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Research Article

The Effect of Biodiesel, Ethanol, and Water on the Performance and Emissions of a Dual-Fuel Diesel Engine with Natural Gas: Sustainable Energy Production through a Life Cycle Assessment Approach

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Diesel fuel (DF) is a significant power supply in agricultural, industrial, and transportation applications. Establishing sustainable and renewable fuel substitutes for diesel has become increasingly common due to the rising expense of petroleum resources and the pollution rate crises. A biodiesel-DF mixture in a dual-fuel (DuF) diesel engine (DE) can bring favorable environmental results. In the present study, three rates of ethanol (0, 2, and 4%), two rates of biodiesel (0 and 5%), and four rates of water (0, 0.3, 0.6, and 0.9%) were blended with DF. All these samples were considered pilot fuel (PF) in the DuF combustion process with an 80% natural gas (NG) replacement percentage. The combustion process was investigated from engine emissions and performance, power cost, and life cycle assessment (LCA) to obtain a sustainable fuel formulation. As a result, water, ethanol, and the combination of water-ethanol and NG can enhance the DE's performance by rising the inside pressure of the cylinder. The presence of oxygen content in ethanol can improve the combustion process by pushing the combustion towards complete combustion. The optimum engine performance point at full load was obtained with a fuel sample containing 1.57% biodiesel, 4.38% ethanol, 1.1% water, and 80% NG. In optimum condition, the brake power (BP) was 24.16 kW, and the brake-specific fuel consumption (BSFC) was 60.64 g/kWh. This fuel sample produces 0.46, 364.08, 1.66, and 1088.29 g/kWh of BSCO, BSCO2, BSNOx, and BSO2, respectively. At this point, the energy production cost was $0.783/kWh. The environmental impacts of the combustion process at optimal fuel formulation were 0.34249, $1.00E+02$, $1.53E+00$, and $1.94E-06$, respectively, for ecosystem quality (EQ) ($PDF^* m^{2*} yr$), resources (R) (MJ primary), climate change (CCh) (kg CO_2 eq), and human health (HH) (DALY). Accordingly, the best fuel combination was selected to be NG+B1.5E4.3W1.1.

1. Introduction

In today's world, the significant development of the world's society, rapid industrialization, and the demand for improving well-being all over the world have caused an increase in the consumption of resources and the need to produce products [1]. Energy is essential to accelerate industrial progress and agricultural production [2]. Between 1900 and 2005, the construction industry experienced a growth factor of 34, while the ore and industrial mineral sector had a growth factor of 27 [3]. This increase in demand plays a vital role in increasing the need for energy consumption, which produces harmful pollutants for the environment's health and affected organisms.

Diesel fuel (DF) is a significant agricultural, industrial, and transportation power source. The rising cost of fossil fuel resources increases pollution rate crises from diesel engines (DEs) and led to a move forward in looking for a renewable and sustainable fuel alternative to diesel [2]. For instance, most agricultural pollutants come from petrodiesel combustion [4]. DEs' carbon monoxide (CO), unburned hydrocarbon (UHC), nitrogen oxide (NOx), and smoke emissions are impressive. Today, experts are looking for methods to reduce emissions without changing the engine's construction. Continued emission leads to suffocation, negatively affecting the lungs and staining the eyes [5, 6].

Applying low-carbon and low-cost alternative fuels is a proper solution to the abovementioned issues [7]. Biodiesel is a low-carbon energy source. Biodiesel is a renewable biofuel extracted from vegetable oil or animal fat. Biodiesel is biodegradable, nontoxic, sulfur-free, and safe in storage biofuel [8], which can also reduce some engine emissions such as CO and UHC. This type of biofuel has higher viscosity and density in comparison with DF as well as lower calorific value (LHV) [9]. Higher viscosity can improve DE vibration characteristics. But, the higher density and viscosity of the biodiesel can affect the injection performance [10].

On the other hand, biodiesel has oxygen content which can improve DE combustion from the viewpoint of combustion efficiency. But, lower LHV can be one of the limitations for enhancing the engine performance characteristics [11]. In many developing nations, alternative DFs will improve energy security and the environment. Balasubramanian et al. examined the test engine's performance, combustion, sound, and emissions using B100, B60, B40, and B20. The test engine performed best with B20 blend fuel, which reduced UHC by 17%, CO by 30%, smoke by 14.08%, CO_2 by 7.35%, and NOx by 16.46%. EGR at 5%, 10%, and 15% reduced NOx emissions in the B20 blend gasoline. Again, B20 mix gasoline was tested with different EGR rates. EGR rates reduced NOx by a good proportion [12].

Diesel-biodiesel with natural gas (NG) in dual-fuel (DuF) engines is another solution [13]. As is mentioned in our previous study in [7], DEs inject diesel or diesel/biodiesel fuel mixtures (as pilot fuel (PF)) into the combustion chamber (CC); then, a mixer imports a preblended air-NG. NG's higher cetane number (CN) than diesel needs compression ratios greater than 40 : 1 to self-ignite, which is unfeasible in traditional DEs [13, 14]. Given that, the role of PF is undeniable for a profitable combustion process of gaseous fuel in DuF combustion.

Using oxygen additives in mixing with pilot diesel-biodiesel fuel in the DuF combustion process is one of the essential main approaches to reducing energy production costs, increasing energy production efficiency, and reducing pollutants. So many researchers have been attracted to this field of research [7]. Zhao et al. [15] studied engine ignition and emission behavior fueled by different fuel samples in the presence of butanol and biodiesel at different DE loads, energy ratios, and EGR rates. According to the findings, fuel samples at low DE loads increased brake thermal efficiency (BTE) for control compared to ICCI and RCCI modes. A further significant result of this research is that ICCI mode can run at a considerably greater load than RCCI mode and fuel mixture. This trend shows that ICCI mode has more chances to increase engine power compared to RCCI mode, since RCCI mode cannot run at greater loads because the noise from the combustion is too loud. Veza et al. used the grasshopper optimization algorithm (GOA) to improve ethanol-biodiesel-diesel DE effectiveness and emissions. Ethanol ratio (vol%), biodiesel ratio (vol%), engine load (Nm), and BSFC (g/kWh) were computed using mathematical equations. These regression equations were then optimized using grasshopper. At 7 Nm engine load, 10% ethanol-biodiesel-diesel blend optimized engine performance. These data suggest that grasshopper optimization technique could increase engine performance and emissions [16].

Nemade and Krishnasamy [17] used oxygenated additives to deal with biodiesel's harmful emissions in PF during a DuF combustion procedure. With oxygenated diesel mixes, the rates of HC are reduced by 44%. Also, BTE raised by 20% and brake-specific fuel consumption (BSFC) decreased by 10%. RCCI's combustion efficiency improved with fuel-bound oxygen and oxygenated alternative fuel blends' greater reactivity range.

A. Singh and S. Singh [18] examined how diethyl ether in diesel and biodiesel fuel mixture with biogas infusion affected DuF-DE performance and emissions. The presence of 10% diethyl ether and B10 at maximum load increased brake thermal efficiency (BTE) by 2.61% and decreased BSFC by 5.23% compared to 20% diethyl ether in B20. At maximum load, blends of 10% diethyl ether in B10 and 20% diethyl ether in B20 decreased CO emissions by 9.4% and 12.3%, respectively, in comparison with diesel and 10% diethyl ether in B10 and 20% diethyl ether in B20 which decreased HC emissions by 7.1% and 10.8%, respectively.

Singla and Mahla [19] employed ethanol-biodiesel-diesel blends as PF. DuF engine performance and emissions were compared to DF. DuF mode significantly reduced NOx emission opacity exhalation compared to diesel. Dual biogas-diesel exhaled more HC than natural diesel. On the other hand, ethanol and biodiesel reduced DE emissions. BTE was inferior to diesel and DuF modes.

Ethanol is one of the promising and low-cost additives for diesel-biodiesel fuel samples in a DuF combustion process with NG [20]. Fighting global warming is an urgent problem now [21]. The relationship between global warming and a broad and holistic understanding and positive attitude towards sustainability is one of the essential considerations in energy production [22]. There are still unanswered questions on why there has only been a small amount of research and instruction on the relationship between marketing and sustainability [23].

Sustainability is a pertinent issue in energy consumption by DEs in the transportation system. As a result, sophisticated methods and standards were utilized in the design of combustion systems and the production of alternative fuels to achieve the most viable solutions in terms of economics, thermodynamics, and environmental impact [24, 25]. Life cycle assessment (LCA) is an approach to cope with the

Table 1: A brief overview of the research conducted on various oil seed crops, oil extraction methods, and biodiesel and biogas production, along with engine combustion.

Surveyed study	GS	System boundary				LCA method	EI	EEP
		OA	nA	SC	DC			
Wang et al. [30]	EU	☑	☒	☒	☑	CML 2001	PS	☒
Ramos et al. [31]	☒	☒	☒	☑	☒	Ecoindicator 99	CS	☑
Hosseinzadeh-Bandbafha et al. [32]	☒	☒	☒	☑	☒	IMPACT 2002+	PS	☒
Ternel et al. [33]	EU	☒	☒	☒	☑	US GREET	PS	☒
Hosseinzadeh-Bandbafha et al. [34]	Iran	☑	☒	☑	☒	IMPACT 2002+	PS	☑
Bilgili [35]	☒	☒	☒	☒	☑	ReCiPe 2008	PS	☒
Perčić et al. [27]	☒	☑	☒	☑	☒	US GREET	PS	☒
Cooper and Balcombe [28]	☒	☒	☒	☒	☑	ReCiPe	PS	☒
Sharma and Strezov [29]	☒	☑	☒	☒	☑	ReCiPe	PS	☒
The present study	Iran	☑	☒	☑	☑	IMPACT 2002+	CS	☑

GS: geographical region; OA: oxygenated additive; nA: nanoadditive; SC: standard combustion; DC: dual combustion; EI: environmental impacts; EEP: engine emissions and performance results; PS: partial survey; CS: complete survey.

environmental concept of sustainable production. A product's life cycle is the "successive and interconnected steps of a manufacturing process, from getting the raw material or making it from natural resources to making it available to the public" [26]. Three steps are pursued in the LCA process: (i) putting together an inventory of related inputs and outputs of a production system, (ii) possible environmental impact assessment connected with mentioned inputs and outputs, and (iii) expounding the inventory analysis consequences and impact evaluation steps associated with the targets of the research.

By applying LCA, opportunities for enhancing the environmental sustainability of products can be identified from various life cycle perspectives [26].

LCA is employed in analyzing the life cycle of energy production through a DuF combustion process in the presence of different pilot fuels, including biodiesel. The research was created by Perčić et al. [27] to lower CO_2 emissions over a ship's lifetime in the Croatian short-sea shipping industry. The study is aimed at finding suitable diesel-powered alternatives considering economic and environmental factors. In addition to diesel, analysis was done on electricity, methanol, dimethyl ether, NG, H2, and biodiesel. Three separate Croatian ro-ro passenger ships traveling on short, medium, moderate, and relatively lengthy routes are used to show the results. The most ecologically friendly power system architecture using alternative fuel was found via life cycle assessment (LCA). When considering the actual Croatian electricity mix, which includes 46% renewable sources, the results showed that an electricity-powered ship is a most environmentally and financially advantageous alternative among those considered. In the study by Cooper and Balcombe [28], a LCA was carried out to compare the effects of NG-fueled trucks on climate change, air pollution, and resource depletion against those of diesel, biodiesel, dimethyl ether, and electricity. In terms of climate change, NG perform better than diesel (17–21%) and are comparable to electric drivetrains; however, if CH4 emissions reach 3.5% of throughput for normal fuel usage, any gains will be lost. The measured slip from the most recent NG trucks is far lower than this, in any case. The least GHG emissions come from biodiesel, but NG may match diesel in terms of climate impact only when it uses the least fuel and emits the least methane. NG performs best for the other parameters and has lower impacts (11-66%) than diesel, while electricity and biodiesel have the lowest results. In the study by Sharma and Strezov [29], LCA was used to analyze the sustainability of several fuels, including diesel, gasoline, NG, biodiesel, ethanol, hydrogen, fuel cells, and electricity. The study found that ethanol had the greatest environmental effects, followed by biodiesel, liquefied petroleum gas, gasoline, diesel, electricity, and NG, and hydrogen technology, which had the fewest effects (only 3% compared to ethanol). The total economic expenditures for battery electric vehicles are the highest per km, followed by ethanol-based flexi fuel vehicles, biodiesel, DF, gasoline, NG, and H2 (fuel cell). Table 1 summarizes the studies carried out on different engine combustion conditions.

According to investigations from the different databases, to the best of our knowledge, investigating the environmental effects of pilot fuel containing a low percentage of ethanol in the diesel-biodiesel fuel mixture in the presence of different percentages of natural gas from the point of view of life cycle assessment has not been fully reported in studies. The lack of complete reporting prevents the movement towards sustainable energy production. It makes decision-making about the effects of ethanol in the DuF power production process ambiguous from the economic, environmental, and energy balance perspectives. Accordingly, this process needs to be optimized from a sustainability point of view. Eventually, the best condition concerning two environmentally friendly approaches and engine characterization of power production will be presented.

The present study has four main steps: (1) to prepare the fuel samples, (2) to conduct the engine test process, (3) to do an LCA analysis in the presence of a proper inventory, and (4) to optimize the process from a sustainability point of view.

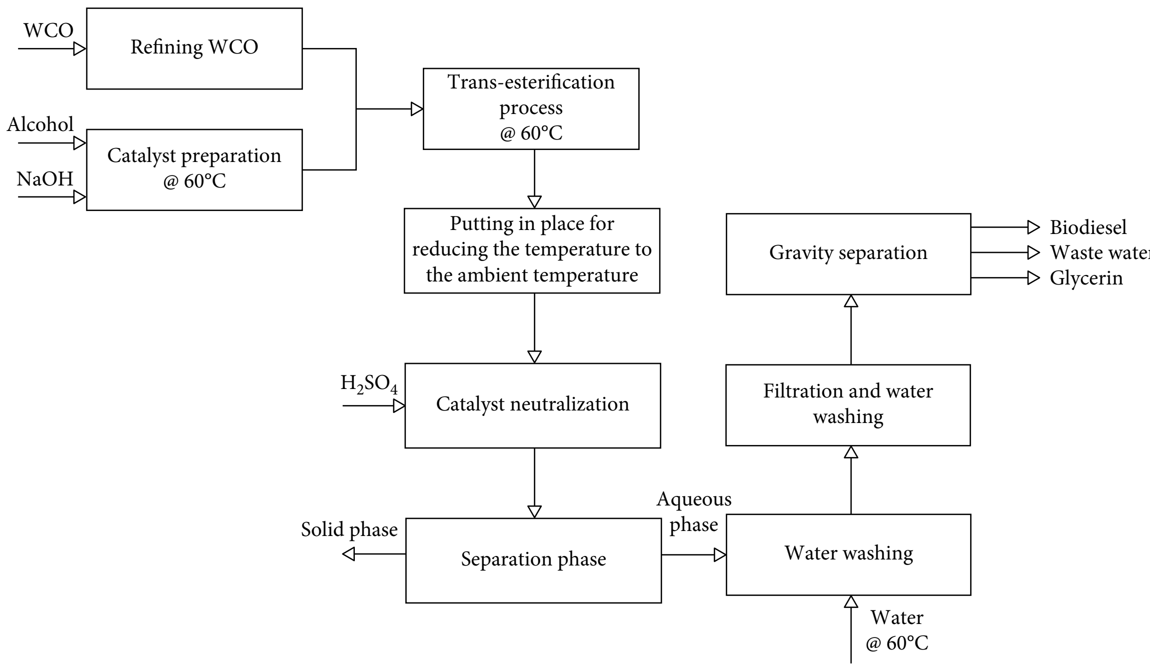

Figure 1: Biodiesel production process.

2. Methodology

2.1. Transesterification for Biodiesel Production. Vegetable oils and animal fats are produced by bonding saturated and unsaturated monocarboxylic acids to the trihydric alcohol glyceride, resulting in triglycerides that can undergo transesterification with methanol/ethanol in the presence of NaOH/KOH [36]. Transesterification, also known as alcoholysis, is a process in which one ester is converted to another using alcohol instead of water [37]. This process is widely used due to its effectiveness in reducing triglyceride viscosity. Palmitic, stearic, oleic, linoleic, and linolenic acid chains are the five primary types of chains present in most vegetable and animal oils. Each step of turning triglyceride into diglyceride, monoglyceride, and glycerol releases 1 mol of the fatty ester [38]. Methanol is frequently used to make biodiesel because of its low cost. However, for an alkali-catalyzed transesterification, the free fatty acid (FFA) reacts with the alkali catalyst to produce soap, which reduces the amount of biodiesel that can be produced and makes it difficult to separate the esters from the glycerol [39]. Additionally, soap binds to the catalyst, necessitating the use of more catalysts and increasing the cost of the process. The triglycerides can be broken down into diglycerides by water, which can come from the oils and fats or the saponification reaction, resulting in the production of more FFA [36]. This reaction is effective for dealing with oils or fats containing many FFA.

Usually, concentrated sulfuric acid is used to speed up this reaction. Acid-catalyzed esterification has not gotten as much attention as alkali-catalyzed transesterification because the reaction happens slowly and requires a high molar ratio of methanol to oil [40].

In the present study, biodiesel was created with methanol at a six-to-one alcohol-to-oil ratio, 710 rpm of mixing velocity, and sodium hydroxide at 1.1% by weight (as a catalyst) through the transesterification process. The manufacturing temperature was maintained constant within the spectrum of methanol's boiling points (about 60°C). The ideal conditions for improving the efficiency of biodiesel production were identified in a report by Faizollahzadeh Ardabili et al. [41]. Figure 1 presents the diagram of biodiesel production. The inputs of the biodiesel production phase contain water, waste cooking oil (WCO), alcohol, NaOH, H_2SO_4, and energy; the outputs are wastewater, methyl ester (biodiesel), and glycerin.

Table 2: Biodiesel properties according to ASTM standard.

Property	Standard	Range	Unit
LHV	ASTM D240	39.9	MJ/kg
Density	ASTM 6751-02	0.87–0.90	g/cm^3
Cloud point	ASTM 2500	Report	°C
Flash point	ASTM D93	>130	°C
Viscosity	ASTM D445	1.9-6	mm^2/s

Thermophysical characteristics of the biodiesel are measured and listed in Table 2 reproduced from [7]. The measurement ranges and standards are displayed in Table 2 for each factor. The fuel's thermal properties are the most critical factors affecting a combustion process's performance and emission characteristics [42]. Accordingly, these parameters are sensitive and are essential to be discussed.

Gas chromatography-mass spectrometry was used to analyze the biodiesel's fatty acid methyl ester profile following ASTM D6584 [43]. In Table 3, we can see the outcomes.

2.2. Fuel Blend Preparation. The current study mainly supplemented the diesel/biodiesel fuel samples with water and ethanol. DF and biodiesel were combined at a volumetric

Table 3: The profile of fatty acid methyl ester.

Ester type	Myristic acid	Palmitic acid	C18:0	Oleic acid	Linoleic acid	C18:3	Eicosenoic acid
wt.%	3.62	20.01	4.24	9.34	56.15	3.31	3.33

Table 4: The properties of the PF samples.

Fuel samples	Viscosity (cSt)	Density (kg/m^3)	Properties LHV (MJ/kg)	Flashpoint (°C)	Cloud point (°C)
Standards	ASTM D445	ASTM 6751-02	ASTM D240	ASTM D93	ASTM D2500
D(E0W0)	7.5	0.83486	41.3	87	3
DE0W0.3	7.58	0.8379	40.8	86	3
DE0W0.6	7.62	0.841	40.1	85	3
DE0W0.9	7.62	0.8442	39.2	83	2
DE2W0	7.6	0.8342	40.5	50	1
DE2W0.3	7.38	0.83462	39.9	48	1
DE2W0.6	7.44	0.835	39.1	43	0
DE2W0.9	7.5	0.8656	38.8	40	0
DE4W0	7.5	0.8335	39.4	35	-2
DE4W0.3	7.14	0.834	38.7	30	-2
DE4W0.6	7.02	0.8346	38.1	27	-1
DE4W0.9	7.1	0.83471	37.7	25	-1
B5E0W0	7.56	0.8368	40.8	60	10
B5E0W0.3	7.48	0.8371	40.2	58	9
B5E0W0.6	7.5	0.8377	39.6	57	8
B5E0W0.9	7.5	0.838	39	54	8
B5E2W0	7.44	0.8361	40.2	40	8
B5E2W0.3	7.48	0.8365	39.4	40	8
B5E2W0.6	7.74	0.8368	38.9	42	7
B5E2W0.9	7.62	0.8375	38.2	43	7
B5E4W0	7.28	0.8353	39.6	30	7
B5E4W0.3	7.16	0.8359	38.8	25	6
B5E4W0.6	7.08	0.8397	38	24	6
B5E4W0.9	7.02	0.8369	37.6	28	5

ratio of 5% (B5). We require surfactants to create a stable emulsion because water and ethanol are not soluble in DF and biodiesel fuel. According to the research by Faizollahzadeh Ardabili et al., a 1 : 2 mixture of the surfactants Span 80 and Tween 80 (Merck, Germany) was then added to the manufactured B5 and DFs to create a homogenous emulsion of the diesel-water and B5-water fuel samples [7]. All fuel samples had a water content of 0, 0.3, 0.6, and 0.9 ml/l. The generated fuel samples were then combined with ethanol in three treatments (0, 2, or 4 vol%). Fuel samples are named D (diesel as control), DE0W0.3 (including 0% of biodiesel, 0% of ethanol, and 0.3 ml/l of water), DE0W0.6, DE0W0.9, DE2W0, DE2W0.3, DE2W0.6, DE2W0.9, DE4W0, DE4W0.3, DE4W0.6, DE4W0.9, B5 (including 95% of DF and 5% of biodiesel), B5E0W0.3, B5E0W0.6, B5E0W0.9, B5E2W0, B5E2W0.3, B5E2W0.6, B5E2W0.9, B5E4W0, B5E4W0.3, B5E4W0.6, and B5E4W0.9. The generated emulsion specimens of fuel were homogenized for 15 minutes at ambient temperatures using a Polytron® homogenizer.

Following 30 days, the created emulsion fuels' stability with various water and ethanol concentrations was investigated. Throughout the trial, there was no sedimentation, and the water and ethanol as an additive remained steady. This trend might be considered a vital benefit of the fuel compositions created for this study. The top physical characteristics of the examined fuel samples are shown in Table 4.

2.3. Engine Test Procedure. For the current research, a constant-speed Kirloskar DE engine with natural aspiration, direct injection, and a single cylinder was transformed into a DuF-DE engine through the use of a cut-off valve, an NG fuel regulator valve, an NG flow meter, and an air-NG mixer (Figure 2) (according to our previous study in [7]). The engine specifications are listed in Table 5 (according to our previous study in [7]).

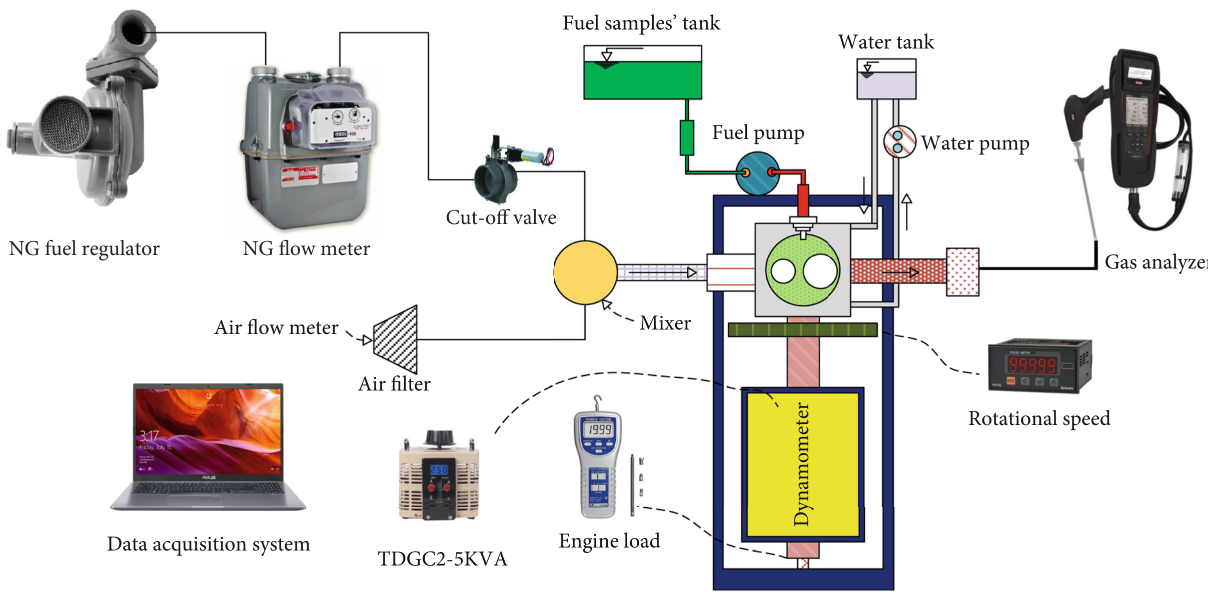

Figure 2: A schematic of the engine test.

To put the engine under the load, a magnetic dynamometer and a load control device were utilized (TDGC2-5KVA). The dynamometer was outfitted with a load cell that had a capacity of 200 kN and a 30 cm arm. A Lutron FG-5100 force gauge was used as a load cell to get an accurate reading of the load being applied (according to our previous study in [7]). A gas analyzer was used for the combustion gas analyzer known as the KIGAZ 210, and it measured the emissions of exhaust gas, which included O_2, CO, CO_2, and NOx (according to our previous study in [7]).

Equation (1) was employed to calculate the uncertainty associated with measurement errors as follows:

$$\delta r = \left(\left[\frac{\partial r}{\partial k_1} \Delta k_1 \right]^2 + \left[\frac{\partial r}{\partial k_2} \Delta k_2 \right]^2 + \cdots + \left[\frac{\partial r}{\partial k_n} \Delta k_n \right]^2 \right)^{0.5}, \quad (1)$$

where r refers to the total uncertainty, i.e., $k_1, k_2, \cdots, k_n$, and their uncertainties, i.e., $\Delta k_1, \Delta k_2, \cdots, \Delta k_n$ while $\partial r/\partial k_i$ is the partial derivative of r concerning Δk_i (according to our previous study in [7]). Table 6 presents the uncertainty values and precision for the instruments employed in the experiment (according to our previous study in [7]).

The experiments were performed under full load conditions at a constant engine speed of 1500 rpm [7]. As previously stated, various PF samples were tested at an 80% ratio of PF to gaseous fuel (M) (according to our previous study in [7]). Equation (2) was utilized to establish the value of "M," which indicates the energy worth of natural gas relative to the entire energy of the fuel blend. In total, 48 different scenarios were examined using the DuF engine to evaluate the objectives of this study.

$$M = \frac{\dot{E}_{NG}}{\dot{E}_{NG} + \dot{E}_{PF}}, \quad (2)$$

Table 5: Engine specifications.

Name	Kirloskar Oil Engines Ltd.
Stroke	Four
Cylinder	One
Power	7.4 kW
Rated speed	1500 rpm
Volume	0.9 liter
Compression ratio	17.5
Cooling system	Water circulation
BMEP	6.21 bar at rated speed

where $\dot{E}_{PF}$ refers to the energy ratio of the consumed PF computed as [7]

$$\dot{E}_{PF} = \dot{V}_{PF} \times \rho_{PF} \times LHV_{PF}, \quad (3)$$

where $\dot{V}_{PF}$, ρ_{PF}, and LHV_{PF} refer to PF volumetric ratio, PF density, and PF LHV, respectively. $\dot{E}_{NG}$ is the energy ratio of the NG that can be obtained by [7]

$$\dot{E}_{NG} = \dot{V}_{NG} \times \rho_{NG} \times LHV_{NG}, \quad (4)$$

where $\dot{V}_{NG}$, ρ_{NG}, and LHV_{NG} refer to NG volumetric ratio, NG density, and NG LHV, respectively. An NG flow meter was utilized to monitor the consumption rate of natural gas (NG) fuel. The experimentation was conducted at an 80% substitution rate of NG. Figure 3 illustrates the DuF engine testing process flowchart used in this investigation. It is important to note that the engine was initially run with DF and operated for five minutes to attain a stable state. Additionally, the engine ran on DF for five minutes between tests to ensure the accuracy and validity of the collected data [7].

Table 6: Uncertainty and accuracies of measuring instruments.

Factor	Resolution	Accuracy	Unit	Factor	Uncertainty	Uncertainty (%)
Load	0.1	±1	N	NG flow	0.02 (g/h)	1.85
Speed	1	±1	rpm	PF flow	0.35 (g/h)	4.45
CO_2 emission	0.1	±1	%	Airflow	0.98 (g/h)	4.53
NOx emission	1	±1	ppm	BP	0.05 (kW)	0.02
CO emission	1	±1	ppm	BSFC	0.19 (g/kWh)	1.06
O_2 emission	0.1	±1	%			

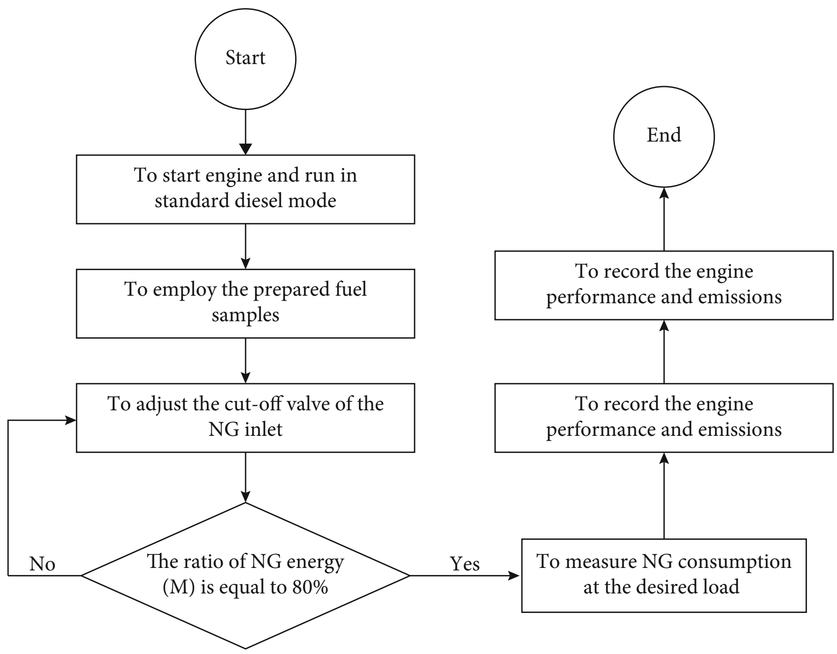

Figure 3: The flowchart of the DuF test procedure.

2.4. Calculation of the Engine Performance Parameters. Engine efficiency is calculated using some indicators. These indicators enable us to make informed decisions and recommend suitable future tactics. The following list includes essential engine efficiency indicators.

2.4.1. Engine Power. BP refers to the power produced by the engine's drive shaft without accounting for any power losses resulting from gear, transmission friction, and other factors.

$$BP = \frac{2\pi T n}{60000}. \quad (5)$$

T refers to the torque (N.m) and n to the engine rotational speed (rpm).

2.4.2. Fuel Consumption. BSFC is a calculation standard for a motor that burns fuel to produce shaft or rotatory power. Typically, this criterion compares the practicality of IC engines with shaft outputs. It is a gauge of fuel consumption distributed through the power produced. It could also be regarded as fuel utilization tailored to power. BSFC enables direct comparisons between the fuel efficiency of various engines. To determine the BSFC, Equation (6) is used.

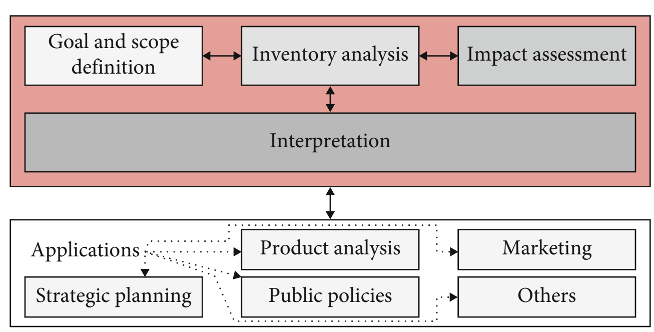

Figure 4: Schematic diagram of LCA steps.

$$BSFC = \frac{\dot{m}}{T \times \omega}, \quad (6)$$

where $\dot{m}$ refers to fuel consumption (g/s), T refers to the torque (N.m), and ω refers to the engine angular frequency (rad/s).

2.5. Life Cycle Assessment. LCA is an expert procedure used to evaluate the resources, processes, and services utilized throughout the production cycle, from raw material

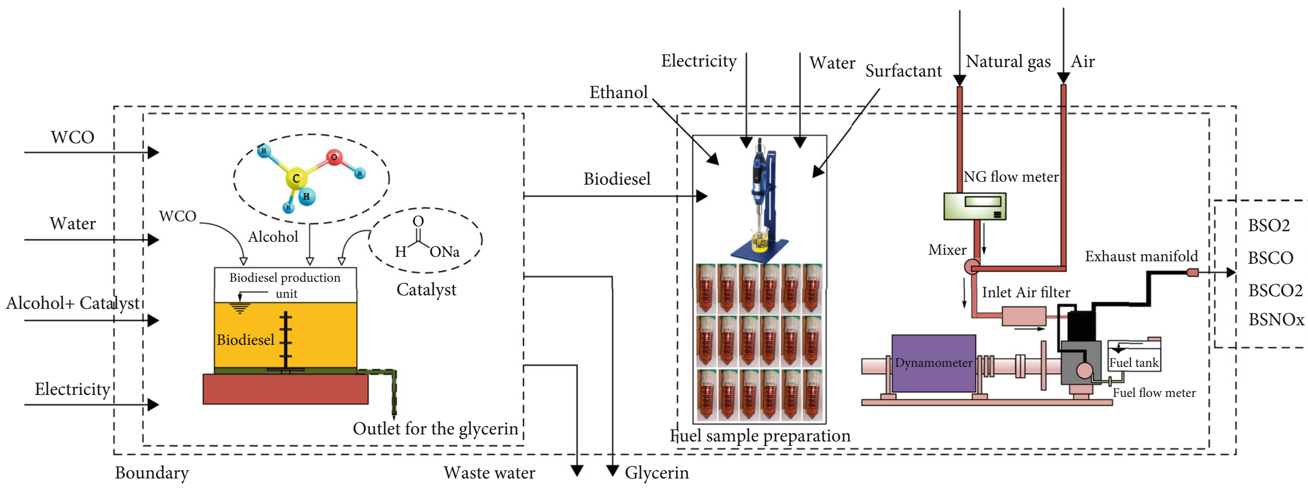

Figure 5: The system boundary.

acquisition, generation, and steps to different production systems and the potential environmental effects of those activities [26]. Initially, LCA employs a method of contrasting how various items affect the environment. LCA is a standardized approach to providing businesses and governments with a solid scientific basis for environmental sustainability [44]. LCA analyzes the ecological effects of composite materials about their recyclable nature [45]. Cradle-to-grave analysis (LCA) examines the environmental impact of a product or service from when it is conceived to when it is discarded, including all stages of manufacture, transportation, end-user consumption, and waste disposal [46, 47]. LCA has four steps: defining objectives and scope, doing an inventory analysis, conducting an impact assessment, and interpreting the results. Figure 4 is a simplified illustration of the LCA steps.

2.5.1. Goal and Scope Definition. The LCA methodology incorporates the system boundaries and rate of detail required, which can vary based on the research's specific application and subject matter. The depth and scope of an LCA study can significantly differ depending on the study's objectives. For the current study, the system boundaries encompass the production of biodiesel, fuel preparation, and the combustion phase of the fuel samples [48]. The system boundary is presented in Figure 5. The primary goal of this LCA study is to conduct a comprehensive assessment of the environmental impact of biodiesel production, fuel preparation, and power generation and utilization through ethanol and water blends in conjunction with natural gas to enhance engine efficiency and minimize emissions.

In LCA, the functional unit (FU) refers to a team of references for inventory data [49]. FU is typically described in the system's output [48, 50]. In this study, the ultimate FU for each fuel mixture is determined to be 1 GJ of shaft power generated by combustion. Moreover, to comprehend the environmental effects of each step, numerous subsystems are explored independently of the preceding stages. Indeed, this type of computation in LCA can provide additional insight into the operational nature of each stage from the perspective of environmental effects.

2.5.2. Life Cycle Inventory (LCI). LCI is a crucial part of the life cycle assessment process, which aims to quantify all inputs and outputs of a system. This stage consists of four substages that are carried out concurrently [48]. In the first phase, all operations involved in the product life cycle must be identified, starting from harvesting energy and raw materials from the environment. The second stage is the most challenging and requires extracting essential data for each procedure. Data can be obtained from scientific studies, LCA practitioner publications, and business and government records. The third stage involves revising system boundaries to identify important vectors of system borders and eliminate processes that exceed system boundaries [48]. Eventually, all processes' inputs and outputs are regulated by FU [26]. The LCA evaluation generally consists of two key components, direct and indirect emissions.

Direct emissions come from sources that the reporting business owns or has control over. This study associates direct emissions with the combustion step, known as exhaust emission. Previous investigations identified NOx, O_2, CO_2, and CO as the principal pollutant contributors to compression ignition engine exhaust [51, 52].

Indirect emissions are those that come from the operations of the reporting organization but come from sources that belong to or are governed by other parties. Indeed, these emissions are related to the creation of numerous chemicals in various power generation system components. The quantity of each input is required for these emissions. Table 7 presents the LCI prepared for this study.

2.5.3. Life Cycle Impact Assessment (LCIA). LCIA is aimed at giving more information about a product system's LCI effects so that their importance to the environment can be better understood. LCIA's goal is to help people understand how vital possible environmental impacts are for manufacturing systems based on the results of the LCI assessment. LCIA should look at the potential effects on

Table 7: LCI of fuel sample preparation and combustion process.

Item	Value	Unit
Biodiesel production (FU = 1 kg of biodiesel)		
Steel	0.0012	kg
Water	3	kg
Methanol	0.15	kg
NaOH	0.01	kg
HCL	0.005	kg
Electricity	0.23	kWh
Fuel sample preparation (FU = 1 kg of fuel sample)		
Ethanol	Based on fuel sample requirement	kg
Span	Based on fuel sample requirement	kg
Tween	Based on fuel sample requirement	kg
Water	Based on fuel sample requirement	kg
Biodiesel	Based on fuel sample requirement	kg
Diesel	Based on fuel sample requirement	kg
Steel	0.00098	kg
Polyethylene	0.0017	kg
Acrylonitrile butadiene styrene	0.0063	kg
Electricity	0.39	kWh
Combustion of fuel samples (FU = 1 MJ shaft power produced)		
Indirect emissions		
WCO	Based on WCO requirement	kg
Biodiesel	According to PF sample	kg
Ethanol	According to PF sample	kg
NG	According to PF sample	kg
Diesel	According to PF sample	kg
Engine body	0.0000085	kg
Direct emissions		
NOx	Measured for each scenario	kg
O_2	Measured for each scenario	kg
CO_2	Measured for each scenario	kg
CO	Measured for each scenario	kg

"protected areas," including the ecological landscape, HH, human environment, and r. In the last ten years, many methods for evaluating the effects on the environment have been improved. IMPACT 2002+ is used to measure environmental loads in this research. It shows how a written midpoint/damage strategy can be implemented. This approach links several LCI outcomes (such as primary streams and other interventions) using fifteen intermediate categories: human health (HH), ecosystem quality (EQ), climate change (CCh), and resources (R) [48]. The intermediate approach is considered to have a lower rate of scientific support and a lower degree of uncertainty.

On the other hand, the endpoint index describes conservation areas, while the midpoint index shows how inventory results and endpoints affect each other. The endpoint strategy is much less clear but can have pretty clear results, making it easier to decide. Figure 6 shows how the midpoints and ends of the IMPACT 2002+ strategy are linked.

2.5.4. Life Cycle Interpretation. The last step of the LCA process is the life cycle interpretation. This trend is where the effects of LCI, LCIA, or both are summed up so that conclusions, suggestions, and decisions can be made that align with the objectives.

2.5.5. Sensitivity Analysis. Sensitivity analysis is all about analyzing the sources of uncertainty in the inputs to a mathematical model or system and their effects on the model's or system's output [53]. By making 10% changes to the information and the output factor, we can do a sensitivity analysis of the four damage categories. The four damage outcomes are treated as dependent variables, and the independent variables are fuel compositions, including biodiesel percentage, ethanol percentage, water percentage, and NG percentage in the combustion process. Parameters and several analyses are calculated using an Excel 2019 spreadsheet. Moreover, SimaPro V8.2.3 software is used to perform research on LCA categorizations.

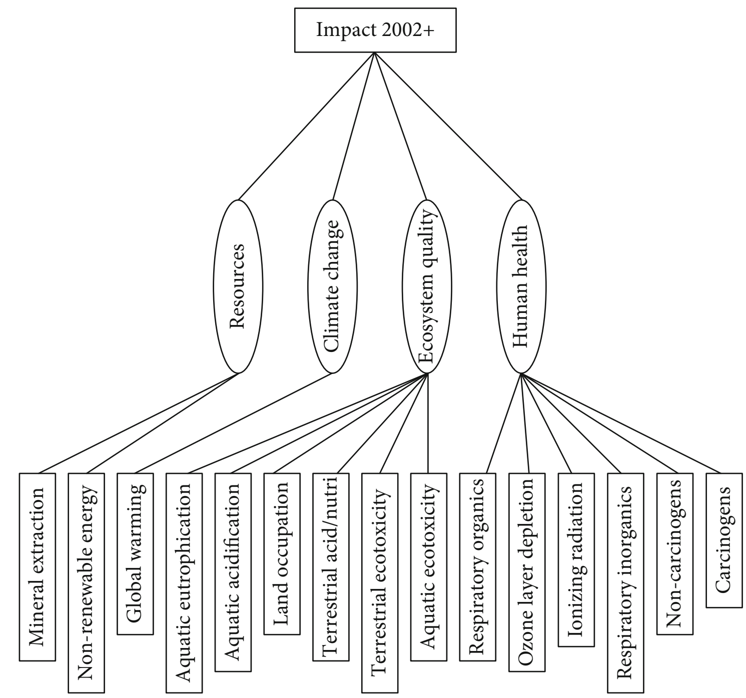

Figure 6: The relation between midpoints and endpoint indicators of IMPACT 2002+.

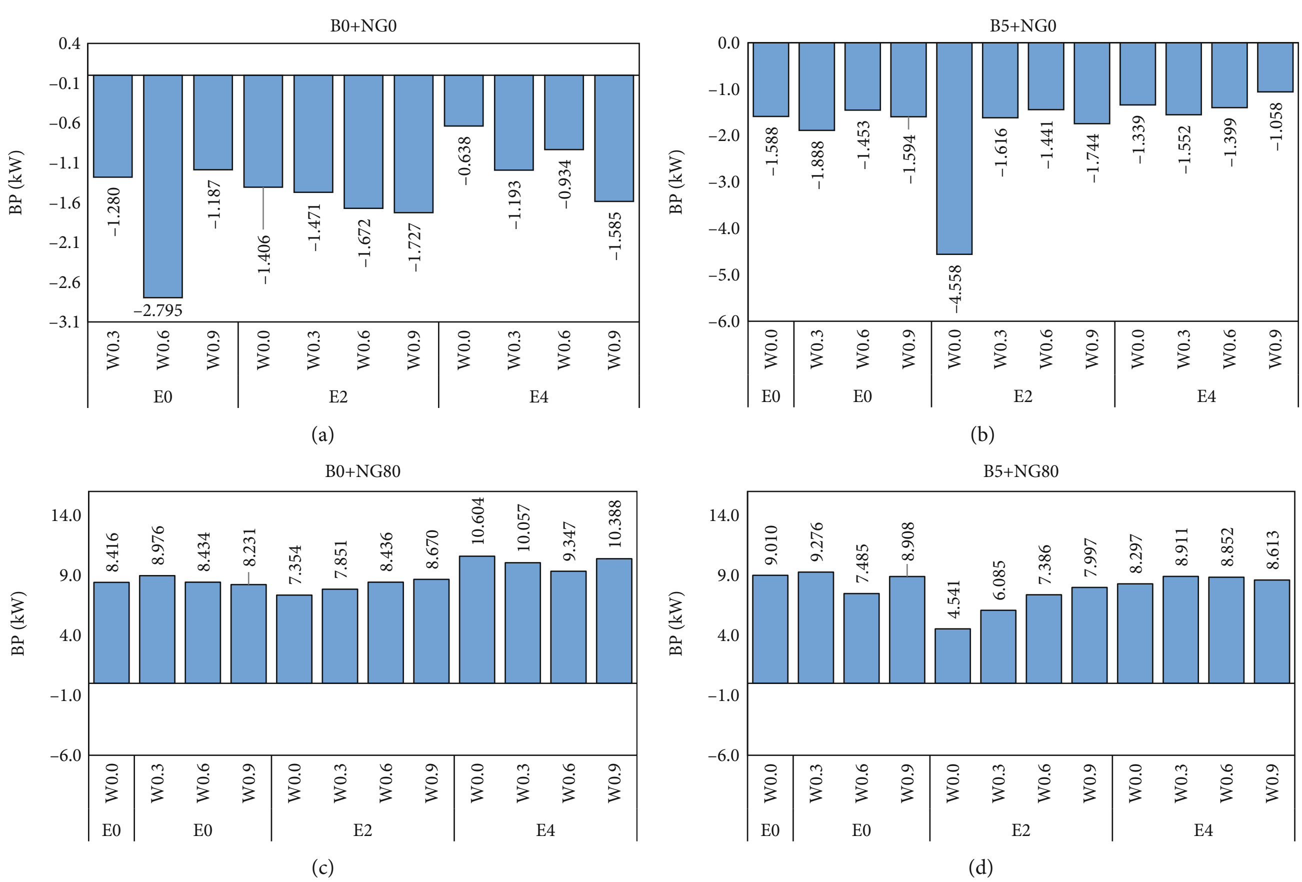

Figure 7: BP trend for each fuel sample in comparison with control. (a) DF in diesel mode, (b) B5 fuel in diesel mode, (c) DF in DuF mode, and (d) B5 in DuF mode.

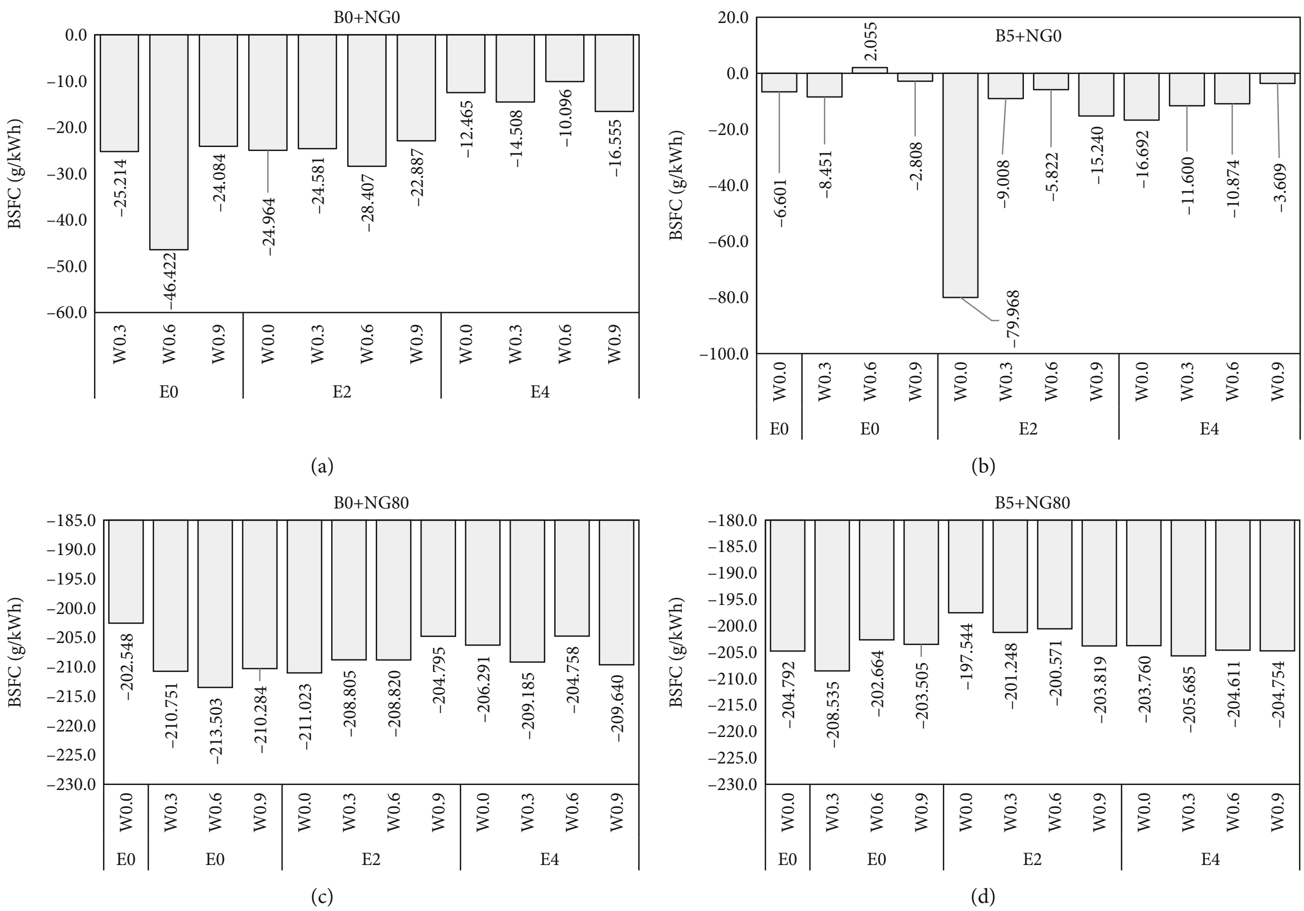

Figure 8: BSFC trend for each fuel sample in comparison with control. (a) DF in diesel mode, (b) B5 fuel in diesel mode, (c) DF in DuF mode, and (d) B5 in DuF mode.

3. Results and Discussion

3.1. Results of the Thermophysical Properties. This part of the results deals with presenting the thermophysical characteristics of the prepared fuel samples (Table 4). The trend of changes in the density of fuel samples is shown in Table 4. The DE4W0 has the lowest fuel-specific weight. The presence of biodiesel and water in fuel samples increases fuel density. On the other hand, ethanol reduces the specific weight of the fuel sample. The density of biodiesel, water, and ethanol is higher, higher, and lower than pure diesel, respectively [54]. The simultaneous addition of biodiesel and water increases the density of the slope. Raising the standard value's thickness can disrupt the combustion chamber's fuel atomization. As a result, the quality of combustion and emission of engine pollutants will be affected.

According to Table 4, the DF sample as a reference fuel has the highest LHV among the fuel samples. The presence of 5% biodiesel in DF (B5) reduces the LHV of the fuel to a relative amount of approximately 1.2% compared to pure DF. Biodiesel has a lower LHV than DF, so adding biodiesel to DF reduces the LHV of the fuel sample [55, 56]. As it is clear from Table 4, adding water and ethanol to DF and B5 fuels reduces the LHV of the fuel samples. Because ethanol and water have lower LHVs than DF and biodiesel fuels [57]. The fuel sample B5E4W0.9 has the lowest fuel LHV, because this fuel sample has the highest content of biodiesel, ethanol, and water. The LHV of fuel is one of the influencing factors in the amount of energy released inside the combustion chamber. The energy released in the combustion chamber has a direct relationship with the BP produced by the engine [13]. As the LHV of the fuel sample increases, the probability of making BP also increases because the heat value is only one of the influencing factors in the production of BP.

According to Table 4, the presence of biodiesel, water, and ethanol has reduced the flash point. The slope of reducing the flash point in the ethanol samples is higher than in the samples without ethanol. But the trend of flash point changes in fuel samples containing a mixture of biodiesel and ethanol is slightly different from other fuel samples. Thus, in the fuel sample containing 5% biodiesel and 2% ethanol, the flash point increased with the increase in water percentage. The flash point of a fuel is known as one of the most critical parameters in fuel autoignition in increasing pressure and temperature as well as fuel storage and storage. Lowering the flash point can disrupt the combustion process at high temperatures and pressures inside the chamber [3]. The highest flash point corresponds to DF (87°C), and the lowest ignition point (24°C) corresponds to the B5E4W0.6 fuel sample.

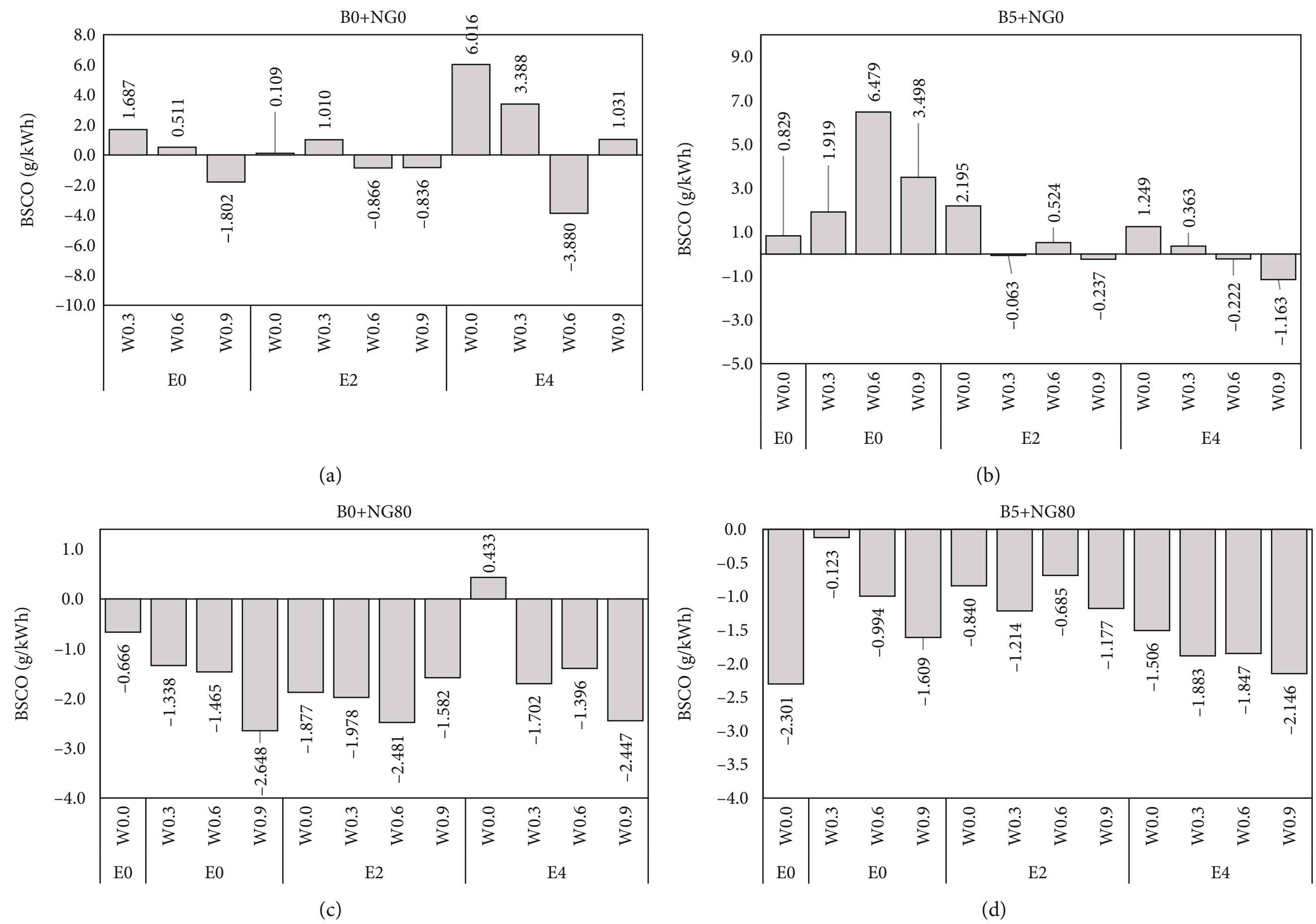

Figure 9: BSCO trend for each fuel sample in comparison with control. (a) DF in diesel mode, (b) B5 fuel in diesel mode, (c) DF in DuF mode, and (d) B5 in DuF mode.

Compared to diesel, biodiesel exhibits a higher level of viscosity [58, 59]. As shown in Table 4, the density of the fuel sample is elevated in the presence of biodiesel. When 5% biodiesel is present in DF, the viscosity of the fuel increases by roughly 1% compared to pure DF. Increasing the ethanol content has reduced the fuel viscosity, and increasing the water content has relatively improved the fuel viscosity. The lowest density is related to B0E4W0.6 and B5E4W0.9 fuels. The highest fuel viscosity corresponds to the B5E2W0.6 fuel sample. This fuel sample differs by about 3% from the DF sample. The amounts of water and biodiesel can play an influential role in this 3% difference. Fuel viscosity is also one of the factors that can affect the quality of fuel injection in the combustion chamber and directly affect the combustion quality [42].

3.2. Results of the Engine Performance. Table 7 presents the variation of the BP in comparison with DF (as control) for all fuel samples and combustion modes (standard single-fuel and DuF modes). Zero rate refers to possession. According to Figure 7, DF in DuF mode with 80% of natural gas has the highest braking power production. Because the LHV of DF is higher compared to other types of fuel. The presence of biodiesel in the fuel sample reduces the braking power because the LHV of biodiesel is lower than that of DF. The presence of ethanol and water in the sample of fuels containing biodiesel positively improves braking power compared to the sample of fuels without biodiesel. The positive effect of ethanol in the sample of fuels containing biodiesel is due to the presence of oxygen content in ethanol, which has a positive impact on the combustion process and leads the combustion to completion and can cover the disadvantages of biodiesel in reducing braking power [60, 61]. The presence of water in the sample of fuels containing biodiesel can also cause the microcombustion phenomenon, improve the atomization of the fuel containing biodiesel, and increase the production power of the engine [7]. But in the example of fuels without biodiesel, this assumption can be ruled out due to the low viscosity and density of DF compared to the fuel containing biodiesel. The reason for the decrease in braking power with the increase of ethanol and water in the sample of DFs without biodiesel can be the low LHV of ethanol and water compared to DF.

The presence of gaseous fuel in the combustion process has increased the braking power significantly (about 82% and 81%, respectively, compared to the single-fuel mode for DF and B5). With the presence of natural gas in the combustion chamber, the pressure inside the cylinder increases and increases the production power. As it is clear from Figures 7(c) and 7(d), the presence or absence of biodiesel

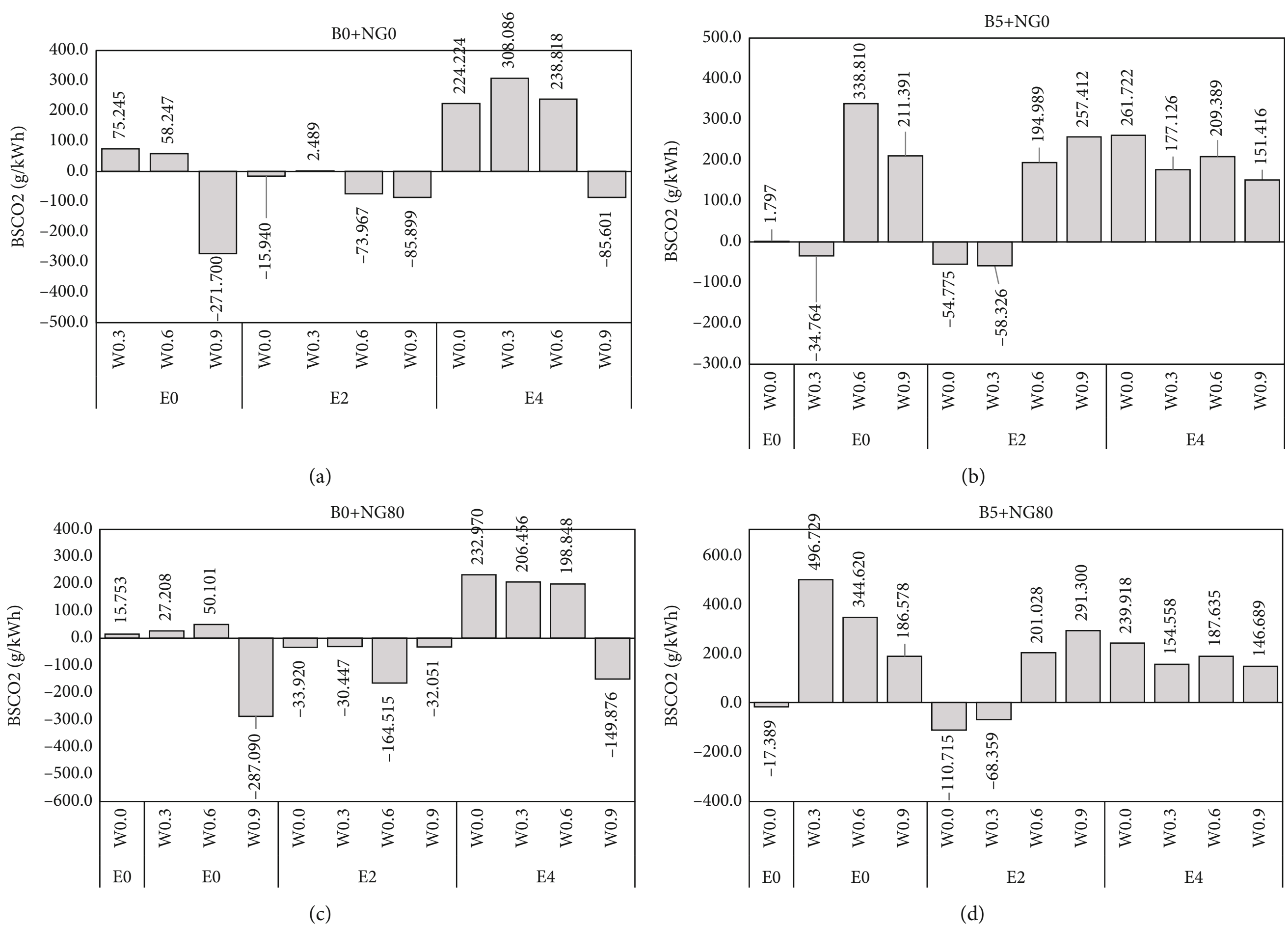

Figure 10: BSCO2 trend for each fuel sample in comparison with control. (a) DF in diesel mode, (b) B5 fuel in diesel mode, (c) DF in DuF mode, and (d) B5 in DuF mode.

affects the process of changes in braking power. Because biodiesel has different physical-thermal properties than DF, the other physical-thermal properties of biodiesel compared to DF make the combustion quality of DF higher than the combustion quality of biodiesel fuel. Based on this, the presence of natural gas, ethanol, and water positively affects the process of braking power changes compared to fuel without biodiesel. Based on this, it can be concluded that additives can positively affect fuel samples when biodiesel is included in DF content.

Figure 8 shows the variations in BSFC for the fuel samples compared to the control. The horizontal rate (zero rate) refers to the control. The lowest specific fuel consumption for braking is related to the sample of fuels combusted in the DuF process (about 73 and 71% less than the single-fuel mode for diesel and B5 fuels, respectively). Because natural gas has value and is present in the combustion chamber, it produces a significant part of the power. Therefore, the power generation load of the pilot fuel is less consumed. Even in cases where less braking energy is produced, the specific fuel consumption increases so that the engine with high fuel consumption can cover the lack of production power [7].

3.3. Results of the Engine Emissions. Combustion is a chemical process. Incomplete combustion produces carbon monoxide instead of part of the carbon dioxide emissions. Based on this, carbon monoxide emission is a product of incomplete combustion [7]. Various reports indicate high CO emissions when using biodiesel fuel compared to pure DF [62]. Figure 9 shows the specific carbon monoxide (BSCO) emission rate for fuel samples compared to the control. The horizontal rate (zero rate) refers to the control. In general, BSCO emissions are, on average, 47 and 50% lower in DuF mode than in single-fuel mode, respectively, compared to DF (Figure 9(a)) and B5 (Figure 9(b)).

Adding biodiesel to the fuel sample has increased BSCO emissions by 16% and 10% compared to the fuel containing pure diesel for single-fuel and DuF conditions. As can be seen, the presence of NG has reduced the increase in BSCO emissions by about 6% compared to the single-burned state. This trend can be due to the participation of natural gas in increasing the pressure inside the CC, which reduces the ignition delay and leads the combustion to complete combustion. Accordingly, BSCO emissions are reduced. Also, the presence of water, ethanol, and the combination of water-ethanol increases the amount of BSCO emission by approximately -21, +37, and -1% in single-fuel mode and -31, -2, and -38% in DuF mode for DF and +1, +19, and -20% in single-fuel mode and +28, +68, and +50% in DuF mode for B5 fuel, respectively. The presence of oxygen

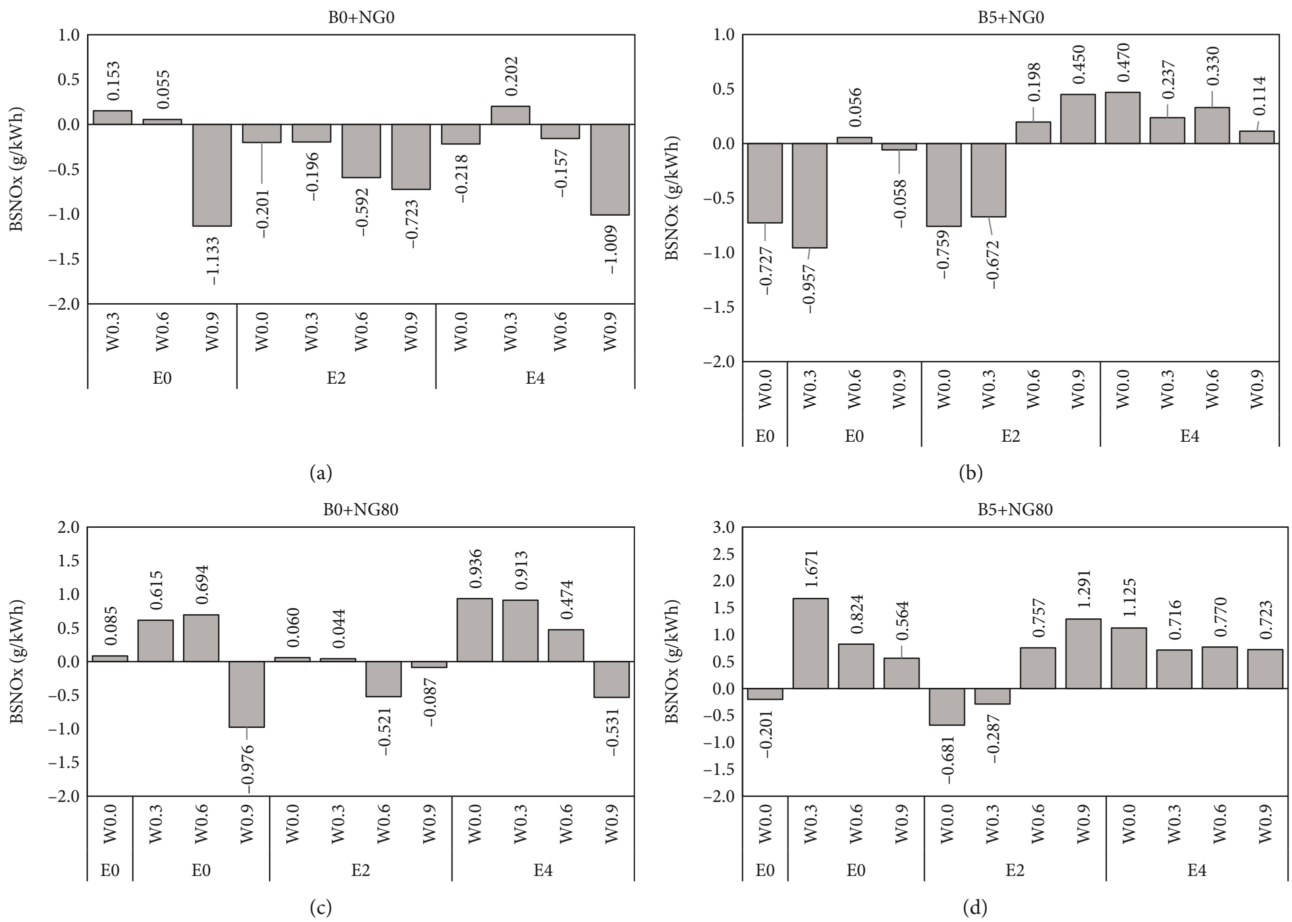

Figure 11: BSNOx trend for each fuel sample in comparison with the control. (a) DF in diesel mode, (b) B5 fuel in diesel mode, (c) DF in DuF mode, and (d) B5 in DuF mode.

content in ethanol can improve the combustion process by pushing the combustion towards complete combustion. This trend is very evident in 2% ethanol (Figure 9). By increasing the ethanol content from 2 to 4%, the process of carbon monoxide emission has increased. The presence of water has also successfully reduced the amount of carbon monoxide emissions relatively. This trend can be due to the positive effect of water in creating the microcombustion process and improving the atomization of the pilot fuel. However, the highest amount of carbon monoxide emission improvement occurs in the combined use of water and ethanol for both the single-fuel and DuF conditions (Figure 9). This process can occur due to the combustion-enhancing properties of water and ethanol. Based on the changes, the best suggestion for using a water, ethanol, and water-ethanol combination is in DuF mode and without biodiesel fuel (Figure 9).

Figure 10 shows the emission of specific carbon dioxide (BSCO2) in the presence of fuel samples compared to the control. The presence of CO_2 in engine emissions can occur in several ways. One possibility is the presence of carbon content in fuel compounds. But pushing the combustion towards complete combustion is another possibility. According to Figure 10, on average, BSCO2 emission in the presence of water, ethanol, and the water-ethanol combination is about -7, +17, and +8% in single-fuel mode and -12, +12, and -2% in dual-burning mode, respectively, for DF and +16, +15, and +23% in single-fuel mode and +31, +12, and +27% in DuF mode for B5 fuel samples, respectively. The increase in BSCO2 for fuel containing B5 is somewhat higher than for fuel containing pure diesel. But in general, the combination of water-ethanol has increased the amount of BSCO2 emissions. Part of this increase in emissions can be due to the improvement of the combustion process due to the oxygen content in biodiesel and ethanol and the microcombustion properties of water in improving fuel atomization for better combustion. On the other hand, the DuF combustion process has increased the amount of BSCO2 emissions by about 4 and 5 percent, respectively, compared to pure diesel and B5. This process can also be carefully considered due to the improvement of combustion in the presence of natural gas due to increased combustion pressure and pushing the combustion towards complete combustion.

Figure 11 shows the emission trend of specific nitrogen oxides (BSNOx) in engine emissions compared to control. From the changes in Figure 11, it can be seen that the average release of BSNOx in the presence of water, ethanol, and the water-ethanol combination is about -10, -5, and -18% in single-fuel mode and -9, +17, and -2% in DuF mode for DF and +20, +35, and +50% in single-fuel mode and +39, +20,

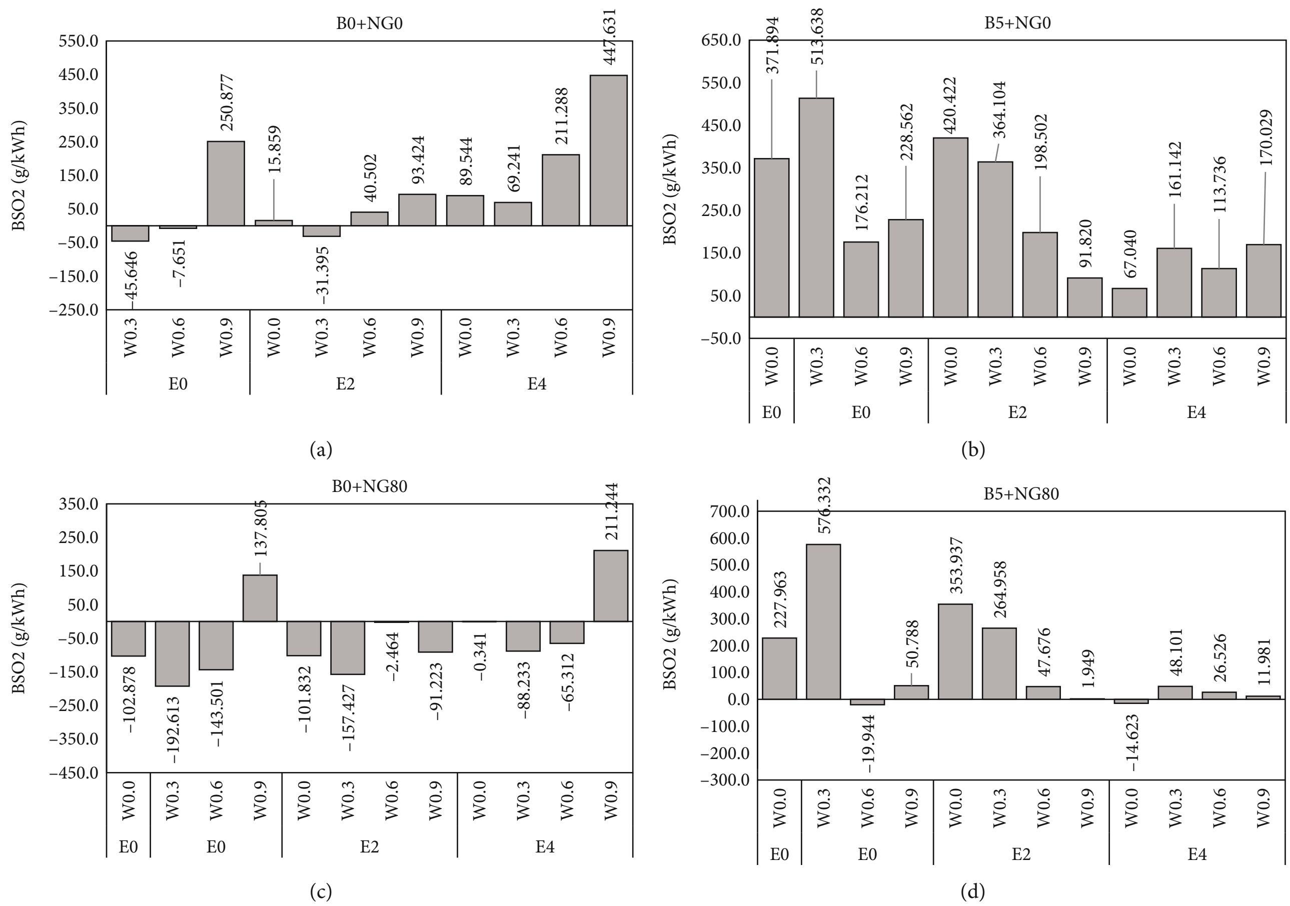

FIGURE 12: BSO2 trend for each fuel sample in comparison with control. (a) DF in diesel mode, (b) B5 fuel in diesel mode, (c) DF in DuF mode, and (d) B5 in DuF mode.

and +40% in DuF mode for B5 fuel, respectively. The presence of water in fuel samples containing pure diesel has successfully reduced the emission of BSNOx. Because the high concentration of heat in the combustion chamber is one of the main factors in creating the composition of NOx, water has a high specific heat capacity. Accordingly, it can reduce any heat concentration inside the combustion chamber and then affect the emission of NOx [13]. This trend is attenuated in the case of ethanol additive, especially when the dual combustion is conducted and the presence of NG increases the pressure and temperature of the combustion chamber. The presence of water in the double-fuel combustion process has reduced the emission of BSNOx only for pure DF compounds. In other cases, the emission of BSNOx has increased especially when NG is included in the combustion process of B5 compounds.

Figure 12 shows the specific oxygen (BSO2) emission with changes in the fuel samples compared to the control. By observing the trend of changes in Figure 12, it can be said that on average, the BSO2 release in the presence of water, ethanol, and the water-ethanol combination is about +14, +9, and +27% in single-fuel mode and +6, +13, and +17 in DuF mode for DF and -5, -15, and -21% in single-fuel mode and -8, -8, and -22% in DuF mode for B5 fuel, respectively. The presence of biodiesel in the fuel sample has relatively reduced oxygen emissions compared to the fuel sample containing diesel. It can be said that in the presence of biodiesel, combustion is carried out with better intensity, and less oxygen is released from the exhaust [3].

3.4. Results of the Power Cost Economic Analysis. Figure 13 presents the power cost changes of produced energy in the presence of fuel samples compared to the control. The horizontal zero rate is related to the control in all figures. In Figure 13, the functional unit of production is 1 kWh of power production. In this chart, the cost of energy produced was calculated using biodiesel at $5/l, ethanol at $3/l, water at $0.1/l, and NG at $0.01/m^3 which is compared to the amount of fuel consumed and production power [3]. This trend can be directly related to the consumption of BSFC and the LHV of the fuel samples and NG. As it is clear from Figure 13, the lowest energy production cost occurs in the DuF combustion process. Because the price of natural gas in Iran is very low, the addition of ethanol, except in the B5E2W0.3 fuel sample, has caused a relative increase in the cost of energy production.

3.5. Results of the Life Cycle Assessment. The LCA is figuring out how much damage combustion fuel samples do to the environment to make a profile of them and find their hot

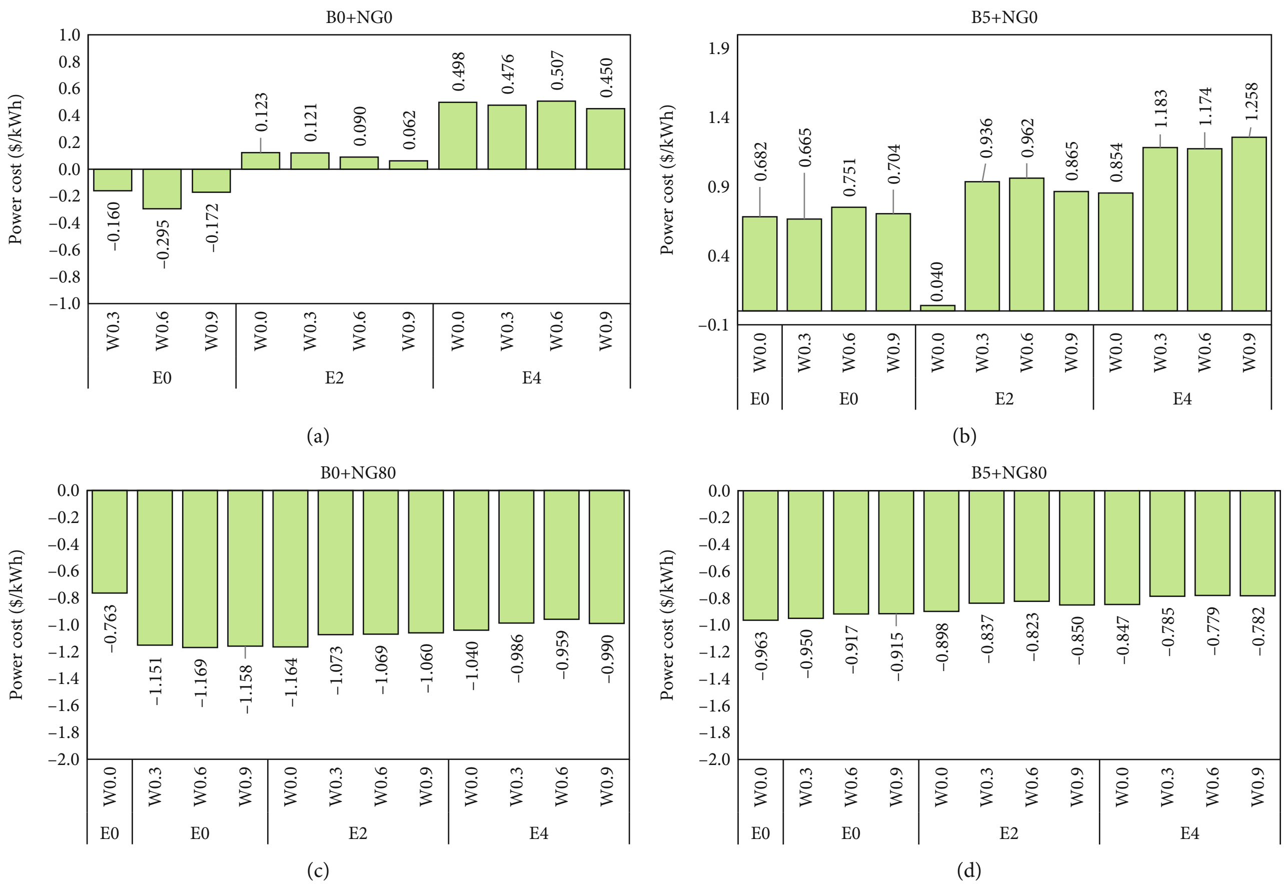

Figure 13: Power cost trend for each fuel sample in comparison with control. (a) DF in diesel mode, (b) B5 fuel in diesel mode, (c) DF in DuF mode, and (d) B5 in DuF mode.

spots. FU is being thought about as a 1 MJ shaft of fuel-produced energy. For fuel samples to be made, several parts are needed. The main part is the burning of samples of fuel that have been created. The LCI is implemented by making biodiesel, preparing, and burning fuel samples. Table 7 has a complete list of the LCI of power production by fuel samples.

The environmental impacts of various fuel samples used in combustion processes are outlined in Table 8, which may be found here. The life cycle assessment (LCA) for each environmental consequence comprises the manufacturing of biodiesel, fuel preparation, engine body emissions, and exhaust emissions. They are broken down into four distinct types of damage (EQ, HH, R, and CCh). According to the information shown in Table 8, the NG+DE0W0.9 followed by NG+B5E2W0 blends have been selected as the candidate for the best blend in terms of the total environmental impacts. This particular mixture (NG+DE0W0.9 with an NG percentage of 80%, biodiesel and ethanol 0%, and water 0.9% and NG+B5E2W0 with an NG percentage of 80%, biodiesel 5%, ethanol 2%, and water 0% at the maximum engine load) causes the least amount of overall damages.

The proportion of normal impact that various fuel samples have on HH, EQ, CCh, and R destruction is shown in Figure 14. Figure 14 also depicts the proportion of various fuel samples in HH, EQ, CCh, and resource damage.

As is clear, the effect of fuel sample preparation and combustion on R followed by HH is higher than that for CCh and EQ. The full damage assessment is, respectively, related to B5E0W0.6 (0.0077 $PDF^{*}m^{2*}yr$, 1.506 MJ primary, 0.037 kg CO_2 eq, and $2.18E-08$ DALY, respectively, for EQ, R, CCh, and HH), B5 (0.0077 $PDF^{*}m^{2*}yr$, 1.515 MJ primary, 0.0294 kg CO_2 eq, and $2.03E-08$ DALY, respectively, for EQ, R, CCh, and HH), and B5E4W0 (0.0113 $PDF^{*}m^{2*}$ yr, 1.461 MJ primary, 0.0352 kg CO_2 eq, and $3.08E-08$ DALY, respectively, for EQ, R, CCh, and HH).

In Figure 15, we see a sensitivity analysis of four types of damage concerning the independent variables cooperating in the fuel combustion process. The vertical line in the graph depicts the average environmental impact across all damage categories. The deviation of the vertical line from the mean value of each input and output parameter explains the sensitivity of the independent variable on the impact category.

It is clear from the findings of the sensitivity analysis that the NG has the most influence on all impact categories. The second independent variable that greatly influences impact categories is biodiesel on HH, CCh, and R. As is apparent, on average, the effect of independent variables on EQ followed by R is higher than those for the other impact categories.

3.6. Optimization. The optimization method used the response surface method in the presence of quadratic

Table 8: The endpoint impacts of the fuel samples in the combustion process.

Damage category Unit	EQ PDF*m^{2*}yr	R MJ primary	CCh kg CO_2 eq	HH DALY
Diesel	0.007664136	1.498415452	0.027173865	$2.07325E-08$
DE0W0.3	0.007690395	1.493920936	0.030256799	$2.14728E-08$
DE0W0.6	0.00769962	1.489426407	0.032027718	$2.19044E-08$
DE0W0.9	0.007480402	1.48493188	0.022212879	$1.87306E-08$
DE2W0	0.009349492	1.472662172	0.028484589	$2.47171E-08$
DE2W0.3	0.009329453	1.468167652	0.028971345	$2.47163E-08$
DE2W0.6	0.009259813	1.463673125	0.027345209	$2.38955E-08$
DE2W0.9	0.009221398	1.459178596	0.027089655	$2.35933E-08$
DE4W0	0.011009895	1.446908894	0.033079885	$2.83916E-08$
DE4W0.3	0.011052964	1.442414377	0.035656537	$2.93248E-08$
DE4W0.6	0.010979387	1.437919848	0.03341765	$2.83547E-08$
DE4W0.9	0.010860626	1.433425319	0.027145535	$2.688E-08$
B5	0.007701813	1.515646417	0.029420543	$2.02994E-08$
B5E0W0.3	0.007653265	1.510915345	0.028943159	$1.98747E-08$
B5E0W0.6	0.007754286	1.506184262	0.037025995	$2.18362E-08$
B5E0W0.9	0.007719846	1.50145318	0.034213167	$2.15629E-08$
B5E2W0	0.00953582	1.488537707	0.032851609	$2.54772E-08$
B5E2W0.3	0.009453939	1.483806628	0.028140277	$2.44399E-08$
B5E2W0.6	0.009540045	1.479075546	0.033671758	$2.61052E-08$
B5E2W0.9	0.009558882	1.474344464	0.035544508	$2.67005E-08$
B5E4W0	0.011386483	1.461428996	0.03527085	$3.08071E-08$
B5E4W0.3	0.01133932	1.456697917	0.033622163	$3.03699E-08$
B5E4W0.6	0.011323725	1.451966835	0.034048786	$3.04282E-08$
B5E4W0.9	0.011263624	1.447235752	0.032167245	$2.97855E-08$
NG+diesel	0.002986815	0.996957455	0.01701165	$1.81132E-08$
NG+DE0W0.3	0.002938896	1.010726402	0.017012196	$1.90796E-08$
NG+DE0W0.6	0.00290622	1.0177294	0.017543563	$1.94893E-08$
NG+DE0W0.9	0.002840297	1.005994554	0.013252009	$1.72631E-08$
NG+DE2W0	0.003227067	1.002712395	0.016842964	$1.92082E-08$
NG+DE2W0.3	0.003219654	1.0016983	0.016687827	$1.91062E-08$
NG+DE2W0.6	0.003140214	1.004935422	0.014796609	$1.8485E-08$
NG+DE2W0.9	0.003182317	1.002012647	0.016377086	$1.88904E-08$
NG+DE4W0	0.003463926	1.006536508	0.01890735	$2.054E-08$
NG+DE4W0.3	0.003438366	1.008405628	0.018799554	$2.06164E-08$
NG+DE4W0.6	0.003478656	1.000874131	0.018981952	$2.01244E-08$
NG+DE4W0.9	0.003307968	1.009627185	0.014535433	$1.91083E-08$
NG+B5	0.002867558	1.009007798	0.016459076	$1.82157E-08$
NG+B5E0W0.3	0.002960205	1.014576469	0.022661775	$2.04143E-08$
NG+B5E0W0.6	0.002999062	0.997023472	0.021723604	$1.92601E-08$
NG+B5E0W0.9	0.002921032	1.004635651	0.018983107	$1.89811E-08$
NG+B5E2W0	0.003427168	0.966722491	0.016801353	$1.79133E-08$
NG+B5E2W0.3	0.003306139	0.98413461	0.016829041	$1.86444E-08$
NG+B5E2W0.6	0.003321557	0.989874076	0.019910699	$1.98583E-08$

Table 8: Continued.

Damage category Unit	EQ $PDF^{*}m^{2*}yr$	R MJ primary	CCh kg CO_2 eq	HH DALY
NG+B5E2W0.9	0.003308331	0.994786528	0.020762447	$2.04849E-08$
NG+B5E4W0	0.003588905	0.994225923	0.019995435	$2.09851E-08$
NG+B5E4W0.3	0.003505152	0.998030092	0.018646689	$2.04942E-08$
NG+B5E4W0.6	0.003523378	0.995423681	0.019064997	$2.05238E-08$
NG+B5E4W0.9	0.003540772	0.992297633	0.018641339	$2.04581E-08$

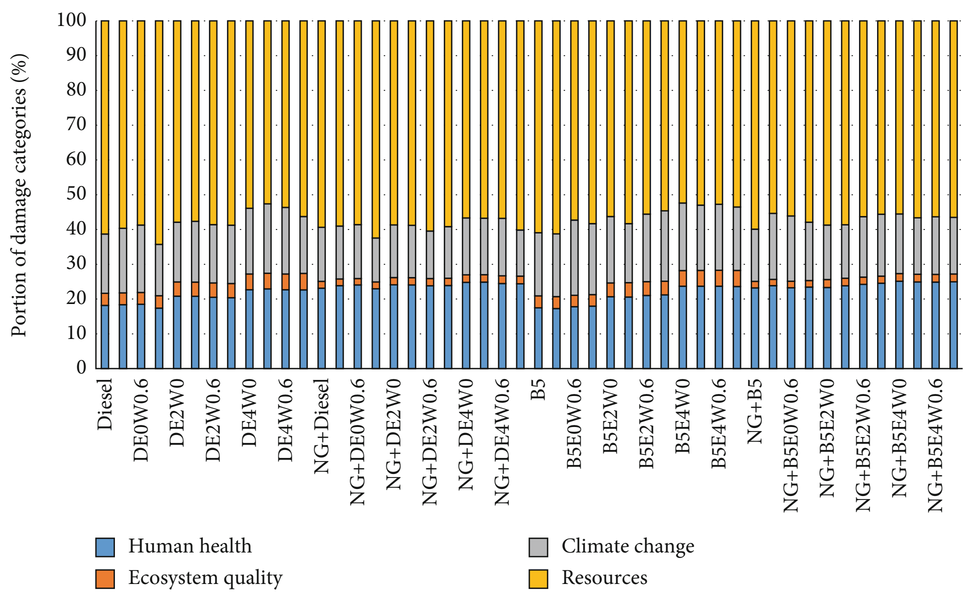

Figure 14: The portion of each damage category for each fuel sample.

relationships. The variables were divided into independent and dependent parts. Dependent variables include engine power, fuel consumption, emissions of CO, CO_2, NOx, and O_2, power cost, and endpoint impacts (EQ, R, HH, and CCh), and independent variables include amounts of biodiesel, water, ethanol, and NG. This optimization method relates the values of dependent and independent variables by creating a quadratic multivariate mathematical equation. In the following, with the mechanisms and operations of derivation based on the constraints that are determined as the main optimization conditions by the operator, it can produce the optimal values of the independent variables. Finally, the process achieves a desirability score between 0 and 1. The desirability number between 0.5 and 1 can produce the best optimization results [3]. Optimization is aimed at maximizing BP; minimizing BSFC, BSCO, BSNOx, and BSO2 emissions; and minimizing power cost and midpoint impacts for increasing the desirability score. In general, we would like to obtain a sustainable power generation condition from the economic, energy, and environmental points of view.

Table 9 presents the optimal values of dependent variables versus independent variables. Also, Figure 16 shows the changes in the desirability score concerning the independent variables.

Based on the changes in the variables in Figure 16, it is possible to examine the changes of the dependent variables about the independent variables in more detail. Figure 16(a) shows the trend of changes in the utility score against the changes in biodiesel and NG values. Based on the slope of the changes, it can be said that the effectiveness of the desirability score of NG changes is slightly higher compared to biodiesel. Also, increasing biodiesel decreases the desirability score, and increasing NG increases the desirability score.

Figure 16(b) presents the effect of ethanol and NG on the changes in the desirability score. Based on the changes, it can be said that the slope of the changes in the desirability score with the change of NG is higher than the slope of the changes with the change of ethanol. Therefore, it can be concluded that the effectiveness of the desirability score of NG changes is more than that of ethanol changes. Increasing the ethanol content decreases desirability score, and increasing the NG content increases the desirability score.

Figure 16(c) shows the trend of changes in the desirability score based on changes in water and NG. Based on the

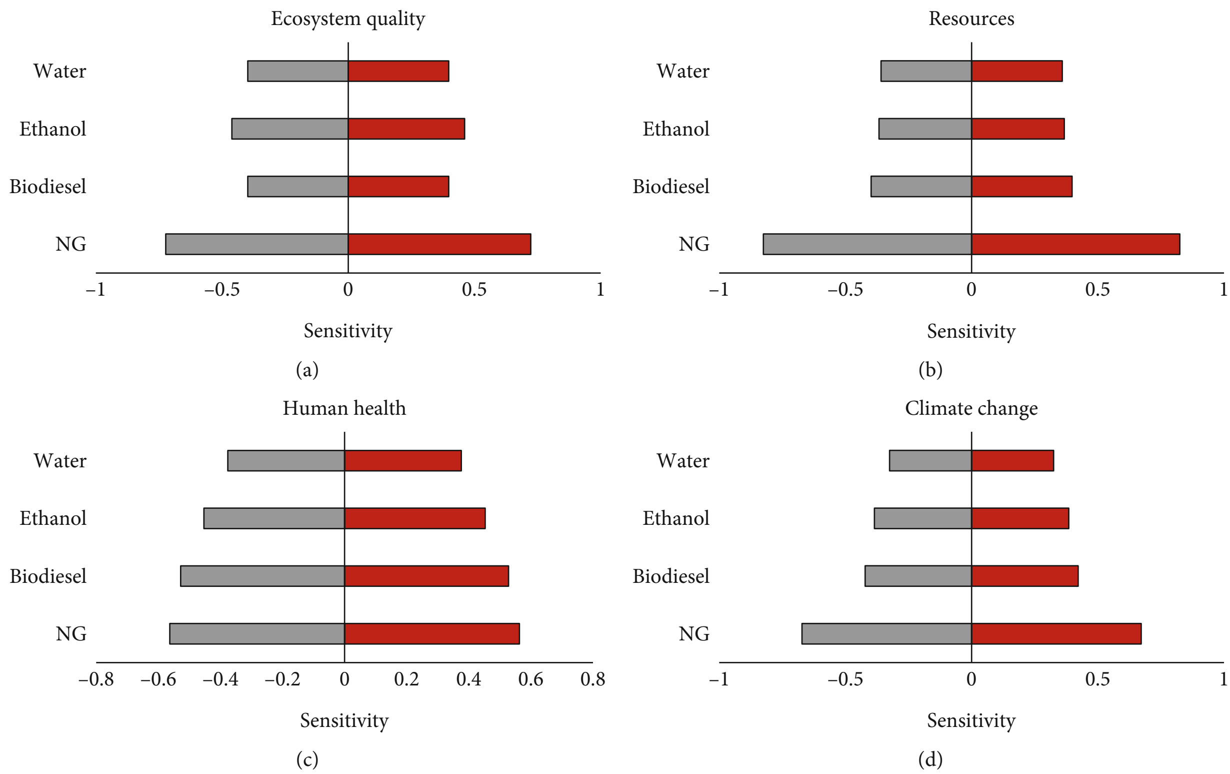

Figure 15: The results of sensitivity analysis for each independent value in each impact category. (a) EQ, (b) R, (c) HH, and (d) CCh.

Table 9: The sustainable operating condition of the engine.

Fuel combination			
NG (%)	Water (%)	Ethanol (%)	Biodiesel (%)
80	1.1	4.38	1.57
Engine performance parameters (energy)			
BP (kW)	BSFC (g/kWh)		
24.16	60.64		
Engine emission parameters (environmental)			
BSCO (g/kWh)	BSCO2 (g/kWh)	BSNOx (g/kWh)	BSO2 (g/kWh)
0.46	364.08	1.66	1088.29
Environmental impact assessment			
EQ ($PDF^* m^{2*} yr$)	R (MJ primary)	CCh (kg CO_2 eq)	HH (DALY)
0.34249	$1.00E+02$	$1.53E+00$	$1.94E-06$
Power cost (economy)			
Power cost ($/kWh)			
0.783			

direction of changes, it can be said that the slope of changes in the desirability score based on changes in NG is higher than the slope of water changes. With the increase in NG, the desirability score has increased relatively. What is confident from the observations is that the optimal conditions should occur in the fuel composition with low amounts of biodiesel and ethanol and a high amount of water and NG with a desirability value of 0.94.

Table 9 shows the optimal values of independent and dependent parameters. At full load, the optimum engine performance point occurs with a fuel sample containing 1.57% biodiesel, 4.38% ethanol, 1.1% water, and 80% NG. In this condition, the BP is 24.16 kW, and the specific fuel consumption is 60.64 g/kWh. This fuel sample produces 0.46, 364.08, 1.66, and 1088.29 g/kWh of BSCO, BSCO2, BSNOx, and BSO2, respectively. At this point, the energy production cost is $0.783/kWh. The environmental impacts of the combustion process at optimal fuel formulation are 0.34249, $1.00E+02$, $1.53E+00$, and $1.94E-06$, respectively, for EQ ($PDF^* m^{2*} yr$), R (MJ primary), CC (kg CO_2

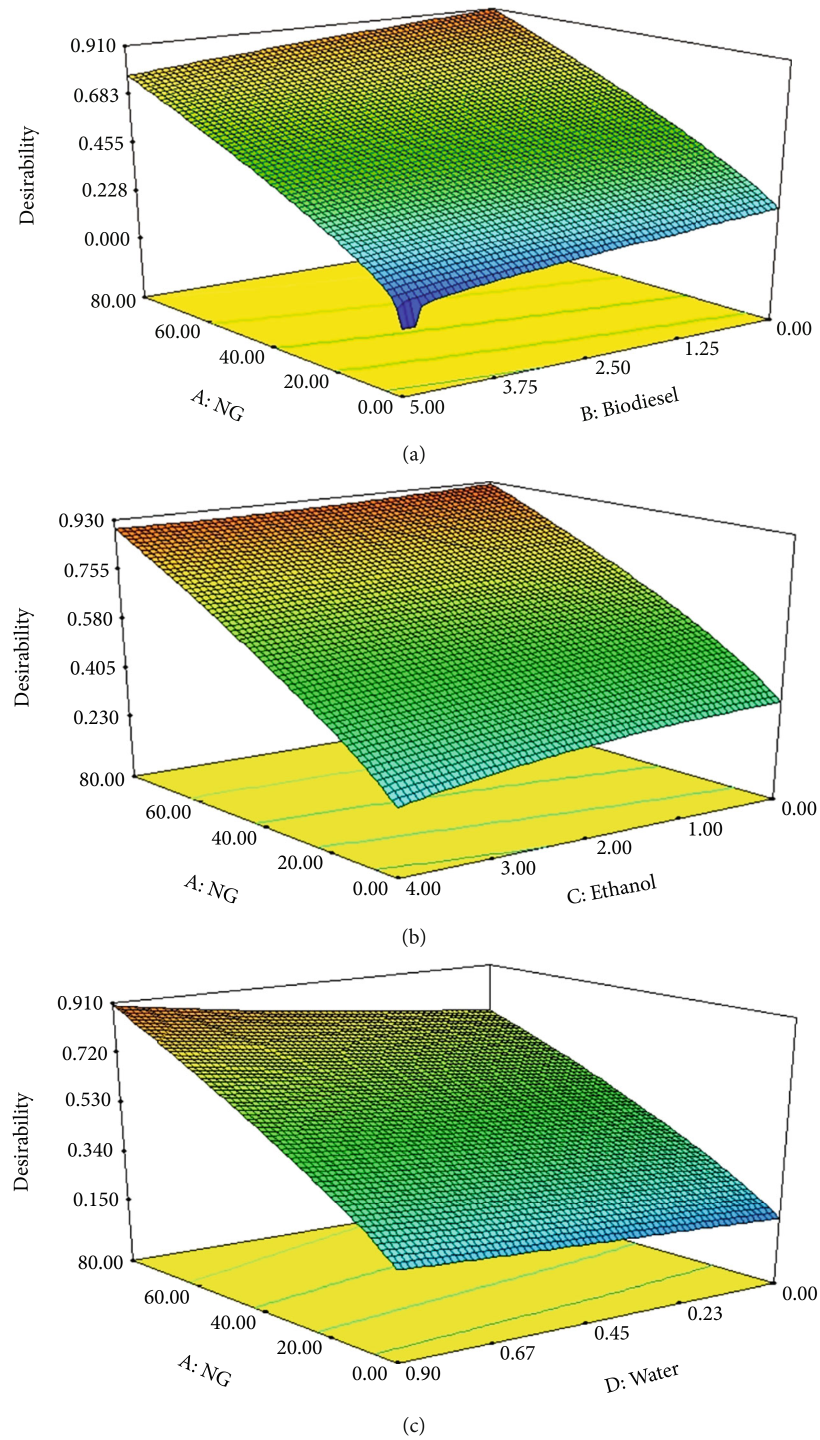

Figure 16: Optimized rates of variables for reaching a sustainable power generation: (a) biodiesel-NG, (b) ethanol-NG, and (c) water-NG.

eq), and HH (DALY). Accordingly, the best fuel combination was selected to be NG+B1.5E4.3W1.1.

4. Conclusion

This study examines the effects of water, ethanol, and biodiesel combined in DF in two combustion modes, including standard and DuF modes with NG, and discusses the performance and emissions of the DE from the viewpoint of life cycle assessment and power cost to reach a sustainable fuel formulation. Based on the observations, optimization was conducted to achieve the best engine performance, negligible environmental impacts, and power cost by applying the response surface method (RSM). This process can lead us towards sustainable energy production. The results showed that the additives used significantly affect the performance and emissions of the DE both in the standard process and in the DuF process. It is concluded that

(i) the presence of biodiesel and water in the fuel sample increases the fuel density

(ii) the presence of ethanol reduces the specific weight of fuel samples

(iii) the presence of 5% biodiesel in DF (B5) reduces the LHV of the fuel to a relative amount of approximately 1.2% compared to pure DF

(iv) adding water and ethanol to diesel and B5 fuels reduces the LHV of the fuel sample

(v) the highest ignition point corresponds to DF (87°C), and the lowest ignition point (24°C) corresponds to the B5E4W0.6 fuel sample

(vi) increasing the ethanol content has reduced the fuel viscosity, and increasing the water content has relatively improved the fuel viscosity

(vii) the presence of ethanol and water in the sample of fuels with biodiesel positively improves braking power compared to the sample of fuels without biodiesel

(viii) the presence of gaseous fuel in the combustion process has increased the braking power significantly (about 82% and 81%, respectively, compared to the single-fuel mode for diesel and B5)

(ix) the presence of natural gas, ethanol, and water positively affects the process of braking power changes compared to fuel without biodiesel

(x) the lowest BSFC is related to the sample of fuels that have been combusted in the DuF process (about 73 and 71% less than the single-fuel mode for diesel and B5 fuels, respectively)

(xi) carbon monoxide emission is, on average, 47 and 50% less in DuF mode than single-fuel mode, respectively, compared to DF

(xii) adding biodiesel to the fuel sample has increased carbon monoxide emissions by 16% and 10% compared to the fuel containing pure diesel for single-fuel and DuF conditions

(xiii) the presence of water in fuel samples containing pure diesel has successfully reduced the emission of nitrogen oxides

(xiv) the lowest energy production cost occurs in the DuF combustion process

(xv) the effect of fuel sample preparation and combustion on R followed by HH is higher than that for CCh and EQ. The maximum damage assessment is, respectively, related to B5E0W0.6 (0.0077 $PDF^{*}m^{2*}yr$, 1.506 MJ primary, 0.037 kg CO_2 eq, and $2.18E-08$ DALY, respectively, for EQ, R, CCh, and HH)

(xvi) according to sensitivity analysis, it has been obtained that NG has the most influence on all impact categories

(xvii) the optimal engine operation point at full load occurs with a fuel sample containing 1.57% biodiesel, 4.38% ethanol, 1.1% water, and 80% NG

However, various deep research gaps exist in obtaining a sustainable energy production path. Accordingly, further research needs to examine the economic implications of multiple additions. Also, technical analysis allows for considering fuel additive consistency aspects across a range of operational contexts. The future direction for studies is to move towards fuels with effective additives and small amounts because the economic cost for the preparation and use of additives can be considered a limiting factor. Also, using carbon-free fuels such as hydrogen as extra and gaseous fuel in the DuF combustion process can be the primary way to move towards sustainable production.

Abbreviations

ASTM: American Society for Testing and Materials
BSFC: Brake-specific fuel consumption (g/kWh)
BP: Brake power (kW)
BS: Brake specific
B5: Diesel/biodiesel blend containing five vol% biodiesel (%)
DE: Diesel engine
DF: Diesel fuel
DuF: Dual fuel
CO: Carbon monoxide (g/kWh)
CCh: Climate change (kg CO_2 eq)
CO_2: Carbon dioxide (g/kWh)
HH: Human health (DALY)
EQ: Ecosystem quality ($PDF^{*}m^{2*}yr$)
R: Resources (MJ primary)
NO_x: Nitrogen oxides (g/kWh)
PF: Pilot fuel (%)
NG: Natural gas (%)
O_2: Oxygen (g/kWh).

Nomenclatures

LHV: Lower heating value (kJ/kg)
r: The function of the uncertainty
M: Pilot fuel to gaseous fuel ratio
$\dot{m}$: Mass flow rate (kg/s)
k: Uncertainty of the measured parameter
$\dot{V}$: Volumetric flow rate (m^3/s).

Greek

ρ: Density (kg/m^3).

Subscripts

NG: Natural gas (%)
PF: Pilot fuel (%).

Data Availability

Data are available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] B. Chatterjee and D. Mazumder, "Role of stage-separation in the ubiquitous development of anaerobic digestion of organic fraction of municipal solid waste: a critical review," *Renewable and Sustainable Energy Reviews*, vol. 104, pp. 439–469, 2019.

[2] N. Banapurmath, W. M. Budzianowski, Y. Basavarajappa, R. Hosmath, V. Yaliwal, and P. Tewari, "Effects of compression ratio, swirl augmentation techniques and ethanol addition on the combustion of CNG–biodiesel in a dual-fuel engine," *International Journal of Sustainable Engineering*, vol. 7, no. 1, pp. 55–70, 2014.

[3] F. Ardabili, "Improving the combustion process of biodiesel using additives, [Ph.D. thesis]," in *Fundamental, Biosystem Engineering*, University of Mohaghegh Ardabili, Ardabil, Iran, 2021.

[4] M. Morales, G. Aroca, R. Rubilar, E. Acuna, B. Mola-Yudego, and S. González-García, "Cradle-to-gate life cycle assessment of *Eucalyptus globulus* short rotation plantations in Chile," *Journal of Cleaner Production*, vol. 99, pp. 239–249, 2015.

[5] A. Sharma, N. Kumar, V. Vibhanshu, and A. Deep, *Emission Studies on a VCR Engine Using Stable Diesel Water Emulsion*, no. article 0148-7191, 2013SAE Technical Paper, 2013.

[6] R. Vigneswaran, K. Annamalai, B. Dhinesh, and R. Krishnamoorthy, "Experimental investigation of unmodified diesel engine performance, combustion and emission with multipurpose additive along with water-in-diesel emulsion fuel," *Energy Conversion and Management*, vol. 172, pp. 370–380, 2018.

[7] S. F. Ardabili, B. Najafi, M. Aghbashlo, Z. Khounani, and M. Tabatabaei, "Performance and emission analysis of a dual-fuel engine operating on high natural gas substitution rates ignited by aqueous carbon nanoparticles-laden diesel/biodiesel emulsions," *Fuel*, vol. 294, article 120246, 2021.

[8] A. T. Hoang, M. Tabatabaei, M. Aghbashlo et al., "Rice bran oil-based biodiesel as a promising renewable fuel alternative to petrodiesel: a review," *Renewable and Sustainable Energy Reviews*, vol. 135, article 110204, 2021.

[9] A. T. Hoang, "Prediction of the density and viscosity of biodiesel and the influence of biodiesel properties on a diesel engine fuel supply system," *Journal of Marine Engineering Technology*, vol. 20, no. 5, pp. 299–311, 2021.

[10] A. T. Hoang and A. T. Le, "A review on deposit formation in the injector of diesel engines running on biodiesel," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 41, no. 5, pp. 584–599, 2019.

[11] A. T. Hoang, "Combustion behavior, performance and emission characteristics of diesel engine fuelled with biodiesel containing cerium oxide nanoparticles: a review," *Fuel Processing Technology*, vol. 218, article 106840, 2021.

[12] D. Balasubramanian, A. T. Hoang, I. P. Venugopal, A. Shanmugam, J. Gao, and T. Wongwuttanasatian, "Numerical and experimental evaluation on the pooled effect of waste cooking oil biodiesel/diesel blends and exhaust gas recirculation in a twin-cylinder diesel engine," *Fuel*, vol. 287, article 119815, 2021.

[13] E. Akbarian, B. Najafi, M. Jafari, S. Faizollahzadeh Ardabili, S. Shamshirband, and K. W. Chau, "Experimental and computational fluid dynamics-based numerical simulation of using natural gas in a dual-fueled diesel engine," *Engineering Applications of Computational Fluid Mechanics*, vol. 12, no. 1, pp. 517–534, 2018.

[14] E. Akbarian and B. Najafi, "A novel fuel containing glycerol triacetate additive, biodiesel and diesel blends to improve dual-fuelled diesel engines performance and exhaust emissions," *Fuel*, vol. 236, pp. 666–676, 2019.

[15] W. Zhao, Y. Zhang, G. Huang, Z. He, Y. Qian, and X. Lu, "Experimental investigation on combustion and emission characteristics of butanol/biodiesel under blend fuel mode, dual fuel RCCI and ICCI modes," *Fuel*, vol. 305, article 121590, 2021.

[16] I. Veza, A. D. Karaoglan, E. Ileri et al., "Grasshopper optimization algorithm for diesel engine fuelled with ethanol-biodiesel-diesel blends," *Case Studies in Thermal Engineering*, vol. 31, article 101817, 2022.

[17] P. Nemade and A. Krishnasamy, *Experimental Investigation on Reactivity Controlled Compression Ignition with Oxygenated Alternative Fuel Blends to Reduce Unburned Hydrocarbon Emissions*, no. article 0148-7191, 2021SAE Technical Paper, 2021.

[18] A. Singh and S. Singh, "Impact of biodiesel–diesel and diethyl ether blends on the performance and emissions of a dual fuel diesel engine," *Journal of The Institution of Engineers (India): Series C*, vol. 102, no. 3, pp. 705–711, 2021.

[19] S. Singla, N. S. Mahla, and G. Goga, "Investigations on performance and emission characteristics of diesel engine fuelled with biogas and ethanol-biodiesel-diesel blend," *International Journal on Emerging Technologies*, vol. 10, no. 3, pp. 141–147, 2019.

[20] L. Tarabet, K. Loubar, M. Lounici, K. Khiari, T. Belmrabet, and M. Tazerout, "Experimental investigation of DI diesel engine operating with eucalyptus biodiesel/natural gas under dual fuel mode," *Fuel*, vol. 133, pp. 129–138, 2014.

[21] E. Tomita, N. Kawahara, U. Azimov, E. Tomita, N. Kawahara, and U. Azimov, "Significance of biogas, its production and utilization in gas engines," in *Biogas Combustion Engines for Green Energy Generation*, pp. 1–12, Springer, 2022.

[22] S. Bilgen, S. Keleş, A. Kaygusuz, A. Sarı, and K. Kaygusuz, "Global warming and renewable energy sources for sustainable development: a case study in Turkey," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 2, pp. 372–396, 2008.

[23] J. A. Kemper, P. W. Ballantine, and C. M. Hall, "Global warming and sustainability: understanding the beliefs of marketing faculty," *Journal of Public Affairs*, vol. 18, no. 4, article e1664, 2018.

[24] A. Murugesan, C. Umarani, R. Subramanian, and N. Nedunchezhian, "Bio-diesel as an alternative fuel for diesel engines–a review," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 3, pp. 653–662, 2009.

[25] H. Valera and A. K. Agarwal, "Methanol as an alternative fuel for diesel engines," in *Methanol and the Alternate Fuel Economy*, pp. 9–33, Springer, 2019.

[26] ISO, "ISO 14040 International Standard," in *Environmental Management-Life Cycle Assessment-Principles Framework*, International Organisation for Standardization, 2006.

[27] M. Perčić, N. Vladimir, and A. Fan, "Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: a case study of Croatia," *Applied Energy*, vol. 279, article 115848, 2020.

[28] J. Cooper and P. Balcombe, "Life cycle environmental impacts of natural gas drivetrains used in road freighting," *Procedia CIRP*, vol. 80, pp. 334–339, 2019.

[29] A. Sharma and V. Strezov, "Life cycle environmental and economic impact assessment of alternative transport fuels and power-train technologies," *Energy*, vol. 133, pp. 1132–1141, 2017.

[30] Y. Wang, H. Maidment, V. Boccolini, and L. Wright, "Life cycle assessment of alternative marine fuels for super yacht," *Regional Studies in Marine Science*, vol. 55, article 102525, 2022.

[31] P. A. R. Ramos, I. T. Pérez, J. Suárez-Hernández, R. Piloto-Rodriguez, and S. Pohl, "On the environmental and economic issues associated with the Jatropha curcas shell gasification to heat and electricity for biodiesel production," *Afinidad. Journal of Chemical Engineering Theoretical and Applied Chemistry*, vol. 79, no. 596, 2022.

[32] H. Hosseinzadeh-Bandbafha, F. Nazemi, Z. Khounani et al., "Safflower-based biorefinery producing a broad spectrum of biofuels and biochemicals: a life cycle assessment perspective," *Science of the Total Environment*, vol. 802, article 149842, 2022.

[33] C. Ternel, A. Bouter, and J. Melgar, "Life cycle assessment of mid-range passenger cars powered by liquid and gaseous biofuels: comparison with greenhouse gas emissions of electric vehicles and forecast to 2030," *Transportation Research Part D: Transport and Environment*, vol. 97, article 102897, 2021.

[34] H. Hosseinzadeh-Bandbafha, S. Rafiee, P. Mohammadi et al., "Exergetic, economic, and environmental life cycle assessment analyses of a heavy-duty tractor diesel engine fueled with diesel-biodiesel-bioethanol blends," *Energy Conversion and Management*, vol. 241, article 114300, 2021.

[35] L. Bilgili, "Comparative assessment of alternative marine fuels in life cycle perspective," *Renewable and Sustainable Energy Reviews*, vol. 144, article 110985, 2021.

[36] D. Y. Leung, X. Wu, and M. Leung, "A review on biodiesel production using catalyzed transesterification," *Applied Energy*, vol. 87, no. 4, pp. 1083–1095, 2010.

[37] A. Srivastava and R. Prasad, "Triglycerides-based diesel fuels," *Renewable and Sustainable Energy Reviews*, vol. 4, no. 2, pp. 111–133, 2000.

[38] F. Ma and M. A. Hanna, "Biodiesel production: a review[1]," *Bioresource Technology*, vol. 70, no. 1, pp. 1–15, 1999.

[39] B. Najafi, S. Faizollahzadeh Ardabili, S. Shamshirband, K. W. Chau, and T. Rabczuk, "Application of ANNs, ANFIS and RSM to estimating and optimizing the parameters that affect the yield and cost of biodiesel production," *Engineering Applications of Computational Fluid Mechanics*, vol. 12, no. 1, pp. 611–624, 2018.

[40] N. U. Soriano Jr., R. Venditti, and D. S. Argyropoulos, "Biodiesel synthesis via homogeneous Lewis acid-catalyzed transesterification," *Fuel*, vol. 88, no. 3, pp. 560–565, 2009.

[41] S. Faizollahzadeh Ardabili, B. Najafi, M. Alizamir, A. Mosavi, S. Shamshirband, and T. Rabczuk, "Using SVM-RSM and ELM-RSM approaches for optimizing the production process of methyl and ethyl esters," *Energies*, vol. 11, no. 11, p. 2889, 2018.

[42] S. Faizollahzadeh Ardabili, B. Najafi, and S. Shamshirband, "Fuzzy logic method for the prediction of cetane number using carbon number, double bounds, iodic, and saponification values of biodiesel fuels," *Environmental Progress & Sustainable Energy*, vol. 38, no. 2, pp. 584–599, 2019.

[43] J. Ghazanfari, B. Najafi, S. Faizollahzadeh Ardabili, and S. J. C. E. Shamshirband, "Limiting factors for the use of palm oil biodiesel in a diesel engine in the context of the ASTM standard," *Cogent Engineering*, vol. 4, no. 1, article 1411221, 2017.

[44] E. Yılmaz, H. Arslan, and A. Bideci, "Environmental performance analysis of insulated composite facade panels using life cycle assessment (LCA)," *Construction and Building Materials*, vol. 202, pp. 806–813, 2019.

[45] A. La Rosa, D. Banatao, S. Pastine, A. Latteri, and G. Cicala, "Recycling treatment of carbon fibre/epoxy composites: materials recovery and characterization and environmental impacts through life cycle assessment," *Composites Part B: Engineering*, vol. 104, pp. 17–25, 2016.

[46] G. Rebitzer, T. Ekvall, R. Frischknecht et al., "Life cycle assessment: part 1: framework, goal and scope definition, inventory analysis, and applications," *Environment International*, vol. 30, no. 5, pp. 701–720, 2004.

[47] P. Van den Heede and N. De Belie, "Environmental impact and life cycle assessment (LCA) of traditional and 'green' concretes: literature review and theoretical calculations," *Cement and Concrete Composites*, vol. 34, no. 4, pp. 431–442, 2012.

[48] A. Nabavi-Pelesaraei, H. Azadi, S. Van Passel et al., "Prospects of solar systems in production chain of sunflower oil using cold press method with concentrating energy and life cycle assessment," *Energy*, vol. 223, article 120117, 2021.

[49] A. Kylili, E. Christoforou, and P. A. Fokaides, "Environmental evaluation of biomass pelleting using life cycle assessment," *Biomass and Bioenergy*, vol. 84, pp. 107–117, 2016.

[50] F. Cherubini, S. Bargigli, and S. Ulgiati, "Life cycle assessment (LCA) of waste management strategies: landfilling, sorting plant and incineration," *Energy*, vol. 34, no. 12, pp. 2116–2123, 2009.

[51] J. B. Heywood, *Internal Combustion Engine Fundamentals*, McGraw-Hill Education, 2018.

[52] D. Lovarelli, M. Fiala, and G. Larsson, "Fuel consumption and exhaust emissions during on-field tractor activity: a possible improving strategy for the environmental load of agricultural mechanisation," *Computers and Electronics in Agriculture*, vol. 151, pp. 238–248, 2018.

[53] A. Saltelli, M. Ratto, T. Andres et al., *Global Sensitivity Analysis: The Primer*, John Wiley & Sons, 2008.

[54] M. J. Pratas, S. V. Freitas, M. B. Oliveira, S. C. Monteiro, Á. S. Lima, and J. A. Coutinho, "Biodiesel density: experimental measurements and prediction models," *Energy & Fuels*, vol. 25, no. 5, pp. 2333–2340, 2011.

[55] B. Tesfa, F. Gu, R. Mishra, and A. Ball, "LHV predication models and LHV effect on the performance of CI engine running with biodiesel blends," *Energy Conversion and Management*, vol. 71, pp. 217–226, 2013.

[56] P. S. Mehta and K. Anand, "Estimation of a lower heating value of vegetable oil and biodiesel fuel," *Energy & Fuels*, vol. 23, no. 8, pp. 3893–3898, 2009.

[57] W.-J. Lee, Y.-C. Liu, F. K. Mwangi et al., "Assessment of energy performance and air pollutant emissions in a diesel engine generator fueled with water-containing ethanol-biodiesel-diesel blend of fuels," *Energy*, vol. 36, no. 9, pp. 5591–5599, 2011.

[58] L. F. R. Verduzco, "Density and viscosity of biodiesel as a function of temperature: empirical models," *Renewable and Sustainable Energy Reviews*, vol. 19, pp. 652–665, 2013.

[59] K. Krisnangkura, T. Yimsuwan, and R. Pairintra, "An empirical approach in predicting biodiesel viscosity at various temperatures," *Fuel*, vol. 85, no. 1, pp. 107–113, 2006.

[60] L. Razzaq, M. Mujtaba, M. Shahbaz et al., "Effect of biodiesel-dimethyl carbonate blends on engine performance, combustion and emission characteristics," *Alexandria Engineering Journal*, vol. 61, no. 7, pp. 5111–5121, 2022.

[61] P. Patel, B. Patel, E. Vekaria, and M. Shah, "Biophysical economics and management of biodiesel, a harbinger of clean and sustainable energy," *International Journal of Energy and Water Resources*, vol. 4, no. 4, pp. 411–423, 2020.

[62] C. Venkataraman and G. U. M. Rao, "Emission factors of carbon monoxide and size-resolved aerosols from biofuel combustion," *Environmental Science & Technology*, vol. 35, no. 10, pp. 2100–2107, 2001.