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ENVIRONMENTAL ASSESSMENT OF EMISSION AND PERFORMANCE OF DIESEL ENGINE FUELLED BY PROPYLENE GLYCOL-BIODIESEL-DIESEL

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The environmental aspect of combustion can be considered one of the main factors in achieving sustainable power production. While various studies emphasised the positive aspect of propylene glycol as an additive for diesel-biodiesel fuel composition on emission and performance metrics of a diesel engine, an unknown element of the role of this additive in sustainable power generation cycles is still not achieved. The role of this additive in the sustainable power generation cycle is unclear, and this is considered a research gap. In this study, an environmental assessment of engine performance and emission specifications was conducted in the propylene glycol, diesel, and biodiesel fuel combination. Propylene glycol was mixed with B2 and B5 fuels at 3, 5, and 7% ratios. Fuel samples were examined in a diesel engine. Environmental assessment was conducted using life cycle assessment according to IMPACT2002+ life cycle inventory analysis instruction. According to the results, the lowest midpoint and endpoint indicators of environmental impacts were related to B5PG7, i.e., 18% lower than the control. Accordingly, B5PG7 was selected as the best fuel sample from an environmental and efficiency point of view.

Keywords: propylene glycol; life cycle assessment; biodiesel; diesel engine; sustainable production; sustainable agriculture; renewable energy

Fossil fuels remain the primary source of energy worldwide. Their consumption is projected to continue increasing over the coming decades. However, fossil fuels are non-renewable resources, and their combustion releases harmful pollutants such as carbon monoxide (CO) and nitrogen oxides (NO_x) which contribute to environmental and health challenges (Xue, 2015; Schobert, 2013; Larki et al., 2023). Hence, the international community's attention has been drawn to using non-fossil and renewable fuels (Sivalingam et al., 2024). The physical-chemical characteristics of biodiesel are similar to those of fossil diesel, while emissions are less polluting. Biodiesel production will reach more than 39.9 million tonnes by 2020 (Katryniok et al., 2013). In this case, about 3.99 million tonnes of glycerol will be produced this year (more than the global demand), although glycerol has many applications in various industries such as pharmaceuticals, cosmetics, soap making, and food. Glycerol resulting from the process of trans-esterification has many impurities and is a cheap material (Katryniok et al., 2013).

In the past, diesel engines have been the most used engine in agricultural work, valued for their energy efficiency, durability, and ability to yield the torque that is needed to perform strenuous field work (Şen, 2024). Yet, increased concern about environmental impact has raised the search for cleaner, more environmentally friendly fuels. Biodiesel has been a viable option, with the prospect of decreasing harmful emissions without compromising engine performance essential to agricultural equipment (Zheng et al., 2022). Several biodiesel blends and optimisation processes have been considered in new research to maximise engine efficiency and minimise environmental imprints. It was shown that combining isopropyl alcohol with diesel, optimised by AI modelling (Şen, 2024), is an effective way to improve engine performance. Zheng et al. (2022) applied advanced predictive models to farm harvest engines and demonstrated that biodiesel-diesel blends can yield favorable emission outcomes without compromising performance (Zheng et al., 2022). The study by Akbari et al. (2024) also confirmed that biodiesel lowers farm tractor emissions consistently with little loss of performance (Akbari et al., 2024). Experiments using the blends of ethanol with biodiesel proved additional performance benefits and emissions reduction, alluding to biofuel flexibility towards multiple agricultural scenarios (IACONO et al., 2024). Prolonged service with other mixes, however, introduces further challenges, which underscored management efforts for engine maintenance (Thongchai et al., 2024; Kovacs, et al., 2024). Such technologies as tri-fuel diesel systems, biodiesel derived from algae, and hydrogen are also being discovered suitable for optimising combustion dynamics and reducing environmental emissions (Aravind et al., 2025). Nonetheless, the research gap which concerns the modelling and evaluation of the environmental benefits of emissions and performance of propylene glycol-biodiesel-diesel blends-based diesel engines is large. Studying alternative fuels can therefore contribute in sustainable agricultural engineering.

The excretion of glycerol from the trans-esterification process has become a new environmental problem (Bohon et al., 2011). The price of crude glycerol has fallen drastically, and many biodiesel manufacturers are burying it. Glycerol combustion may be one of the most straightforward solutions. Research shows that glycerol combustion is problematic and challenging due to the high viscosity, low vapour pressure, and high auto-ignition temperature. Recently, some of the hydrocarbons produced by glycerol have been burned in diesel engines. Table 1 summarises different studies in which glycerol-derived hydrocarbons have been used to enhance efficiency and decrease the emission characteristics of different diesel/biodiesel fuel blends in diesel engines.

The reviews of articles have shown that several glycerol-derived materials have been used as diesel fuel additives. However, many substances derived from glycerol are unknown in terms of the impact of adding them to diesel. Propylene glycol (PG) is one such item. Propylene glycol is a flammable substance derived from glycerol (Nakagawa and Tomishige, 2011; Herrero Dávila, 2013) and has the potential to burn in internal combustion engines.

However, not all of the study's concerns are finding a suitable engine efficiency additive. However, its environmental concerns should also be considered. The life cycle assessment (LCA) method is reliable and familiar to extract the ecological cycle of production and use of a product, which can be regarded as one of the main bases of sustainable production. Based on this, according to investigations, a study that can produce and use the cycle of PG was not found, and the present study is one of the leading studies in this field. Hence, it wants to provide a solution to the environmental concern of the combustion process. In this study, PG-biodiesel blends were introduced

Table 1 A summary of studies conducted on the effects of glycerol-derived hydrocarbons on diesel engines' efficiency and emissions parameters

Type of fuel	Efficiency			Emission						Reference
Fuel sample specifications	**BP**	**BSFC**	**BTE**	**CO**	**CO_2**	**NO_x**	**UHC**	**PM**	**Soot**	
Iso-butanol and n-butanol into diesel containing 10 and 20%	×	↑+	↑+	↓	X	↓	↓	X	X	Algayyim et al. (2017)
Butanol-acetone into diesel containing in three relativities: 10, 20, and 30% by volume	×	X	↑+	↓+	X	↓+	↓+	X	X	Algayyim et al. (2018)
5, 10, 15 and 20% n-butanol/diesel	×	↑	↑	↓+	X	↓+	↓+	X	↓+	Doğan (2011)
5, 10, 15 and 20% iso-butanol/diesel	×	↑	↑	↓	X	↓	↓	X	X	Karabektas and Hosoz (2009)
Waste edible oil biodiesel, acetone, and isopropyl alcohol	X	X	X	↓+	X	X	X	↓+	X	Tsai et al. (2013)
Diesel, ethanol, isopropanol, 15%E-85%D, and 15%isopropanol-85%D	X	↑	X	↑	X	↑	X	X	X	Alptekin (2017)
15% isopropanol-butanol-ethanol and 85% diesel; 30% isopropanol-butanol-ethanol and 70% diesel	X	X	X	X	X	↓	X	X	↑	Li et al. (2018)
15%propanol-85%diesel blend	X	↓	X	X	X	↓	X	X	↓	Şen (2019)
Biodiesel, diesel, and propanol blends	X	↑	↑	↓	X	↓	X	X	↓	Bencheikh et al. (2019)
WCO biodiesel, n-propanol and diesel blends	X	↑	↑	↓	↓	↓	X	X	↓	Dhanasekaran et al. (2019)
Biodiesel, diesel, propanol, n-butanol blends	X	↑	↑	↑	X	↓	X	X	X	Atmanli (2016)
Ethanol/diesel, 1-propanol/diesel fuel blends	X	X	X	↑	X	↓	X	X	↓	Pinzi et al. (2017)
PG methyl ether, PG ethyl ether, di-PG methyl ether	X	↓	X	↓	X	↓	↓	X	X	Gómez-Cuenca et al. (2013)

X – not available; BP – brake power; BSFC – brake-specific fuel consumption; BTE – brake thermal efficiency; UHC – unburned hydrocarbon; PM – particulate matter; WCO – waste cooking oil as an additive to diesel. The environmental effect of using ternary fuel blends of PG/biodiesel/diesel on the efficiency and emissions of the diesel engine was also investigated.

Material and methods

Preparation of fuel samples

Waste cooking oil methyl ester (WCOME) is produced according to the optimal conditions stated in the reference (Faizollahzadeh Ardabili et al., 2018). The transesterification reaction conditions were methanol to oil relativity 6:1, NaOH to oil relativity 1 wt./wt.%, mixing intensity 700 rpm, 70oC, and 60 min. Then, glycerol and biodiesel were separated. The Crude biodiesel was purified by the wet washing technique (Faizollahzadeh Ardabili et al., 2018). This study blended biodiesel fuel from cooking waste oil and diesel at three levels of 0, 2, and 5 vol.%. Then, the prepared PG was added at four levels of 0, 3, 5, and 7 vol.% of biodiesel. In general, twelve fuel samples were prepared. After preparing fuel samples, the ASTM standard measured some of their essential properties, such as flash point, cloud point, density, kinematic viscosity, and heat value (Nadkarni, 2007).

Engine test set-up

The engine experiments were conducted using a single-cylinder, four-stroke, direct injection, and water-cooling diesel engine made in India, the Kirloskar TV1. The engine specifications are presented in Table 2.

Table 2 The characterisation of the diesel

Type	single-cylinder DI diesel engine, vertical, four-stroke
Power	7.4 kW @ 1500 rpm
Stroke	102 × 116 mm
Displacement	0.948 l
Compression relativity	17.5 : 1
Fuel injection timing	26° CA BTDC
Injection pressure	200 bar
Type of cooling	water

The diesel engine was connected to a 10 kW ST-10 generator. A 0.3 m arm connected the generator to a 200 kg FG-6100SD load cell. The electricity generated by the variable resistor TDGC2-5KVA was transferred to a 10 kW heater. As the resistance of the variable changed, electrical power consumption changed, and the engine was under load. An Autonics PR12-4-DP magnetic sensor was used to measure engine speed. A screw was installed on the coupler that passed through the front of the magnetic sensor once during each crankshaft. The pulse generated by Autonics MP5W-4N was measured, and engine speed was displayed in rpm. Brake power was calculated by measuring engine load and speed (Najafi et al., 2018).

Engine tests were performed at full load conditions (constant torque at 1500 rpm). Therefore, the engine was fully loaded. In this case, the load cell measured the braking force. Fuel volumetric flow rate was measured using a cylindrical method presented by Najafi et al. (2018) with an accuracy of 0.1%.

The KIGAZ 210 gas detector was used to monitor the emissions of O_2, CO_2, SO_2, NO_x, and CO of engines. Table 3 shows the accuracy of the gas analyser measurement.

Life cycle assessment

The LCA technique is a skilled method for assessing the supplies, mechanisms, and facilities employed throughout the production process. Life cycle assessment begins with a technique of dividing how distinct products influence the environment. Life cycle assessment is a standardised method for supplying companies with a solid scientific foundation for ecological stability (Yılmaz et al., 2019). Life cycle assessment examines the environmental impacts of composite materials in terms of their reusable nature (La Rosa et al., 2016). Life cycle assessment investigates the ecological effects of a production based on conception to disposal, covering all the steps of manufacturing, shipping, and waste management (Van den Heede and De Belie, 2012). The four stages of LCA are definedas: aims and scope, conducting an inventory check, implementing an impact analysis, and evaluating the findings. Direct emissions are those emitted by sources controlled by the reporting entity. This study links direct emissions to biogas production. Indirect emissions are those caused by the reported object's actions but originate at facilities controlled or owned by

Table 3 The accuracies of instruments

Parameter	Unit	Range	Resolution	Accuracy (%)
Load	N	0–100	1	0.1
Engine speed	rpm	1–9999	1	±1
Exhaust temperature	°C	0–850	0.35	±1
Airflow rate (AFR)	$l \cdot s^{-1}$	0–10	0.27	±4
Fuel flow rate (FFR)	$g \cdot h^{-1}$	0–2000	27.57	±2.4
O_2	vol. %	4–22	0.1	±1
CO_2	vol. %	0–99	0.1	±1
SO_2	ppm	0–99	1	±1
NO_x	ppm	0–5155	1	±1
CO	ppm	0–8000	1	±1

Table 4 LCI of examination

Item	Value	Unit	Item	Value	Unit
PG (FU = 1 kg of PG)			**Fuel sample (FU = 1 kg of fuel sample)**		
Steel	0.001	kg	**PG**	in accordance with the scenario	kg
Deionised water	0.15	kg	**Span**	in accordance with the scenario	kg
Hydrogen	per each stoichiometric process	kg	**Tween**	in accordance with the scenario	kg
Glycerol	0.8	kg	**Biodiesel**	in accordance with the scenario	kg
Catalyst	0.002	kg	**Diesel**	in accordance with the scenario	kg
Electricity	0.25	kWh	**Steel**	0.0008	kg
Biodiesel (FU = 1 kg of biodiesel)			**Polyethylene**	0.0019	kg
Steel	0.001	kg	**Electricity**	0.51	kWh
Water	3.15	kg	**Combustion of fuel samples (FU = 1 MJ shaft power produced)**		
Methanol	0.16	kg	**Indirect emissions**		
NaOH	0.01	kg	**WCO**	in accordance with the scenario	kg
HCL	0.003	kg	**Biodiesel**	in accordance with the scenario	kg
Electricity	0.45	kWh	**PG**	in accordance with the scenario	kg
Direct emissions			**NG**	based on the scenario	kg
NO_x	in accordance with the scenario	kg	**Diesel**	in accordance with the scenario	kg
CO_2	in accordance with the scenario	kg	**Engine body**	0.0000091	kg
CO	in accordance with the scenario	kg			

FU – functional unit; NG – natural gas

third parties. Table 4 shows the life cycle inventory (LCI) developed for this study.

Implementing LCA

In this study, environmental loads are measured using IMPACT 2002+. It demonstrates how to put a specified midpoint/damage strategy into action. It accomplishes this by connecting all the types of LCI effects (main streams and other projects) to four impact indicators: human health (HH), climate change (CC), ecological quality (EQ), and resources (r), via fifteen midpoint impacts indicators. The midpoint index is regarded as having less science and less uncertainty behind it. The endpoint index, on the other hand, describes conservation zones, whereas the midway index demonstrates how inventory data and endpoints interact. The endpoint category is much less apparent, although it can produce obvious outcomes, making a selection more straightforward.

Sensitivity analysis

Sensitivity analysis evaluates the uncertainties in the inputs to a quantitative system and their interactions with the output of the system. The SimaPro V9 software is also employed to analyse LCA characteristics.

Results and Discussion

Properties of PG, biodiesel, and diesel fuel blends

Table 5 reports the properties of fuel samples. The results showed that PG density was greater than biodiesel and diesel. The viscosity of PG is greater than that of diesel but lower than that of biodiesel. The heat value of PG is about 19.22 $MJ\cdot kg^{-1}$, much lower than diesel and WCO biodiesel. This can be related to the high oxygen quantity of PG and biodiesel. The cloud point for biodiesel fuel is about 10 °C, which limits its use in cold regions (Ghazanfari et al., 2017). Adding PG and biodiesel to diesel fuel enhances the oxygen quantity of fuel blends by 39.3%. Propylene glycol and biodiesel enhanced the density and viscosity of fuel blends but reduced their calorific value.

Effect of PG, biodiesel, and diesel fuel blends on BSFC

The BSFC is the relativity of fuel utilisation to brake power produced, an important parameter reflecting engine efficiency. The effects of PG and biodiesel on BSFC in different blends compared to control fuel are shown in Fig. 1. The results indicated that by adding PG to biodiesel-diesel fuels, the BSFC quantity decreased. The lowest BSFC was associated with fuels with 7% PG at higher biodiesel quantities. The results also indicated that adding 2 and 5% biodiesel to diesel fuel would reduce BSFC slightly compared to control. Also, the results demonstrated that the BSFC quantity in B2 fuel enhanced because of biodiesel

Table 5 Fuel samples properties

Property	Density at 15 °C ($g \cdot cm^{-3}$)	Viscosity at 40 °C ($mm^2 \cdot s^{-1}$)	Calorific value ($MJ \cdot kg^{-1}$)	Flashpoint (°C)	Cloud point (°C)
Standard	D1298	D445	D445	D93	D2500
Control	0.839	3.090	42.570	88.000	-5.000
B2PG0	0.840	3.112	42.464	89.200	-4.700
B2PG3	0.840	3.112	42.450	89.207	-4.726
B2PG5	0.840	3.112	42.440	89.211	-4.743
B2PG7	0.840	3.112	42.431	89.215	-4.760
B5PG0	0.841	3.144	42.304	91.000	-4.250
B5PG3	0.842	3.145	42.269	91.017	-4.315
B5PG5	0.842	3.146	42.246	91.028	-4.358
B5PG7	0.842	3.146	42.222	91.039	-4.401

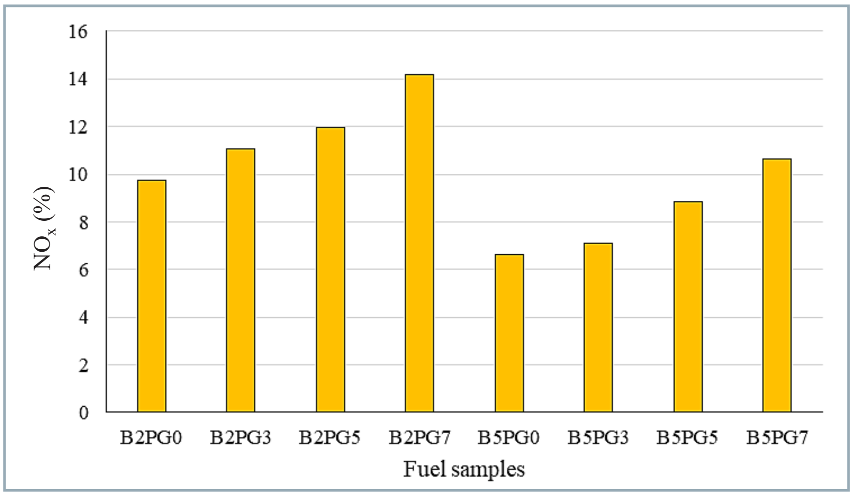

Fig. 1 Results of BSFC by different fuel samples

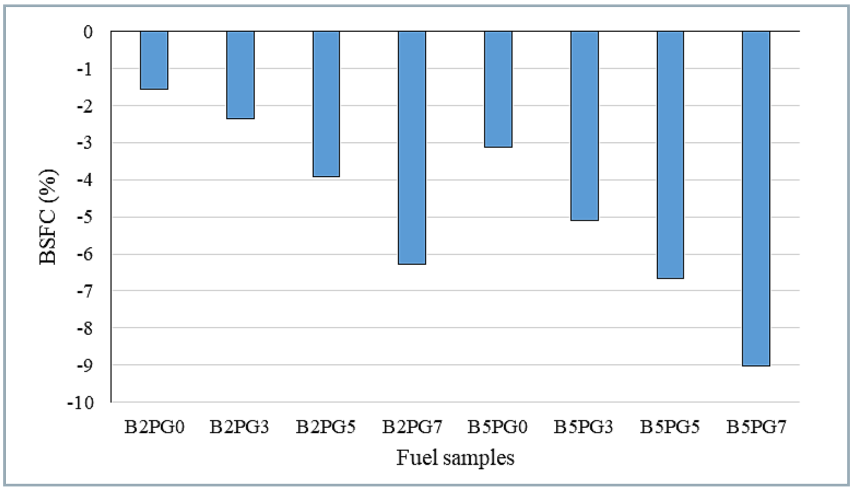

Fig. 2 Results of NO_x by different fuel samples

fuel's low heat value effects. Biodiesel and PG are both oxygenated fuels. Research demonstrates that oxygen in fuel improves combustion (Pal et al., 2010; Ghazanfari et al., 2017).

Effect of PG, biodiesel, and diesel fuel combinatiosn on NO_x emission

The formation of NO_x strongly depends on the concentration of oxygen, the temperature inside the cylinder, and the delay time in ignition (Jamrozik et al., 2017). Oxygen in the structure of PG and biodiesel can play an essential role in the formation of NO_x. The structural oxygen of fuels can intensify oxidation (Saravanan et al., 2012; Ashok et al., 2017). As a result, the peak of temperature and in-cylinder pressure in the combustion chamber enhance (Mueller et al., 2009; Bittle et al., 2010). At high combustion temperatures, oxygen molecules dissociate into atomic oxygen, initiating a nitrogen oxide chain reaction. Propylene glycol and biodiesel have oxygen in their structure and can create oxygen-rich areas in the combustion chamber. As a result, NO_x formation enhances. Figure 2 shows the effect of PG on NO_x emission compared to control. As can be seen by adding biodiesel and PG to diesel fuel, NO_x emission enhances compared to control. Also, increasing the NO_x concentration can be attributed to the high density of PG and biodiesel. The high fuel density causes larger fuel droplets to form when the fuel is sprayed and atomised (Najafi, 2009).

Effect of PG, biodiesel, and diesel fuel samples on CO_2 emission

Figure 3 shows the effect of adding biodiesel fuel and PG to diesel fuel on CO_2 emissions compared to control. As can be seen, the emissions of CO_2 in B2 fuels are higher than in control, but in B5 fuel samples, CO_2 emission is lower than that for the control. The high oxygen quantity of PG and biodiesel can contribute to carbon oxidation (Coronado et al., 2009; Can, 2014). The

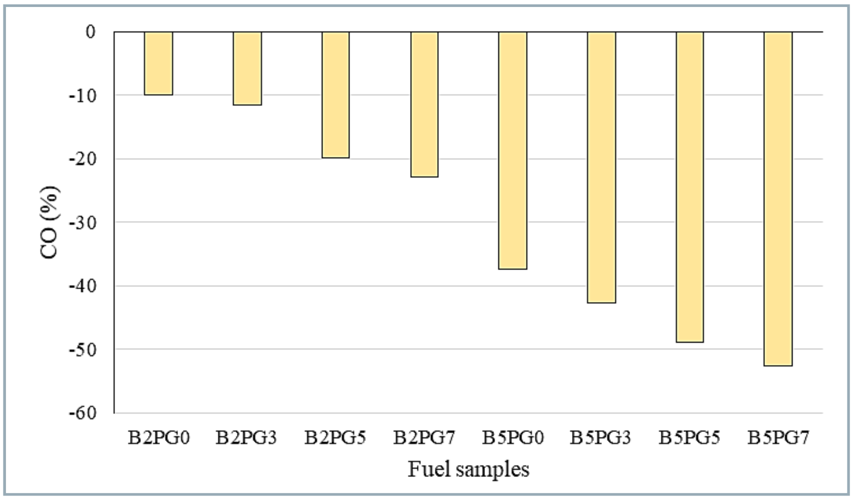

Fig. 3 Emissions of CO_2 by fuel samples

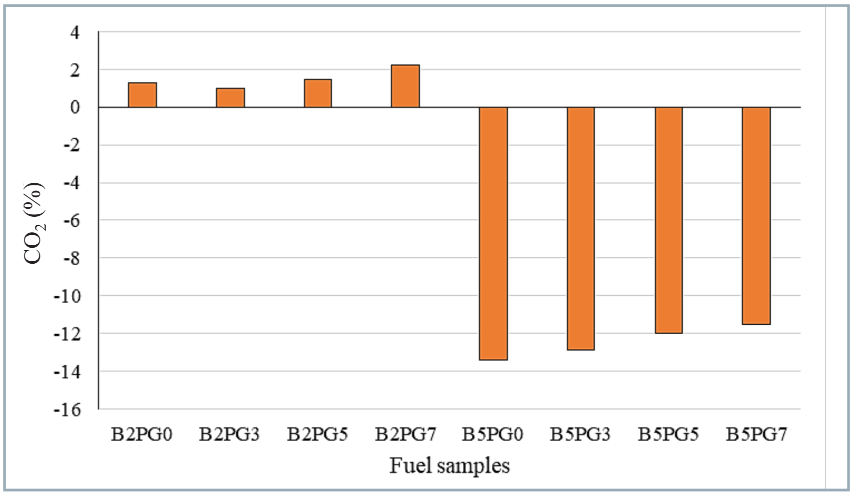

Fig. 4 Emissions of CO by fuel samples

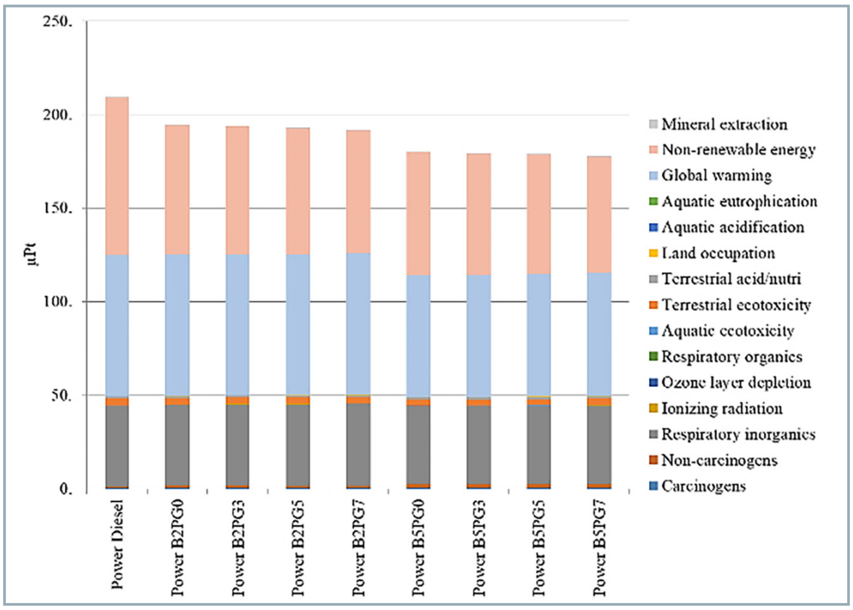

Fig. 5 Midpoint impacts of the fuel samples for 1 kWh power generation

results also showed that by adding PG to biodiesel-diesel fuels, CO_2 emission was higher than the base fuels B2 and B5. This is due to the presence of 42.1% oxygen in the chemical formula of PG, which results in more complete combustion of fuel and thus converts more CO to CO_2 (Bari, 2014).

Effect of PG, biodiesel, and diesel fuel blends on CO emission

The CO emission in different PG-biodiesel-diesel fuel blends is shown in Fig. 4. As can be seen by adding PG and biodiesel to the diesel fuel, the CO emission is reduced compared to the diesel fuel, which is similar to the results of (Aransiola et al. (2012) and Qasim et al. (2017). This is due to the oxidation of more fuels containing PG and biodiesel than pure diesel fuel (An et al., 2012; Nayak et al., 2017). Propylene glycol and biodiesel, in addition to containing oxygen molecules, have lower carbon quantity, which helps reduce CO emissions (Bhaskar, 2018). Based on the results, it can be said that PG enhances the oxygen quantity of biodiesel fuel and reduces CO emissions from engine exhaust.

Life cycle assessment results

This section presents the environmental assessment of power generation using the fuel samples from the viewpoint of LCA. Figure 5 presents the midpoint impacts of the fuel samples for generating 1 kWh of power from a diesel engine. According to the findings, the lowest environmental impacts are related to B5PG7 fuel samples, which is about 19% lower than that for the control. The highest impact category is linked to global warming, followed by non-renewable energy and respiratory inorganics. According to Fig. 5, adding biodiesel from 2 to 5% has the highest impact on midpoint impacts compared with adding PG. On average, adding 2% biodiesel to fuel samples reduces the midpoint environmental impacts by about 10%, while adding 5% biodiesel reduces the midpoint environmental impacts by about 16% compared with the control. Adding PG has a smooth slope compared with adding biodiesel. Finally, adding PG also reduces the midpoint environmental impacts.

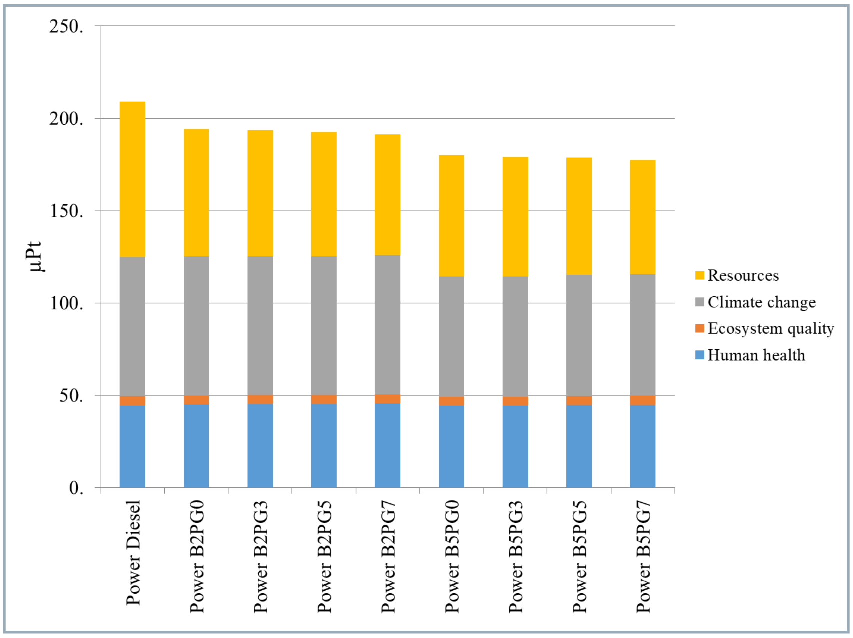

Fig. 6 Endpoint impacts of the fuel samples for 1 kWh power generation

Figure 6 presents the endpoint impacts of fuel samples for the generation of 1 kWh power. As it is clear, the lowest impact is related to B5PG7 (about 18% lower than control). Climate change, followed by resource quality and human health, has the highest environmental effect among the endpoint impact indicators. The lowest impact is related to ecosystem quality.

Figure 7 presents the sensitivity analysis results for each endpoint category. According to the results, power generation has the highest impact on human health, and PG production has the lowest. Biodiesel production has the highest impact on resource quality, while power generation has the lowest impact. For ecosystem quality, the lowest impact is related to fuel preparation,

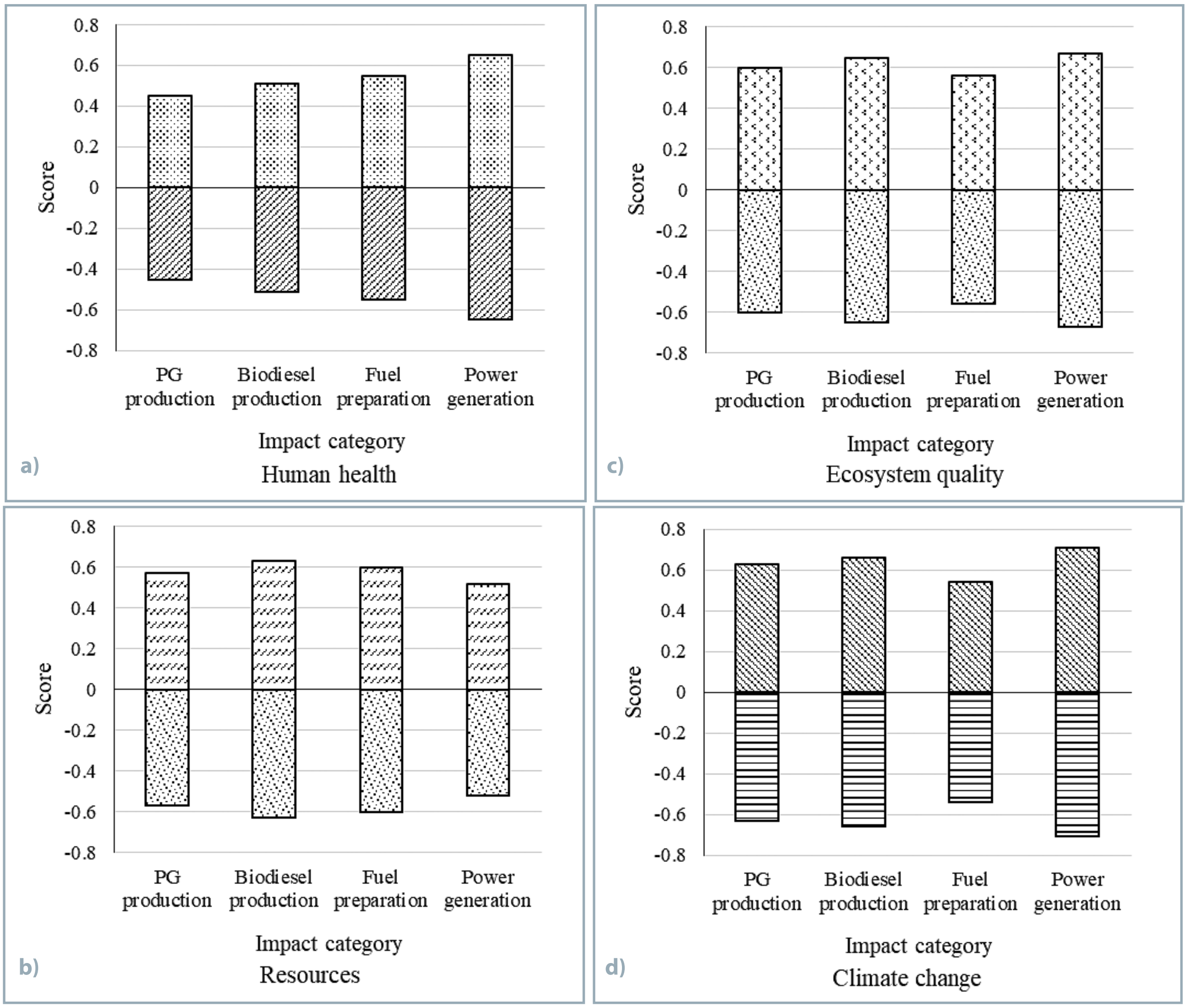

Fig. 7 The sensitivity analysis results: a) Human health; b) Resource quality; c) Ecosystem quality; d) Climate changes

and the highest is related to power generation. For climate change, the highest impact is related to power generation, and the lowest impact is associated with the fuel preparation phase.

Conclusion

In this study, PG was introduced for the first time as an additive to diesel and biodiesel fuels, and its effects on engine performance and exhaust emissions were systematically investigated. Fuel samples were prepared by blending PG at the concentrations of 0%, 3%, 5%, and 7% into three base fuels: B0, B2, and B5. The results indicated that PG, due to its high oxygen content – i.e., 42.1% compared to 11.35% in biodiesel, can function effectively as an oxygenated additive in diesel-biodiesel fuel blends. Although PG exhibits viscosity higher than that of neat diesel but lower than biodiesel, and possesses a lower heating value, i.e., attributable to its elevated oxygen content – these characteristics did not negatively impact overall engine performance. Notably, the incorporation of PG improved BSFC, with the B5PG7 blend yielding the most favorable result, i.e., approximately 7.5% lower than that of the control fuel. Emission analysis revealed that PG generally contributed to reductions in CO and carbon dioxide (CO_2) emissions, particularly at higher biodiesel blend levels, although a slight increase in nitrogen oxides (NO_x) emissions was observed. From an economic standpoint, the cost of generating brake power using the B5PG7 blend was approximately 6% higher than that of the control; however, this increase was offset by substantial environmental benefits – i.e., the reductions of approximately 11% and 52% in CO and CO_2 emissions, respectively. Furthermore, LCA based on the IMPACT2002+ methodology demonstrated that the B5PG7 blend exhibited the lowest environmental impact, with midpoint and endpoint indicators reduced by approximately 18% compared to the control. Overall, the findings suggest that the addition of 7% PG to B5 fuel constitutes a viable strategy for enhancing diesel engine environmental performance and sustainability, i.e., without necessitating modifications to the engine design or structure. For future research, we aim to employ artificial intelligence methods to model performance and simulate scenarios in agricultural applications.

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