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Environmental impact assessment of the mechanical shaft work produced in a diesel engine running on diesel/biodiesel blends containing glycerol-derived triacetin

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ABSTRACT

Global application of biodiesel in the transport sector has rapidly expanded over the last decade, however, efforts to overcome its main shortcoming, i.e., increase in NO_x emissions compared with diesel, are still underway. In light of that, parameters/strategies capable of mitigating biodiesel NO_x emissions are of wide interest to further enhance the sustainability aspects of this green fuel. Among various options put to test, the use of fuel additives due to its simplicity and cost-effectiveness has attracted a great deal of attention. In this study, the mechanical shaft work produced by a diesel engine fueled with various diesel/biodiesel blends (B5 and B20) containing glycerol-derived triacetin was scrutinized from environmental viewpoint. Neat petro-diesel, B5, and B20 were also considered as control fuels. Two environmental evaluation methodologies, namely discrete emissions analysis and consolidated life cycle assessment (LCA) were considered to assess the impacts of fuel composition, engine speed, and engine load on the environmental burdens of the shaft work produced. According to the results obtained, the outcomes of both methods considered herein were profoundly affected by engine load and speed. Even though triacetin inclusion into both B5 and B20 profoundly affected the outcomes of emissions analysis, its application did not lead to any spectacular differences in the results of LCA method compared with petro-diesel. More specifically, triacetin incorporation into fuel blends neutralized the unfavorable impacts of biodiesel addition in terms of NO_x emissions. However, incorporating triacetin into diesel/biodiesel blends in general did not profoundly mitigate the environmental impacts of the shaft work produced in terms of LCA damage categories as well as the total environmental impacts. Overall, using triacetin as combustion improving agent did appear to be an efficient strategy from the LCA viewpoint considering the current production technologies. In addition, LCA approach was found to be more a comprehensive decision-making approach compared with discrete emissions analysis for evaluating the environmental impacts of the shaft work produced by internal combustion engines.

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1. Introduction

In order to reduce the current high dependency on conventional fossil fuels and to subsequently reduce the consequent greenhouse gases (GHGs) emissions on one hand and to comply with the increasingly stringent automobile emissions standards on the other hand, renewable fuels are more than just a choice (Aghbashlo et al., 2018b, 2017c). Interestingly, fossil-dependent global transportation contributed to over 25% of the total GHGs emissions. In parallel with the improvements made in diesel engine technologies over the last decades to overcome the above-mentioned challenges, renewable alternatives such as biodiesel have also been at the core of attention (Sahin et al., 2014; Srivastava and Prasad, 2000). Biodiesel offers some notable advantages such as biodegradability, lubricity, indigenous availability of its feedstock, non-toxicity, low combustion emissions, and physicochemical analogy with petrodiesel (Hosseinpour et al., 2018). In addition, the biodiesel application requires no or little modifications to the existing diesel engines (Akbarian et al., 2018; Ghazanfari et al., 2017).

Biodiesel is produced from various oil resources such as edible/nonedible vegetable oils and animal fats (Aghbashlo et al., 2018f). Nevertheless, among these feedstocks, low-cost waste oil resources such as waste cooking oil (WCO) are of greater interest for economic, environmental, and food security reasons (Aghbashlo et al., 2018a, 2017a). Today, the most widely employed method for biodiesel production at industrial level is alcoholysis of triglycerides (also known as transesterification) using a basic catalyst (commonly KOH or NaOH) (Aghbashlo et al., 2018c, 2018e, 2017b). Depending on the alcohol used, i.e., methanol or ethanol, the resultant product includes methyl/ethyl esters (biodiesel) of the fatty acids contained in the feedstock used, respectively (Mohadesi et al., 2014; Tabatabaei et al., 2015). In addition, glycerol is generated by 10 wt% of total biodiesel production based on the stoichiometric relations and the growing global demands for biodiesel has led to a glut of glycerol supply. Therefore, value-added chemicals should be synthesized from biodiesel-derived glycerol in order to enhance the economic viability of biodiesel industry. This by-product can be used by chemical, pharmaceutical, food, and fuel industries in its raw and purified forms. Among the various chemicals potentially produced from glycerol, triacetin ($C_9H_{14}O_6$) generally obtained through glycerol esterification with acetic acid has attracted a considerable deal of attention as fuel additive (Casas et al., 2010). According to Casas et al. (2010), triacetin incorporation into neat biodiesel up to 20 wt% can improve fuel quality with respect to the ASTM D6751 guidelines.

Biodiesel combustion generally results in lower unburned hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) exhaust emissions compared to fossil diesel. However, biodiesel in neat and blend form unfavorably increases nitrogen oxides (NO_x) (Karabektas, 2009; Nabi et al., 2009; Panigrahi et al., 2014; Puhan et al., 2007; Zheng et al., 2008). This could be occurred due to the relatively high oxygen content (~11%) of fatty acid methyl/ethyl esters, leading to more complete combustion processes, higher combustion chamber temperature, and consequently higher NO_x formation (Hoekman and Robbins, 2012). To justify the findings of the reports which have claimed otherwise (Kalligeros et al., 2003; Misra and Murthy, 2011; Redel-Macías et al., 2012), the impact of biodiesel inclusion on increasing the cetane number of the fuel blend should be taken into consideration. More specifically, through increasing cetane number, the premixed combustion phases and consequently the ignition delay will be shortened (Kalligeros et al., 2003). Shorter ignition delays are generally translated into slower rate of increases in combustion pressure (i.e., more time for heat transfer and therefore, lower localized in-cylinder temperature) and therefore, lowered NO_x formation. Hence, it could be concluded that a trade-off exists between the favorable and unfavorable effect of biodiesel on NO_x generation in the combustion chamber. Nevertheless, it should also be noted that if cetane number is too high such as in the case of high biodiesel inclusion rates, it could also result in incomplete combustion and build-up of unburned hydrocarbon deposits (Chukwuezie et al., 2017).

A great deal of efforts have been put into mitigating pollutant formation, particularly NO_x emissions, during combustion of fatty acid methyl/ethyl esters and its blends (Gumus et al., 2016; Mirzajanzadeh et al., 2015; Mohammadi et al., 2013; Senthilkumar and Prabu, 2015; Srinivasa Rao and Anand, 2016; Velmurugan and Sathiyagnanam, 2016). To this end, incorporation of various fuel additives like alcohols (ethanol, n-butanol, and methanol), water, acetal, and metals has been examined by various research groups (Ganesh and Gowrishankar, 2011; Ithnin et al., 2015; Lee et al., 2011; Yang et al., 2013). Furthermore, the effect of glycerol-derived triacetin as fuel additive on engine combustion characteristics has been studied in a number of studies. For instance, Lacerda et al. (2015) added 5–10 %v/v triacetin to neat diesel and neat biodiesel and reported a more complete combustion and accordingly, lower CO emissions by approximately 50% for diesel and to a lower extent for biodiesel owing to the inclusion of the additive. They also stated that triacetin led to lower viscosity of the fuel blends by 2–3% while it increased the density of the fuels within the limits of the standard. Concerning the NO_x formation, the authors claimed increased emissions by increasing the engine power for all fuel blends tested, highlighting that the increases recorded were more pronounced for biodiesel and its blends with triacetin in comparison with their diesel counterparts. In another work, Rao and Rao (2011) investigated the effect of adding triacetin in the range of 5–25 %v/v on the engine performance and exhaust emissions characteristics of coconut oil methyl ester in a diesel engine. They reported that the fuel blend containing 10% triacetin led to the most favorable outcomes. Zare et al. (2016) also studied the effect of oxygenated fuels containing WCO biodiesel and triacetin on the exhaust emissions. They found that increasing the oxygen content of the fuel decreased CO_2, CO, HC, and PM emissions, while increased NO_x formation.

According to the above-mentioned studies, both biodiesel and triacetin have their own pros and cons on the pollutants generated during the combustion process. Hence, decision making about these additives and their inclusion rates on the basis of regulated exhaust emissions like CO_2, CO, NO_x, SO_x, HC, and PM in the discrete form is very difficult or even impossible (Hosseinzadeh-Bandbafha et al., 2018). This problem also becomes even more complicated in a multi-objective optimization problem since taking into consideration all emissions indices for diagnosing a global optimal point is very problematic as a result of incompatible objectives. In addition, exhaust emissions analysis does not take into account the environmental burdens imposed during the synthesis of biofuels/additives. The main disadvantage of discrete emissions analysis is that it requires subjective weighting to make decisions owing to the fact that the level and degree of harmfulness of pollutants are not comparable with each other. Life cycle assessment (LCA) approach can be a promising alternative to the conventional emissions analysis for coping with such complexity and plurality (Hosseinzadeh-Bandbafha et al., 2018). Using this method, all emissions indicators of each fuel blend can be converted to a consolidated basis, i.e., climate change, resource depletion, human health, and eco-system quality as well as total environmental impacts. Accordingly, data emerged from emissions analysis not only can be easily interpreted but also multi-objective optimization can be facilitated by consolidating the environmental impacts related to each fuel blend.

Despite the fact that LCA approach has been broadly used in various sectors for evaluating the sustainability index of their products and services, this comprehensive decision making tool has rarely been considered up to date for investigating diesel engines fueled with renewable and nonrenewable fuels. Therefore, the present study was aimed at experimentally investigating the performance metrics and analyzing the exhaust emissions of a diesel engine fueled with various diesel/biodiesel blends (B5 and B20) containing different concentrations of glycerol-derived triacetin in the range of 3–7 %v/v. LCA approach was also taken into account as a complementary tool to make decisions on the biodiesel and triacetin inclusion rates. The optimal fuel blend and engine operating conditions were also selected on the basis of four LCA-based damage categories such as climate change, resource depletion, human health, and eco-system quality as well as total environmental impacts.

2. Material and methods

2.1. Biodiesel synthesis and assessment

Methyl esters were synthesized by transesterifying (1 h at 60 °C) pre-treated WCO using potassium hydroxide (KOH) catalyst. Once the reaction completed, the mixture was left at room temperature to separate the biodiesel phase from the glycerol phase as much as possible (Aghbashlo et al., 2018d). Subsequently, wet washing procedure was conducted to purify biodiesel as described by Jaber et al. (2015). Biodiesel properties including flash point, cloud point, density, and viscosity were analyzed by laboratorial procedures set forth by the ASTM standards while the other properties were estimated by using “Biodiesel Analyzer© software” (Talebi et al., 2014).

2.2. Triacetin production

Triacetin production was carried out in a continuous-flow reactor as developed by Rastegari and Ghaziaskar (2015). Briefly, glycerol was esterified with acetic acid in the first reactor using Amberlyst 36 as catalyst. Then, the reaction mixture was introduced into a water separation reactor coupled to the end of the first reactor. The water separation reactor was designed to remove water from the reaction medium as well as to catalyze the reaction simultaneously. Toluene was pumped continuously into this reactor for continuous removal of water from the reaction medium and Amberlyst 36 was used as catalyst. As a result of these two simultaneous processes, the chemical equilibrium shifted toward the triacetin production. Once the reaction completed, the mixture was purified through distillation steps. Most of the acetic acid and toluene were removed by the first distillation at reduced pressure followed by triacetin distillation through the procedure described by Trevoy and Derek (1963). The purity of the distilled triacetin sample was investigated using gas chromatography-flame ionization detection (GC-FID) and gas chromatography-mass spectrometry (GC-MS).

2.3. Fuel blends preparation

To prepare the fuel blends, triacetin were blended with two sulfur-free diesel/biodiesel blends (B5 and B20) in three different volumetric ratios (3, 5, and 7 %v/v) named as B5A3, B5A5, B5A7, B20A3, B20A5, and B20A7, respectively. Therefore, the experimental tests were carried out using six different diesel/biodiesel/triacetin blends while B5, B20, and neat diesel fuels were taken into account as control fuels.

2.4. Engine test set-up

Combustion trials were carried out using a turbocharged direct injection four-cylinder MT4-244 diesel engine manufactured by Motor Sazan (Tabriz, Iran) coupled with Schankk W700 magnetic dynamometer (10 kW). Table 1 tabulates the engine technical specifications. The experimental procedure is schematically indicated in Fig. 1. Engine test was carried out in eight modes at different loads (25, 50, 75, and 100% of full load) and two engine speeds (1500 and 2000 rpm). CO_2, NO_x, HC, CO, and PM were measured using an A-8020 AVL Dicom Ditest Gbhm gas analyzer. Table 2 presents the measurements accuracies and the computed parameters uncertainties.

2.5. Life cycle assessment (LCA) approach

LCA as an objective and standardized approach is capable of investigating the behavior of products, processes, and systems in the entire life cycle considering their impacts on the environment, resources, and human health (Cabeza et al., 2014; Maham et al., 2018; Neri et al., 2018; Rajaeifar et al., 2017b). In better words, LCA attempts to attain more sustainable production and consumption systems using its structured, internationally-standardized, and comprehensive method (Rajaeifar et al., 2019; Yunos et al., 2017). LCA can also identify the key process steps and areas where changes in the processes can significantly reduce the negative impacts on the environment, resource, and human health (Koroneos et al., 2004).

The general LCA framework is defined by ISO 14040 and 14044 (ISO, 2006), consisting of four steps, i.e., aim and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and interpretation of the results. In the goal and scope definition step, purpose, audiences, and system boundaries are defined (Ortiz et al., 2009). In this study, the aim was to investigate and compare the environmental impacts of the synthesis and combustion of six different diesel/biodiesel/triacetin blends at two engine speeds and four engine loads. The environmental impacts of these fuel blends were compared with those of B5, B20, and neat diesel as control fuels. The system boundary including different stages of diesel/biodiesel/triacetin blends production and consumption considered throughout this study is shown in Fig. 2. In addition, two sub-systems of WCO biodiesel and triacetin synthesis were also separately studied in terms of their environmental impacts.

The function of a system under investigation is presented by *Functional unit* (FU). It is important to note that the choice of the FU has a profound effect on the interpretation of the final results (Gaudreault et al., 2009). The FU was considered to be 1 GJ shaft power produced from the combustion of each fuel blend. For the two sub-systems of WCO biodiesel and triacetin synthesis, the FU considered was environmental impacts associated with 1 kg WCO biodiesel and 1 kg of triacetin, from the extraction of raw materials to the end of the production stage.

In the LCI step, information concerning total relevant energy and

Table 1
The specifications of the four-stroke, four-cylinder Motor Sazan engine test bed used in the present study.

Engine parameter	Specification
Number of cylinder	4
Bore and Stroke	100 × 127 mm
Displacement	3.99 L
Compression ratio	17.5:1
Peak power	61.5 kW@2000 rpm
Peak torque	330 Nm@1300 rpm

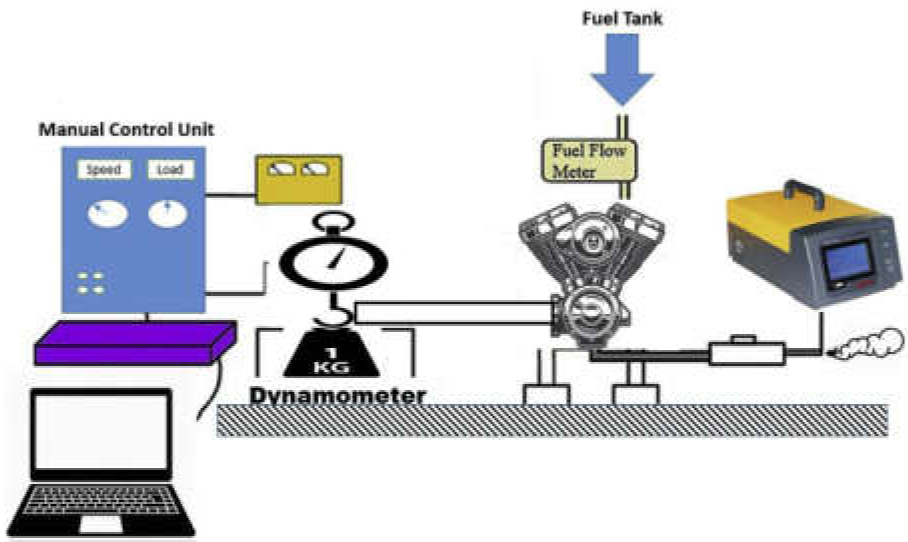

Fig. 1. The schematic diagram of the engine setup used for the combustion experiments.

Table 2
The specifications of the A-8020 AVL Dicom Ditest Gbhm gas analyzer used.

	Measuring instrument	Accuracy
Dynamometer	Pmid company (model E400)	Power, 1 Hp; Torque, 1 Nm; Speed, 1 rpm
Fuel flow meter	Pmid company	0.01 kg/h
Air flow meter	ABB Sensyflow p (Germany)	0.3 kg/h
CO	AVL Digas4000	0.01%
CO_2	AVL Digas4000 Light	0.01%
NO_x	AVL DiCom4000	1 ppm
Soot	AVL 4155 smoke meter	0.1 mg/m^3
O_2	AVL DiCom4000	0.01%
Computed parameters		*Uncertainty (%)*
P_b	–	1%
Bsfc, bte	–	1.4%

mass inflows and outflows as well as data on pollutants release to air, water, and soil are collected (Ortiz et al., 2009). These insights are obtained based on two kinds of data set, i.e., the *background* and *foreground data*. The background data are associated with the production of the inputs and energy consumed in the process, which can be taken from EcoInvent database. The foreground data are associated with the amount of materials and energy used in the process, which can be obtained from the experiments. The photovoltaic electricity was assumed to be the power source used in the triacetin synthesize from biodiesel-derived glycerol.

In the LCIA step, potential environmental impacts are assessed while resources depletion of the system under investigation is estimated by different methods. Two groups of indicators, i.e., midpoints (problem-oriented methods) and end points (damage-oriented methods) are considered in this step to quantify the environmental impacts (Audenaert et al., 2012; Ortiz et al., 2009). Midpoints reveal the environmental impacts related to global warming, eutrophication, acidification, human and ecosystem toxicity, and potential photochemical ozone creation while end points translate mid points into various environmental themes such as human health, natural environment, and resources. Several methods have been developed and applied during the past decade for environmental impact assessment like Eco-indicator 99, EPS2000, IMPACT 2002+, and CML methods (Klinglmair et al., 2014). In the present survey, IMPACT 2002 + method was considered for determining the endpoints. Finally, the obtained results are interpreted and explained in the last stage of an LCA analysis for identifying significant problems and presenting conclusions and recommendations (Rashid and Yusoff, 2015).

2.6. Sensitivity and uncertainty analyses

The sensitivity of the investigated damage categories to input and output parameters was analyzed by their percentile changes. The effective parameters on each damage category denoted by X_n include exhaust emissions gasses, diesel production, biodiesel production, and triacetin production. The mean amount of each parameter (X) for the tested fuels was variated by ±10%. Moreover, it was assumed that other parameters would remain constant at their mean amount values when variating each parameter. Accordingly, the sensitivity of the effective parameters on each damage category was identified. Finally, based on the probability distribution of the computed damage assessment results, the uncertainty ranges of different damage categories for different fuel types (per GJ shaft power generated) were obtained.

3. Results and discussion

3.1. Fuel properties

Table 3 presents some thermophysical properties of all the prepared fuels measured on the basis of the ASTM standard guidelines. The density and viscosity of the WCO biodiesel were higher than those of neat diesel. In addition, these attributes of the fuel blends

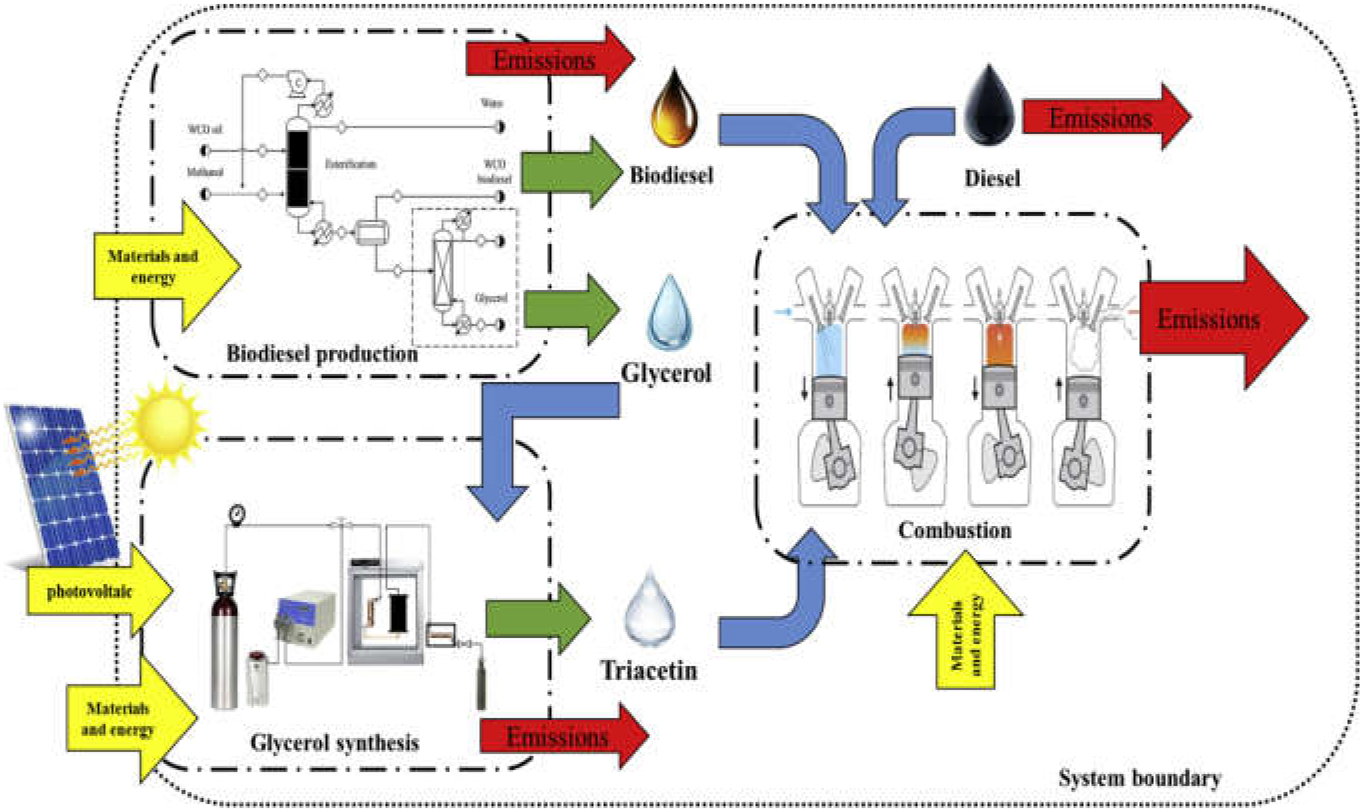

Fig. 2. System boundary including different stages of production and consumption of diesel/biodiesel/triacetin blends.

were further increased by incorporating triacetin. More specifically, the maximum density and viscosity values were recorded for B20A7 at 0.8527 kg/L and 3.358 mm^2/s, respectively. The calorific value of the fuel blends was negatively correlated with biodiesel and triacetin inclusion rates. This could be related to high structural oxygen content of the resultant blends. The lowest calorific value (41.176 MJ/kg) was recorded for B20A7.

3.2. Engine performance metrics and exhaust emissions

3.2.1. Brake specific fuel consumption (BSFC)

BSFC can be defined as the ratio of the of fuel consumption rate to the power generated. The changes in the BSFC for various fuel blends at different engine loads and speeds are presented in Fig. 3. Obviously, elevating engine load decreased BSFC for all the prepared fuels at both engine speeds. In fact, total energy release was increased with increasing engine load while the frictional loss was remained almost unchanged. Accordingly, the fraction of produced power was increased by increasing engine load, leading to comparatively lower fuel consumption (Fahd et al., 2013). Interestingly, this reduction was more marked in engine speed of 2000 rpm compared with 1500 rpm.

According to the data presented in Fig. 3, biodiesel inclusion resulted in lower BSFC at the engine speed of 1500 rpm than neat diesel likely because of oxygen content of biodiesel and, more importantly, its positive impact on obtaining a more complete combustion (Khalife et al., 2017a). However, an opposite trend was detected at the engine speed of 2000 rpm possibly due to the higher viscosity of the fuel which led to poor fuel atomization and, consequently, less efficient combustion (Gogoi et al., 2011). In addition to that, the lower calorific value of the blends containing methyl esters than neat diesel could also be considered as the reason behind the BSFC reductions observed at higher engine speeds (Lapuerta et al., 2008). Similar findings were reported in the previous studies as well (Baiju et al., 2009; Mohammadi et al., 2014, 2013). Generally, triacetin incorporation into both B5 and B20 resulted in higher BSFC values in comparison with the triacetin-free B5 and B20 blends under different engine test conditions (Fig. 3). These findings could be explained by the lower calorific value of triacetin (or in another word its higher oxygen content of 49.5%) compared with the biodiesel/diesel fuel blends (Table 3) (Casas et al., 2010; Zare et al., 2016). Moreover, the more pronounced

Table 3
The measured physicochemical properties of neat diesel, biodiesel (B5 and B20) with and without triacetin (3–7 %v/v).

	ASTM	Units	Fuel samples								
			D	B5	B5A3	B5A5	B5A7	B20	B20A3	B20A5	B20A7
Density at 15 °C	–	kg/L	0.839	0.8413	0.8417	0.8421	0.8424	0.8482	0.8501	0.851	0.8527
Kinematic Viscosity at 40 °C	D-445	mm^2/s	3.09	3.144	3.149	3.152	3.155	3.314	3.333	3.345	3.358
Calorific value	–	kJ/kg	42.57	42.304	42.268	42.245	42.221	41.506	41.364	41.270	41.176
Flash point	D-92	°C	88	91	97	94	90	98	100	97	94
Cloud point	D-2500	°C	−5	−4	+3	+1	+2	−2	0	−2	−1

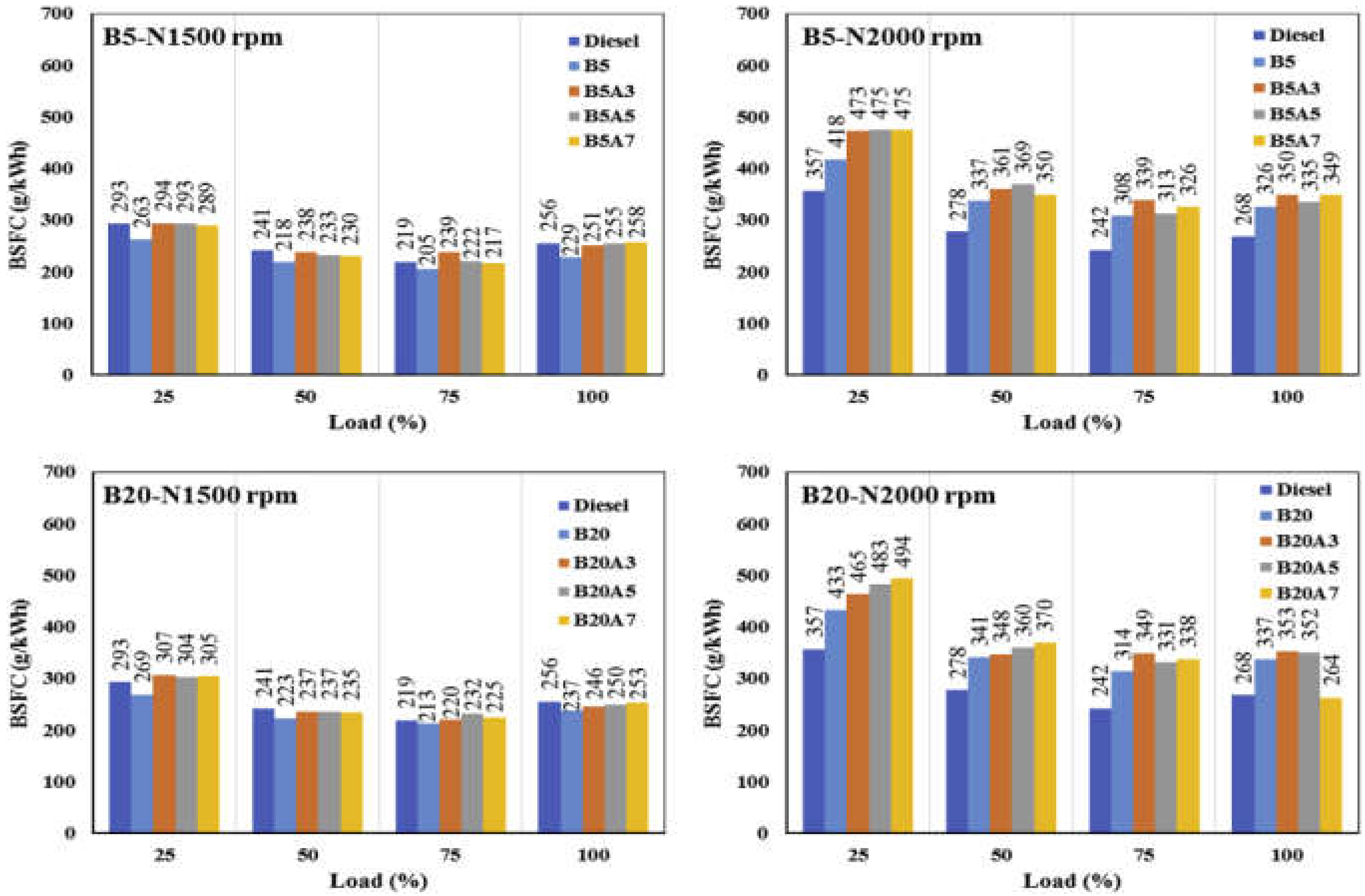

Fig. 3. Variations in the BSFC for neat diesel, biodiesel (B5 and B20) with and without triacetin (3–7 %v/v) at different engine loads and speeds.

increase in BSFC at higher engine speeds could be probably attributed to the lower volumetric efficiency and consequently, incomplete combustion at higher engine speeds (Agrell et al., 2003; Cheenkachorn et al., 2013).

3.2.2. Brake thermal efficiency (BTE)

BTE can be defined as the ratio of the brake power to the energy supplied by fuel. The variations in the BTE for various fuels at different engine loads and speeds are presented in Fig. 4. It is obvious from the figure that BTE was increased by increasing engine load. In fact, at lower engine loads, higher power would be demanded to overcome the frictional losses. However, at higher engine loads, the engine could generate more useful work against such frictional losses which in turn led to an improved efficiency (Fahd et al., 2013). As shown in Fig. 4, the combustion of B5 and B20 led to higher BTE values at the engine speed of 1500 rpm in comparison with neat diesel, while lower BTE values were recorded at the engine speed of 2000 rpm. These findings were in line with those of the other studies reported previously (Chauhan et al., 2012; Haşimoğlu et al., 2008; Kumar et al., 2013; Misra and Murthy, 2011). The positive impacts of biodiesel inclusion on BTE could be attributed to its oxygen content while on the other hand, its lower calorific value could to some extent overshadow such positive impacts (Khalife et al., 2017b; Kumar et al., 2013). Furthermore, triacetin incorporation into both low and high levels of biodiesel (B5 and B20) led to lower BTE values in comparison with those of their triacetin-free counterparts. More specifically, at the engine speed of 1500 rpm, the average changes in the BTE for low and high levels of biodiesel (B5 and B20) in response to triacetin addition stood at about −5.87% and −6.45%, respectively. Similar trend was also observed at the engine speed of 2000 rpm. Overall, it could be concluded that the addition of triacetin into both B5 and B20 in general deteriorated the BTE of the fuels prepared. This phenomenon could be attributed to the higher viscosity, higher density, and lower calorific value of the blends containing triacetin (Zare et al., 2016).

3.2.3. NO_X emissions

Fig. 5 depicts the variations in NO_X formation for various fuels at different engine loads and speeds. Similar to the findings of the majority of the reports published previously in this domain (Sayin et al., 2013; Xue et al., 2011), the addition of biodiesel into petroleum diesel proportionally increased NO_x formation. In general, NO_x formation is driven by factors such as combustion timing, ignition timing (injection timing), maximum temperature, and maximum heat release rate (Hoekman and Robbins, 2012). Therefore, apart from the oxygen content of biodiesel, its higher cetane number and the resultant higher in-cylinder temperature would also contribute to the formation of higher NO_x emissions (Can, 2014; Song and Zhang, 2008). Similar reasons could also be offered for the increasing effect of load on NO_x formation. More specifically, the overall fuel–air ratio would be augmented by increasing engine load which could in turn lead to a boost in the mean combustion chamber temperature and consequently, NO_x formation (Raheman and Ghadge, 2007).

The addition of triacetin into diesel/biodiesel blend at both low and high speeds under full load condition decreased NO_X emissions possibly owing to the quenching of the chamber temperature

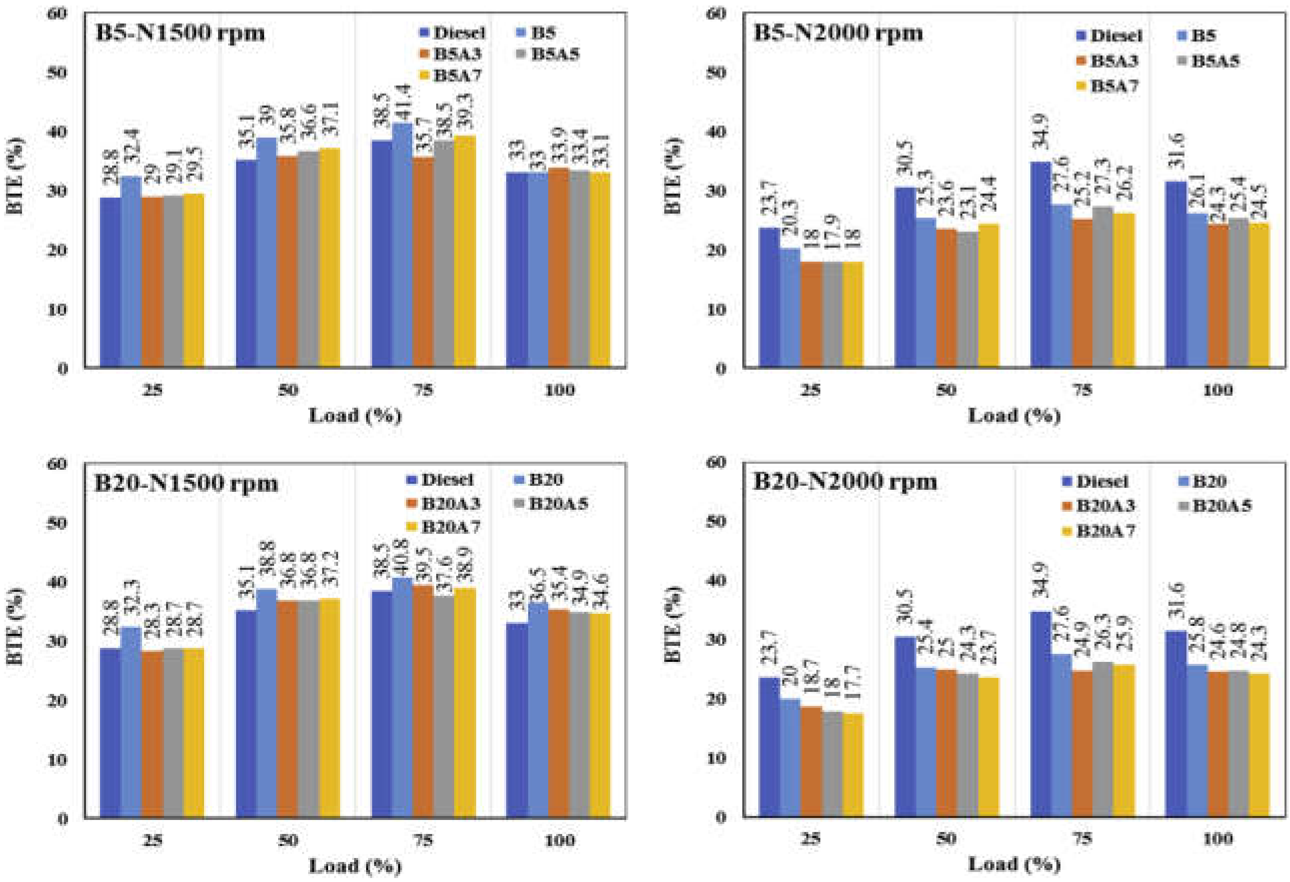

Fig. 4. Variations in the BTE for neat diesel, biodiesel (B5 and B20) with and without triacetin (3–7 %v/v) at different engine loads and speeds.

caused by the lower cetane number of triacetin, i.e., 15 (Casas et al., 2010), compared with those of diesel and biodiesel (Fig. 5). More specifically, triacetin addition must have partially decreased the cetane number of the whole fuel blends in comparison with triacetin-free fuel blends, leading to a partial increase in ignition delay (Kidoguchi et al., 2000), reducing the in-cylinder temperature, and subsequently NO_x generation. However, at high triacetin inclusion rate of 7%, its negative impact on decreasing cetane number apparently overshadowed its favorable impact on reducing combustion temperature and as a result, higher NO_x emissions were recorded. Moreover, this could also be attributed to the higher viscosity and the consequent poor atomization of diesel/biodiesel fuel blends containing high triacetin contents. Therefore, triacetin content of 5% in both B5 and B20 could be regarded as optimal inclusion rate, leading to 13.5% and 18.7% reduction in NO_x emissions, respectively. In better words, 5% triacetin was found to be efficient in compensating for the unfavorable impact of biodiesel inclusion and decreased NO_x emissions of the fuel blend to approximately the same value recorded for neat diesel. These findings were in agreement with those of the exhaust gas temperature (Fig. 6).

Higher reductions in NO_x formation were obtained at higher engine speeds in response to triacetin incorporation into both B5 and B20 blends (Fig. 5). This could also be justified by the fact that higher engine speeds could be associated with higher in-cylinder temperature. Accordingly, triacetin inclusion could to some extent discount this trend, leading to less NO_x formation as elaborated earlier. Overall, the highest mitigation in NO_x generation achieved throughout this study stood at 19.3% corresponding to the combustion of B20A5 at the engine speed of 2000 rpm under 75% of full load condition.

3.2.4. HC emissions

HC emissions is regarded as a good indicator representing combustion quality in the combustion chamber (Gogoi et al., 2011). In general, the main driver of HC emissions is poor fuel mixtures, either fuel-rich and fuel-lean mixtures (Hosseinzadeh-Bandbafha et al., 2018). Low/excessive injection pressure, non-stoichiometric air-fuel ratio, small nozzle holes, poor atomization, sac volume/hole dribble, under or over penetration, deposits on combustion chamber walls, and excessive ignition delay are among the factors presented in the published literature contributing to poor fuel mixture formation (Greeves et al., 1977; Khalife et al., 2017b). Fig. 7 presents variations in HC emissions of the fuels investigated at different engine speeds and loads. The result obtained showed that the addition of biodiesel into diesel fuel in general resulted in lower HC emissions in comparison with neat diesel, especially at lower loads. This result was in agreement with those of the previously published studies (Buyukkaya, 2010; Kim and Choi, 2010; Özener et al., 2014). The oxygen content of methyl esters and the consequent more complete combustion on one hand and its higher cetane number leading to shorter ignition delay and longer combustion duration on the other hand, could be highlighted as the factors contributing to lower HC emissions compared with neat diesel (Monyem and Van Gerpen, 2001; Som et al., 2011).

An inconsistent trend in HC emissions was observed in response to the inclusion of different concentrations of triacetin into B5 than B20. In general, the combustion of B5 containing triacetin resulted in reduced HC emissions compared with B5 and neat diesel fuel (Fig. 7). The highest triacetin inclusion rate of 7% into B20 increased

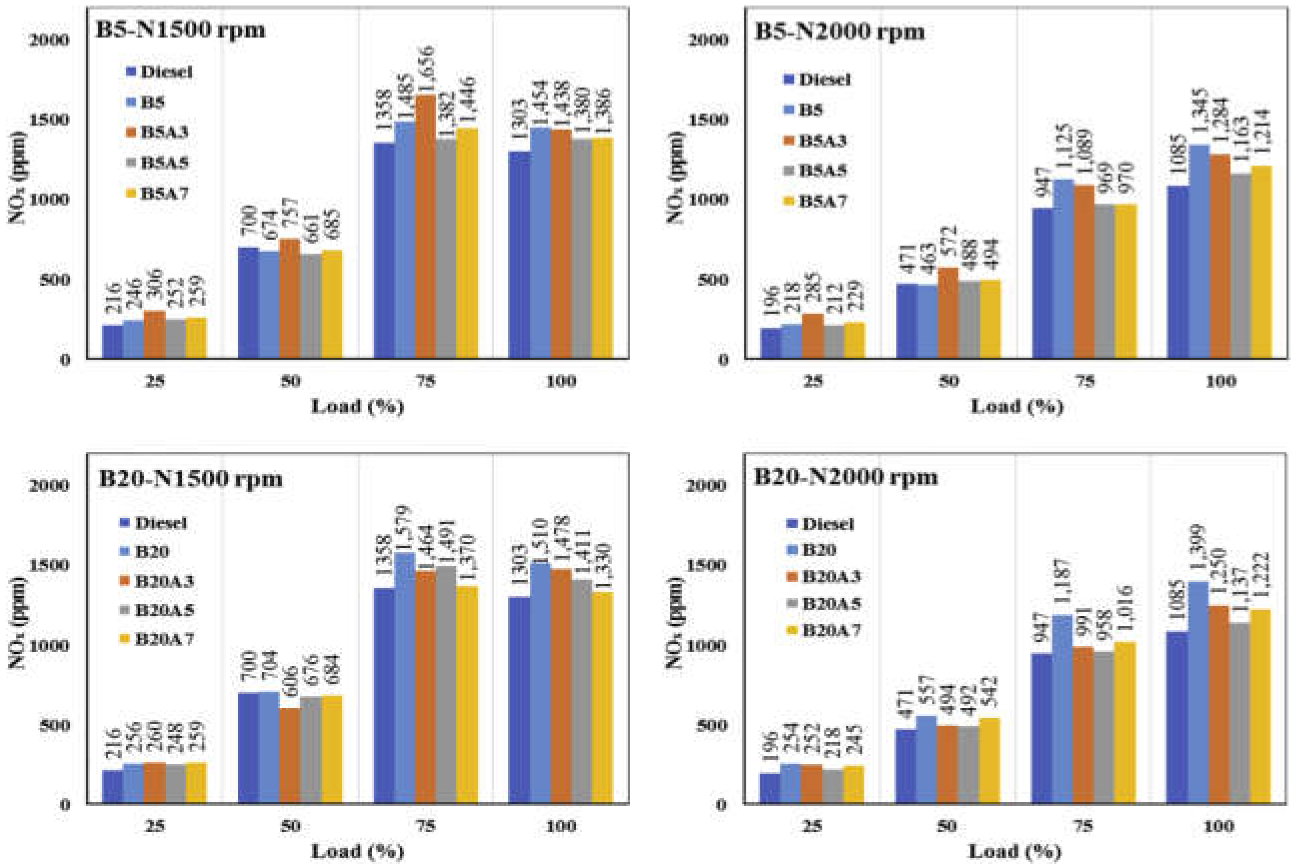

Fig. 5. Variations in NO_x formation for neat diesel, biodiesel (B5 and B20) with and without triacetin (3−7 %v/v) at different engine loads and speeds.

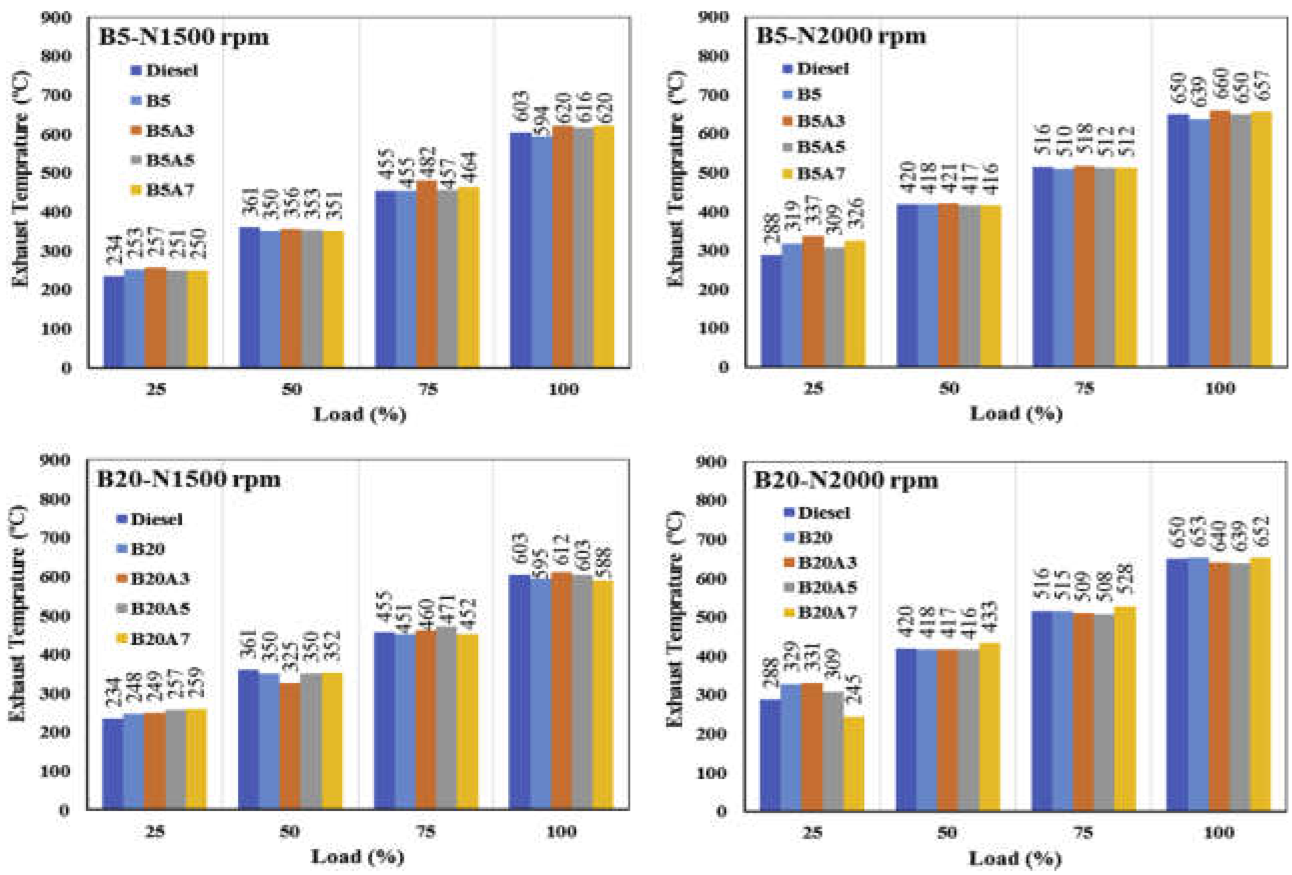

Fig. 6. Variations in exhaust combustion gas temperature for neat diesel, biodiesel (B5 and B20) with and without triacetin (3−7 %v/v) at different engine loads and speeds.

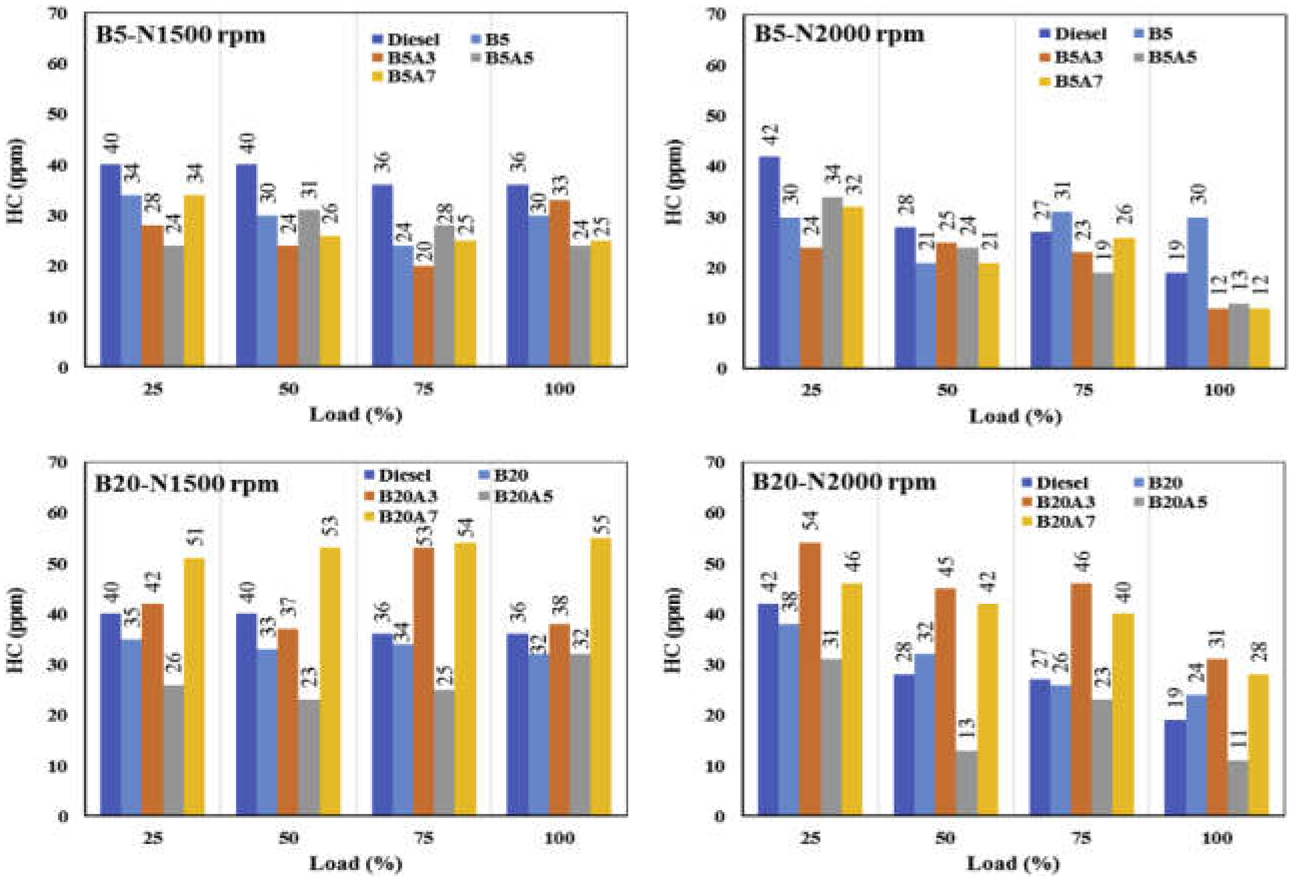

Fig. 7. Variations in HC emissions of neat diesel, biodiesel (B5 and B20) with and without triacetin (3–7 %v/v) at different engine speeds and loads.

HC emissions compared with triacetin-free B20 and neat diesel, while on the contrary, addition of 5% triacetin into B20 resulted in a steady reduction in HC emissions. This phenomenon could be explained by the fact that increasing triacetin content resulted in to increased oxygen content of the fuel blend which could have in turn led a more complete combustion and lower HC emissions. However, higher triacetin concentrations must have increased the viscosity of the fuel blend (Table 3), negatively affecting fuel atomization. In addition, high triacetin inclusion rate lowered cetane number of the blend, negatively influencing the combustion process. The latter could increase ignition delay and subsequently deteriorate the combustion quality, i.e., higher emissions of unburned HC. As presented in Fig. 7, addition of 5% triacetin into both B5 and B20 in general led to considerable HC emissions reductions. More specifically, combusting B5A5 led to approximately 31% and 56% reduction in HC emissions at engine speed of 2000 rpm under full load condition compared with neat diesel and B5, respectively. While combusting B20A5 resulted in 42% and 54% reduction in HC emissions under the same engine operating conditions.

3.2.5. CO_2 emissions

Fig. 8 manifests the changes recorded in CO_2 emissions during the combustion of the studied diesel/biodiesel blends containing various amounts of triacetin. CO_2 emissions in the exhaust gas were increased for all the fuel samples studied as engine load increased. Moreover, the inclusion of biodiesel resulted in minor changes in CO_2 emissions in comparison with neat diesel. Inclusion of triacetin into diesel/biodiesel blends resulted in slight increases in CO_2 emissions over their additive-free counterparts. Similar trends were also reported by Rao and Rao (2011) who also investigated the combustion of neat biodiesel containing triacetin.

3.2.6. PM emissions

Diesel engines are considered as major sources of particulate emissions (Rizwanul Fattah et al., 2013). Particulate matters (PM) are air-suspended particles including solid and liquid materials that differ in size, mass, shape, origin, chemical composition, solubility, and other physicochemical properties (Rizwanul Fattah et al., 2013; Sakurai et al., 2003). Fig. 9 exhibits the changes measured in PM emissions of the investigated fuels under different engine test conditions. Based on the result obtained, PM release was increased by increasing engine load and engine speed possibly due to the insufficient oxygen available during combustion (Khalife et al., 2017b). Incorporating biodiesel into petro-diesel generally decreased PM emissions compared with neat diesel through providing excess oxygen. More specifically, the combustion of B5 and B20 reduced PM emissions by 35% and 30% under full load condition compared with neat diesel, respectively. Improving combustion quality due to the oxygen content of methyl esters and consequent reductions in PM emissions have also been frequently reported by previous studies (Ashraful et al., 2014; Paul et al., 2014; Shahir et al., 2015).

Incorporating triacetin into both B5 and B20 led in general to favorable variations in PM emissions at high engine speed under all engine loads except full load. Moreover, these reductions were more pronounced for B20 than B5 fuel, attributing to its higher biodiesel content (Demirbas, 2007; Khalife et al., 2017b; Rashedul et al., 2014; Shi et al., 2006). The result obtained showed that

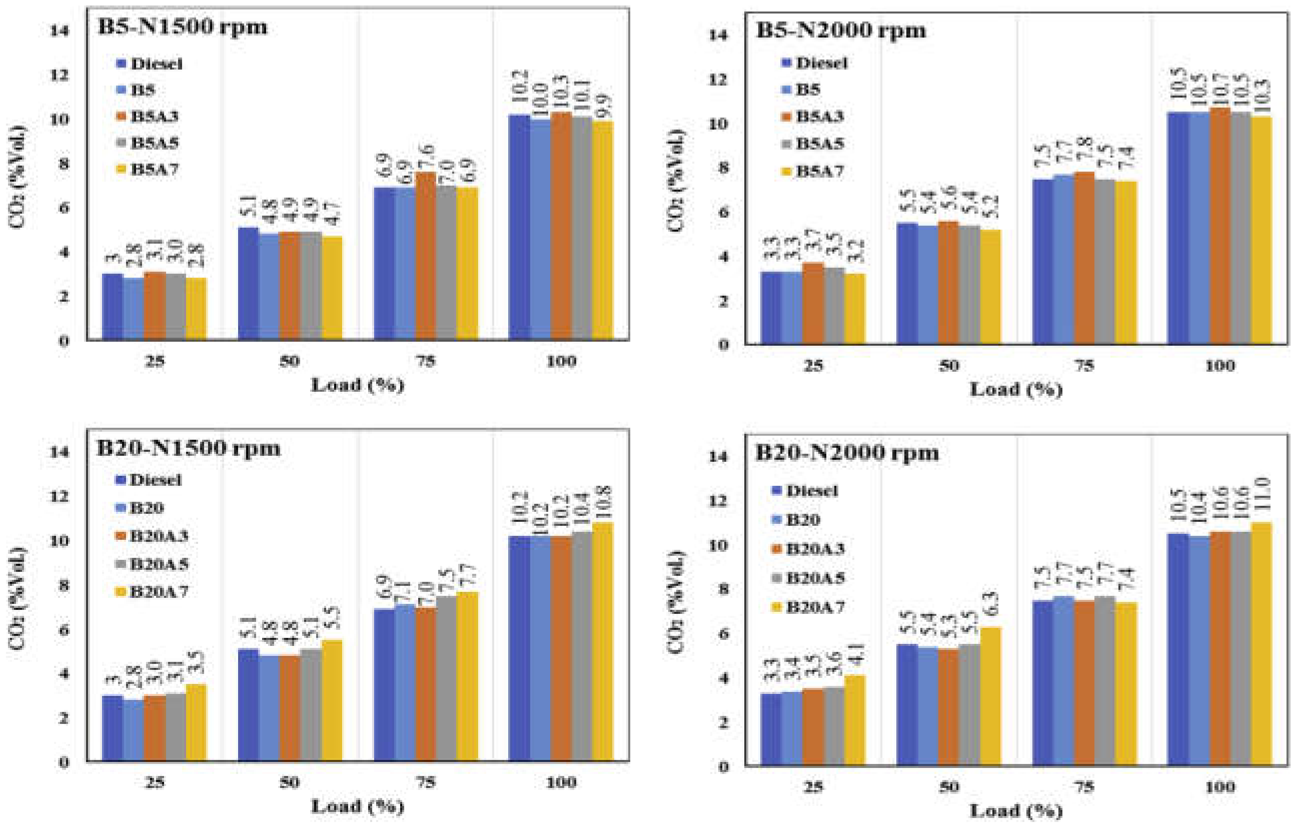

Fig. 8. Variations recorded in CO_2 emissions during the combustion of neat diesel, biodiesel (B5 and B20) with and without triacetin (3–7 %v/v) at different engine speeds and loads.

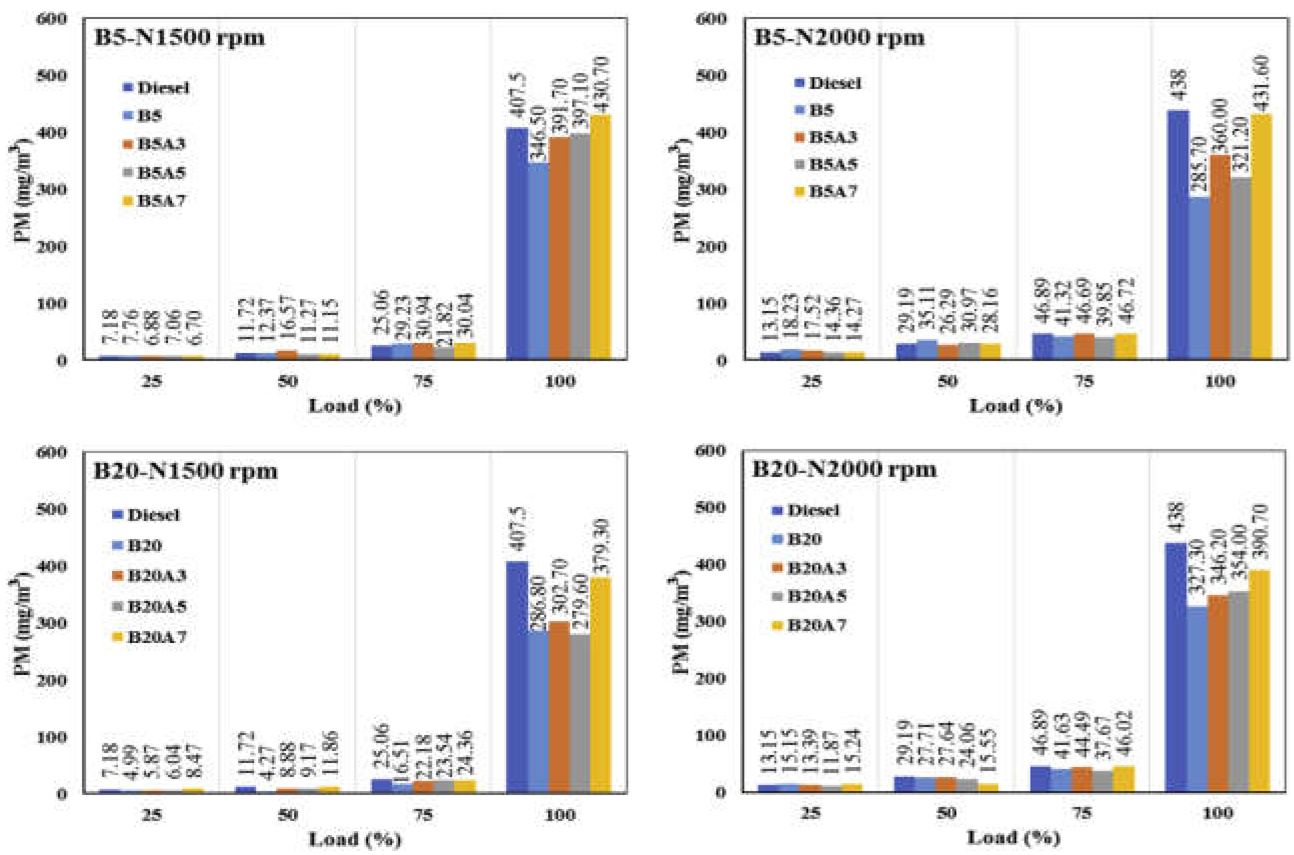

Fig. 9. Variations measured in PM emissions of neat diesel, biodiesel (B5 and B20) with and without triacetin (3–7 %v/v) under different engine test conditions.

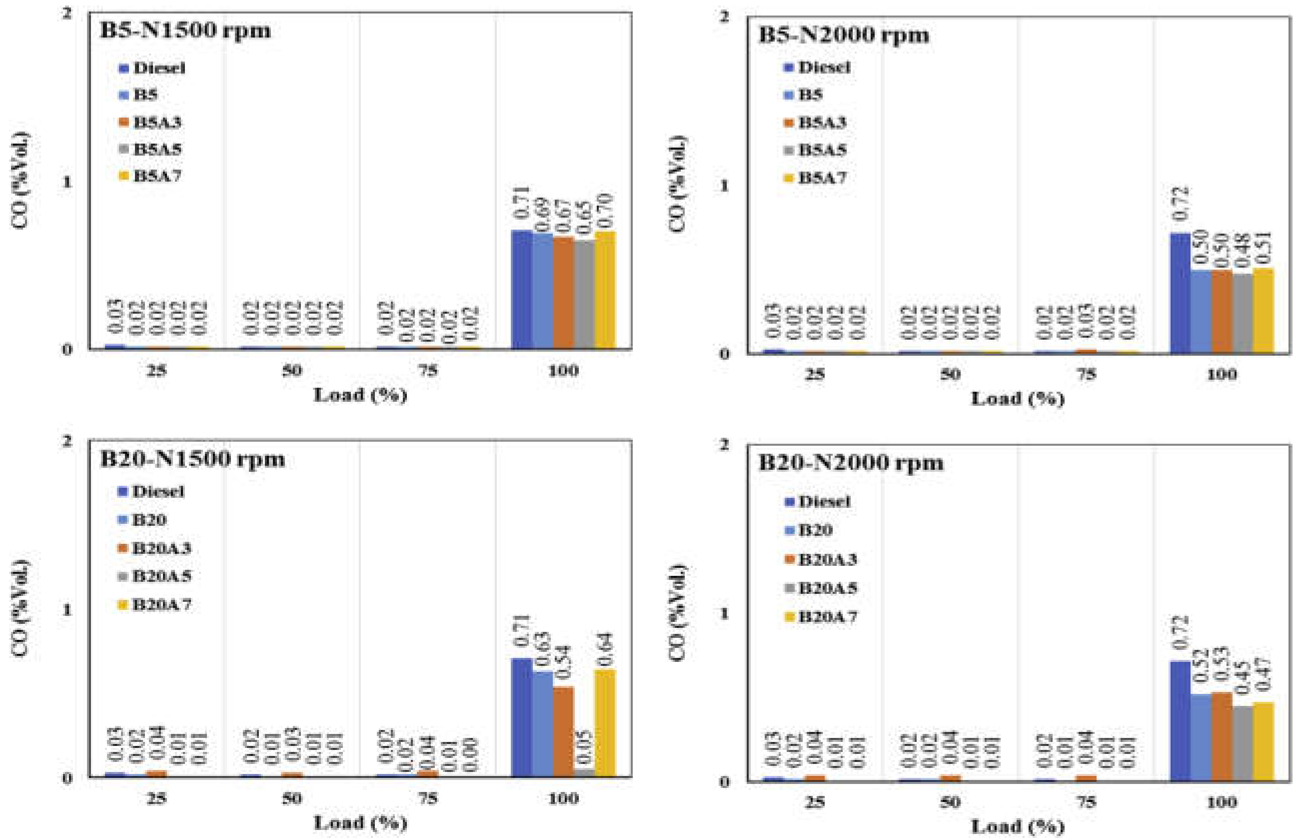

Fig. 10. The effect of different levels of triacetin (3–7 %v/v) inclusion into biodiesel blends (B5 and B20) on the CO emissions under different engine conditions.

Table 4
Values of the environmental impact of production per kg biodiesel (B100) and triacetin.

Damage category	Unit	Biodiesel production (kg)	Triacetin production (kg)
Human health	DALY	6.91×10^{-7}	3.27×10^{-6}
Ecosystem quality	PDF*m^2*yr	9.03×10^{-2}	2.54×10^{-1}
Climate change	kg CO_2 eq.	8.43×10^{-1}	2.51
Resources	MJ primary	17.0	81.7

although maximum PM emissions reduction was measured for B20A7 by 48% and 43% (at engine speed of 2000 rpm under 50% of full load condition) compared with neat diesel and B20, respectively, triacetin inclusion rate of 5% resulted in a more stable reduction in PM emissions (except at 100% engine load). More specifically, addition of 5% triacetin into B5 reduced PM emissions at all engine tests except under full load condition. The maximum decrement in PM release was measured at engine speed of 1500 rpm under 75% of full load condition by 13% and 25% compared with neat diesel and B5, respectively. These mitigations in PM emissions observed throughout this study were in agreement with the results observed by Rao and Rao (2012). They also studied the inclusion of triacetin into neat biodiesel and argued that the reductions observed in PM emissions could be owing to the lower carbon molecules of the fuels. On the contrary, under full load condition in the present study, unfavorable changes in PM emissions were observed when combusting both B5 and B20 fuel blends containing various concentrations of triacetin (Fig. 9). This phenomenon could be related to the higher viscosity of the fuel blends as a result of the additives inclusion, leading to poor atomization of the sprayed fuel and consequently, deteriorated quality of the combustion process.

3.2.7. CO emissions

Low oxygen concentration, low reaction temperature, and short reaction time as the major reasons leading to the formation of CO; the main intermediate product of the combustion process (Li et al., 2014). In fact, under optimal combustion conditions like temperature, this intermediate species would be converted into CO_2 and *vice versa* (Khalife et al., 2017b). Fig. 10 shows the effect of triacetin inclusion into biodiesel blends (B5 and B20) on the CO emissions under different engine conditions. Accordingly, it could be concluded that at both engine speeds under full load condition, biodiesel inclusion improved the combustion process by providing an extra oxygen molecules, leading to lower CO formation (Raheman and Ghadge, 2007). Triacetin inclusion further decreased CO emissions possibly owing to its oxygenated nature. For instance, approximately 4% and 14% reductions in CO emissions was observed at 5% inclusion rate of triacetin in B5 and B20, respectively.

3.2.8. LCA results

In the present study, the environmental impacts associated with the production of neat biodiesel and triacetin were first calculated through their life cycle (cradle to the gate) in four categories, i.e.,

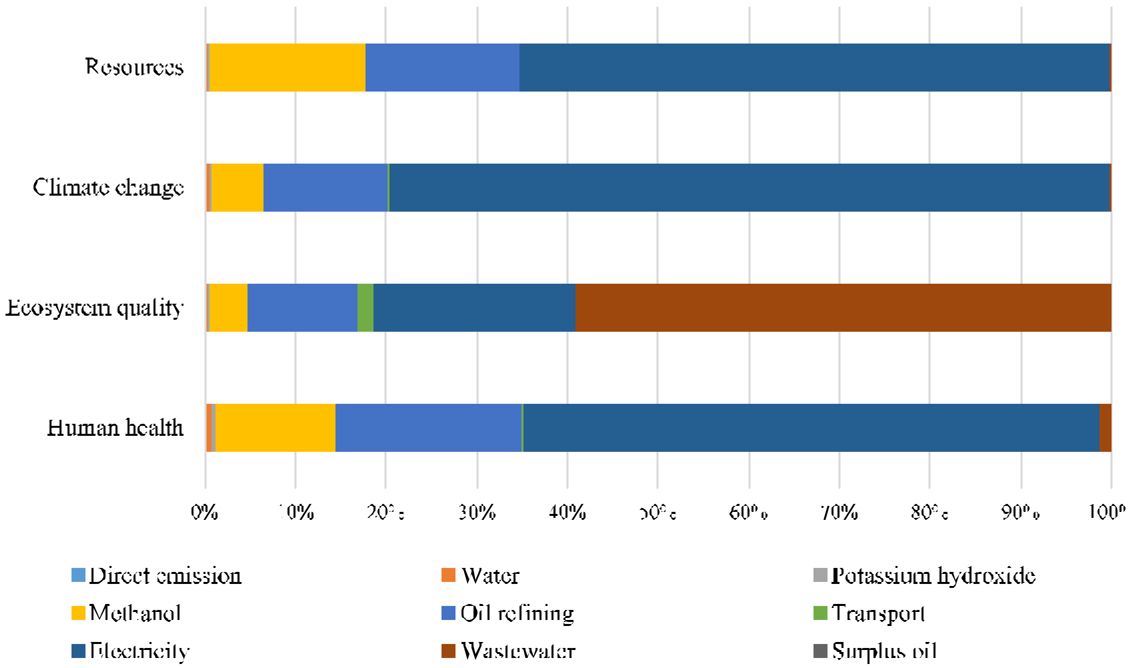

Fig. 11. The contribution of the different input/output parameters to the environmental impact categories throughout the WCO biodiesel production (transesterification).

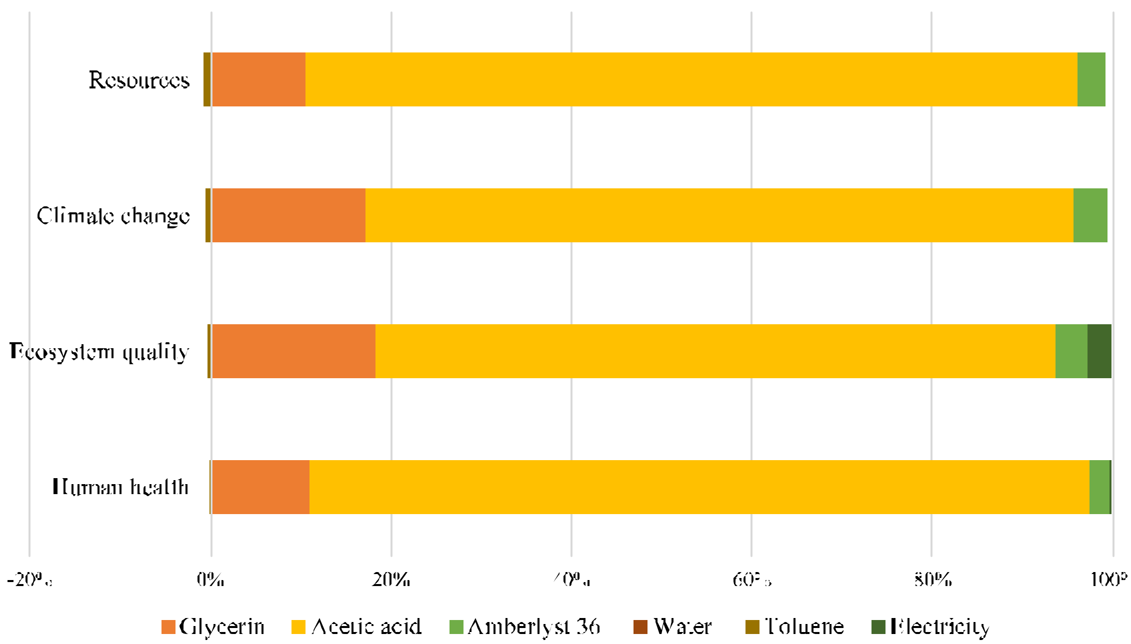

Fig. 12. The contribution of the different input/output parameters to the environmental impact categories throughout the triacetin production.

human health, ecosystem quality, climate change, and recourse damage categories (Table 4).

In biodiesel production (transesterification), biodiesel and glycerol are considered as the main product and co-product of the process, respectively. Therefore, due to the production of more than one item by this system, it would be necessary to allocate the environmental impacts to these items separately. Allocation is in fact one of the long-standing methodological issues in LCA of multi-products systems (Suh et al., 2010). In this study, the allocation between biodiesel and glycerol was calculated using the mass allocation method. Since the mass of biodiesel was about 90% of the total mass produced in the transesterification phase, 90% of the environmental impacts was also allocated to biodiesel and the remaining 10% was allocated to glycerol (glycerol was considered as a product with commercial value).

Figs. 11 and 12 show the relative contributions of all the inputs and processes to the environmental impacts attributed to neat biodiesel and triacetin production, respectively. As seen in Fig. 11,

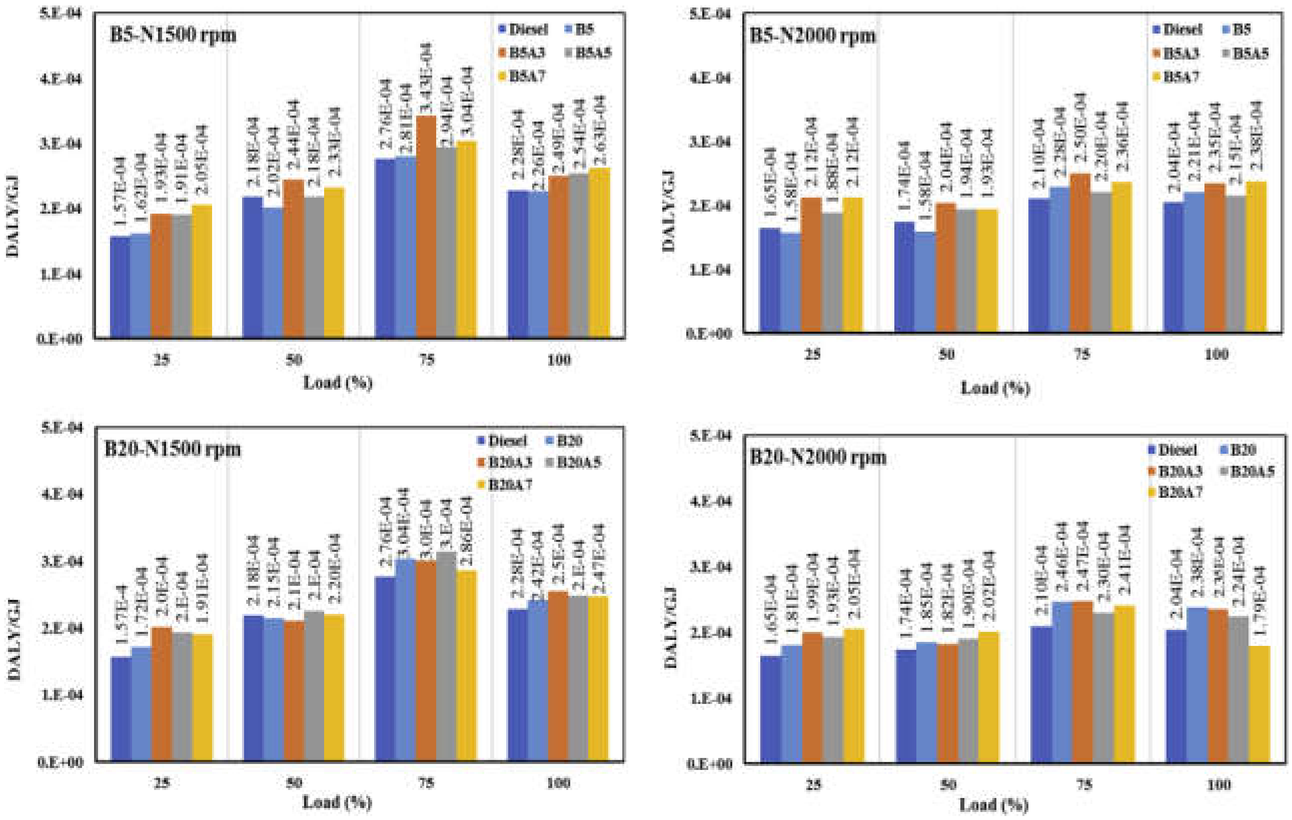

Fig. 13. The effect of the inclusion of different levels of triacetin (3–7 %v/v) into B5 and B20 on the human health damage category under different engine conditions.

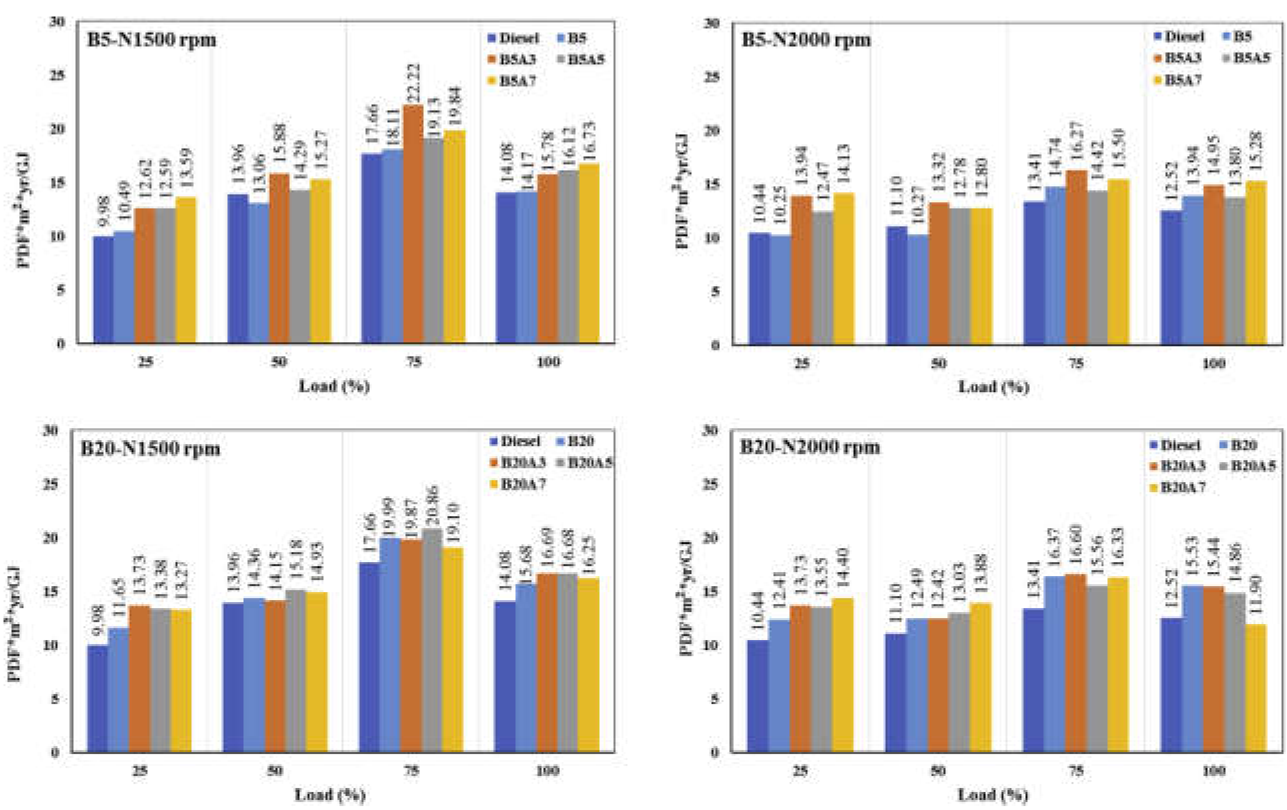

Fig. 14. The effect of the inclusion of different levels of triacetin (3–7 %v/v) into B5 and B20 on the ecosystem quality damage category under different engine conditions.

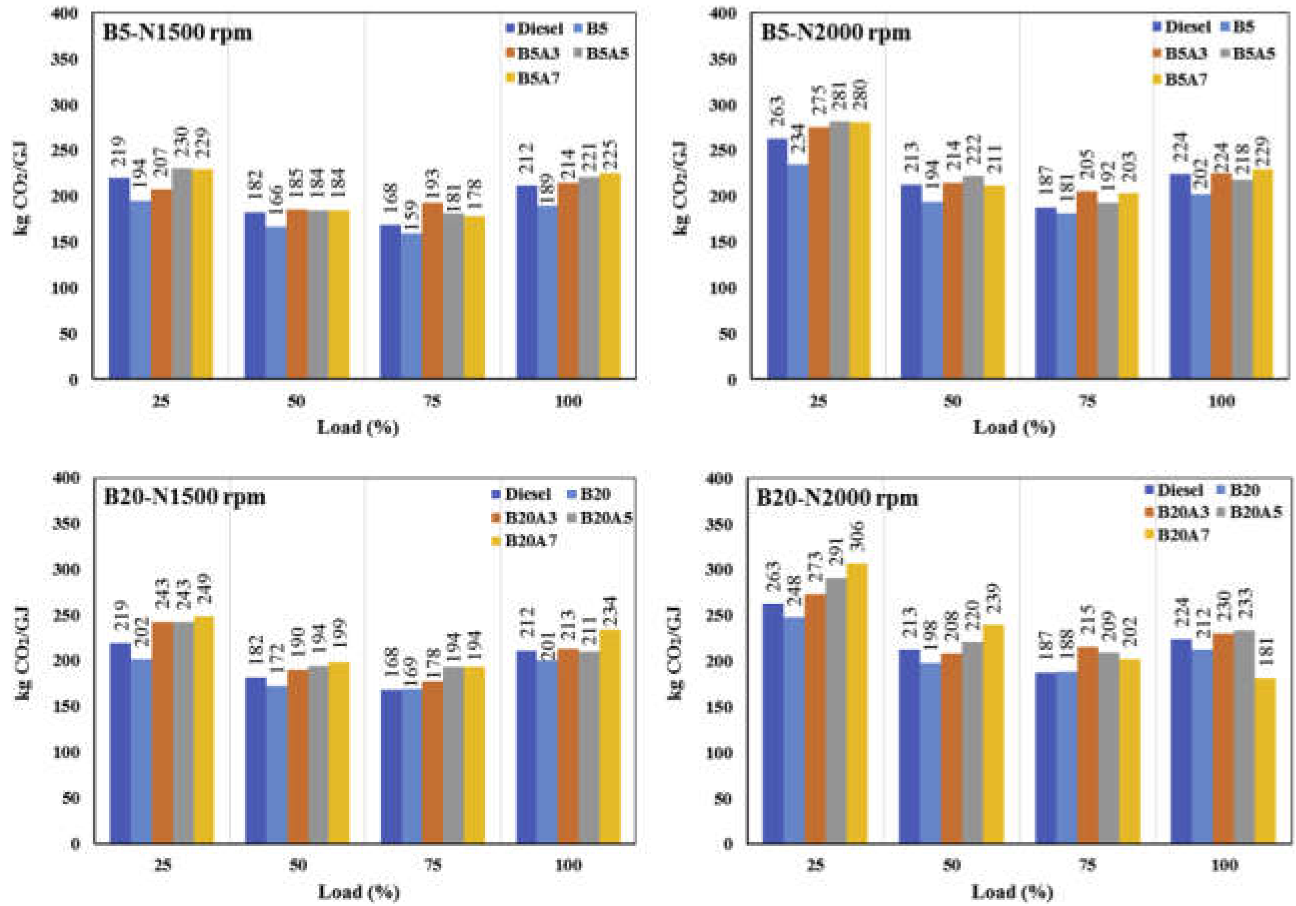

Fig. 15. The effect of the inclusion of different levels of triacetin (3–7 %v/v) into B5 and B20 on the climate change damage category under different engine conditions.

the consumption of electricity in the transesterification step had the most important contribution to the human health damage category. More specifically, WCO biodiesel production led to 6.91×10^{-7} DALY/kg of human health damage category, out of which, about 80% was related to the consumption of electricity in the transesterification step. The main reason to this observation was the release of SO_x due to the production of electricity in power plants. Following SO_x, hydrocarbon aromatics, particulates <2.5 μm, and NO_x played major roles in the human health damage category for WCO biodiesel production due to the production of electricity in the fossil-fueled power plants. In addition, in the resource damage category, the electricity consumed in the transesterification step had the main role because of the use of natural gas and crude oil for electricity production in the conventional power plants. Electricity consumption in the transesterification step also had the largest share in the climate change damage category due to GHG emissions of fossil power plants. Therefore, managing electricity consumption in the WCO biodiesel production plant, as well as changing the type of fuel used for electricity generation, could be effective strategies in improving the environmental impacts and sustainability features of WCO biodiesel. Moreover, WCO biodiesel production led to 9.03×10^{-2} PDF*m^{2*} yr/kg of damage to the ecosystem out of which 5.83×10^{-2} PDF*m^{2*} yr/kg (about 60%) was attributed to the wastewater generated through the transesterification process. On that basis, wastewater recovery in the transesterification step could reduce the environmental burden imposed on the ecosystem quality damage category.

Similarly in the triacetin production, electricity consumption was a very major factor deteriorating the environmental aspects of the process. This would be worsened because of the very low rate of triacetin production reaction (0.15 g/min). To avoid this and to further enhance the sustainability features of this product, photovoltaic electricity was considered for triacetin synthesis. It should be noted that electricity generation from fossil-oriented resources is a key contributor to global emissions of GHG, NO_x, and SO_x and their related environmental impacts (Turconi et al., 2013). On the contrary, according to Hosenuzzaman et al. (2015), photovoltaic power generation could reduce CO_2, NO_x, and SO_x emissions substantially. For instance, it has been reported that photovoltaic systems could save 0.53 kg CO_2 emissions for every kWh of electricity generated (Cheng et al., 2008)). According to the findings presented in Fig. 12, the net consumption of acetic acid and glycerol (i.e., excluding the acetic acid and glycerol recovered) were the main factors in causing the environmental impacts associated with triacetin synthesis.

In the second part of the analysis, the environmental impacts of the mechanical shaft power produced through the combustion of the prepared diesel/biodiesel/triacetin blends were investigated through four damage categories on the basis of IMPACT 2002+. These damage categories included "carcinogenic (kg $_{eq.}$ chloroethylene into air)", "non-carcinogenic (kg $_{eq.}$ chloroethylene into air)", "respiratory organic (kg $_{eq.}$ PM2.5 into air)", "respiratory inorganic (kg $_{eq.}$ ethylene into air)", "ionizing radiation (Bq $_{eq.}$

carbon-14 into air)", and "ozone layer depletion (kg $_{eq}$ CFC-11 into air)" (Maham et al., 2018). Fig. 13 reveals the effect of triacetin incorporation into both B5 and B20 on the human health damage category under different engine test conditions. NO_x emissions, markedly affecting the respiratory inorganic, is one of the midpoints in human health damage category (Mezzullo et al., 2013). Accordingly, it would be expected that triacetin incorporation into both B5 and B20, owing to its favorable impacts on NO_x emissions, would mitigate this damage category. However, the combustion of B5 and B20 containing triacetin did not lead to lower human health damage because of increasing BSFC as a result of triacetin inclusion. As mentioned earlier, the addition of triacetin into both B5 and B20 in general resulted in higher BSFC values compared with the control blends under different engine test conditions. Increasing BSFC increased the fuel consumption rate for the production of 1 GJ shaft work which in turn heightened the human health damage category. In addition to NO_x emissions, CO emissions as well as particulates (soot) formation were adversely affected the human health damage category. As a result, it could be expected that because of decreasing these emissions through triacetin addition, the above-mentioned adverse effects on the human health damage category could be reduced. However, similar to the NO_x emissions, the increase caused in BSFC in response to triacetin addition trivialized its positive effects on the human health damage category by reducing CO emissions and particulates (soot) formation.

In IMPACT 2002+, ecosystem quality damage category consists of four midpoints *viz*. "aquatic ecotoxicity (kg $_{eq}$ triethylene glycol into water)", "terrestrial ecotoxicity (kg $_{eq}$ triethylene glycol into soil)", "terrestrial acid/nutr (kg $_{eq}$ SO_2 into air)", and "land occupation (m^2 $_{eq}$ org. arable)". These midpoints take into consideration the level of disruption in ecosystems on the basis of PDF*m^{2*} yr (Maham et al., 2018). The effect of triacetin incorporation into B5 and B20 on the ecosystem quality damage category under different engine conditions is illustrated in Fig. 14. Analogous to the human health category, NO_x emissions was the main pollutant influencing terrestrial acid/nutr impact category and subsequently, ecosystem quality damage category. Despite the fact that biodiesel/triacetin incorporation into diesel reduced NO_x emissions, their application negatively lowered BTE by increasing BSFC. These in turn collectively increased ecosystem quality damage category.

Fig. 15 indicates the influence of triacetin addition into B5 and B20 on the climate change damage category under different engine conditions. It is obvious from the figure that both B5 and B20 had lower negative effects on the climate change damage category than neat diesel. In general, CO_2 emissions is the main factor affecting this damage category (Borsato et al., 2018; Cellura et al., 2018). Accordingly, both B5 and B20 having lower CO_2 emissions in comparison with neat diesel had lower climate change damage compared with petro-diesel. Indeed, biodiesel incorporation into petrodiesel improved the combustion process as a result of its higher oxygen content. Similarly, Rajaeifar et al. (2017a) compared diesel/biodiesel blends with neat diesel from the LCA perspective. They found that diesel fuel had higher unfavorable effects on the global warming impact category compared with diesel/biodiesel blends. In addition, Xue et al. (2012), Sheehan et al. (1998), and Nanaki and Koroneos (2012) also reported a direct association between biodiesel inclusion rate and mitigation of global warming

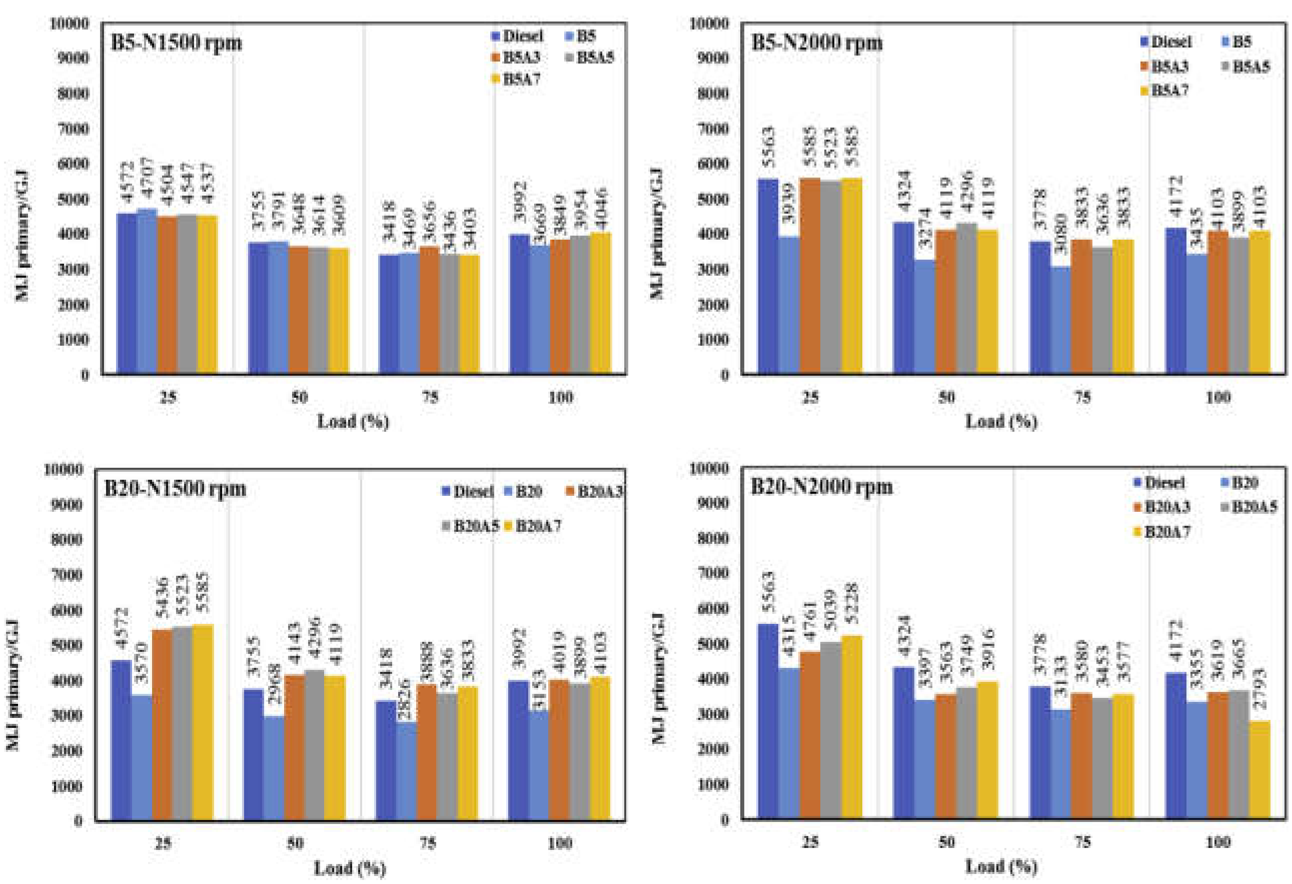

Fig. 16. The effect of the inclusion of different levels of triacetin (3–7 %v/v) into B5 and B20 on the resources damage category under different engine conditions.

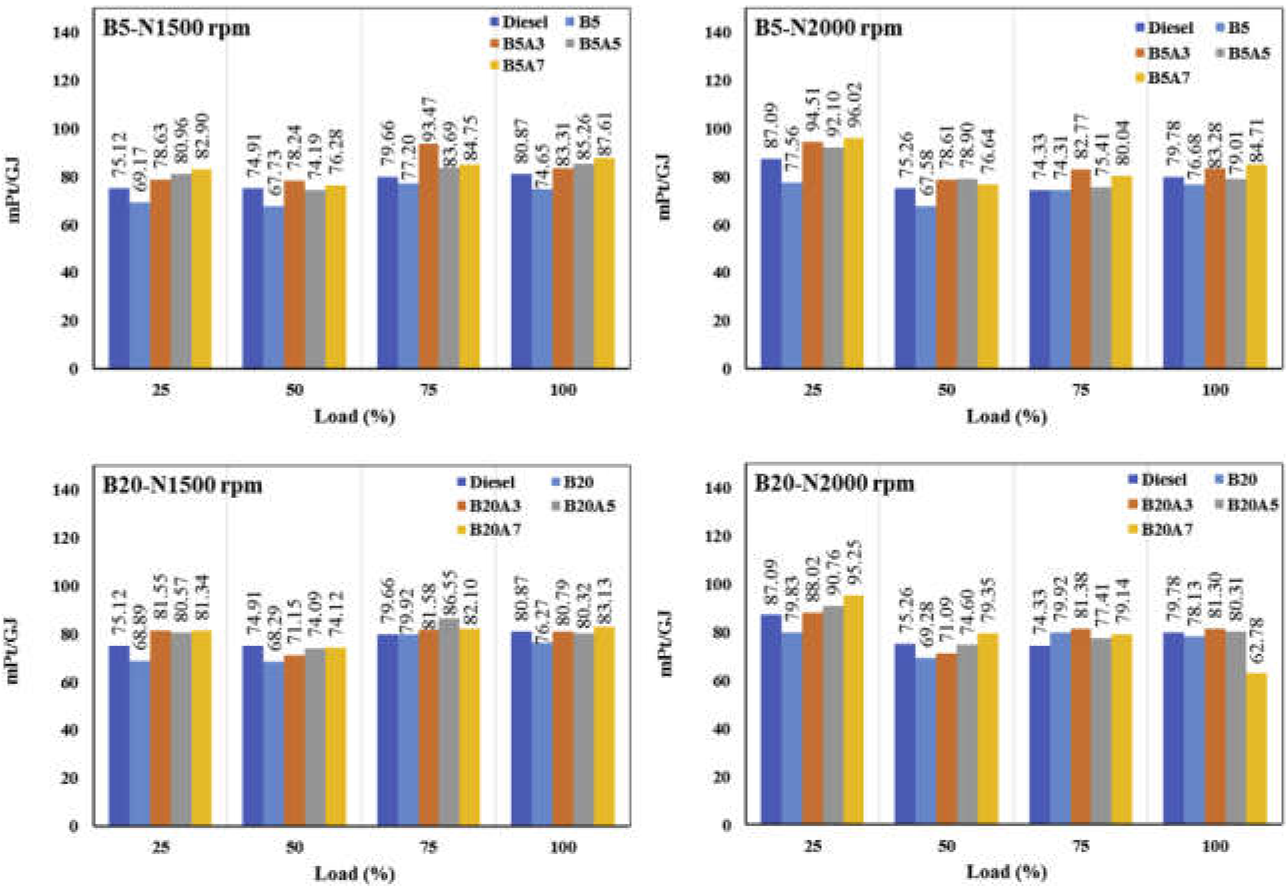

Fig. 17. The effect of the inclusion of different levels of triacetin (3–7 %v/v) into B5 and B20 on the total environmental impacts under different engine conditions.

potential. Furthermore, triacetin inclusion into both B5 and B20 in general released more CO_2 when compared with neat diesel. Interestingly, increasing triacetin inclusion rate increased CO_2 emissions. This could be explained by the fact that increasing triacetin content unfavorably increased BSFC, thereby increasing the rate of fuel consumption for production of 1 GJ shaft work.

Fig. 16 presents the effect of triacetin inclusion into B5 and B20 on the resources depletion category at different engine speeds and loads. Resources depletion category refers to primary energy consumption in a given activity or production process. This environmental impact indicator includes two midpoints, i.e., "non-renewable energy consumption (MJ total primary non-renewable energy or kg $_{eq}$ crude oil (860kg/m^3))" and "mineral extraction (MJ additional or surplus energy or kg $_{eq}$ iron (in ore))" (Maham et al., 2018). Overall, biodiesel/triacetin incorporation into petrodiesel slightly decreased this damage category. This could be attributed to the fact that biodiesel/triacetin application abated diesel fuel consumption and subsequently, mitigated non-renewable energy consumption. According to Cornelissen and Hirs (2002), the depletion of natural resources is probably the main difference between renewable and non-renewable resources. It should also be noted that increasing BSFC as a result of biodiesel/triacetin inclusion depredated their positive effects on the non-renewable energy consumption to a large extent.

The effect of triacetin inclusion into B5 and B20 on the total environmental impacts under different engine conditions is exhibited in Fig. 17. This index consolidates all human health, ecosystem quality, climate change, and resource damage categories into a single score through weighting process, thereby facilitating decision-making.

Weighting could be in fact advantageous by presenting the LCA results as a single score, which could in turn allow easy comparisons of the environmental impacts attributed with different products. Such findings could facilitate decision making by immediately revealing the comparative impacts of different products/processes (ISO, 2006). In light of that, weighting was also used herein to provide an objective indicator for selecting the most environmentally favorable diesel/biodiesel blends at different engine loads and speeds.

The weighting results are presented in Fig. 17, based on which, B20A7 at full load and engine speed of 2000 rpm resulted in the lowest level of environmentally harmful effects. While opposite observations were made at low load of engine operation (Fig. 17). More specifically, the results showed that in general, increasing engine speed could lead to increased total environmental impacts at low load. Moreover, increasing the proportion of biodiesel in the fuel blends containing triacetin resulted in reductions in the total environmental impacts of the fuels (Fig. 17).

The sensitivity analysis is presented in Fig. 18. As could be observed, the vertical line in the graphs represents the mean environmental impacts of each damage category. Deviations from the vertical line show how a damage category would vary by 10% increase or 10% decrease in the mean value of each parameter. Accordingly, the human health, ecosystem quality, and climate change damage categories were mainly affected by the exhaust emissions gasses, while the resource damage category was mainly

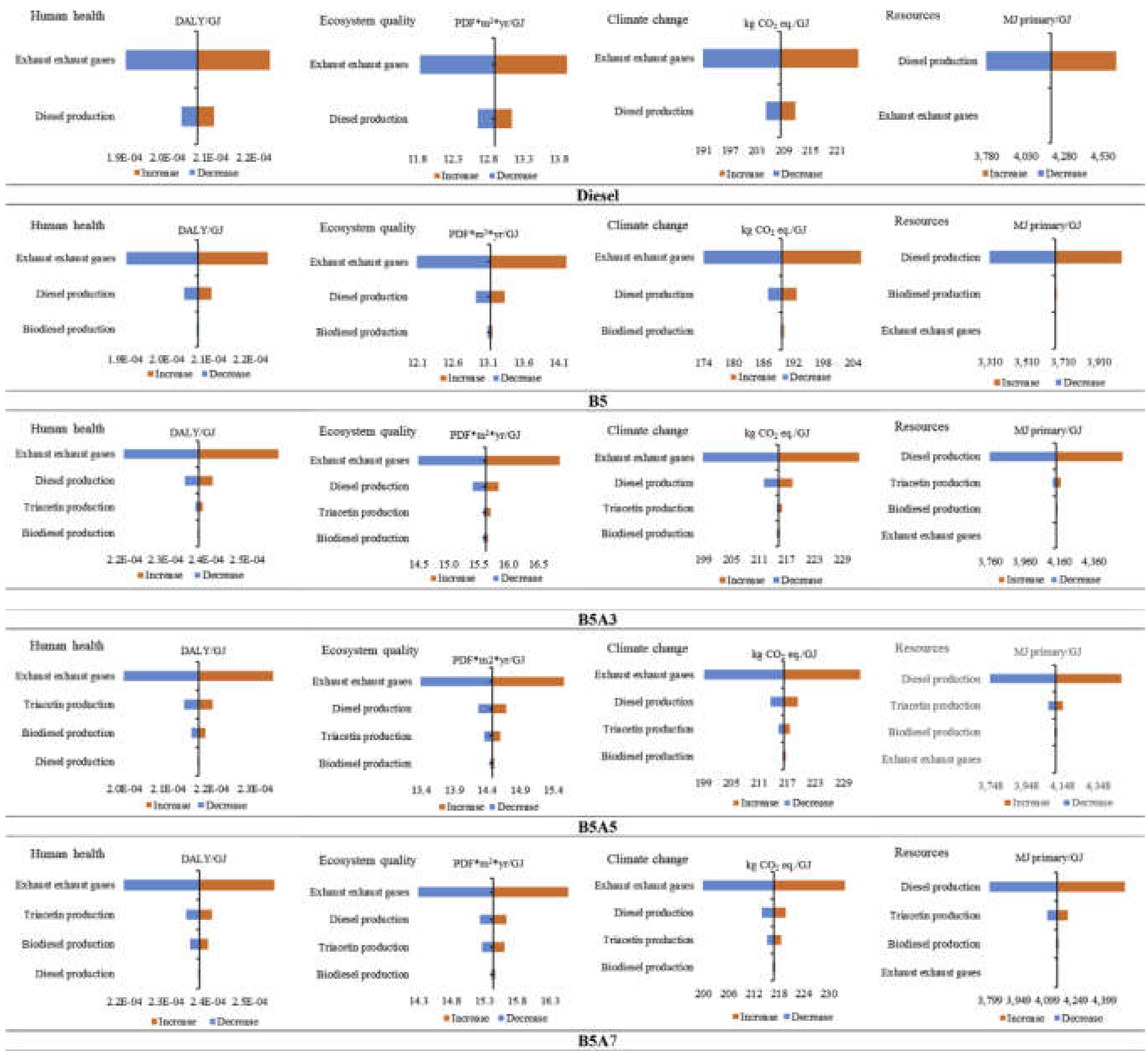

Fig. 18. Sensitivity analysis of the different damage categories related to neat diesel, biodiesel (B5 and B20) with and without triacetin (3–7 %v/v) for the input and output parameters of the diesel engine.

affected by diesel production. Considering the results of the sensitivity analysis, as the first step, the focus should be to reduce the exhaust emissions gasses by implementing different strategies. For instance, since there is a coloration between injection timing and exhaust emissions gasses (Agarwal et al., 2013), proper injection timing settings could be effective in reducing exhaust emissions gasses and consequently, the above mentioned damage categories. On the other hand, since diesel was a very effective parameter on the resource damage category, reducing diesel proportion in the fuel blends by increasing that of biodiesel could contribute to reduced burdens on the resource damage category.

Table 5 presents the results of the uncertainty analysis. The 95% confidence interval reveals that for the 95% of the cases, the results of the damage categories for each GJ shaft power generated would fall within the range (L, U). Moreover, based on the normalized standard distribution, for 1 GJ shaft power generated, the uncertainty percentages of different damage categories range between 9.11% and 20.38% for different fuel types.

Overall, it could can be concluded that triacetin inclusion into B5 and B20 did not lead to a positive outcome in terms of total environmental impacts owing to an increase in BSFC as a result of triacetin incorporation into B5 and B20 blends. Overall, triacetin inclusion into diesel/biodiesel blends does not appear to be an environmentally sound strategy considering the current production technology. For reducing the environmental impacts associated with triacetin production, it could be recommended to employ

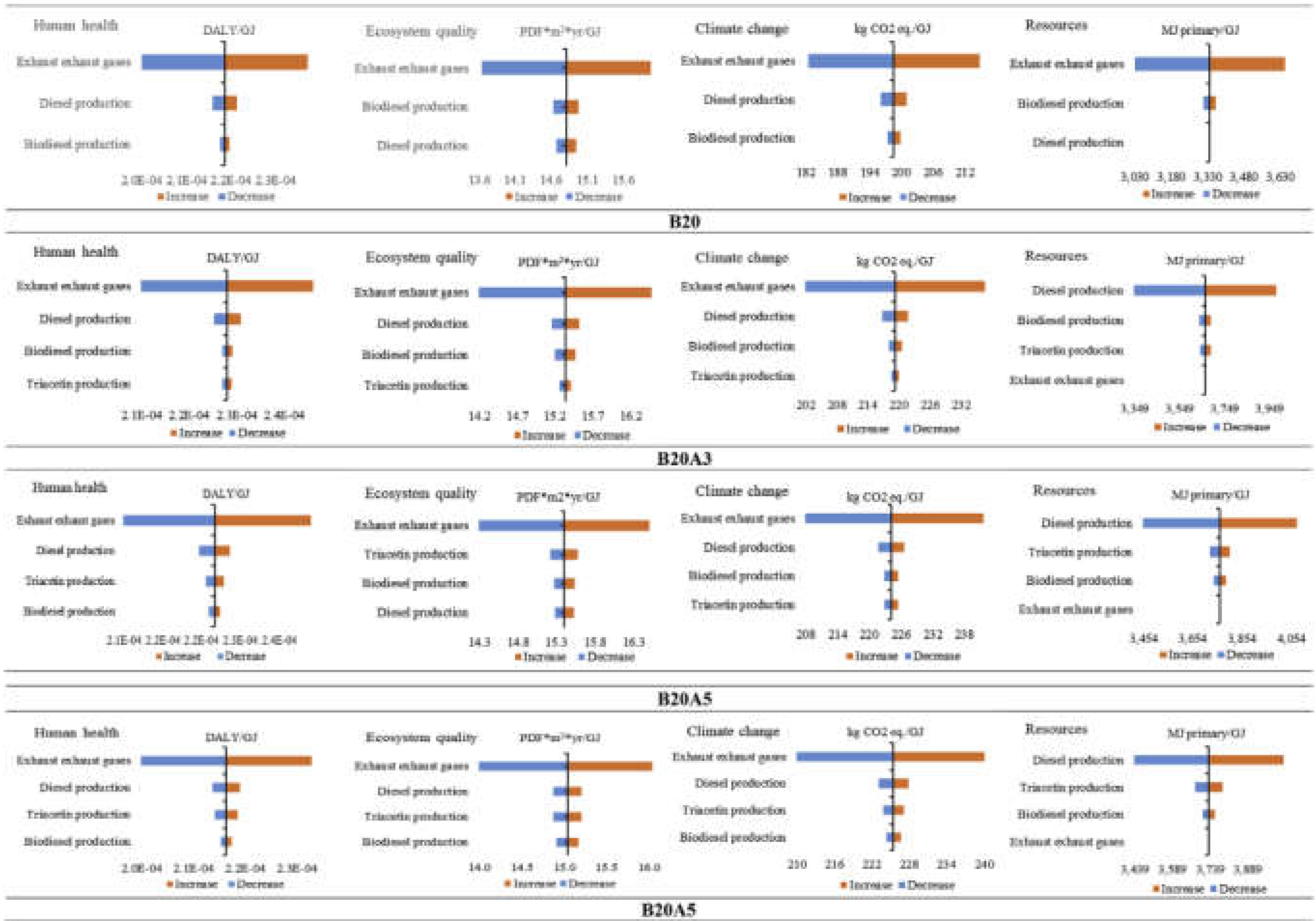

Fig. 18. (*continued*).

methods and technologies capable of further increasing the production speed *vs.* the current production speed of 0.15 g/min., leading to less electricity consumption. In addition, it would be advisable to reduce the environmental impact of biodiesel production at different stages of production. For example, the use of more sustainable energy carriers such as photovoltaic systems in different processes, i.e., oil extraction/purification and transesterification, would result in improvements in the environmental effects attributed to biodiesel production. Another solution would be the implementation of efficient technologies for treating the wastewater produced during biodiesel production. This could also lead to reduced environmental impacts on ecosystem quality damage category.

In addition, the LCA approach was found to be a more comprehensive decision-making approach compared with discrete emissions analysis for evaluating the environmental impacts of the shaft work produced by internal combustion engines. Future investigation should be also directed towards using the consolidation of exergy concept with LCA principles, i.e., exergetic life cycle assessment (ELCA) for better assessment of the overall environmental impacts of shaft work production by internal combustion engines.

4. Conclusions

In this work, a diesel engine fueled with B5 and B20 containing glycerol-derived triacetin was analyzed based on two environmental assessment approaches, i.e., discrete emissions analysis and consolidated LCA method. More specifically, the variations in both exhaust emissions and LCA variables in response to changes in fuel composition, engine speed, and engine load were comprehensively investigated. Based on the results obtained in the present study, the addition of triacetin into B5 and B20 blends slightly decreased the calorific value of the blends and increased their viscosities. In addition, by incorporating triacetin into the B5 and B20 blends, BSFC was increased and subsequently, BTE was decreased. Furthermore, triacetin inclusion into diesel/biodiesel blends markedly mitigated NO_X formation and PM emissions. Nevertheless, HC emissions did not show a clear trend in response to the addition of triacetin into diesel/biodiesel blends.

The results of the experiments also revealed that triacetin inclusion into diesel/biodiesel blends led to decreased CO emissions, while CO_2 emissions was increased by adding triacetin. Despite the reduction of the exhaust emissions (especially NO_x emissions), the LCA variables *viz*. human health, eco-system quality, climate change, and resource depletion damage categories were not remarkably influenced by triacetin incorporation because of the increasing impact of triacetin addition on BSFC. Overall, the results of this study showed that although triacetin could markedly mitigate the environmental performance of the engine in terms of discrete emissions analysis, the LCA approach could not diagnose any substantial differences among the fuel blends with respect to

Table 5
Uncertainty analysis of different damage categories for neat diesel, biodiesel (B5 and B20) with and without triacetin (3–7%v/v) with a 95% confidence interval.

Fuel type	Damage category	Amount of damage category (based on unit of damage category)		Confidence ranges for normalized standard distribution		Uncertainty (%)
		Min	Max	Lower band (L)	Upper band (U)	
Diesel	Human health	1.57×10^{-4}	2.76×10^{-4}	1.28	1.97	12.43
	Ecosystem quality	9.98	17.66	1.25	2.05	12.58
	Climate change	168	263	1.47	1.96	9.63
	Resources	3418	5563	1.26	2.22	11.70
B5	Human health	1.58×10^{-4}	2.81×10^{-4}	1.15	1.88	15.53
	Ecosystem quality	10.25	18.11	1.13	1.94	15.63
	Climate change	159	234	1.44	2.03	9.58
	Resources	3080	4707	1.26	2.21	11.77
B5A3	Human health	1.93×10^{-4}	3.43×10^{-4}	1.12	2.34	14.10
	Ecosystem quality	12.62	22.22	1.08	2.38	14.87
	Climate change	185	275	1.17	2.35	13.04
	Resources	3648	5585	**0.86**	**2.37**	**20.38**
B5A5	Human health	1.88×10^{-4}	2.94×10^{-4}	1.01	2.13	17.28
	Ecosystem quality	12.47	19.13	0.94	2.23	18.65
	Climate change	181	281	1.17	2.25	13.32
	Resources	3436	5523	1.07	2.22	15.55
B5A7	Human health	1.93×10^{-4}	3.04×10^{-4}	1.28	2.08	13.12
	Ecosystem quality	12.80	19.84	1.27	2.18	11.67
	Climate change	178	280	1.31	2.11	11.25
	Resources	3403	5585	1.19	2.27	12.86
B20	Human health	1.72×10^{-4}	3.04×10^{-4}	1.24	1.97	13.12
	Ecosystem quality	11.65	19.99	1.24	2.04	12.83
	Climate change	169	248	1.29	2.12	11.65
	Resources	2826	4315	1.19	2.26	12.88
B20A3	Human health	1.82×10^{-4}	3.00×10^{-4}	1.30	1.99	12.07
	Ecosystem quality	12.42	19.87	1.31	2.05	11.43
	Climate change	178	273	1.45	1.93	9.99
	Resources	3563	5436	0.91	2.12	19.84
B20A5	Human health	1.90×10^{-4}	3.14×10^{-4}	0.98	2.27	17.47
	Ecosystem quality	13.03	20.86	0.99	2.31	17.04
	Climate change	3453	5523	1.02	2.23	16.64
	Resources	194	291	1.01	1.95	18.18
B20A7	Human health	1.79×10^{-4}	2.86×10^{-4}	1.29	1.97	12.32
	Ecosystem quality	**11.90**	**19.10**	**1.50**	**1.97**	**9.11**
	Climate change	181	306	1.17	2.12	13.81
	Resources	2793	5585	1.62	1.73	9.44

their compositions. Moreover, in order to make comprehensive decisions on the environmental performance of internal combustion engines fueled with various alternative and fossil fuels and their blends, the LCA approach appears to be more plausible over discrete emissions analysis.

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