the atomization process due to the reduction in the viscosity of the fuel [6, 21]. Other authors assert the opposite behavior which was explained by the fact that the addition of biodiesel creates a reduction in CN or in LHV of the mixture, that hinders the combustion process [58, 59]. These contradictory behaviors are mainly related to the quality and the origin of the biodiesel.

Engine emissions

In the following sections, the engine exhaust gases emissions will be presented and discussed for all tested fuel blends. Measurements have been performed under full load conditions and for various engine speeds.

The CO emissions

The most influencing factor on the increase of CO production is the lack of oxygen in the combustion chamber which leads to an incomplete combustion reaction [49]. Other studies have stated that the high CN of biodiesel blends reduces the possibility of CO formation [60, 61].

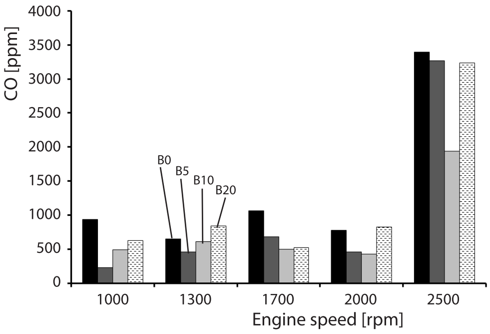

Figure 7. The CO emissions *vs.* engine speed, under full load

The variation of the CO emissions of the Diesel engine, at full load, using four different tests fuels, B0, B5, B10 and B20 is presented in fig. 7. It is clear that CO emissions increase with increasing engine speed. Gassoumi *et al.* [62] attributed this increase to the problem of air-fuel mixture preparation at high engine speed due to the high air velocity. Besides, at high engine speeds, the air density decreases, reducing its mass-flow and making the air-fuel mixture richer. Consequently, more CO is produced.

Comparatively to pure diesel fuel, it is clear that the addition of biodiesel reduces the amount of CO generated during combustion. The best results giving a stable reduction in CO emission, even at high speed, were obtained using B10 with an overall reduction percentage exceeding 40%. The B10 is followed by B5 whose reduction was very significant at low and medium speeds but did not exceed 4% at high speed. The B20 behavior was fluctuating with a reduction in CO at some speeds and an increase in others. Similar results was obtained by Elsanusi *et al.* [63] and Jafarihaghighi *et al.* [64]. Bibin *et al.* [65] attributed the decrease in CO emission with the increase of biodiesel blends, to the presence of oxygen which improves the complete oxidation of CO.

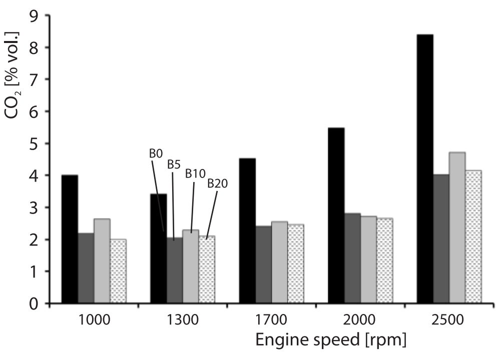

Figure 8. The CO_2 emissions *vs.* engine seed, under full load

The CO_2 emissions

According to Vergel-Ortega *et al.* [66], CO_2 emissions depends on the values of carbon to hydrogen (C/H) atoms ratio, and on the oxygen content. Figure 8 shows the variation of CO_2 emissions function of the engine speed for the different fuel blends. The CO_2 emissions increase with increasing engine speed for all tested fuels, and this is probably due to the rich mixture in combustion chamber at high speeds. The overall mean reductions in CO_2 emissions, comparatively to pure diesel fuel, for B5, B10, and B20 blends are 46.6%, 50% and 46.8%, respectively. Yesilyurt and Aydin [67] and Swaminathan and Sarangan [68] reported similar results using cottonseed oil and fish oil biodiesels, respectively. They also claimed that this reduction is due to the lower carbon content in biodiesel blends leading to a lower C/H ratio comparatively to pure diesel fuel.

The NO_x emissions

The NO_x are considered as one of the main pollutants of Diesel engine. The major reasons for NO_x formation are the high combustion temperature, the residence time of chemical reactions, and the excess amount of oxygen available for the oxidation process.

The NO_x emitted by the engine, under full load conditions, for pure diesel and biodiesel blends are presented in fig. 9 at engine speed ranging from 1000-2500 rpm. One cannote that increasing the engine speed, NO_x emissions increase significantly regardless of fuel type which is due to the increase in the combustion chamber temperature as explained by Yasar and Altun [46]. This phenomenon is accentuated by the increase in friction at high speeds.

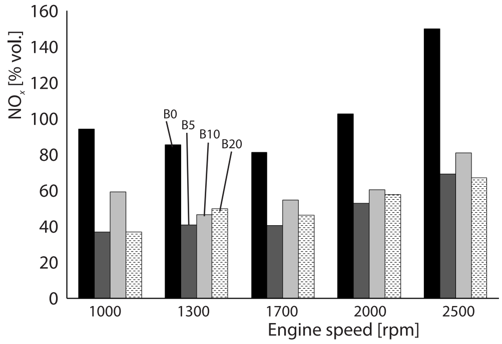

Figure 9. The NO_x emissions *vs.* engine speed, under full load

Figure 9 shows that for all speeds range, addition of biodiesel reduces NO_x emissions compared to B0 by 50%, 35% and 64% for B5, B10, and B20, respectively. This behavior is probably due to the reduction in combustion temperature created by the addition of biodiesel. Another factor is that, initially, biodiesel blends may contain lower amount of nitrogen than pure diesel fuel. This fact has been confirmed by Wei *et al.* [69]. They reported that diesel fuel contains 90 ppm of N while WCO oil biodiesel contains only 5 ppm of N. Kalligeros *et al.* [70] also reported a reduction in NO_x emissions when investigating the effects of SFO and olive oil biodiesels on the performance of a stationary Diesel engine.

Conclusions

The present experimental research study was carried out on a single-cylinder Diesel engine in order to assess the blending effects on the engine performance of biodiesel obtained from a microwave-assisted transesterification process of SFO. Measurements were performed under ½ load and full load conditions and an engine speed varying from 1000-3000 rpm.

Three biodiesel blends, B5, B10 and B20, were evaluated comparatively to pure diesel fuel B0. The effects of these biodiesel blends on the engine performance such as SFC, BP, and BTE and exhausted gas emissions such as CO, CO_2, and NO_x were investigated. The most important results are summarized as follows.

- At full load, SFC of biodiesel blends were higher and showed an increase of 32% at 2400 rpm compared to B0. The SFC of all biodiesel blends became almost equal when the engine speed exceeds 2000 rpm under ½ load. However, adding biodiesel to pure diesel did not affect the engine power output.
- An improvement of BTE was observed for all blends at ½ load. Nevertheless, under full load, especially at medium and high speeds, biodiesel blends showed a decrease of SFC compared to B0.
- A decrease in all biodiesel CO emissions was noticed. The best result in CO emission was performed by B10 with a decrease mean value of 40% compared to B0.
- Due to the lower carbon content in biodiesel blends, CO_2 emissions were significantly decreased.
- At all speeds range, addition of biodiesel reduced NO_x emissions compared to B0 by about 50%, 35%, and 64% for B5, B10, and B20, respectively. This drop is mainly due to the decrease in combustion temperature by adding biodiesel.
- Biodiesel produced by microwave-assisted transesterification and directly mixed with pure diesel fuel exhibits high performance. However, it is crucial to emphasize the need for care-

ful consideration of the long-term storage effects on the mixture's properties, including miscibility and solubility to ensure that engine performance is maintained over time.

Nomenclature

B – blend [%]
BD – biodiesel
BEV – battery electric vehicles
BSFC – brake specific fuel consumption, [$gkW^{-1}h^{-1}$]
BTE – brake thermal efficiency, [–]
BP – brake power, [kW]
CI – compression-ignition, [–]
C/H – carbon to hydrogen
CN – Cetane number, [–]
ICE – internal combustion engine
ICEV – internal combustion engine vehicles
LHV – lower heating value, [$MJkg^{-1}$]
SFC – specific fuel consumption
SFO – sunflower oil
WCO – waste cookong oil

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