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Systematic Review

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To study the effects of physicochemical properties of emulsified biofuel upon CI Engine attributes

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Abstract:

The fossil fuel is presently served as one of the predominant sources of global energy demand. However, due to their finite reserves, international disturbance and the escalating emissions create interest to generate a renewable and cleaner energy alternative fuel. In this context, biofuel derived to the biomass has appeared as a promising substitute for conventional petroleum fuels. Among different biofuels, Emulsified biofuel (EBF) has attracted researchers due to their potential of 100% replacement to fossil fuel without any engine modification and with reduced emissions. Emulsified biofuel is a thermodynamically stable emulsion, a blend of diesel and or biodiesel or vegetable oil, alcohol and or water, and surfactants. This review paper seeks to deliver the intricate correlation between the physiochemical properties of EBF and their effects upon the performance parameters of CI engines. Furthermore, the study investigates how different compositions of EBF affect upon CI engine performance attributes under varied operating conditions. The comparative analyses between petroleum diesel and Emulsified biofuel have conducted to gauge enhancements in engine performance and emission characteristics. As per the literature, the pentanol blended diesel fuels (PE5, PE10, PE20) significantly impact upon the fuel properties and engine behavior. PE20 notably reduces the calorific value (8.12%), density (1.20%), and viscosity (12%), and alters combustion pressure and heat release, indicating pentanol's effectiveness in enhancing BTE and BSFC. Also, the findings underscore the considerable impact of EBF physiochemical

characteristics on combustion processes and overall engine performance. Optimal biofuel compositions show enhanced performance parameters alongside reduced emissions.

Keywords: Emulsions, Brake specific fuel consumption (BSFC), Brake power (BP), Brake thermal efficiency (η_{th}), Exhaust gas temperature (EGT)

EBF	Emulsified biofuels	PM	Particulate Matter
MBBF	Microemulsion based biofuels	CO	Carbon monoxide
JCO	Jatropha Curcas oil	CO₂	Carbon dioxide
CCO	Crude Coconut oil	UHC	Unburned hydrocarbon
CPO	Crude Pongamia Oil	NO_x	Oxides of Nitrogen
VCO	Virgin Coconut oil	SO₂	Sulfur dioxide
PO	Pongamia oil	PM	Particulate matter
DPO	Degummed Pongamia oil	D100	100% diesel
GOME	Grape seed oil methyl ester	B100	100% Biodiesel
SVO	Straight vegetable oil	D50B50	50% Diesel & 50% Biodiesel
DT&E	Diesel with Tung oil & ethanol	DBO P30	50% Diesel + 15% Jatropha BD + 5% Jatropha oil + 30% Pentanol
CI	Compression ignition	B(CIME)	Biodiesel Calophyllum Inophyllum methyl ester
SI	Spark Ignition	B80P20	80% Biodiesel Calophyllum Inophyllum methyl ester + 20% Pentanol
SB	Soybean biodiesel	B60P40	60% Biodiesel Calophyllum Inophyllum methyl ester +40% Pentanol
SBS	Soybean biodiesel Solketal	P100	100% Pentanol
RPM	Revolution per minute	M100	100% methanol
BP	Brake Power	D80P20	80% Diesel & 20% Pentanol
BTE	Brake thermal efficiency	D70 P20 M10	Diesel 70% + Pentanol 20% + Methanol 10%
BSFC	Brake specific fuel consumption	D70 P15 M15	Diesel 70% + Pentanol 15% + Methanol 15%
GCV	Gross calorific value	DF95P5PE5	95% Diesel fuel + 5% Pentanol
PCP	Peak (highest) cylinder pressure	DF80P5PE20	80% Diesel fuel + 20% Pentanol
NHRR	Net(total) heat release rate	JB	Jatropha Biodiesel
HLB	Hydrophilic lipophilic balance	D80J20	80% Diesel +20% Jatropha
CCO+ E+B	Crude coconut oil+ ethanol+ butanol	D60J20P20	60% Diesel + 20% Jatropha + 20% Pentanol
EGT	Exhaust gas temperature	D70J20P10	70% Diesel + 20% Jatropha + 10% Pentanol
PHRR	Peak(highest) heat release rate	TDC	Top dead center
ASTM	American Society for testing and materials	PCT	Peak(highest) cylinder temperature
WCO	Waste cooking oil		

1.1 Introduction

CI engines are favored over SI engines because of their higher efficiency and better fuel economy. CI engines operate using conventional fuel (diesel), which is typically derived to the extraction through crude oil and performs effectively within a temperature range of 180 °C to 360 °C. The diesel is mainly consists of saturated hydrocarbons, including paraffins and naphthenes, which make up approximately 75% of its composition, while the remaining 25% consists of aromatic hydrocarbons compound [1]. The different properties of No. 1 diesel fuel, according to ASTM D975 standards, are presented in Table 1, with a viscosity similar to kerosene, performs better in low-temperature conditions, whereas No. 2 diesel, known for its lower volatility and greater fuel efficiency, is more commonly used in CI engines [2]. The CI engines play a crucial role in multiple industries, including transport (rail, road, and marine), farming, and structure building. However, rising concerns have emerged due to the limited availability and increasing cost of diesel, which pose challenges to energy safety and economic stability. Furthermore, diesel emissions contribute to ecological pollution and adverse health effects. [3-4] To tackle these issues, strict environmental rules have been implemented to reduce emissions of harmful pollutants such as particulate matter (PM), oxides of nitrogen (NO_x), carbon monoxide (CO), unburned hydrocarbon (UHC) and smoke [5-6]. Although CI engines typically produce fewer emissions as compared to spark ignition (SI) engines but, the noteworthy challenges are still presently, especially in terms of PM and NO_x emissions [6]. The particulate matter is known to have serious environmental and health impacts, while the nitrogen oxides lead to the occurrence of acid rain smog, and ground-level ozone [7]. As a result, there is increasing interest in renewable and cleaner energy alternatives to address these concerns [8].

Table 1 Physicochemical properties of petroleum diesel [2-4].

S. No.	Properties	Standard Value for Diesel	Diesel No. 1	Diesel No. 2
1	Kinematic Viscosity (40°C) (mm ² /s)	1.9 - 4.1	1.31-2.41	1.91-4.12
2	Cetane no (CN) min.	≥40	41	41
3	Flash point, min. (°C)	≥52	38.5	53
4	Sulphur, max. (ppm)	≤15	14	61
5	Residue, max. (% mass)	≤0.35	0.011	0.011
6	Ramsbottom carbon filtrate, Max.(%mass)	≤0.35	0.153	0.348
7	Conduction, min. (pS/m)	≥25	26	26
8	Lubrication, max. (micron)	≤520	521	522

The combustion of diesel fuel also releases various other harmful emissions, such carbon monoxide (CO), oxides of sulfur (SO_x), and various unburned hydrocarbons which persist in the environment and contribute to global heating and acid rain [5]. Recent reports from the World Health Organization (WHO) indicate a global increase in air pollution by 8% between 2008 and 2013, with experts warning of worsening conditions in the future [9-10].

The worldwide demand for biofuel will keep rising because of current energy demand and climate change policies [2]. Bioenergy is obtained through biomass, which includes organic substances like animals, plants, and microorganisms, through biochemical processes such as combustion, fermentation, or gasification [11]. Biomass is a renewable resource that has the potential to lower greenhouse gas emissions, reduce reliance on fossil fuels, and boost rural development [5]. There are several forms of biomass sources, including agricultural goods and processing leftovers, timber and logging waste, animal manure, food processing residues, aquatic plants and algae, and municipal solid waste [12]. Biodiesel, which consists of methyl esters, can be made from more than four hundred sources [8-10]. Common edible oils used for biodiesel production include

1 sunflower, soybean, rapeseed, and rice bran etc. Biodiesel can be produced from animal fats such
2 as pork lard, beef tallow, and poultry fat. Alternative feedstocks include algae, certain bacteria,
3 and plants like poplar and switchgrass. [13]

4 Biofuels have emerged as valuable alternatives to conventional diesel fuel [14] due to their
5 potential to moderate greenhouse gas emissions, reduce dependence on fossil resources, and
6 promote sustainable energy development [3]. It is produced to the renewable organic sources
7 through diverse conversion pathways. Biofuels reflect physicochemical properties that can be
8 tailored to approximate those of petrodiesel [15-16]. Among these, straight vegetable oil (SVO),
9 particularly derived from nonedible feedstocks, has involved significant attention [17] because it
10 does not compete openly with food resources and is widely available in many agricultural
11 economies. Its renewable nature and potential for carbon neutrality make it an appealing candidate
12 for CI engine applications [18-19].

13 Despite these advantages, the direct utilization of SVO in CI engines presents considerable
14 technical challenges [17]. The primary limitation arises from its fundamentally high viscosity,
15 which adversely affects fuel injection characteristics [7]. Elevated viscosity leads to reduced
16 atomization, larger droplet formation, and reduced spray penetration, bring about in incomplete
17 combustion and lower thermal efficiency [14-15]. In addition, SVO typically reveals higher
18 density and lower cetane number [20-21] compared with conventional diesel, contributing to
19 lengthy ignition delay and suboptimal combustion phasing. These combustion irregularities may
20 increase fuel consumption and exhaust emissions [17].

21 Operational issues further limit its direct application. Long term engine use with untreated SVO
22 has been allied with injector fouling, carbon deposition on piston crowns and valves, gum

1 formation in fuel systems, and accelerated deprivation of lubricating oil [22-23]. Such effects
2 compromise engine durability and maintenance intervals [24-25]. To overcome these downsides,
3 several fuel modification strategies have been explored. Common methodologies include blending
4 with diesel to dilute viscosity, preheating to enhance fluidity, pyrolysis [22] to reduce molecular
5 complexity, transesterification to produce biodiesel with enhanced properties, hydrotreatment for
6 upgrading fuel quality, and microemulsification [26-28] using suitable surfactants and co solvents
7 to achieve stable, lower viscosity fuel systems [29-30]. These practices aim to optimize
8 combustion behavior while protective the environmental benefits of renewable feedstocks [20-21].

9 Emulsion based biofuels offer a promising alternative energy solution with probable cost savings
10 in production. This methodology involves mixing vegetable or visceral fat oils with lower
11 molecular weight alcohols to recover the compatibility between polar and nonpolar components,
12 aided by surfactants and co surfactants [24]. This method decreases the interfacial tension between
13 the polar detached phase (such as ethanol) and the continuous oil phase, thereby producing a fuel
14 with features similar to conventional diesel and biodiesel [20]. Due to its formation process, it is
15 referred to as emulsification [31]. Emulsification entails blending two liquids that don't naturally
16 mix usually a light alcohol with a combination of vegetable oil and diesel while incorporating
17 surfactants to ensure the mixture remains stable. [25]. Emulsified biofuels are known for their
18 transparency, thermodynamic stability, and uniform structure, resulting from the small micelle size
19 (10-100 nm) [22-24]. The low cost of the product, simplicity of operation, and minimal
20 requirement for fuel processing without chemical reactions are reasons why the emulsification
21 method is better than other methods [30]. Another benefit of this approach is that it may be applied
22 directly to diesel engines without requiring any engine system modifications [32]. Emulsion based
23 biofuel is economical as compared to normal biodiesel production because it avoids energy

1 intensive transesterification, catalysts, and complex downstream purification used in normal
2 biodiesel production [23]. It is generated mainly by low energy mixing of oil, alcohol, water, and
3 surfactant, (simple blending only) which reduces equipment, operating, and processing costs while
4 utilizing cheaper feedstocks such as used cooking oil, animal fat, castor oil, algal oil etc. [25].
5 Emulsions are uniquely important compared to other biofuel strategies. The emulsification
6 technique is a method that can be utilized to minimize the issues related to the use of neat diesel
7 fuels and convert them into acceptable biofuel [33]. It offers several benefits, such as low
8 production costs, simple application, compatibility with existing engines without modifications,
9 and the advantage of not requiring chemical reactions. [34-35]. Emulsion biofuel can be
10 formulated to used or waste and nonedible lipid streams [36-38]. The main feedstocks include
11 waste/used cooking oil, animal fat oil, palm oil or palm biodiesel, mixed vegetable oils, and
12 blends of waste cooking oil with microalgae oils [39]. It carried out an extensive environmental
13 evaluation of biofuel produced through emulsion, using a mixture of palm oil, diesel, and ethanol
14 [36]. The structural characteristics of emulsions were analyzed using particle size [37]. Their study
15 highlighted key properties, including viscosity and temperature dependence, which contribute to
16 the prospective use of emulsified fuels in conventional diesel engines [18]. A key factor in the
17 successful formulation of emulsified biofuels is the careful selection of surfactant systems, such
18 as the use of one octanol and oleyl amine as the surfactant and cosurfactant, respectively [40-42],
19 which play a key role in maintaining phase stability and avoiding issues like phase separation and
20 precipitation. [40,43]. Co-surfactants, like alkanols, are essential in improving surfactant
21 efficiency, facilitating the solubilization of both nonpolar oils and polar ethanol, and affecting
22 system curvature [33]. Research, including our own, has examined how the chain length of
23 cosurfactants such as normal butanol, normal octanol, and normal-decanol influences the

1 formation of water in oil (w/o) emulsions. [35]. Though, research on the role of alkanols in exhaust
2 gas emissions remains limited, particularly in the perspective of palm oil grounded emulsion
3 biofuels [25]. Rising environmental concerns have intensified the search for sustainable alternative
4 fuels where researchers developed emulsion fuels by blending canola oil with diesel and adding
5 ethanol to lower the viscosity [25]. To maintain homogeneity and stability of the fuel, they
6 employed anionic carboxylate-based extended surfactants along with co-surfactants [35]. In a
7 similar approach, canola oil-diesel emulsions were also developed using oleylamine as the
8 surfactant and 1-octanol as the cosurfactant. [39]. The assessment of fuel properties and engine
9 performance indicated that emulsion biofuels complied with American society for testing &
10 materials (ASTM) biodiesel standards [2]. Certain formulations demonstrated reduced NO_x and
11 CO emissions when matched to conventional diesel. Although fuel consumption saw a slight
12 increase in direct injection diesel engines, the possible environmental advantages of emulsion fuels
13 validate continued research and development [44]. Compared to techniques like dilution, thermal
14 cracking (pyrolysis), and transesterification, emulsification presents a simpler, faster, and
15 additional economical alternative [22]. Its advantage lies in the absence of chemical reactions and
16 by product formation, which simplifies the process and lessens production complexities [23, 34].
17 Using vegetable oil directly as fuel or blending it with petrodiesel is impractical due to its high
18 viscosity. This larger viscosity can cause matters such as clogged fuel lines, poor fuel atomization,
19 excessive penetration, engine deposits, oil thickening, and piston ring stabbing [45-47]. To address
20 these challenges, methods like transesterification, dilution, and pyrolysis are normally used.
21 Engine performance and emissions are suggestively influenced by variables like the feedstock
22 used, the percentage of biodiesel in the fuel mixture, and the specific engine technology employed
23 [31,48]. In the catalytic transesterification process, oil reacts with alcohol to generate biodiesel

1 along with alkyl-based monoesters, and glycerol as a byproduct [49]. Glycerol is extensively used
2 in industries such as pharmaceuticals and cosmetics. To encourage the adoption of biofuels in
3 transportation, new energy rules have been introduced in Europe, requiring that 10% of the energy
4 used in the transport sector come from biofuels by 2020 [49]. This regulation is anticipated to drive
5 a considerable rise in glycerol production, surpassing its existing demand in the pharmaceutical
6 and cosmetic industries. As a result, it is essential to identify and develop alternative uses for
7 glycerol to effectively manage the probable surplus. [50]. Solketal, a glycerol derivative, exhibits
8 advantageous properties such as minimizing gum formation and particulate emissions while
9 improving oxidation stability, cetane number, and cold flow performance [51]. These
10 characteristics position solketal as a potential substitute for ethanol, providing similar fuel
11 characteristics [51-52].

12 **1.2 Methodology:** EBF is formulated through low energy blending technique. The selected base
13 oil (non-edible vegetable oil or waste cooking oil (WCO)) was first filtered and dried out to remove
14 impurities and moisture. The pre-determined proportions of diesel, alcohol (ethanol or butanol),
15 surfactant, and cosurfactant were measured accurately. The surfactant was chosen based on
16 hydrophilic lipophilic balance (HLB) necessities to ensure phase stability. The all constituents of
17 EBF were mixed with using of a magnetic stirrer at controlled temperature until a clear,
18 homogeneous, and thermodynamically stable emulsion was obtained. The physical stability was
19 confirmed through visual observation and centrifugation tests. Physicochemical properties
20 including density, kinematic viscosity, calorific value, flash point, and cetane index were measured
21 following ASTM standards before conducting engine performance and emission tests.

22 **1.3 Objective:** The present study aims to review about the effects of physicochemical properties
23 of emulsion-based hybrid biofuels derived from renewable lipid feedstocks as a viable alternative

to petrodiesel for CI engines. This review work also focuses upon the formulation strategies of EBF with using of suitable combinations of vegetable oils, alcohols, surfactants, and cosurfactants to achieve physicochemical properties as good as to ASTM diesel standard values. Additionally, the study intends to investigate fuel characteristics, combustion behavior, engine performance, and emission profiles, while talking viscosity related limitations of SVO. Emphasis is placed on optimizing formulation considerations to enhance stability, efficiency, environmental compatibility, and economic feasibility without requiring engine alterations.

1.4 Research Gap: Although numerous studies have examined on biodiesel, SVO modification, and emulsification techniques but, several critical gaps still exist. Most existing research focuses primarily on improving viscosity and stage stability of emulsion fuels, with limited systematic evaluation of their long-term combustion behavior, ignition characteristics, and permanency impacts in CI engines. Furthermore, the combined influence of surfactant cosurfactant chain length, alcohol type, and water content on emission exchanges particularly NO_x, PM interactions remain insufficiently explored. Studies addressing palm oil and other nonedible feedstock-based emulsions are comparatively uncommon, especially under varied engine loads and speeds. In addition, wide ranging technoeconomic and lifecycle assessments comparing emulsification with transesterification are limited. Therefore, an integrated analysis linking formulation chemistry, engine performance, emissions, and sustainability metrics is required to found optimized emulsion biofuel systems.

1.5 Limitations & challenges of Emulsion based emulsified fuel: emulsion-based biofuels offer advantages in combustion and emission control; however, several limitations remain for long term applications. One major challenge is fuel stability over extended storage periods, as phase separation may occur due to variations in temperature, surfactant concentration, or water content.

The selection and cost of suitable surfactants and co surfactants can also increase the overall production cost of the fuel. In addition, emulsion fuels often exhibit lower calorific value, which may reduce engine power and increase fuel consumption during prolonged operation. Long term engine use may also raise concerns related to fuel system compatibility, corrosion, and deposit formation. Furthermore, limited large scale experimental data and the need for optimized formulation methods remain challenges for widespread commercial adoption.

1.6 Solution & large-scale feasibility: Emulsion biofuels can become a practical alternative fuel if formulation and manufacturing methods are properly optimized. Stable blends can be accomplished by selecting suitable surfactants and retaining suitable ratios of oil, alcohol, and water to prevent phase parting. Enhancing fuel properties such as viscosity and calorific value through additive optimization can boost engine performance. For large scale feasibility, low-cost feedstocks like non edible vegetable oils and WCO should be used. In addition, standardized production processes, fuel quality control, and compatibility with existing diesel engines can support marketable adoption of emulsion biofuels. It can produce gallons of biodiesel as well as 100 percent replaceable to diesel fuel.

2. Fuel Properties of the Emulsified Fuels

2.1 Physicochemical Properties of the Emulsified Fuels

The physicochemical characteristics of the formulated emulsion fuels were considered to evaluate their impact on diesel engine performance and emissions. Tables 2 provide a comparative overview of main properties, including total heating value, density, specific gravity, kinematic viscosity, cetane number, pour point, and flash point. For biodiesel to perform suitably in diesel engines, standards specify a kinematic viscosity of about 1.9–6.0 mm²/s at 40 °C (ASTM D6751)

or 3.5–5.0 mm²/s (EN 14214), and a lowest cetane number of 47 (ASTM D6751) or 51 (EN 14214) [53]. The combustion of the diesel-biodiesel-bioethanol emulsions yielded a heat release of 43.95 MJ/kg, showing an approximate 21% enhancement over pure biodiesel and a slight reduction of around 2% relative to conventional diesel [10]. Notably, the prepared emulsions revealed lower density, specific gravity, kinematic viscosity, pour point, and flash point compared to both diesel and biodiesel, as shown in Table 2. The physicochemical properties outlined in Table 2, including calorific value, density, kinematic viscosity, flash point, and cetane number/index, play a decisive role in determining CI engine performance, combustion, and emissions. The study found that a blend comprising 85% virgin coconut oil, 10% ethanol, and 5% butanol showed the highest GCV among the blends tested [54]. However, the use of this blend adversely impacted the Brake specific fuel consumption (BSFC) of the CI engine compared to petrodiesel. This was recognized to the higher viscosity and lower GCV of the blend compared to petrodiesel, causing in reduced injection and incomplete combustion, ultimately leading to higher emulsion-based hybrid biofuel (EBF) consumption of the blend. The production process of Grape seed oil methyl ester (GOME) involves the utilization of a 1% NaOH catalyst in methanol inside a Radley reactor instrument [31]. To assess various fuel properties, including Density, Specific Gravity, Kinematic Viscosity, and Calorific Value, the ASTM D6751 standards are applied. The study requires the characterization and comparison of different fuel blends, namely B20, B100, MBBF and Petrodiesel [31].

The blending of soybean biodiesel with solketal, observing three fuel types: conventional diesel (D), pure soybean biodiesel (SB), and a blend labeled soybean biodiesel solketal (SBS15), consisting of 15% solketal and 85% soybean biodiesel [49]. Engine performance tests were conducted at three different speeds (1200, 1500, and 2000 RPM) under a constant load of 50%, without applying any modifications to the diesel engine. Fuel properties including kinematic

viscosity and density were measured using a viscometer at 25°C and 40°C and a densimeter, respectively [44]. The lower heating value (LHV) was determined by an oxygen bomb calorimeter, [55] as detailed in Tables 2 and 3. These tables also compare the features of conventional diesel with those of the formulated emulsion fuels. Tung oil, for instance, exhibits a kinematic viscosity approx. 41.5 times as compare of diesel. However, incorporating ethanol into the blend considerably lowers both viscosity and density [40]. At a 40% of ethanol concentration, the emulsions viscosity and density were approx. to those of diesel, at 3.27 mm²/s and 0.839 g/ml, respectively. It is important to note that Tung oil and ethanol have LHV values approximately 16.74% and 37.8% below that of diesel, indicating that higher fuel volumes are required to keep equivalent power output [41]. Furthermore, ethanol's high latent heat of vaporization (LHV) and its low cetane number contribute to prolonged ignition delays. To mitigate combustion challenges, the ethanol content in engine tested emulsions was topped at 40% [38]. The results showed a significant reduction in the kinematic viscosity of Petrodiesel compared to neat palm oil, with a decrease to approximately one third of the original value (36.80-39.60 cSt (40°C)). However, it still remained more than double the kinematic viscosity of standard No. 2 diesel [2]. The higher viscosity of palm oil, in comparison to diesel, is due to its complex molecular structure and higher molecular weight. Earlier research on emulsion fuels has shown kinematic viscosities similar to diesel, ranging from 4.29 to 4.59 cSt (40°C) [38] (Tables 2). To calculate fuel characteristics, engine performance, and exhaust emissions, six stable emulsified fuel blends were created using Pongamia oil, hydrated ethanol, and butanol. These blends consisted of three Degummed Pongamia oil (DPO) combinations, each labeled according to their ethanol, butanol, and oil content [56-57].

1 The comparative evaluation of physicochemical properties of various EBF tells both advantages
2 as well as limiting trends relative to conventional diesel. The reported calorific value of 43.95
3 MJ/kg for diesel biodiesel bioethanol emulsions approaches that of diesel, with only approx. 2%
4 reduction, while considerable improvement over neat biodiesel. However, despite this favorable
5 heat release, several blends exhibited increased BSFC, mainly due to reduced lower heating value
6 (LHV) and altered spray characteristics caused by higher viscosity. Viscosity always remains a
7 critical parameter affecting injection and atomization. While some emulsions successfully reduced
8 viscosity to diesel ranges (3.27-4.59 mm²/s at 40 °C), certain vegetable oils such as tung and palm
9 oil taken significantly higher viscosities even after blending [43]. Fluctuation in viscosity can
10 impair fuel atomization, leading to incomplete combustion and reduced brake thermal efficiency
11 (BTE). On the other hand, ethanol incorporation reduced viscosity and density, improving spray
12 behavior however; excessive ethanol (approaching 40%) introduced combustion instability due to
13 its low cetane number and high latent heat of vaporization, extending ignition delay. Density and
14 specific gravity reductions observed in formulated emulsions may enhance fuel air mixing but can
15 also variation in injection timing and mass flow calibration in unchanged engines. Similarly,
16 reduced flash and pour points improve cold flow properties yet raise safety and volatility
17 considerations during storage and handling. Cetane number variations further explain performance
18 differences. Blends with lower cetane number tend to exhibit delayed combustion phasing,
19 lowering peak pressure development and overall thermal efficiency. Although certain blends (e.g.,
20 coconut oil ethanol butanol systems) proven relatively high GCV, their combined viscosity and
21 ignition quality effects resulted in higher EBF consumption compared with petrodiesel. Overall,
22 while optimized emulsion formulations can achieve diesel comparable viscosity and acceptable
23 heating values, balances between ignition quality, volatility, and energy density significantly

1 influence CI engine performance and emissions. Careful balance of alcohol content, base oil type,
2 and surfactant proportion remains essential for achieving stable combustion and enriched
3 efficiency.

4 **Table 2: Variation in Physicochemical properties of different types of emulsified Biofuel**
5 **[30,37,55,56,57]**

Fuel elements (vol %) & type	Petro diesel	Diesel + Biodiesel (80+20)	D+BD+E (80+15+5)	CCO+E+B (87+10+3)	VCO+E+B (85+10+5)	MBBF	SBS 15	DT30+E20 (80+20)	PO+D (50+50)	DPO
Heating Value ((MJ/kg)	45.11	44.5	43.95	36.45	37.16	38	37.32	37.99	42.5	38.46
Kinematic Viscosity at 40°C (mm²s⁻¹)	5.08	4.098	3.798	19.27	18.22	6.1763	4.52	4.8	11.7	NA
Density at 15°C (kg/m³)	836.5	806	856	901.9	901.2	849.26	923	843	880	920
Specific Gravity	.85	.806	.856	.902	.901	.849	.923	.843	.880	.92
Surface Tension at 20°C (10⁻³N/m)	27	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr
Flash Point (°C)	75	84.5	<40	Nr	Nr	Nr	92	Nr	Nr	Nr
Pour Point (°C)	-12 to 0	-3	-3	Nr	Nr	Nr	Nr	Nr	Nr	-2.98
Cetane No.	46	50.9	51.2	Nr	Nr	Nr	Nr	Nr	Nr	Nr
Oxygen Content %	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr
Ref	30	10	10	30	30	56	57	37	41	58

P100	M100	D80 P20	D70 P20 M10	D70 P15 M15	DF95P E5	DF80 PE20	Jatropha Biodiesel	D80 J20	D60 J20P20	B100	D50 B50	DBO P30	Biodiesel (CIME)	B80 P20	B60 P40
35.16	20.05	43.06	40.64	39.91	46.76	44.37	38.15	38.47	39.37	42.67	43.15	44.08	38	37.13	36.34
2.88	0.58	2.78	2.57	2.46	3.19	3.08	4.33	4.4	3.4	4.34	3.27	3.6	4.7	4.32	3.94
815	791	827	824	822	831	822	882	873	868	874	859	841	868	856.67	852.6
.815	.791	.827	.824	.822	.831	.822	.882	.873	.868	.874	.859	.841	.868	.857	.853
24.7	22.5	26.9	26.4	26.3	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr
Nr	Nr	Nr	Nr	Nr	Nr	Nr	165	80.5	62	130	98.7	80.1	142	122.8	105.4
Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr
20	5	44	39.5	38.8	Nr	Nr	54	53	51	53.7	50.2	47.4	53	46.4	41.2
18.2	50	3.6	8.4	9.9	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr
54	54	54	54	54	55	55	56	56	56	57	57	57	65	65	65

Nr: (not reported)

- 1
- 2
- 3 The pentanol100 (P100) and methanol100 (M100) correspond to pure n pentanol and methanol,
- 4 respectively. The surface tension values for D 100, P 100, and M 100 are sourced, while the surface
- 5 tension values for D80P20 (diesel80 pentanol20), D70P20 M10 (diesel70 pentanol20
- 6 methanol10), and D70P15M15 ((diesel70 pentanol15 methanol15) are computed centered on their

volume ratios [58]. The cetane number for D100 is given by the supplier, and the cetane numbers for P100 and M100 are taken [55]. The cetane numbers for D80P20, D70P20M10, and D70P15M15 are computed.

The figure 1 has shown the density values of four test fuels: Diesel 100, Pentanol100, Methanol100, and the blended fuel D70M15P15. Diesel100 shows the highest density, followed closely by the ternary blend. Pentanol100 exhibits a moderate density, while Methanol100 has the lowest value among the tested fuels [55]. Density influences spray formation and fuel penetration during injection. Higher density increases droplet momentum and penetration length, which may reduce atomization quality, affect air fuel mixing, and vary ignition delay and flame propagation characteristics. The results indicate that blending alcohols with diesel slightly reduces density compared to pure diesel fuel.

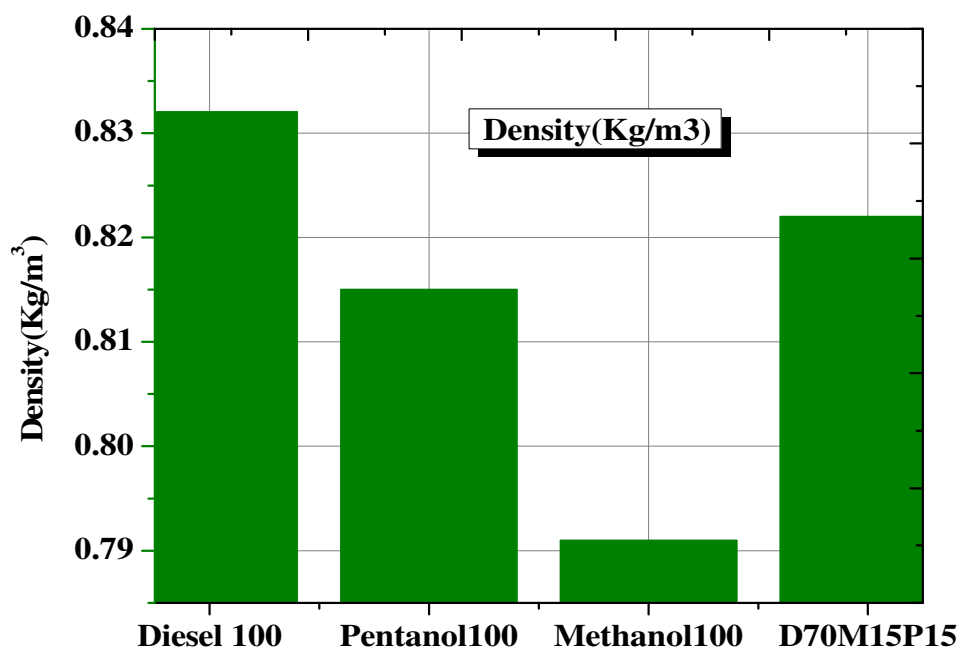


Figure (1) Variation in density for different biofuels [54]

Figure 2 shows the kinematic viscosity of four fuels measured at 40°C: Diesel100, Pentanol100, Methanol100, and the blend D70M15P15. Diesel100 exhibits the highest viscosity, indicating

greater resistance to flow. Pentanol100 shows a moderately lower value, while Methanol100 has very low viscosity compared to the others [54]. The blended fuel demonstrates intermediate behavior, reflecting the combined influence of diesel and alcohol components on flow characteristics at operating temperature.

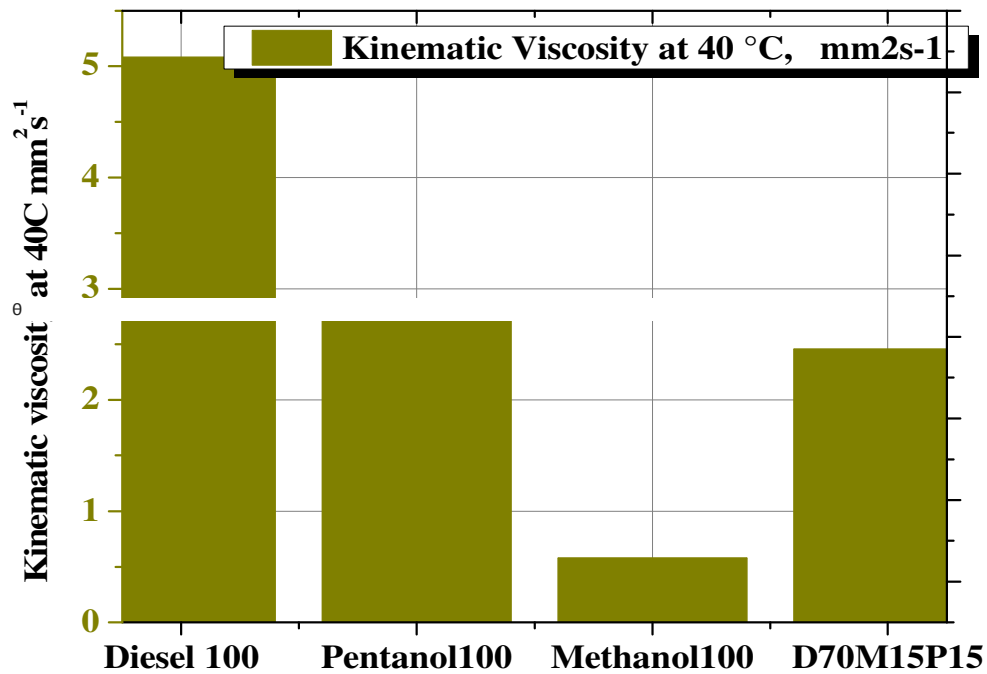


Figure (2) variation in kinematic viscosity of different biofuels at 40°C [54]

In CI engines, the unfavorable fuel properties of biofuel can affect poorly on combustion performance. Kinematic viscosity governs fuel flow and atomization in the injector. Higher viscosity produces larger droplets and poorer spray dispersion, resulting in slower evaporation, delayed ignition, and less uniform flame propagation in the combustion chamber. A low CV lessens the energy released during combustion, which lowers engine power output and increases BSFC. Similarly, an inadequate cetane number causes longer ignition delay, leading to uneven

- 1 combustion, higher pressure fluctuations, and increased emissions of unburned hydrocarbons and
- 2 NO_x, ultimately affecting overall engine efficiency and reliability.

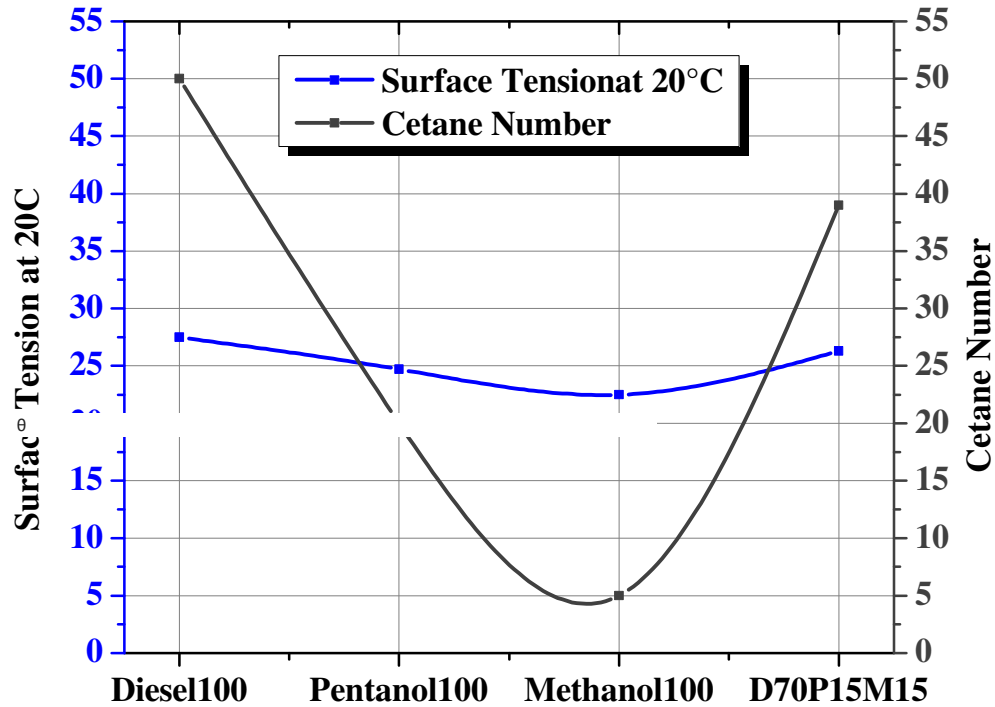


Figure (3) Surface tension variation at 20°C and cetane number values of different biofuels [54]

Figure 3 presents the variation of surface tension at 20°C and cetane number for Diesel100, Pentanol100, Methanol100, and the D70P15M15 blend. Diesel100 shows the highest cetane number and relatively high surface tension [55]. Surface tension affects the breakup of fuel droplets during injection. Lower surface tension promotes better atomization and smaller droplets, enhancing evaporation, improving air fuel mixing, and supporting stable ignition and smoother flame propagation. Methanol100 shows the lowest cetane number along with reduced surface tension. Pentanol100 and the blended fuel display intermediate values [54]. The results indicate that the addition of alcohol declines cetane quality while slightly influencing surface tension characteristics of the fuel mixture.

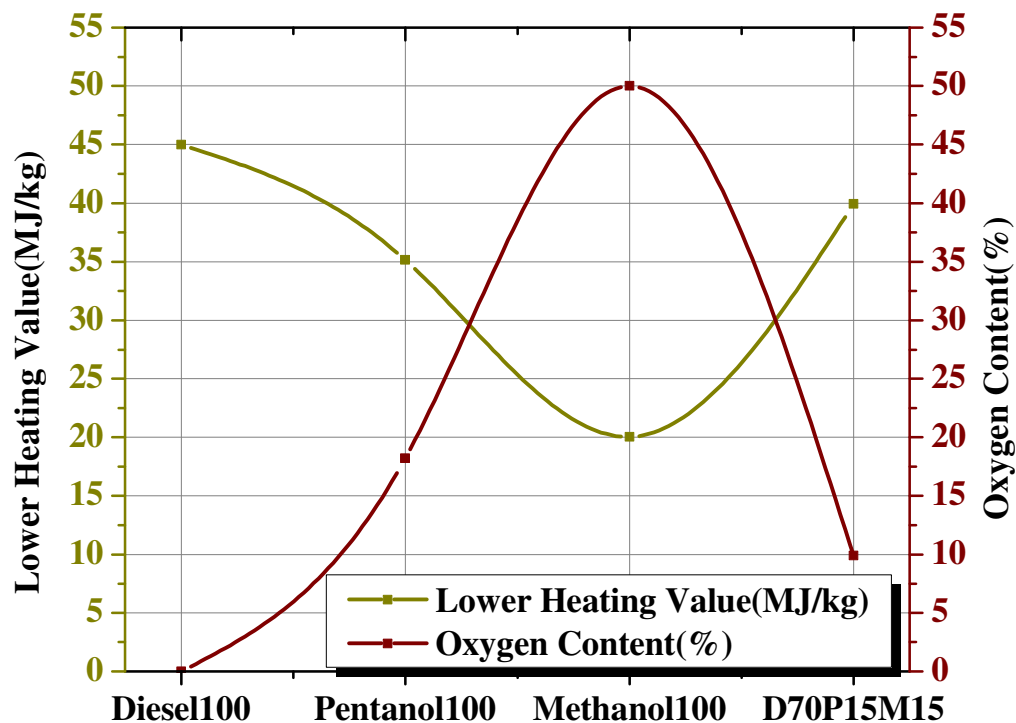


Figure (4) Variation of Lower heating value and oxygen content %age of different biofuels [54]

Figure 4 compares LHV and oxygen content for Diesel100, Pentanol100, Methanol100, and the D70P15M15 blend [55]. Diesel100 shows the highest heating value with negligible oxygen content. As alcohol concentration increases, oxygen content rises significantly, reaching its maximum for Methanol100. Conversely, the heating value drops due to the lower energy density of oxygenated fuels. Lower heating value determines the amount of energy released during combustion. Fuels with higher heating value generate higher combustion temperatures, promoting stronger flame propagation and efficient ignition, while lower values reduce engine power output. The blended fuel demonstrates intermediate characteristics, balancing energy output and oxygen availability, which can affect combustion efficiency and emission behavior in engines.

The thermo-physical properties of the pentanol diesel fuel blend were analyzed in accordance with ASTM standards. As shown in Table 3, the calorific value of PE5 and PE20 lessened by 3.17% and 8.12%, respectively, compared to diesel fuel (DF). Additionally, a rise in pentanol percentage

1 in the fuel blend led to a noticeable reduction in density, with PE5 and PE20 exhibiting decreases
2 of 0.12% and 1.20%, respectively, relative to DF [59-60]. The properties of various test fuels,
3 including D80J20, D60J20P20, jatropha biodiesel, and diesel, along with ASTM standards. The
4 characteristics of jatropha biodiesel closely resemble those of conventional diesel. All stated
5 properties of jatropha biodiesel fall within the ASTM standard limits. A lower cetane value can
6 result in partial combustion and increased smoke emissions. While jatropha biodiesel and pentanol
7 have relatively low cetane numbers, all tested fuel blends complied with the ASTM cetane value
8 standards. The elevated viscosity of jatropha biodiesel was effectively reduced through blending
9 with pure diesel and pentanol. [61-63]. The experimental quaternary fuel blends were formulated
10 by adjusting the pentanol content from 10% to 40% in additions of 10%, while simultaneously
11 varying the biodiesel proportion at 35%, 25%, 15%, and 5%. The concentrations of Jatropha
12 biodiesel, Jatropha oil, diesel fuel, and pentanol were retained at 15%, 5%, 50%, and 30%,
13 respectively. These fuel blends were designated as D BOP30. Additionally, a blend labeled
14 D50BD50 was formed by combining diesel and biodiesel in equal proportions (50% each). The
15 splash blending technique was employed for preparing the fuel mixtures, followed by magnetic
16 stirring before conducting engine performance tests [64-65].

17 Blended with Calophyllum Inophyllum methyl ester (CIME) using the splash blending technique.
18 After preparing the blends, each CIME pentanol mixture was stored in separate containers and
19 monitored for Phase separation was monitored visually over a period of fifteen days. No phase
20 separation was observed in any of the blends throughout the monitoring period, confirming their
21 stability. Consequently, all fuel samples were subjected to experimental analysis. The properties
22 of the blends were evaluated following ASTM standard testing procedures at the fuel testing
23 laboratory of VIT University. The kinematic viscosity of each sample was measured according to

1 standard protocols, while the total heating value and flash point were also determined. Table 3
 2 shows that a higher proportion of n-pentanol in the blend led to a decrease in total heating value.
 3 Moreover, incorporating normal-pentanol into biodiesel (CIME) reduced the cetane number,
 4 density, and flash point, while kinematic viscosity increased relative to pure CIME. [66].

5 **Table3: Thermo-physical properties of different Biodiesels [55,56 ,57, 66]**

Fuel Properties	Unit	DF	PE5	PE20	D80J20	D60J20P20	DBOP30	D50BD50	Biodiesel (CIME)	n-pentanol
Calorific value	MJ/kg	48.28	46.75	44.35	38.47	39.37	44.076	43.15	38	34.64
Density	kg/m ³	832.1	832	823	833	868	841	829	869	815
Kinematic viscosity	mm ² /s	3.51	3.2	3.11	4.4	3.4	3.6	3.7	4.7	2.89

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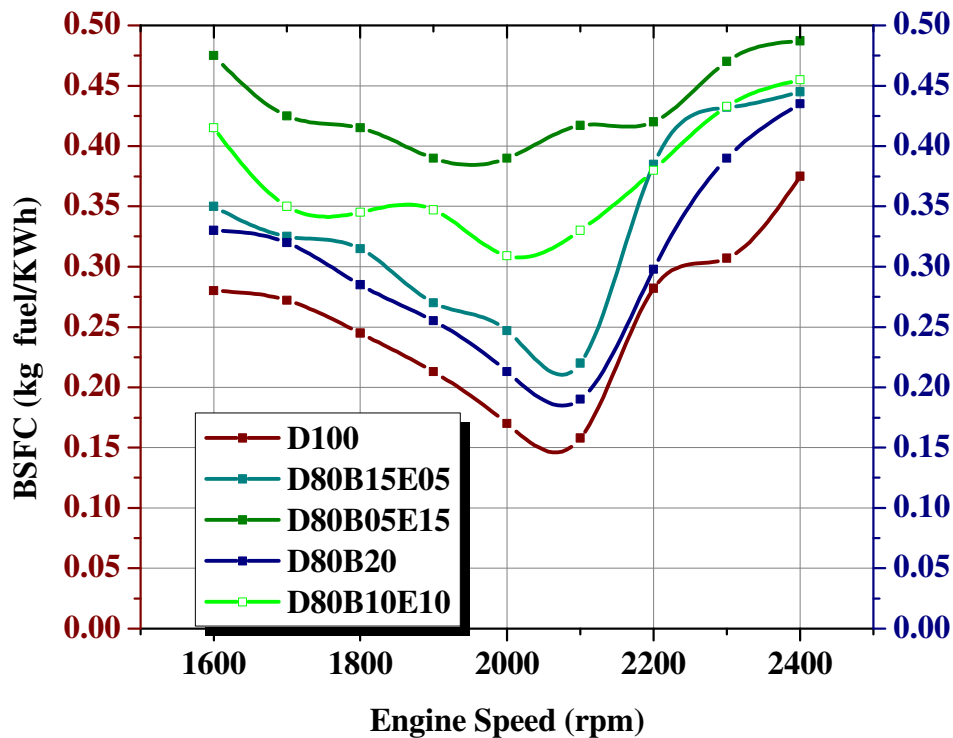
7 **3. CI Engine Performance Analysis**

8 The effects of physicochemical properties on performance parameters for various test fuels blends
 9 that are taken into consideration are reported in this section. The comparative assessment and the
 10 best suited emulsion are recommended for fueling in the CI Engine.

11 **3.1 Brake Specific Fuel Consumption (BSFC):**

12 Brake Specific Fuel Consumption (BSFC) represents the quantity of fuel consumed in 01 hour to
 13 produce 01 KW of brake power. Several physio-chemical properties, such as viscosity, density,
 14 cetane number, and heating value, affect the fuel consumption characteristics of diesel engines
 15 [67-68]. The numerical values of figure 5 are reproduced to the literature and compiled for the
 16 analysis. As depicted in Figure 5, the BSFC for diesel, biodiesel, and diesel biodiesel bioethanol
 17 blends varies with engine speed [69-70]. BSFC initially decreases, reaching a minimum at 2100
 18 rpm, then increases as engine speed continues to rise. The upward trend at higher speeds is
 19 attributed to raise mechanical friction, while at slower speeds, higher BSFC is due to prolonged
 20 heat transfer from combustion gases to engine components like the piston and cylinder walls. This

1 trend is steady with prior studies [71-72]. Emulsion fuels generally exhibit higher BSFC than pure
2 diesel, largely due to their lower heating value, which leads to reduced combustion temperatures.
3 The BSFC tends to rise with higher bioethanol content in the fuel blend. As shown in Figure 05,
4 across all tested engine speeds, the highest BSFC was recorded for the D80B05E15 blend,
5 followed in downward order by D80B10E10, D80B15E05, D80B20, and D100, with respective
6 BSFC values of 0.4868, 0.4584, 0.4476, 0.4381, and 0.37589 kg/kWh. [10].



7
8 **Figure (5)** Variations of BSFC vs Engine speed for diesel and different emulsion biofuels [10]

9 Figure 6 illustrates the relationship between brake specific fuel consumption (BSFC) and engine
10 speed for different fuel blends: D80J20, D70J200P10, D60J20P20, and conventional diesel [56].
11 The numerical values of figure 6 are reproduced to the literature and compiled for the analysis. At
12 2400 rpm, the highest BSFC value of 548.62 g/kWh was recorded for D60 J20 P20, while diesel
13 fuel exhibited the lowest BSFC at 403.952 g/kWh. Compared to diesel, the BSFC values for
14 D70J20P10 and D70J20P20 increased by approximately 10.71%, 17.29%, and 29.61%,

respectively. This increase is attributed to the lower calorific value and reduced energy density of pentanol, leading to higher fuel consumption in D70J20P10 and D70J20P20 compared to D80J20 and diesel fuel. These results align with previous studies [73-74]. A higher pentanol concentration negatively affects combustion quality, ensuing in increased fuel [74-75] consumption due to lower peak cylinder pressure and extended delay [76-78].

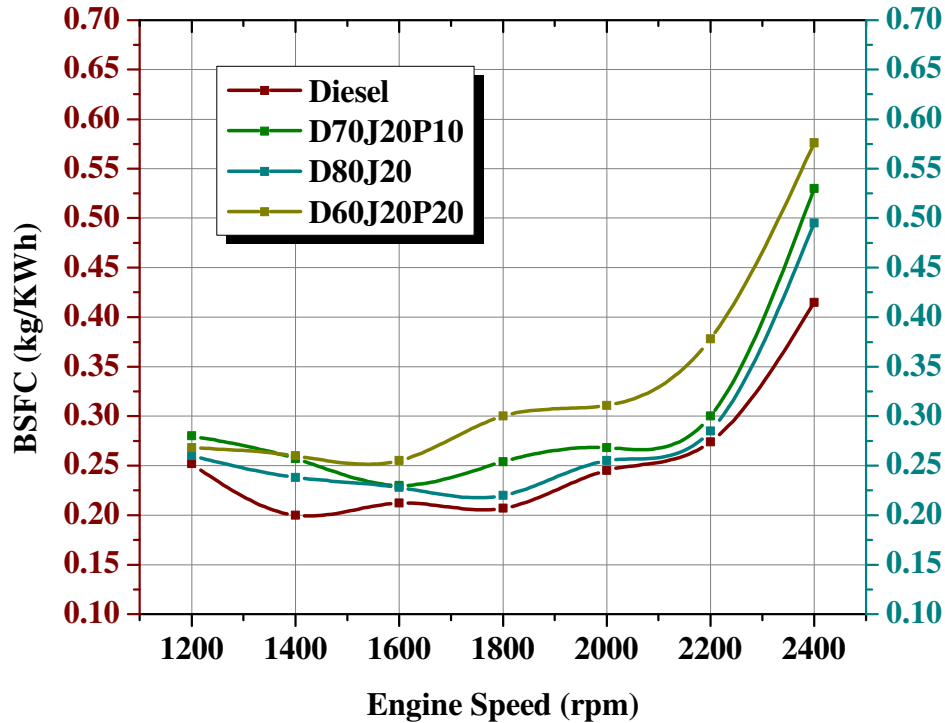


Figure (6) Variation of BSFC vs Engine speed for diesel and different biofuels blends [56]

3.2 Brake Thermal Efficiency (η_{th}):

Brake Thermal Efficiency (BTE) measures how effectively an engine transforms the chemical energy of fuel into mechanical output. The numerical values of figure 7 are reproduced to the literature and compiled for the analysis. The decline in BTE in emulsion biofuels is primarily attributed to reduced calorific value, heat absorption during water vaporization, delayed ignition, and lower peak combustion temperature, which jointly reduce effective energy conversion in CI engines. The use of emulsions generally leads to a decline in brake power, primarily due to the

1 lower calorific values of constituent alcohols and water. Yet, certain formulations, such as ethanol
2 ethyl acetate diesel emulsions, have shown enhancements in brake power by approximately 0.29%
3 to 2.39% over conventional diesel [79]. BTE is inversely related to BSFC. Several studies indicate
4 that emulsions can enhance BTE compared to neat diesel, a phenomenon largely attributed to
5 improved premixed combustion eased by emulsions. Conversely, in some cases, a reduction in
6 BTE has been observed, often linked to lower fuel energy content and improved BSFC. For
7 example, ethanol ethyl acetate diesel blends have reported BTE values ranging from 22.8% to
8 30.1%, in contrast to 25.4% for standard diesel fuel [80]. Additionally, BTE was found to increase
9 with 95% aqueous ethanol but decline with 100% anhydrous ethanol under full load conditions.
10 Similarly, bio-oil diesel emulsions exhibited lower BTE at partial loads because of their
11 diminished calorific values. However, as the load increased, their efficiency became comparable
12 to pure diesel, attributed to enhanced combustion from emulsions. As the load increases, brake
13 thermal efficiency improves due to poor combustion conditions at lower loads, which lead to
14 reduced efficiency. From figure 7 it is seen that the brake thermal efficiency of B20 was observed
15 to be slightly higher than that of conventional diesel. While MBBF exhibited similar efficiency at
16 lower loads, their performance at higher and partial loads remained lower compared to petrodiesel
17 [31].

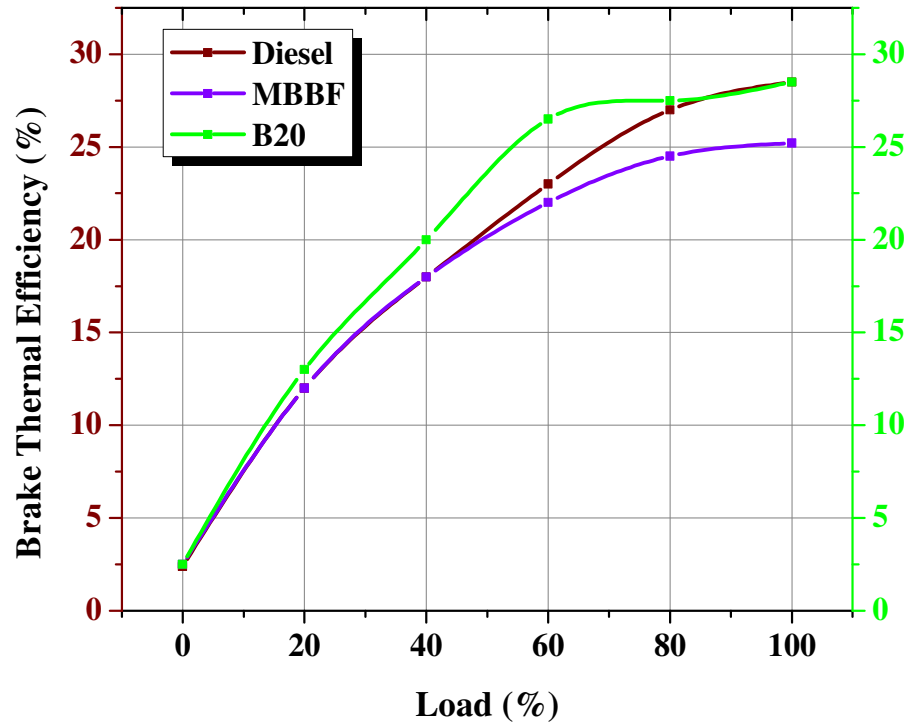


Figure (7) Variation of BTE vs Engine different loads for diesel and different biofuels [56]

3.3 Torque output & Brake Power (BP):

As the engine load rises, the BP also rises. This upward trend is noticeable across all types of fuels. Very few minor differences have been observed among the various fuels under different load conditions. The numerical values of figure 8 are reproduced to the literature and compiled for the analysis. Figure 8 presents the changes in torque output at changing engine speeds for D80J20, D60J20P20, and conventional diesel fuels. As the engine speed rises, torque progressively declines due to an excess of fuel entering the combustion chamber. Among the tested fuels, diesel generates the highest torque, followed by D80J20 and D60J20P20 [56]. The maximum torque for all fuel types is observed at 1800 rpm. However, adding 20% pentanol leads to a 3.5% decrease in peak torque. Figure 9 depicts the peak torque occurring around 1800 rpm, influenced by the addition of pentanol to JB-diesel blends. In comparison to conventional diesel, the D60J20P20 blend exhibited a 2.6% reduction in average torque. Furthermore, the highest brake power for all tested fuels was

1 observed at 2200 rpm. This decline in torque and brake power is mainly due to the lower energy
2 density of pentanol compared to jatropha biodiesel diesel blends, along with the oxygen content
3 present in both jatropha biodiesel and pentanol. Figure 10 validates the relationship between brake
4 power and engine speed for various test fuels. Across all fuel types, the peak brake power occurs
5 at 2200 rpm. However, incorporating jatropha biodiesel and pentanol results in a decline in brake
6 power output. This reduction is primarily attributed to the lower energy density of pentanol relative
7 to jatropha biodiesel-diesel blends, as well as the influence of oxygen content in both pentanol and
8 jatropha biodiesel on engine performance. [60].

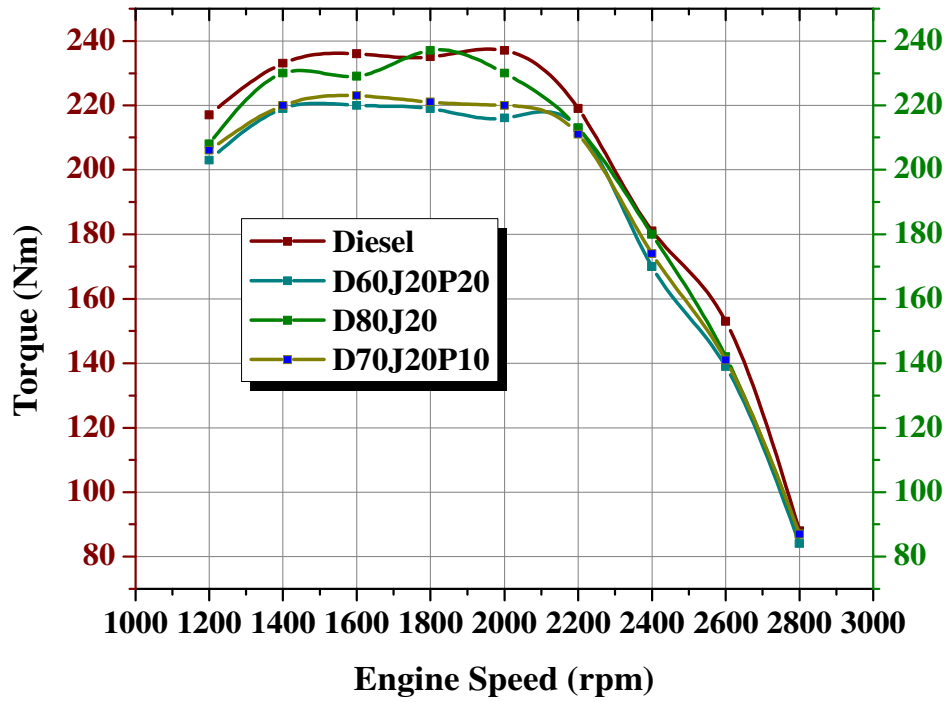


Figure (8) variation of Torque vs Engine speed of diesel and different biofuels [56]

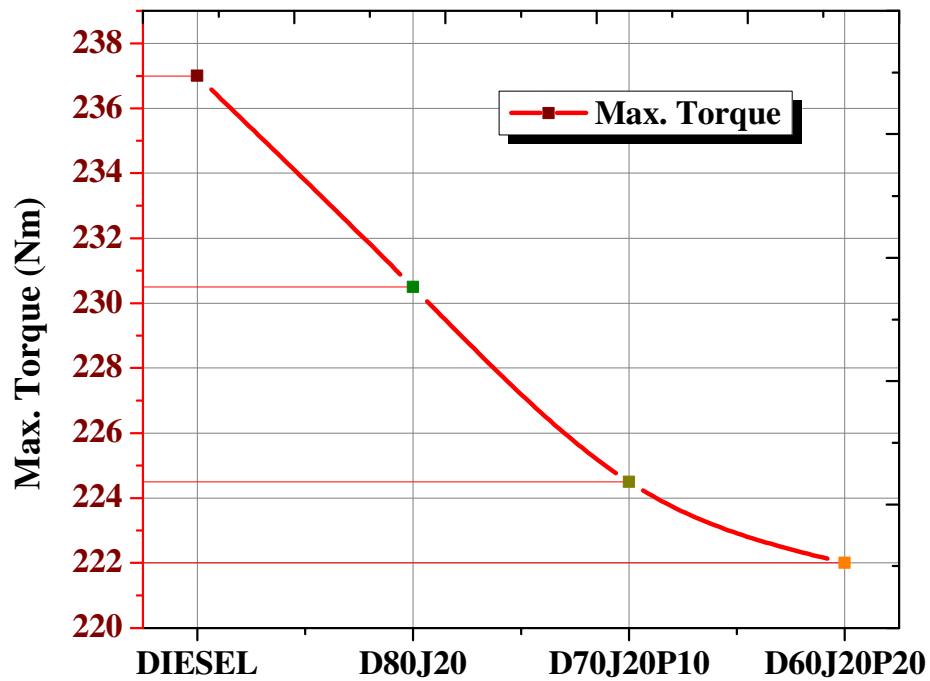


Figure (9) Max. Torque values of diesel and different biofuels [56]

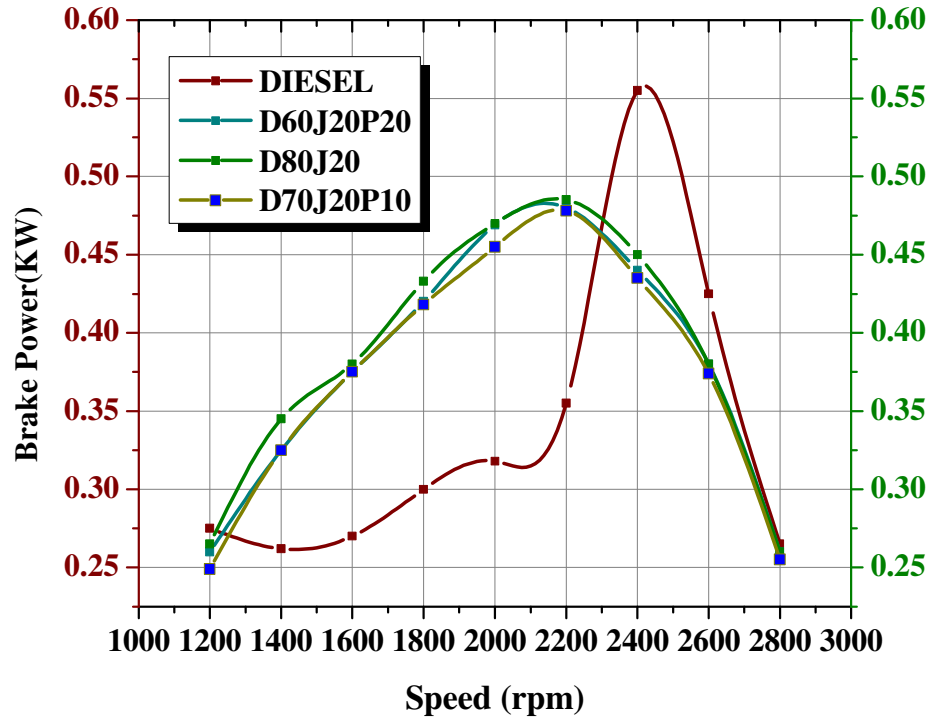


Figure (10) Variation of BP vs Engine speed of diesel and different biofuels [56]

3.4 Volumetric Efficiency ($\eta_{Vol.}$):

The table 4 and table 5 displays the volumetric efficiency ($\eta_{Vol.}$) data measured for various test fuels at engine speeds ranging from 1600 to 2400 rpm. Volumetric efficiency ($\eta_{Vol.}$) refers to the proportion of air mass drawn into the engine combustion chamber during the intake stroke relative to the air mass corresponding to the engine's swept volume under standard atmospheric conditions. Since the air intake is directly influenced by the engine's volumetric efficiency, it determines the maximum amount of fuel that can be effectively combusted, thereby impacting the engine's power output. [81]. Volumetric efficiency is influenced by various factors, including the type of fuel used, throttle position, engine speed, and the design of the suction and exhaust systems. Additionally, size of the port, timing of valve movement and the span of valve opening also play significant roles. [82]. However, increasing the percentage of biodiesel and bioethanol in the emulsion fuel

1 results in a decline in volumetric efficiency ($\eta_{vol.}$). This reduction is linked to the (LHV) of
 2 emulsion fuels compared to conventional diesel. On average, volumetric efficiency was reduced
 3 by 3.4%, 3.8%, 6.8%, and 9.4% for D80B20, D80B15E5, D80B10E10, and D80B05E15
 4 respectively, in comparison to pure diesel [10]

5 **Table 4:** Analysis for Performance parameters of diesel and different emulsified biofuels [10]

Fuel components (volume %) & type	BSFC (Kg fuel/KWH) vs Engine Speed (RPM)			BTE (%) vs Engine Speed (RPM)			Volumetric Efficiency ($\eta_{vol.}$) (%) vs Engine Speed (RPM)			Brake Power (KW) vs Speed (RPM)			Exhaust Temp.(°C) vs Speed (RPM)			Ref
	1600	2000	2400	1600	2000	2400	1600	2000	2400	1600	2000	2400	1600	2000	2400	
Petrodiesel	.285	.185	.37	28.5	47.5	23	13	60	70	4.7	5.25	6.0	300	330	355	10
Diesel (80) + Biodiesel (20)	.38	.22	.43	25	38	20	41	58	68	3.85	4.0	4.5	187	250	330	10
Diesel (80) + Biodiesel (15) + Ethanol (05)	.35	.24	.44	23.5	32	20	41	58	65	3.75	3.85	4.3	168	178	310	10

6

7

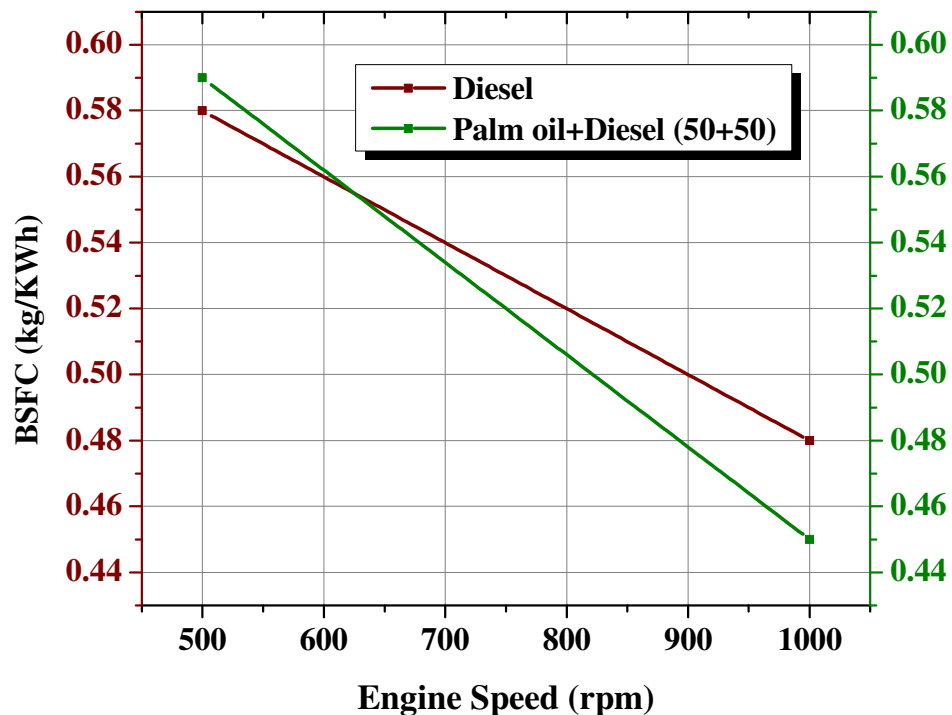
8 **Table 5:** Analysis for Performance parameters of diesel and different emulsified biofuels
 9 (30,52,61)

Fuel components (volume %) & type	BSFC (Kg fuel/KWH) vs Load (%)			BTE vs Load (%)			Brake Power (KW) vs Load (%)			Ref
	20	60	100	20	60	100	20	60	100	
Petrodiesel	0.2	0.18	0.18	13	27	33	Nr	Nr	Nr	30
CCO+E+B (87+10+3)	0.75	0.48	0.47	12	22.5	24	Nr	Nr	Nr	30
VCO+E+B (85+10+5)	0.7	0.5	0.48	13	23.5	25	Nr	Nr	Nr	30
MBBF	0.75	0.45	0.39	11.75	21.5	24	1	2.7	4.35	61
DPO	1.25	.675	.455	7	13	18	Nr	Nr	Nr	52

10

Nr (not reported)

1 The petrodiesel (PD) fuel blend consists of an equal volumetric ratio of palm oil and diesel (1:1).
2 Under both engine load conditions, fuel consumption for PD was only marginally higher (by about
3 1-2 %) compared to pure diesel. The numerical values of figure 11 are reproduced to the literature
4 and compiled for the analysis. These findings suggest that the fuel consumption remained largely
5 unaffected by the blend composition, likely due to its heat of combustion. Figure 11 presents the
6 BSFC results for the tested fuels. BSFC represents the fuel consumption required to produce the
7 same energy output. As engine load increased, BSFC values for all fuels declined due to enhanced
8 fuel combustion efficiency and reduced heat losses. Notably, BSFC values for all emulsion
9 biofuels showed an overall increase at every engine load. However, the rate of increase diminished
10 as engine load rose. The higher fuel consumption of emulsion biofuels compared to neat diesel
11 was attributed to the lower energy content of alcohol present in the fuel blends [44].



12
13 **Figure (11)** Variation of BSFC vs Engine speed for diesel and different biofuels [42]

Figure 12 illustrates the variations in exhaust gas temperatures (EGT) for all inspected fuels under two engine load conditions. The numerical values of figure 12 are reproduced to the literature and compiled for the analysis. The results indicate that emulsion fuels produced lower EGT compared to other fuels. This reduction is attributed to the LHV of ethanol and the presence of cosurfactants in the emulsion fuels. Consequently, the decreased EGT correlates with reduced NO_x emissions from these fuels.

Furthermore, an analysis of different co-surfactants in the emulsion fuels revealed no significant impact on NO_x emissions based on variations in carbon chain length. This is due to the similarity in heating values and EGT among the emulsion biofuels [40].

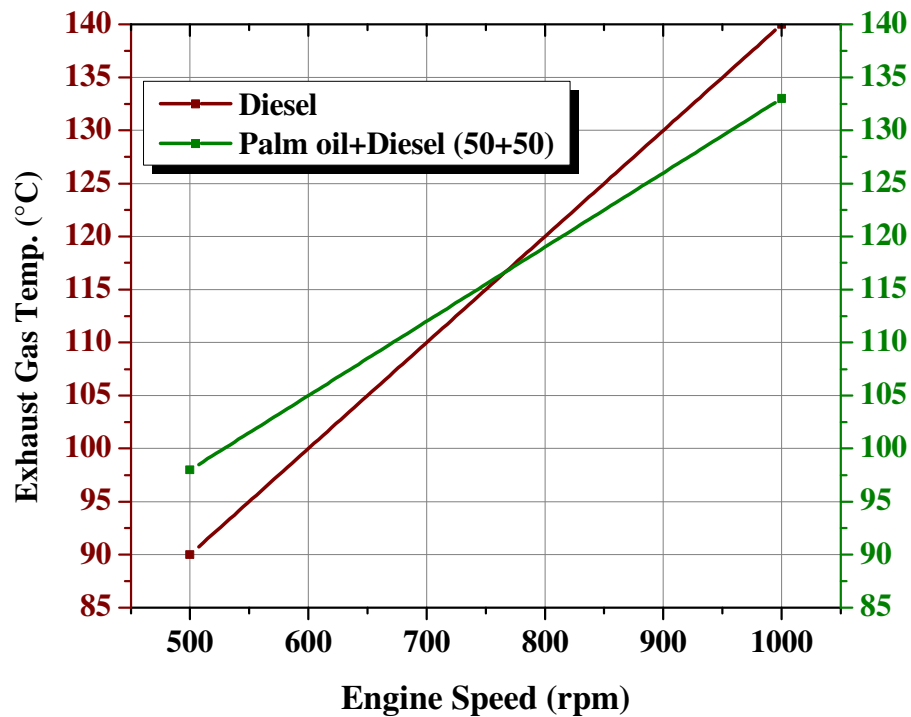


Figure (12) Variation of Exhaust Gas Temp. vs Engine speed for diesel and different biofuels [40]

Blending solketal with soybean biodiesel results in higher flash points, thereby improving the safety of fuel handling [57]. Nevertheless, the increased density and viscosity of these blends contribute to elevated fuel consumption. Brake Specific Fuel Consumption (BSFC) is a vital metric

for evaluating the performance of different fuels and their mixtures in engine systems. As depicted in Figure 13, BSFC values tend to increase with engine speed. The inherently higher density of biodiesel blends relative to conventional diesel contributes to this trend, leading to greater BSFC values for biodiesel and its solketal mixtures. Furthermore, the addition of solketal amplifies this effect, with the SBS15 blend exhibiting the highest BSFC across all engine speeds. [65].

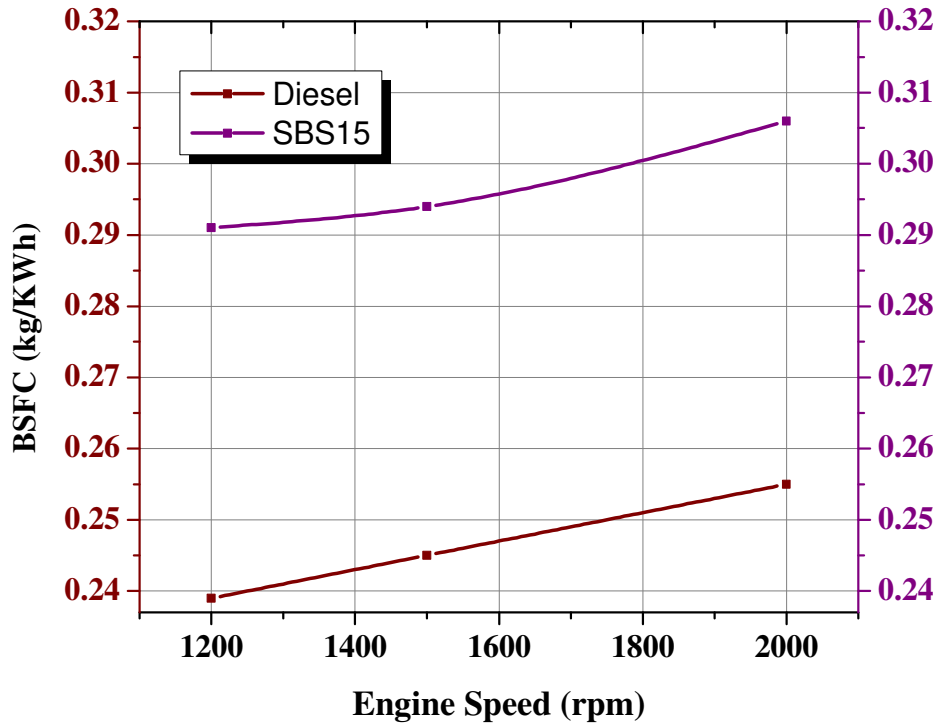


Figure (13) Variation of BSFC vs Engine speed for diesel and different biofuels [57]

BSFC is an important metric used to assess fuel efficiency. Figure 14 illustrates how BSFC varies with engine load for different inspected fuels at engine speeds of 1000 rev./min and 1400 rev./min. Generally, emulsion fuels exhibit slightly higher BSFC values than conventional diesel across most engine load conditions. Moreover, BSFC tends to rise as the ethanol content in the fuel increases. At 1000 r/min, the BSFC for DT30E20 and DT30E40 exceeds of diesel by 12.26% and 20.26%, respectively [36]. At 1400 r/min, the increases are 9.2% and 15.8%, respectively. In contrast, LHV of DT30E20 and DT30E40 are 13.51% and 23.58% lower than that of diesel. This

discrepancy between BSFC and LHV changes can be attributed to several factors, including interactions between the volumetric fuel injection system and properties like fuel density and viscosity. [41].

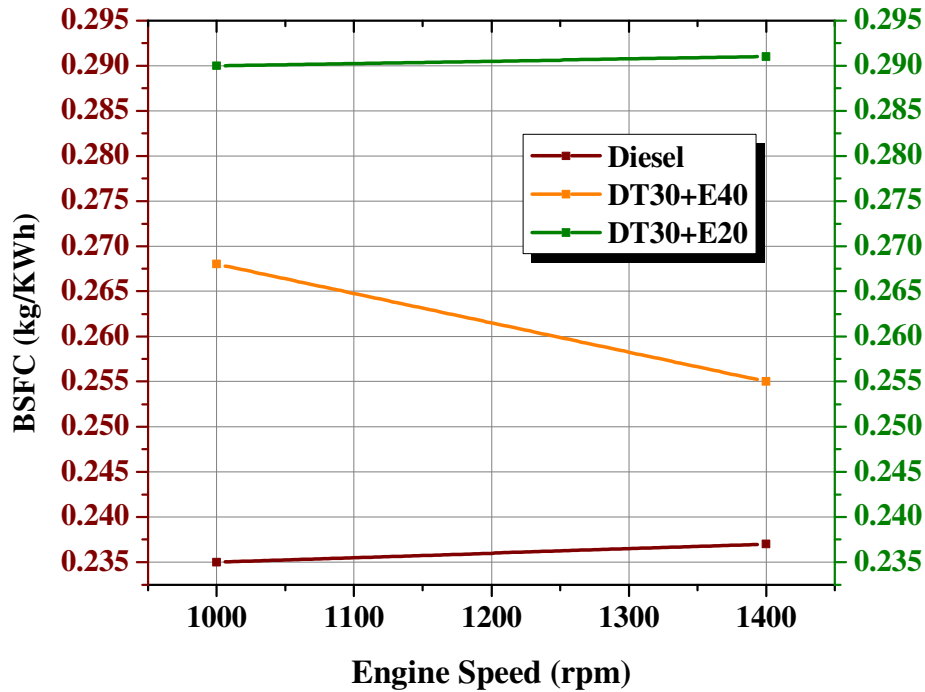


Figure (14) Variation of BSFC vs Engine speed for diesel and different biofuels [37]

The figure 15 presents the BSFC values for different fuel blends at varying engine loads (20%, 60%, and 100%). Petrodiesel exhibits the lowest BSFC across all loads. Blends such as CCO+E+B (87+10+3), VCO+E+B (85+10+5), and MBBF show reasonable BSFC values, while DPO demonstrates the maximum BSFC at all loads [30]. At 20% load, DPO records the highest BSFC, while petro-diesel remains the lowest. At 60% and 100% load, BSFC decreases for all fuels, but biodiesel blends remain higher than petro-diesel, with DPO still showing relatively high values [30, 56, 64].

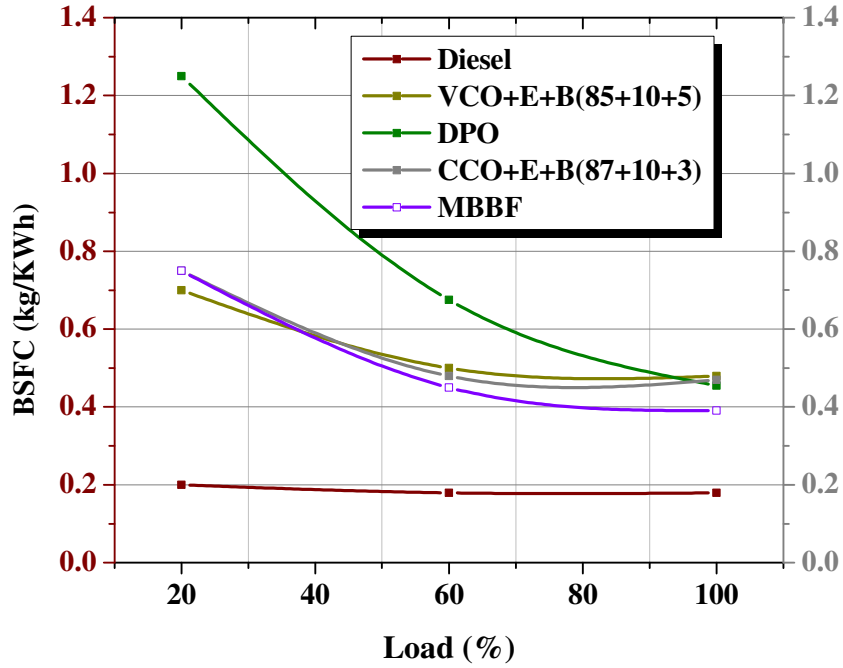


Figure (15) Variation of BSFC vs Engine load for diesel and different biofuels [30]

BTE indicates how effectively an engine converts the chemical energy in fuel into mechanical work. It is calculated as the ratio of the brake power output at the shaft to the total energy supplied to the engine. As illustrated in Fig. 16, the BTE values for emulsion fuels surpass those of conventional diesel, particularly at an engine speed of 1400 r/min. This improvement can be attributed to the presence of ethanol, which increases the oxygen content in the emulsion, enhancing combustion in fuel-rich zones and promoting more complete burning. Furthermore, the difference in volatility between ethanol and the base fuel leads to micro-explosions within the droplets, enhancing atomization and mixing, thereby accelerating heat release and further improving combustion efficiency. [84].

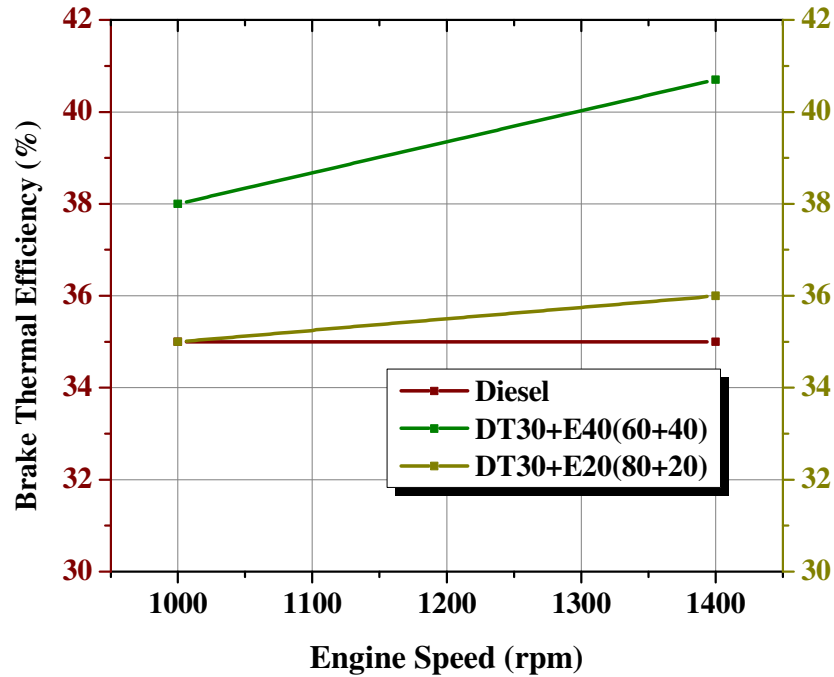


Figure (16) Variation of BTE vs Engine speed of diesel and different biofuels [36]

3.5 Heat release rate and combustion temperature:

Table 6 summarizes the peak heat release rates (PHRR) and peak combustion temperatures (PCT) of various fuel blends under different engine loads. At a brake mean effective pressure (BMEP) of 0.159 MPa, the fuel blends D80P20, D70P20M10, and D70P15M15 exhibit higher PHRRs compared to conventional diesel (D100), with the peaks happening at 1.5° crank angle, 2.5° crank angle, and 2.5° crank angle after top dead center (TDC), respectively. In contrast, D100 reaches its peak at 0.5° crank angle after TDC. When the BMEP is increased to 0.479 MPa, the blended fuels show progressively higher PHRRs than D 100 as the methanol proportion increases. The peak heat release rates (PHRRs) measured for D100, D80P20, D70P20M10, and D70P15M15 were 155.6, 203.3, 262, and 279.2 J/° crank angle, respectively, occurring at -0.5° crank angle, 0° crank angle, and 1° crank angle after top dead center (TDC) for the last two blends [30,54]. The corresponding peak combustion temperatures (PCTs) recorded were 1834.6 K for D 100, 1847.2

1 K for D80P20, 1889.7 K for D70P20M10, and 1944.8 K for D70P15M15. The peak temperatures
 2 for D80P20 occurred at 12° crank angle after TDC, while for D70P20M10, D70P15M15, it was
 3 observed at 10° crank angle after TDC [54]. Under low and medium engine load conditions, the
 4 blended fuels exhibited longer ignition delays (IDs), resulting in a greater proportion of premixed
 5 combustion. This, combined with the higher oxygen content of the blends, enhances combustion
 6 efficiency and reduces the duration of combustion, contributing to higher PHRRs, especially with
 7 increasing methanol levels. The resulting higher PHRRs and shorter combustion durations also
 8 yield elevated PCTs. While the PHRR peaks of the blends tend to shift later relative to TDC, the
 9 PCT peaks occur earlier, consistent with the shorter combustion period. At a BMEP of 0.809 MPa,
 10 both the initial and secondary PHRRs for the blends surpass those of D 100 [30]. The increased
 11 first PHRR is mainly due to a prolonged ignition delay that promotes greater fuel–air mixing,
 12 whereas the higher second PHRR is linked to enhanced combustion facilitated by the oxygen-rich
 13 nature of the blends and the presence of reactive OH radicals. However, at a higher load of 1.289
 14 MPa BMEP, HRR curves display a smoother, more consistent pattern without distinct dual peaks,
 15 suggesting an integration of premixed and diffusion combustion phases. At this load condition,
 16 PHRRs recorded for D100, D80P20, D70P20M10, and D70P15M15 are 214.9, 217.2, 211.5, and
 17 204.4 J/° crank angle, respectively, occurring at 4° crank angle, 4.5° crank angle, 6° crank angle,
 18 and 9° crank angle after top dead center (ATDC). Additionally, the peak combustion temperatures
 19 (PCTs) for these fuels are observed at 2223.7 K, 2246.5 K, 2266.0 K, and 2280.4 K, respectively
 20 [84].

21 **Table 6:** Peak HRR and Peak CT of diesel and different test fuels at various loads [84].

Different loads and injection parameters	Peak HRR (Arising)	Peak CT (Arising)
	Joule/°Crank Angle (°Crank Angle After TDC)	K (°Crank Angle After TDC)

	D 100	D80 P20	D70 P20 M10	D70 P15 M15	D 100	D80 P20	D70 P20 M10	D70 P15 M15
B.M.E.P =0.159 MPa $\theta_{in}= 8^\circ$ Crank Angle Pr.(in)=84.39 MPa	195.8 (0.5)	230.6 (1.5)	255 (2.5)	252.1 (2.5)	1504.8 (8.5)	1559.2 (9)	1573.1 (9)	1583.6 (6.5)
B.M.E.P =0.319 MPa $\theta_{in}= 8^\circ$ Crank Angle Pr.(in)=90.1 MPa	199.7 (0)	236 (1)	295 .1 (1.5)	294.1 (2)	1662.5 (10)	1681 (10.5)	1721 (8)	1840.5 (9.5)
B.M.E.P =0.479 MPa $\theta_{in}= 8^\circ$ Crank Angle Pr.(in)=94.96 MPa	155.6 (-.5)	203.3 (0)	262 (1)	279.2 (1)	1834.6 (12)	1847.2 (12)	1889.7 (10)	1944.8 (10)
B.M.E.P =0.639 MPa $\theta_{in}= 8^\circ$ Crank Angle Pr.(in)=97.1 MPa	179.7 (3)	178.4 (4)	231.5 (.5)	264.2 (0.5)	1950.2 (12.5)	1979.6 (13)	1992.4 (14)	2043.7 (13.5)
B.M.E.P =0.809 MPa $\theta_{in}= 8^\circ$ Crank Angle Pr.(in)=101.9 MPa	195.7 (3)	205 (4.5)	199.3 (3.5)	207.3 (3.5)	2088 (14)	21101 (12.5)	2118.3 (12.5)	2182.6 (12.5)
B.M.E.P =0.969 MPa $\theta_{in}= 8^\circ$ Crank Angle Pr.(in)=105.1 MPa	197.6 (6)	195.5 (3.5)	199.7 (7)	211.4 (4.5)	2070.2 (16)	2076.5 (14)	2107.2 (15)	2115.7 (15.5)
B.M.E.P =1.129 MPa $\theta_{in}= 8^\circ$ Crank Angle Pr.(in)=106.95 MPa	231.5 (3.5)	229.6 (3.5)	223.7 (2.5)	203.8 (2.5)	2525.7 (18.5)	2511.4 (19)	2548.2 (19.5)	2370.8 (20.5)
B.M.E.P =1.289 MPa $\theta_{in}= 8^\circ$ Crank Angle Pr.(in) =111.1 MPa	214.9 (4)	217.2 (4.5)	211.5 (6)	204.4 (9)	2223.7 (18)	2246.5 (19)	2266 (15)	2280.4 (19)

1

2 The variation of in-cylinder pressure and heat release rate (HRR) with crank angle was analyzed

3 for all fuel blends (DF, PE5, and PE20) at a constant engine speed of 1800 rpm and under different

4 engine loads. As illustrated in Figures (17, 18, 19), both the in-cylinder pressure and HRR rise

5 with increasing engine load. According to Figure 17, all tested fuels exhibited peak in-cylinder

6 pressure at 4° crank angle. The ignition delay observed for the PE5 and PE20 blends was

7 comparable to that of conventional diesel fuel (DF) [55]. At a low engine load of 25%, the in-

1 cylinder pressure dropped by 1.76% for PE5 and 6.54% for PE20 relative to DF, with the most
2 significant decrease recorded for PE20. This reduction is attributed to PE20's lower density 0.822
3 kg/m³ less than DF which contributes to reduced premixed combustion. Furthermore, PE20's
4 lower kinematic viscosity (by 3.08 mm²/s) promoted better mixing of fuel and air during the
5 ignition delay period, thereby enhancing the combustion process. As depicted in Figure 18, at a
6 moderate engine load of 50%, the in-cylinder pressure showed a decline of 1.14% for PE5 and
7 2.46% for PE20 when compared with DF. In contrast, Figure 19 explains that at a high engine load
8 of 100%, the in-cylinder pressure raised by 1.24% and 14.71% for PE5 and PE20, respectively.
9 The most notable increase 14.71% was observed with the PE20 blend at full engine load. This rise
10 is mainly due to the oxygen content in pentanol, which enhances premixed combustion and results
11 in a peak pressure of 76.97 bar. Furthermore, the shorter ignition delay and greater quantity of fuel
12 burned during combustion led to higher power output and better atomization. These findings align
13 with earlier studies showing that long chain alcohols tend to produce higher in cylinder pressures
14 than diesel fuel. [85-86] Figure 17 to 19 illustrate the HRR for numerous fuel blends under
15 different engine load conditions, all measured at a constant engine speed of 1800 rpm. The peak
16 HRR for each case occurs at 2° crank angle and differs with the fuel composition. At low engine
17 load (25%), as shown in Figure 17 the HRR for blends PE5 and PE20 decreased by 6.74% and
18 18.54%, respectively, compared to DF. The ignition delay for the fuel blends was slightly extended
19 due to the oxygenated nature of the pentanol component. The presence of additional oxygen in the
20 pentanol diesel blends results in a higher HRR, as more fuel is involved in speedy combustion
21 during the prolonged ignition delay. Previous studies have also indicated that alcohol diesel blends
22 normally exhibit higher HRR values than pure diesel [87]. Figure 18 indicates that the HRR for
23 PE5 and PE20 increases by 1.82% and 17.19%, respectively, compared to DF at a 50% engine

1 load. This increase in HRR is attributed to improved fuel air mixing and enhanced atomization
2 resulting from the addition of pentanol. Moreover, Figure 19 reveals that at full engine load
3 (100%), the HRR for PE5 and PE20 exceeds that of DF by 8.01% and 80.02%, respectively.
4 Notably, the substantial increase in HRR for PE20 is due to the higher oxygen content in the
5 pentanol diesel blend. Also, during the premixed combustion phase, the HRR peak increases by
6 7.63%, with the crank angle advancing from 1° to 2° . Moreover, the elevated oxygen
7 concentration in the blended fuels contributes to a longer ignition delay, which in turn boosts the
8 peak HRR. A prolonged ignition delay causes a larger portion of the fuel to combust during the
9 premixed phase, thereby enhancing overall combustion efficiency [88].

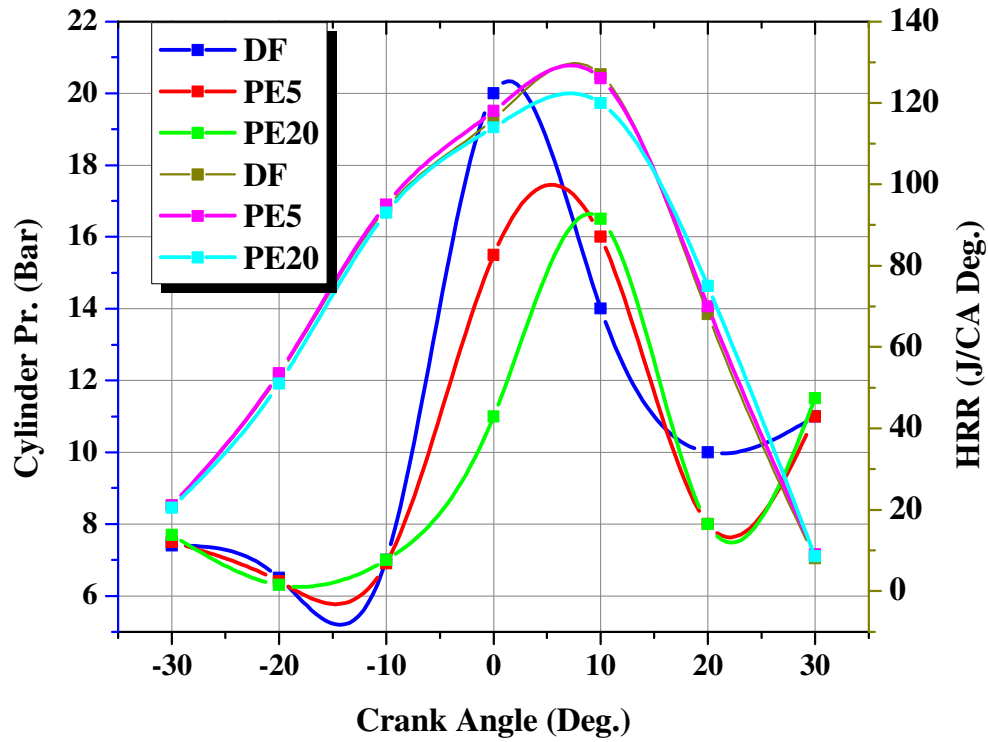


Figure (17) Variation of CP and HRR of diesel fuel and different biofuels at 25% load [55]

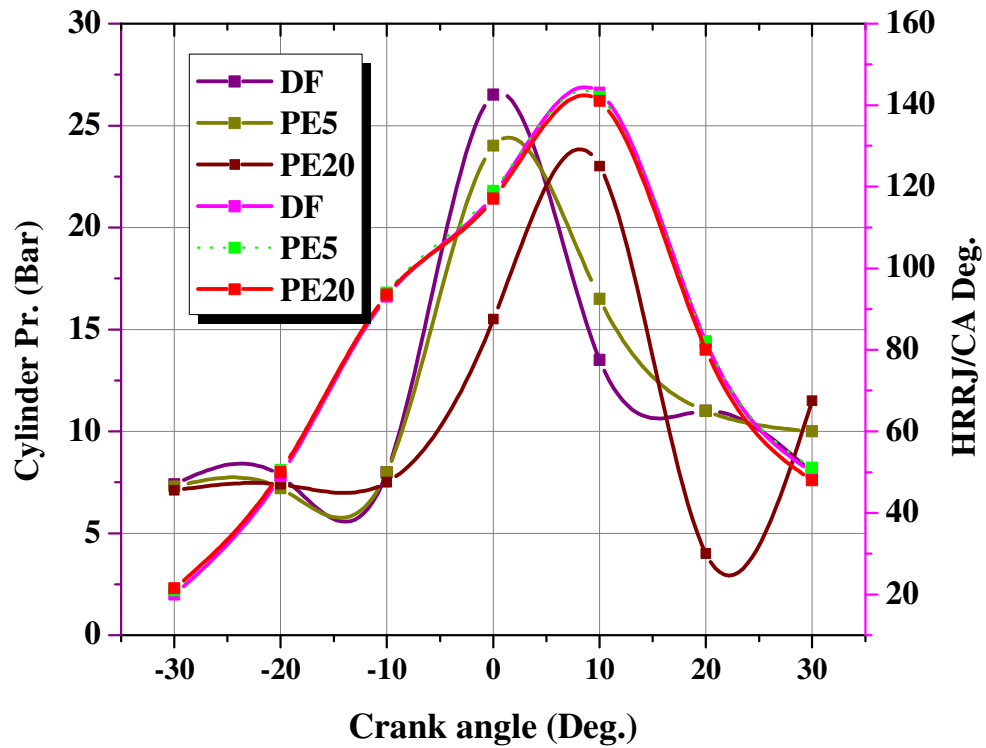


Figure (18) Variation of CP and HRR of diesel fuel and different biofuels at 50% load [55]

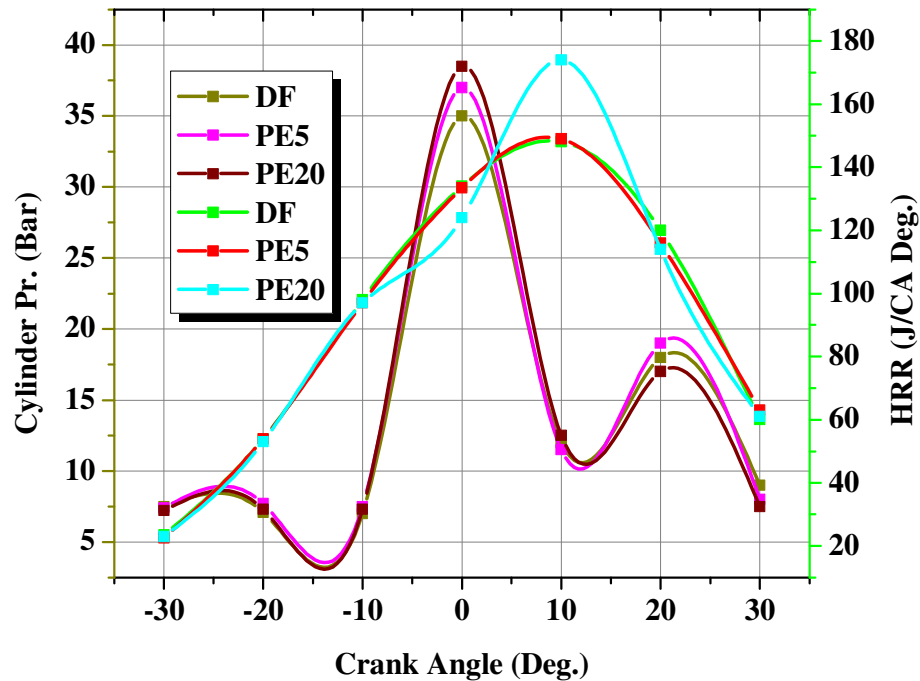


Figure (19) Variation of CP and HRR of diesel fuel and different biofuels at 100% load [55]

4. Emission analysis:

4.1 Carbon monoxide (CO) emission

Carbon monoxide (CO) emissions typically result from incomplete combustion processes and are inversely related to engine load in compression ignition (CI) engines. Researches have shown varying trends for CO emissions when using emulsion-based hybrid biofuels. Some conclusions indicate that MBBFs produce higher CO emissions than conventional petrodiesel [48], while other reports recommend the opposite that CO levels are lower and closely match those observed with B20 and B100 biodiesel blends [54,89]. Table 7 depicts about the CO emissions from MBBFs at different load conditions. These dissimilarities, clearly also depicted in Fig. 20, can be attributed to differences in MBBF composition and the chemical nature of the vegetable oil feedstocks used [90-92]. The occurrence of alcohols in MBBFs is believed to aid in reducing CO emissions, largely due to their higher vaporization rates [91-95]. CO levels tend to be raised under low load conditions

1 but decrease at medium and full loads [95-97]. This behavior is linked to the relatively low in
2 cylinder temperatures at low loads, which are not sufficient to stabilize the cooling effect induced
3 by alcohols, resulting in incomplete combustion. However, at higher loads, the increase in cylinder
4 temperature balances this cooling effect, promoting more complete combustion. As engine load
5 increases, the CO emissions from MBBFs decline further support their classification as oxygenated
6 fuels. The higher CO emissions seen with MBBFs at lower loads may also stem from the cooling
7 impact of alcohols, which weakens combustion efficiency due to reduce in cylinder temperatures.
8 At uniform engine speed of 1000 rev./min, CO emissions from emulsion fuels were noticeably
9 higher than diesel at low loads but became similar or lower at higher loads. Comparative studies
10 of different fuel types including pure diesel, emulsified fuels, palm oil & diesel mixtures, and
11 biodiesel diesel blends indicate that carbon monoxide (CO) emissions from emulsion biofuels are
12 little bit higher than those from neat diesel, particularly under low and medium engine loads. This
13 slight increase in CO emissions can be attributed to the greater viscosity and reduced air-fuel ratio
14 of the blended oil/ethanol-oxygen fuels, which likely leads to incomplete combustion [98-99].
15 Furthermore, all emulsified fuel blends, such as those incorporating DPO were observed to
16 produce more CO emissions compared to conventional diesel fuel.

17 **Table 7:** Changes in CO emissions for diesel and different emulsified fuel blends [95,100-102].

Fuel components (volume %) & type	Load (%)			Brake Torque (Nm) vs ppm			BMEP (MPa)			Load mg/Kg of fuel		Ref.
	20	60	100	0	12	24	0.2	0.6	1	500	1000	
Petrodiesel	0.02	0.01	0.01	150	185	205	0.007	0.0098	0.061	19	41	95
CCO+E+B (87+10+3)	0.014	0.018	0.041	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	95
VCO+E+B (85+10+5)	0.013	0.017	0.041	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	95
MBBF	0.03	0.01	0.02	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	100
DT30+E20 (80+20)	Nr	Nr	Nr	Nr	Nr	Nr	0.017	0.0065	0.045	Nr	Nr	101

PO+D (50+50)	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	39	72	102
DPO	Nr	Nr	Nr	295	260	250	Nr	Nr	Nr	Nr	Nr	103

1

nr (not reported)

2

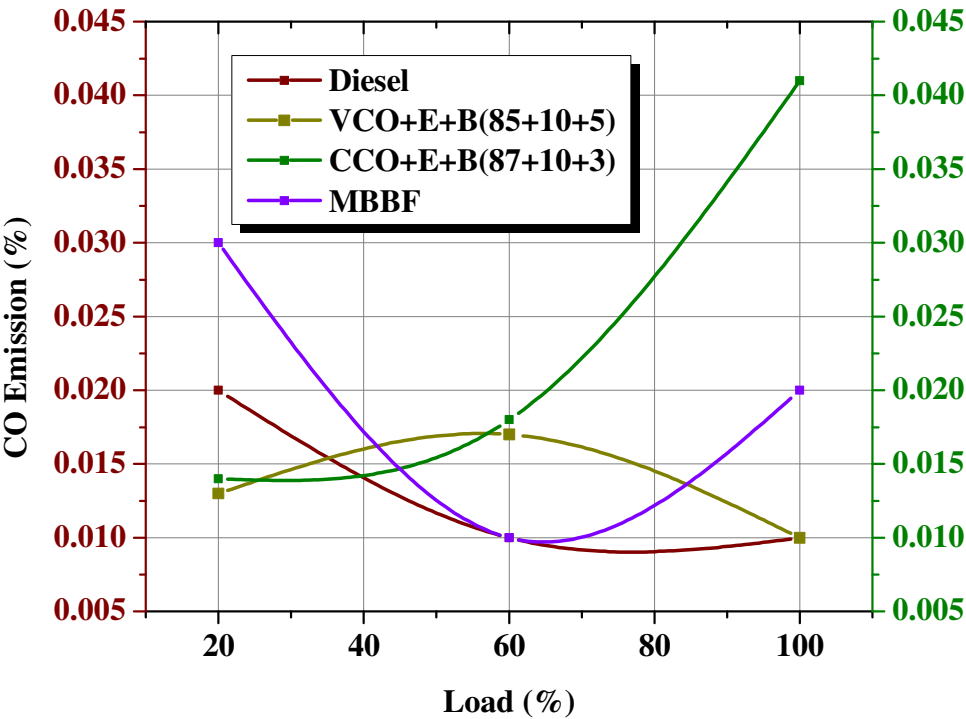


Figure (20) Variation in CO emissions for diesel and different emulsified fuel blends. [30, 56]

4.2 Carbon dioxide (CO₂) emission:

CO₂ is a gaseous emission produced during combustion in compression ignition (CI) engines, and its levels are influenced by the efficiency of combustion. MBBF, being a multi-component fuel blend, exhibits oxygenation properties that vary with the composition of its constituents. [104-106]

Compared to conventional petrodiesel and biodiesel, MBBF contains a lower carbon content, which results in reduced CO₂ emissions upon combustion, as noted in previous studies [106-107].

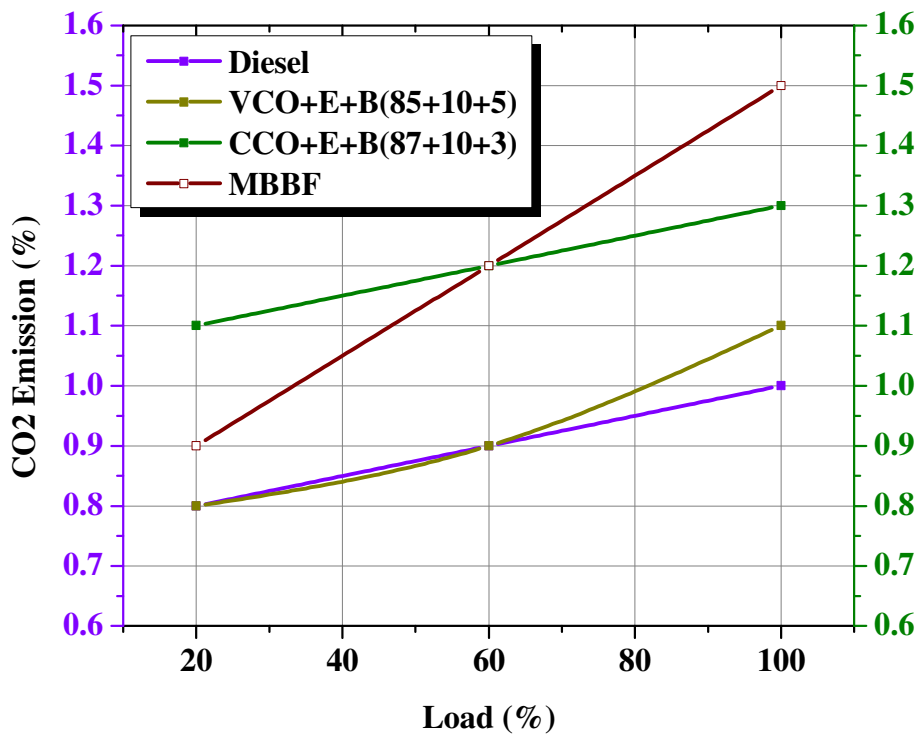
As shown in Table 8, CO₂ emissions from MBBFs are lower than those from petrodiesel, particularly under full load conditions [54]. Given that CO₂ is a key greenhouse gas driving global warming and climate change, this decrease holds substantial environmental importance. When comparing CCO87E10B03, VCO85E10B05 and MBBF to petrodiesel across various load

1 conditions, the CO₂ emission levels were found to be largely similar, with only a few exceptions
2 [108].

3 **Table 8:** Different Emission properties of Carbon Dioxide (CO₂) for diesel and different biofuels
4 [95,100,102-103].

Fuel components (volume %) & type	Load (%)			Brake Torque (Nm) vs ppm			Load mg/Kg of fuel		Ref.
	20	60	100	0	12	24	500	1000	
Petrodiesel	0.08	0.09	1	0.42	0.74	0.97	3050	3100	95
CCO+E+B (87+10+3)	1.1	1.2	1.3	Nr	Nr	Nr	Nr	Nr	95
VCO+E+B (85+10+5)	0.8	0.9	1.1	Nr	Nr	Nr	Nr	Nr	95
MBBF	0.9	1.2	1.5	Nr	Nr	Nr	Nr	Nr	100
PO+D (50+50)	Nr	Nr	Nr	Nr	Nr	Nr	2800	2800	102
DPO	Nr	Nr	Nr	0.39	0.68	0.99	Nr	Nr	103

5
6 nr (not reported)



6
7 **Figure (21)** Variation in CO₂ emissions for diesel and different emulsified fuel blends [95,100]

8 **4.3 NO_x Emissions:**

1 NOx emissions are primarily determined by the temperature inside the combustion chamber, which
2 depends on the fuel type, engine configuration, and operational parameters, as emphasized in
3 research [95,109-110]. These emissions contribute significantly to smog and acid rain formation.
4 NOx typically forms over a high temperature reaction between nitrogen and oxygen. Crucial
5 factors influencing NOx production include the combustion temperature, nitrogen content in the
6 intake air, and the oxygen level in the fuel. Pure biodiesel (B100) showed considerably higher
7 NOx emissions, particularly under full load conditions [57]. Generally, NOx levels rise with
8 increasing engine load but tend to lessening as engine speed increases. These opposing trends
9 interact, resulting in variability in NOx emissions under different engine operating conditions.

10 **Table 9:** Variation in Emission properties of Nitrogen oxides (NO_x) for diesel and different
11 biofuels [95, 100-103]

Fuel components (volume %) & type	Load (%)			Brake Torque (Nm) vs ppm			BMEP (MPa)			Load mg/Kg of fuel		Ref.
	20	60	100	0	12	24	0.2	0.6	1	500	1000	
Petrodiesel	135	355	550	150	280	405	400	1050	1400	51.5	41	95
CCO+E+B (87+10+3)	98	120	250	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	95
VCO+E+B (85+10+5)	88	115	148	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	95
MBBF	46	112	125	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	100
DT30+E20 (80+20)	Nr	Nr	Nr	Nr	Nr	Nr	400	1470	1680	Nr	Nr	101
PO+D (50+50)	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	Nr	38	37	102
DPO	Nr	nr	Nr	118	215	310	Nr	Nr	Nr	Nr	Nr	103

Nr (not reported)

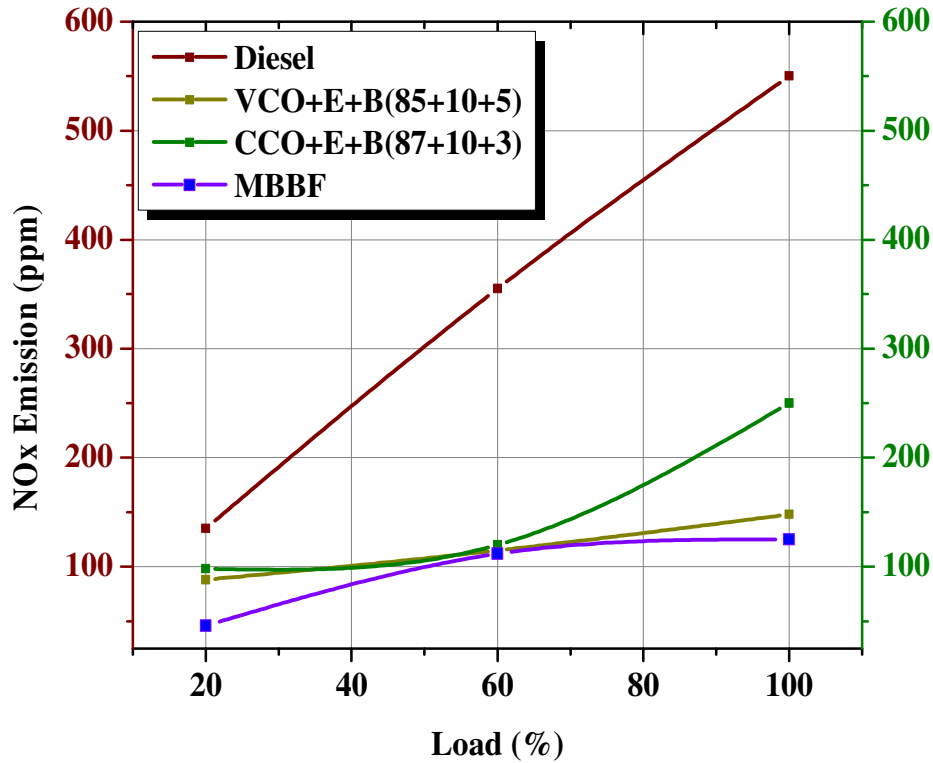


Figure (22) Variation of NO_x emissions for diesel and different emulsified fuel blends [95, 100]

4.4 Unburned hydrocarbon (UHC) Emissions:

UHC emissions from CI engines are significantly affected by the efficiency of air fuel mixing. Despite the importance of maintaining a stoichiometric air fuel ratio, UHC emissions tend to be raised up under both lean and rich mixture conditions [111-113]. As shown in Table 10, [100-101] the use of MBBF results in greater UHC emissions [54, 87] compared to conventional petrodiesel [110]. This indicates a probable area for further investigation, particularly in optimizing injection timing to promote complete combustion and minimize UHC formation when using MBBF [56]. UHC emissions assist as a key indicator of engine emission characteristics. According to the data in Table 9, emulsion-based fuels generally reveal increased UHC emissions across most engine load conditions, with particularly high levels detected at lower speeds and loads. B100 consistently shows higher UHC emissions under similar conditions, as highlighted in Table 10.

Table 10: Various Emission properties of Unburned Hydrocarbons (UHC) for diesel and different biofuels [95, 100-101]

Fuel components (vol %) & type	Load (%)			BMEP (MPa)			Ref.
	20	60	100	0.2	0.6	1	
Petrodiesel	5	6.5	3	5.5	5.5	6.2	95
MBBF	18	28	38	Nr	Nr	Nr	100
DT30+E20 (80+20)	Nr	Nr	Nr	7	7.2	5.9	101

Nr (not reported)

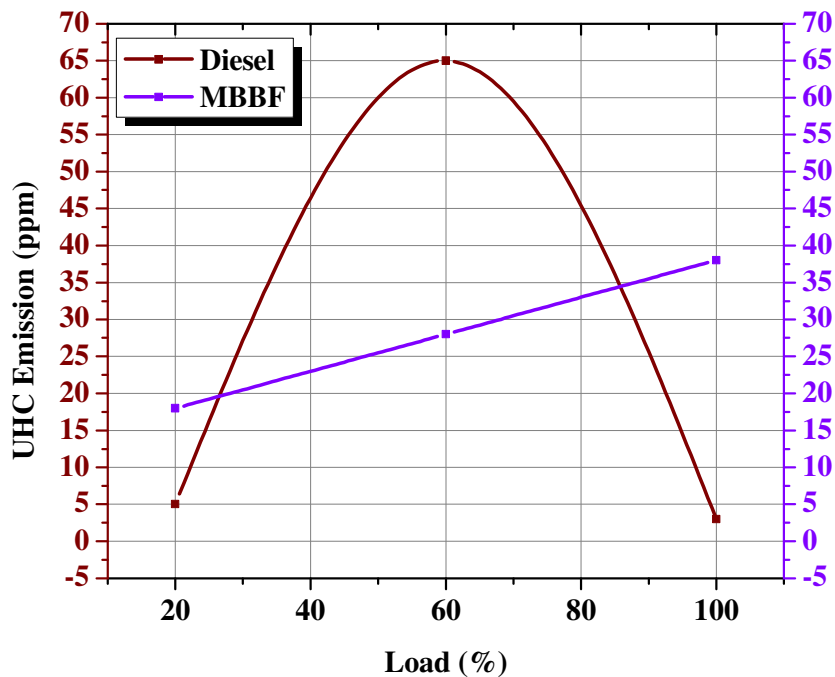


Figure (23) Variation of UHC emissions for diesel and MBBF blends [100]

4.5 Oxides of sulfur (SO_x) Emissions:

The performance of different fuel types was evaluated by measuring brake torque (in Newton-meters) across varying levels of particulate matter concentration (ppm). Pure petrodiesel used as a reference fuel, exhibited brake torque values of 5 Nm, 7 Nm, and 7 Nm at 0 ppm, 12 ppm, and 24 ppm, respectively shown in Table no. 11. In comparison, DPO demonstrated slightly higher

consistency in performance, maintaining a uniform brake torque of 6 Nm across all tested ppm levels [51]. These results suggest that DPO may offer comparable, if not slightly more stable, engine performance under varying particulate conditions as shown in Table no. 11.

Table 11: Variation in Emission Properties of Sulfur Dioxides (SO_x) for diesel and different biofuels [101]

Fuel components (vol %) & type	Brake Torque (Nm) vs ppm			Ref.
	0	12	24	
Petrodiesel	5	7	7	95
DPO	6	6	6	103

5. Conclusions:

This review work observed the effect of various derivatives of hybrid emulsion biofuels upon performance, combustion, and emission profiles of a CI engine. The results emphasize upon the unique performance characteristics for each biofuel type, highlighting the effect of constituents' properties of different biofuels on engine performance. The conclusive remarks are based upon the comparative valuation of various biofuel on CI Engine in comparison with petroleum diesel.

- Diesel/n pentanol/methanol blends reveal extended ignition delays and reduced combustion durations, resulting in steep PHRRs at 10° and more focused combustion, particularly at lower engine loads. Higher methanol content lifts both premixed and diffusion combustion due to its high oxygen content.
- Pentanol blended diesel fuels (PE5, PE10, PE20) significantly influence fuel properties and engine behavior. PE20 notably reduces calorific value (8.12%), density (1.20%), and viscosity

(12%), and modifies combustion pressure and heat release, indicating pentanol's effectiveness in increasing BTE and BSFC.

- Diesel jatropha pentanol blends fit in to ASTM fuel standards. Despite slight drops in brake power and torque, the D60J20P20 blend illustrates improved combustion performance (0.3kg/KWh@1800rpm), indicating its promise as a drop in fuel for existing diesel engines.
- Quaternary blends with pentanol improve engine performance and combustion efficiency associated to pure biodiesel or binary blends. These blends show reduced BSFC and brake specific energy consumption (BSEC), and better air fuel ratio, volumetric efficiency ($\eta_{Vol.}$) and BTE, although highest pressures remain below those of conventional diesel.
- Blending n pentanol with CIME offers good miscibility and combustion characteristics. A 10% blend (B90P10) delivers optimal engine performance, while higher amounts reduce efficiency due to lower energy density and cetane number.
- Bioethanol diesel biodiesel emulsions with up to 15% bioethanol form stable blends with fine spreading. These blends maintain strong combustion performance, slightly reduced heating values, and run smoothly in diesel engines without modification, though at the cost of decreased brake power and increased BSFC.
- EBFs, made from vegetable oils and surfactants, shows favorable high load engine performance and significantly lower NO_x emissions. However, their reduced GCV limits output at lower loads and raises UHC emissions, suggesting a need for combustion optimization.
- MBBFs reduce CO emissions at peak load (0.02%) but increase them at low load. NO_x and HC emissions show different trends depending on engine load, while CO₂ emissions (1.5%)

1 remain stable. These fuels boost BTE and reduce BSFC at low load but show the opposite
2 effects under high load.

- 3 • Solketal as a biodiesel additive develops fuel safety through an increased flash point and
4 reduces CO and emissions at higher engine speeds. However, it lifts NO_x and CO₂ emissions
5 and increases BSFC, though it remains usable in diesel engines without modification.
- 6 • Tung oil diesel ethanol emulsions advantage from reduced viscosity and compatibility with
7 CRDI engines. These blends parade improved combustion dynamics and slightly better BTE,
8 although with higher BSFC. Emission outcomes vary by load, with CO and UHC increasing
9 at low load but aligning with diesel at high load.

10 **6. Recommendations:**

11 As per the comparative evaluation of various biodiesel and biofuel blends in CI engines, numerous
12 recommendations can be proposed to improve engine performance, combustion efficiency, and
13 emission features.

- 14 • Oxygenated alcohol additives such as pentanol, methanol, and ethanol can be effectively used
15 in biodiesel diesel blends to improve combustion quality. Among these, pentanol blends in
16 reasonable proportions (around 10–20%) appear particularly favorable because they improve
17 BTE, reduce BSFC, and maintain acceptable fuel properties. Therefore, optimized ternary or
18 quaternary blends having diesel, biodiesel, and pentanol should be suggested to consider for
19 practical engine applications.
- 20 • Biodiesel derived from nonedible feedstocks such as jatropha and CIME illustrates good
21 compatibility with conventional diesel engines and satisfies standard fuel quality requirements.
22 Blends such as B90P10 or D60J20P20 reveal balanced combustion characteristics and can be

suggested as potential fall in fuels for existing diesel engines without requiring major modifications.

- Emulsion-based hybrid biofuels containing bioethanol or surfactants provide enhanced fuel atomization and mixing, which enhance combustion performance. These fuels also contribute to reduced NO_x emissions under certain functioning conditions. However, their lower calorific value requires further optimization in blend ratios to avoid too much increases in BSFC.
- The use of oxygenated additives such as solketal may improve fuel safety and decrease certain emissions such as CO. Nevertheless, optimization of additive concentration is necessary to regulate increases in NO_x emissions and fuel consumption.

Future research recommendations should focus on optimizing blend composition, improving combustion plans, and integrating advanced fuel injection technologies to maximize the advantages of biodiesel-based fuels. Prominence should also be placed on evolving stable multi component biofuel blends that simultaneously improve engine efficiency, reduce harmful emissions, and maintain fuel stability for long time engine operation.

7. Variability, Reproducibility & Environmental Tradeoffs:

EBF display certain variability due to differences in feedstock composition, surfactant concentration, and preparation conditions. Variations in alcohol type, biodiesel diesel ratio, and temperature can affect stability, viscosity, and combustion characteristics of the fuel. However, with organized formulation parameters and standardized mixing procedures, the reproducibility of emulsion fuels can be improved, ensuring steady physicochemical properties and engine performance. From an environmental viewpoint, these fuels offer advantages such as reduced particulate matter, CO and UHC emissions compared with conventional diesel. Still, the use of surfactants and cosolvents may introduce additional environmental concerns related to toxicity and

production processes. Therefore, optimizing formulation while selecting ecofriendly additives is essential to balance performance benefits with environmental sustainability.

8. Engineering applications of Emulsion based biofuels:

Emulsion biofuels have several promising engineering applications due to their improved fuel properties and better combustion behavior. They can be used as unconventional fuels in CI engines for transportation, agricultural machinery, and stationary power generation systems. The adequate dispersal of fuel components in emulsions improves atomization and mixing with air, leading to more efficient combustion and lesser emissions. These fuels are also suitable for small scale power plants and diesel generators where renewable fuel integration is preferred. In addition, emulsion biofuels can be functional in marine engines and industrial engines to reduce dependence on conventional petroleum-based fuels while subsidiary cleaner energy utilization.

9. Limitations:

Emulsion based algae biodiesel faces significant limitations impacting commercial capability. Phase stability issues arise from thermodynamic uncertainty, leading to unification under temperature variations or mechanical stress, which disrupts nanoscale droplet dispersal and upraises viscosity beyond ASTM limits (1.9–6.0 mm²/s). Cold flow problems are strengthened by high saturated fatty acids in algal lipids, causing cloud point elevation and gelling at subzero temperatures, weakening pumpability. Long term durability concerns include surfactant degradation, oxidative rancidity of polyunsaturated algal oils, and injector fouling from residue formation, reducing engine lifespan and necessitating frequent maintenance. These challenges demand advanced stabilizers and formulation optimization.

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7 **Data Availability Statement**

8 Not applicable

9 **Declarations**

10 **Ethical Approval**

11 This study did not involve human participants or animals; therefore, ethical approval was not
12 required.

13 **Consent to Participate**

14 Not applicable.

15 **Consent to Publish**

16 All authors consent to the publication of this manuscript.

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18 curation, Writing- Original draft preparation, **Himansh Kumar:** Reviewing and Editing,
19 Supervision, Vishal Saxena: Visualization, Investigation.

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