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Analysis of combustion instability and complexity in diesel-biodiesel blends: Effects on performance, emissions, energy, and exergy

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Abstract

Diesel engines are a major source of nitrogen oxides, carbon dioxide, and particulate matter emissions. While biodiesel blends offer potential emission reductions, challenges remain in viscosity, flash point, cold weather performance, and combustion characteristics. This study examines the performance and emission behavior of biodiesel–diesel blends to enhance efficiency and reduce environmental impact. Multiscale entropy analysis was employed to assess combustion instability and complexity, focusing on the influence of fuel composition and engine speed at full load. Experimental investigations were conducted using biodiesel derived from tomato, papaya, and apricot, blended with diesel. The tested fuels included binary and ternary biodiesel–diesel blends with varying levels of complexity. Results indicate that at optimal operating conditions, biodiesel blends enhance energy and exergy efficiency while exhibiting higher carbon dioxide and nitrogen oxide emissions compared to pure diesel. Hydrocarbon emissions decreased under optimized conditions, while fuels with lower chemical complexity demonstrated improved torque output. Diesel, characterized by greater combustion complexity, resulted in lower exergy and useful work. These findings contribute to the understanding of biodiesel application in compression ignition engines, providing insights into performance optimization and emission control strategies.

Keywords: Biodiesel blends; combustion stability; engine emissions; energy efficiency; exergy analysis.

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1. INTRODUCTION

Diesel engines, vital in agriculture, transportation, and industry, promise efficiency but emit pollutants like NOx and PM. Much research focuses on biodiesel from diverse sources as a cleaner alternative (Viswanathan et al., 2022; Taipabu et al., 2022; Damian et al., 2023; Çakmak, 2024). Biodiesels possess dual usability: direct application in compression ignition engines or blending with diesel (Knothe & Razon 2017). This blending alters the fuel's physical and chemical characteristics, impacting engine performance and emissions (Zare et al., 2017; Giakoumis et al., 2012). To tackle challenges like low heating value and high viscosity in biodiesel, researchers propose blending it with high-viscosity methyl ester. This mixture aims to create a stable fuel alternative, facilitating easier integration and reduced emissions in compression ignition engines. Thus, it is essential to examine how these fuels burn when used in contemporary engines to determine whether they can be modified for other uses. Combustion instability serves as one of the engine efficiency indicators.

Since the early development of internal combustion (IC) engines, instability in combustion processes has been a recognized challenge. Understanding the characteristics of combustion instability is crucial in the field of combustion control, as its presence can lead to low thermal efficiency and increased emissions (Muhammed Raji et al., 2025). Combustion instabilities can result in fluctuations in power output and burned fuel mass, which may reduce the mean effective torque by up to 20%. As a result, combustion instability is considered a fundamental issue in IC engine technology, with its unpredictable occurrence posing significant challenges in engine control. Identifying and mitigating the sources of these instabilities has been a primary focus of research in engine technology for decades (Wagner et al., 2000).

High levels of combustion instability can negatively impact engine performance and increase hydrocarbon (HC) and carbon monoxide (CO) emissions (Giakoumis et al., 2017; Arumugam et al., 2024). Research suggests that several factors contribute to this instability, including residual gases, fuel characteristics, injection timing, fuel pressure, and ambient temperature. For instance, Henein et al. investigated combustion instability in a single-cylinder engine during cold starts, observing its presence even with fuels of varying Cetane numbers (Zare et al., 2017). Another study highlighted an increase in instability at lower ambient temperatures (Han, 2000). Cycle-to-cycle variation, which results from combustion failure in certain cycles, is a primary contributor to instability (Zare et al., 2017) Extensive research has been conducted on inter-cycle variability in IC engines (Pham et al., 2013; Bodisco & Brown 2013).

In recent decades, there has been a growing focus on quantifying the complexity of physical systems (Costa et al., 2002). Complexity arises when system components undergo unpredictable transformations and changes. Mathematically defining complexity remains a challenging task, as it is often tied to the understanding of a phenomenon. While entropy-based measures are commonly employed, they may not fully capture complexity, especially in time series data analysis. Traditional algorithms may misinterpret randomness as complexity, particularly when applied to time series data. Multiscale entropy (MSE) analysis addresses this issue by calculating entropy across multiple scales (Litak et al., 2009). Internal combustion engines exemplify such complexity due to the unpredictable variations in cyclic pressure and angle. Managing these complexities presents significant challenges in compression ignition (CI) engine technology (Sen et al., 2008). Addressing variations in the combustion cycle could enhance engine output power while minimizing fluctuations in fuel consumption. Contributing factors to cyclic combustion changes include aerodynamics, fuel-air mixture dynamics, and exhaust gas recirculation (Wendeker et al., 2004; Chen et al., 2023). Nonperiodic models of combustion cycle variations emphasize their dependence on initial conditions (Litak et al., 2009). Some studies have observed predictable combustion variability, while others have noted anomalous occurrences. Inter-cycle variability has been characterized by Wendeker et al., (2004) as chaotic behavior arising from intrinsically nonlinear combustion.

1.1. Purpose of study

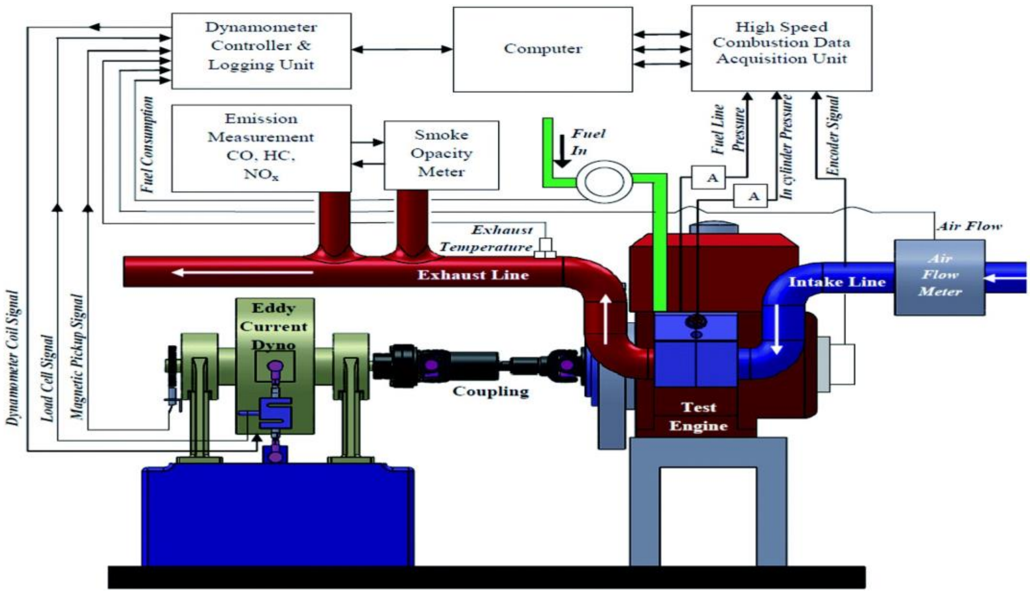
This study investigates the cyclic changes of peak pressure and peak pressure angle in a four-cylinder engine, utilizing binary and ternary mixtures of various biodiesels at different engine speeds. The complexity of each of these variables is quantified using the multiscale entropy method. Additionally, the effects of changes in the cyclic complexity of pressure peaks, pressure angle peaks, heat release rate (HRR), and other parameters on engine performance and emissions are discussed.

2. MATERIALS AND METHODS

2.1 Specifications of the engine and measuring equipment

Tests for emissions and engine performance were conducted based on the ISO 8178 standard procedures in short-term multiple factorial designs at Central Queensland University. Utilizing a Kubota V3300 four-cylinder diesel engine, tests assessed parameters such as power, torque, and speed. Fuel consumption was measured using the Dina Engine system, while emissions were monitored using the MAHA-MGT5 device. Exhaust gas temperature data were recorded via an AVL DISMOKE 480 BT device, enabling analysis of CO, CO_2, HC, O_2, and NOx emissions. This comprehensive setup ensured accurate evaluation of engine performance and emissions. Table 1 presents the technical features and characteristics of the Kubota V3300 engine used in the study. Figure 1a illustrates the Kubota V3300 Combustion System, while Figure 1b shows a schematic setup of the testing devices.

Figure 1
Combustion System and a schematic setup of the testing devices



Note: (a, top) V3300 Kubota Combustion System; and (b, bottom) engine and dynamometer schematic.

Table 1

Kubota V3300 engine specifications

Kubota V3300–T specifications	
Type	Vertical, 4 cycle liquid cooled diesel
No. of cylinders	4
Bore (mm)	98
Stroke (mm)	110
Total displacement (Lit)	3.32
Compression ratio	22.6
Intake system	Naturally aspirated
Output gross intermittent (kW/rpm)	54.5/2600
Fuel Diesel	No-2-D fuel (ASTM D975)

2.2 Conditions of experiment and biodiesel fuel

This study utilized three different methyl esters. Initially, tomato waste seed oil was used to create biodiesel converted via a double-stage transesterification method conducted at Tarbiat Modares University, Iran (Karami et al., 2018). Secondly, In Central Queensland University, Australia, a local provider provided the biodiesel made from papaya seed oil (Anwar et al., 2019). Lastly, biodiesel derived from apricot seed oil was acquired from a nearby Queensland producer, Australia (Anwar et al., 2019). Table 2 presents pure Diesel's (D) chemical and physical characteristics and biodiesels derived from the papaya (P), apricot (A), and tomato (T), as well as their binary and ternary blends based on ASTM standards. The engine operated at various speeds (1200–2400 rpm) and at maximum load, crucial for traffic flow calculations. Only B20 blends were investigated due to their popularity and for ease of comparison. Engine testing conditions are detailed in Table 3. Performance metrics and exhaust emissions from ternary and binary fuels were measured under various conditions. Comparison with pure diesel performance was conducted for five fuel types: The available blends of diesel biodiesel are: pure diesel (D), 80% diesel and 20% tomato biodiesel (TD), 80% diesel and 20% binary mix biodiesel of tomato and papaya (TPD), 80% diesel and 20% binary blend biodiesel of tomato and apricot (TAD), and 80% diesel and 20% ternary blend biodiesel of tomato, apricot, and papaya (TAPD).

Table 2

Karami R., Rasul M. G., Maleki A., Hoseionpur M, & Hassan N.M.S. (2025). Analysis of combustion instability and complexity in diesel-biodiesel blends: Effects on performance, emissions, energy, and exergy. *World Journal of Environmental Research, 15*(1), 84-98. https://doi.org/10.18844/wjer.v15i1.9731

The investigated biodiesels' specifications according to ASTM standards

Property Name	Unit	D	T	P	A	TAD	TPD	TAPD	Limit range	Test Method STM
Molecular Formula		$C_{14}H_{25}$	$C_{17}H_{31}O_2$	$C_{18}H_{33}O_2$	$C_{17}H_{32}O_2$	$C_{17}H_{32}O_2$	$C_{18}H_{32}O_2$	$C_{17}H_{32}O_2$		
Kin. Viscosity @ 40°C	cSt	3.23	5	3.53	4.26	4.25	4.22	4.23	1.9-6	D445
Density - @15°C	Kg/m3	827.2	883	840	855	841.1	833.6	840.64	max 900	D4052
Flash Point (Closed Cup)	°C	68.5	190	112	105				min 130	D93
TAN	mg KOH/g	0.05	0.74	0.42	0.25				max 0.8	D974
Cetane Index	0	48	47.7	48.29	50.45				min 47	D976
Lower Calorific Value	J/g	45300	36666	38490	39640	38174	37808	38460		
Oxygen Content	wt%	1	11.29	11.27	11.21	11.92	11.83	11.7		
Carbon Content	wt%	87	75.41	75.9	75.23	76.01	77.87	76.02		
Hydrogen Content	wt%	12	11.57	11.72	11.72	11.72	11.86	11.69		

Table 3

Conditions of engine test

Biodiesel type	D	TD	TPD	TAD	TAPD
Percentage of Biodiesel	20%	20%	20%	20%	20%
Percentage of Load	100%	100%	100%	100%	100%
	1200	1200	1200	1200	1200
	1400	1400	1400	1400	1400
	1600	1600	1600	1600	1600
Engine Speeds	1800	1800	1800	1800	1800
	2000	2000	2000	2000	2000
	2200	2200	2200	2200	2200
	2400	2400	2400	2400	2400

2.3. Multi-scale entropy (MSE) analysis

The study begins by creating sequential coarse-grained time series from a time series, {x1;: : :; xi;: : :; xN}, by averaging progressively more data points in nonoverlapping windows (Figure 2). The coarse-grained time series yj((τ), element per element, is computed using the following formula (1):

$$y_j^{(\tau)} = 1/\tau \sum_{i=(j-1)\tau+1}^{j\tau} x_i \, , \tag{1}$$

where 1 ≤ j ≤ N/τ and represents the scaling factor, respectively. Each coarse-grained time series is N/τ in length. The original time series is what the coarse-grained time series for scale 1 looks like. Next, we determined SampEn (Richman & Moorman 2000) for every coarse-grained time series that is plotted in relation to the scale factor.

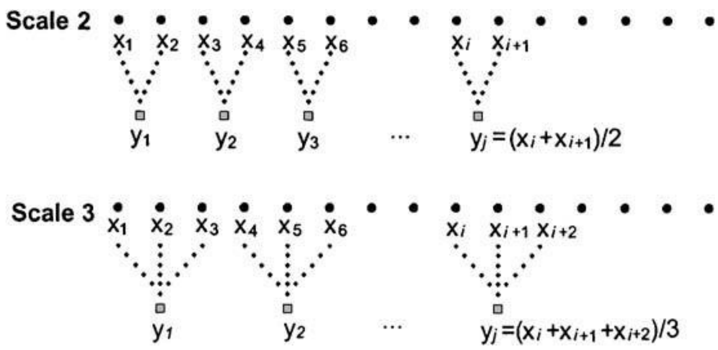


Figure 2. Schematic diagram of the process of course-graining for scales 2 and 3.

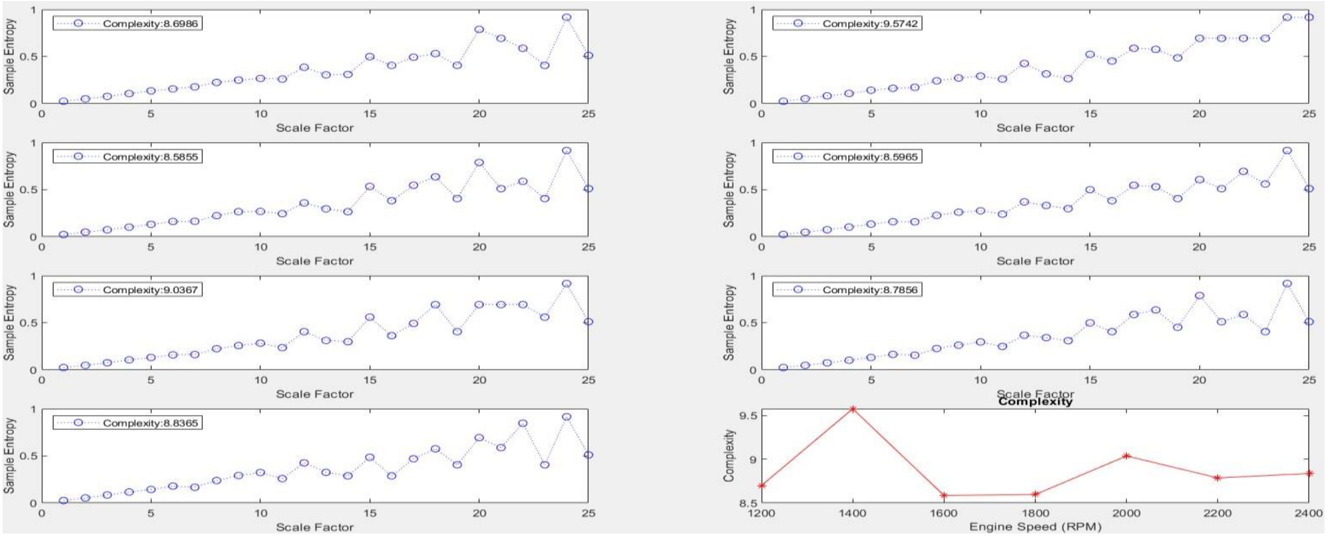
SampEn assesses time series regularity, indicating the likelihood that two similar sequences of m consecutive data points remain similar with the addition of one more consecutive point. Similarity is defined by a distance measure less than r, making SampEn dependent on m and r parameters. In our cases, m = 2 and 3 as well r = 0.1, falling within the suggested range for physiological time series analysis. Empirically, our results were not highly reliant on specific m or r values. The time series' limited length and complexity were calculated using MATLAB software.

3. RESULTS

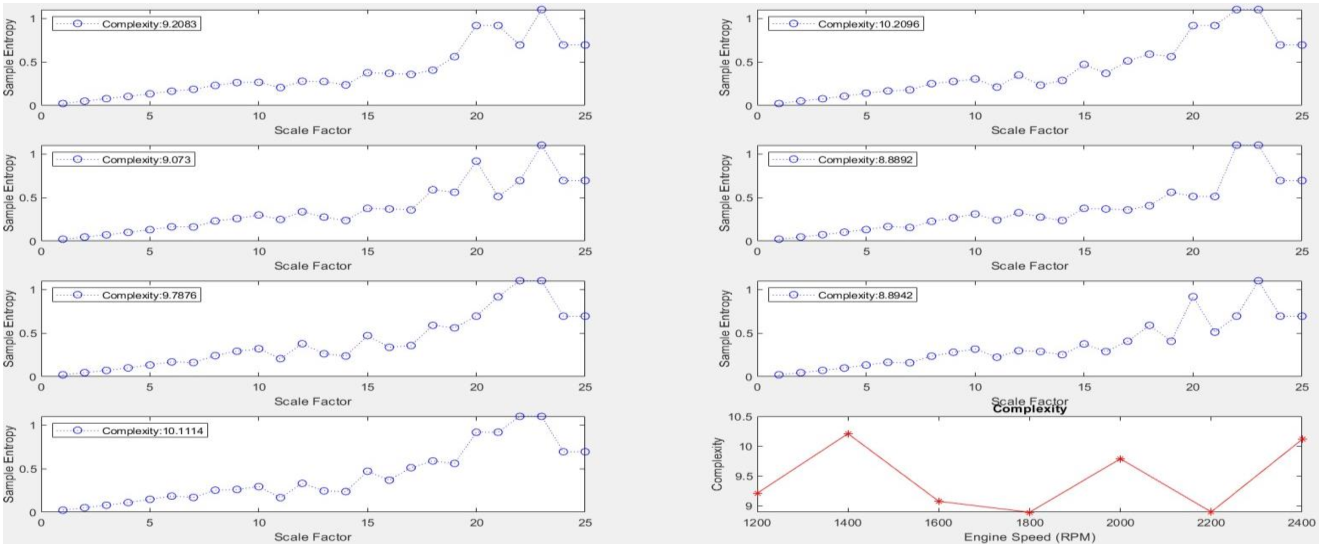
As previously noted, the desired number of components significantly influences sample entropy calculation, adjustable in our approach, the MCC (Multi-Component Complexity) method. We maintained a constant M (following the multi-scale entropy method) while deriving sample entropy across scales τ=1 to τ=40. Using Zhang's formula as seen in Costa et al., (2002), we computed the system's complexity for fixed m values (from m=2 to m=3), iterating this process. In our analysis on two series samples, each with 102 and 103 data points, *r* is set at 0.1 of the standard deviation. Increasing the scale beyond 3 posed challenges, including reduced analysis accuracy and increased computational complexity. However, a higher scale risked losing crucial data information and overlooking important patterns in shorter time frames. Balancing accuracy, computational efficiency, and interpretability led us to choose scale 3 for analysis. Scale 3 provided greater precision, displaying patterns more clearly compared to scale 2, as shown in Figures 3a and 3b. This clarity, along with fewer noises observed, made scale 3 more suitable for analysis. Figure 4 illustrates pressure complexity diagrams in scales 2 (a) and 3 (b) at various engine speeds, highlighting the superior discernibility of fuel complexity in scale 3.

Figure 3

Entropy and complexity of (a) scale 2 and (b) scale 3



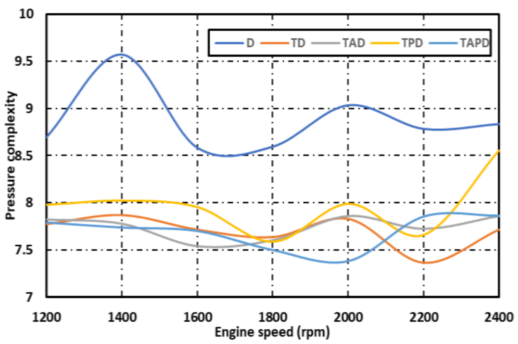
(a)

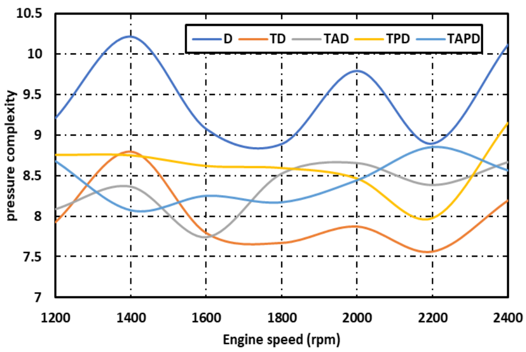


(b)

Figure 4

Pressure complexity of (a) scale 2 and (b) scale 3.





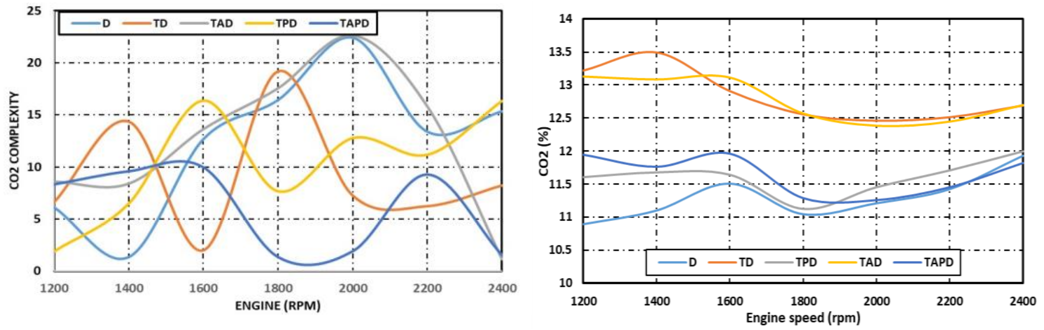
(a) Simulation (b) Experimental

3.1. Emissions analysis

Figure 5a shows the complexity of CO_2 according to engine speed, and Figure 5b displays the levels of CO_2 as the speed increases during the experimental test. In Figure 5a, the complexity of TPD and TD has a regular pattern. A regular and sinusoidal thermodynamic complexity map can indicate a uniform and controlled combustion process. On the other hand, if the fuel used causes more complete combustion, the amount of carbon dioxide production will be higher. Complete combustion means the complete reaction of fuel with oxygen, which results in the production of carbon dioxide and water with the least production of other pollutants (Bouras et al., 2015). If we compare these results with Figure 5b, the amount of produced CO_2 for these two fuels is higher than for other fuels. Moreover, it has been shown that increased combustion efficiency results in increased CO_2 emissions (Fontaras et al., 2010). In these two figures, it can be observed that as the engine speed increases, the complexity pattern becomes less regular. This irregularity can be attributed to increased thermodynamic entropy or disordered combustion within the combustion chamber, leading to a reduction in CO_2 emissions (Bouras et al., 2015). Notably, CO_2 emission decreases when the engine speed reaches 1400 rpm or higher. However, a slight increase in CO_2 emissions from 1600 to 2400 rpm deviates from this trend, likely due to suboptimal engine performance at its maximum speed (Karami et al., 2020).

Figure 5

(a) CO_2 complexity and (b) CO_2 emissions production in relation to engine speed for various fuels.

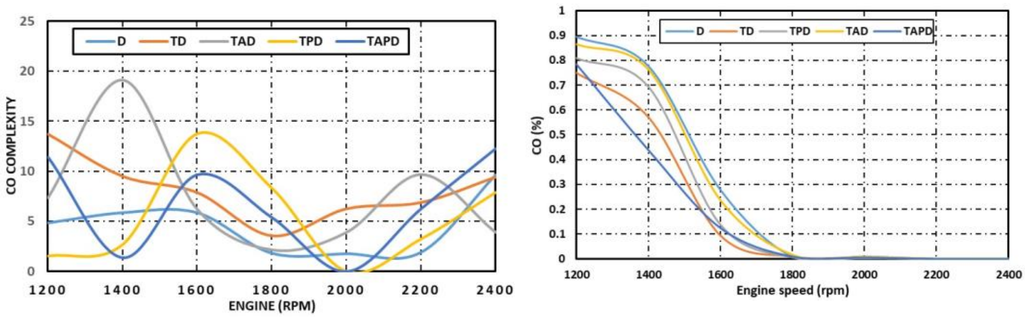


(a) Simulation (b) Experimental

Figure 6a illustrates the complexity of CO relative to engine speed, while Figure 6b presents the levels of CO as speed increases during the experimental test. Figures 6a depicts the erratic and elevated complexity of CO emissions, particularly noticeable up to an engine speed of 1600 rpm. This heightened complexity contributes to increased CO production at these speeds. The complexity of internal combustion engines correlates with increased carbon monoxide emissions due to the intricate processes involved in fuel combustion and engine operation, which can lead to incomplete combustion of fuel (Bebkiewicz et al., 2021). Moreover, as engine speed exceeds this threshold, complexity diminishes for fuels, fostering improved air-fuel mixing and optimizing the fuel/air equivalence ratio (Qi et al., 2009). Additionally, turbulence within the mixture intensifies, enhancing its uniformity. Consequently, CO production approaches negligible levels. Figure 6a further demonstrates that the fuel TAPD exhibits uniform fluctuations and regular complexity, facilitating cleaner and more thorough combustion. Consequently, the minimum CO emissions were associated with TAPD.

Figure 6

(a) CO complexity and (b) CO emissions production versus engine speed for different fuels



(a) Simulation (b) Experimental

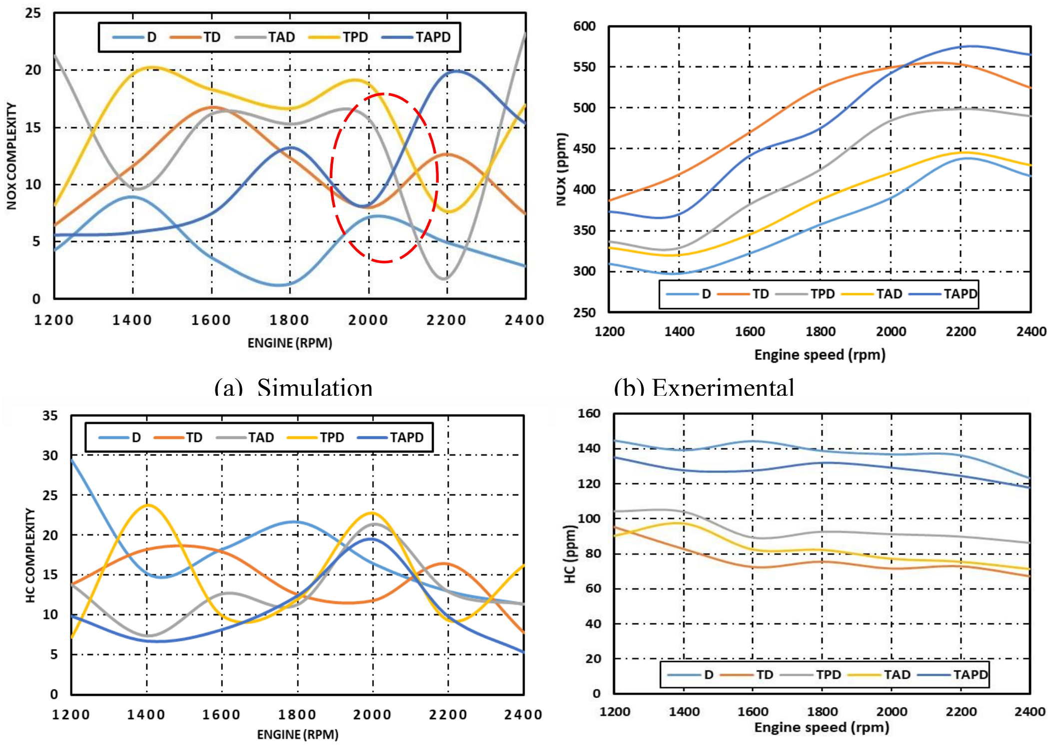
Figure 7a reveals that at 2200 rpm, there is a maximum swing in NOx complexity (Red dashed oval area), reflected by a rise in NOx levels to approximately between 440 and 570 ppm. However, experimental tests indicate that this trend subsides slightly to around between 420 and 560 ppm at 2400 rpm, as depicted in Figure 7b. The high complexity and entropy in the combustion process correlate with increased nitrogen oxide emissions due to the intricate mixture formation, high-pressure combustion conditions, and thermal gradients within the combustion chamber, all contributing to elevated temperatures where nitrogen and oxygen react to form NOx (Bebkiewicz et al., 2021). Additionally, this phenomenon could be attributed to the reactant mixture's increased flow velocity and volumetric efficiency at higher engine speeds (Karami et al., 2019; Luján et al., 2009). As depicted in Figure 7c, the oscillation of the complexity diagram diminishes notably at speeds surpassing 1600, leading to enhanced atomization and swirling within the cylinder. The oscillation of complexity and entropy during combustion correlates with reduced hydrocarbon emissions. This phenomenon can be attributed to the efficient combustion process, where the less oscillation of complexity and entropy and the high compression ratios and lean air-to-fuel ratios promote complete combustion of fuel, leading to fewer unburned hydrocarbons (Bebkiewicz et al., 2021). In addition, this improvement fosters more effective mixing of fuel and air molecules, resulting in a more homogeneous fuel mixture. These optimized conditions contribute to a reduction in emissions of HC by as much as 15%–25% with increasing speed of the engine Figure 7d during the experimental test, as observed in studies by (Canakci et al., 2009).

3.2. Performance analysis

Figure 8a depicts the complexity of compression pressure within the engine cylinder, while Figures 8b and 8c present the experimental data of engine torque output and exhaust gas temperature, respectively, in relation to the engine speed. In Figure 8a, it is evident that pure diesel (D) exhibits significantly higher complexity compared to blends of diesel and biodiesel. This observation suggests that the addition of 20% biodiesel to diesel enhances combustion regularity notably. Moreover, the graph illustrates that the TD and TAD fuels have the lower combustion complexity than that of other fuels. From Figure 8b, it becomes apparent that fuels with lower complexity, such as TD and TAD, yield higher torque output, while diesel, with higher complexity, generates relatively lower torque. The reduced entropy and thermodynamic complexity during combustion in an engine can enhance the torque output. This is primarily due to more efficient energy conversion processes facilitated by lower entropy, which allows for a more organized and effective conversion of chemical energy from fuel into mechanical work. Additionally, lower complexity implies a simpler and more predictable combustion process, reducing losses and optimizing the utilization of energy for torque production (Liu et al., 2020).

Figure 7

(a) NOx, (c) HC complexity and (b) NOx, (d) HC emissions production versus engine speed for different fuels

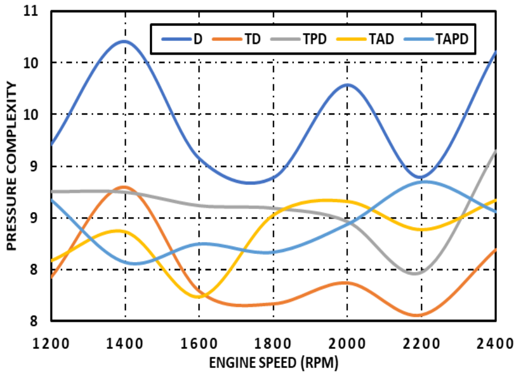


(b) Experimental (d) Experimental

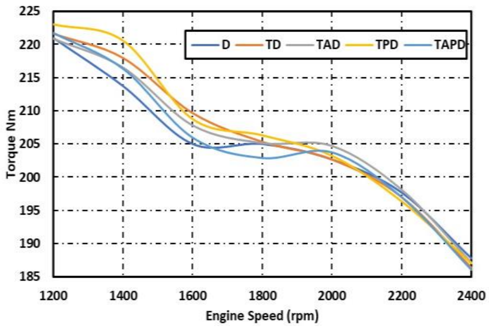
Additionally, a comparison between Figures 8a and 8c reveals that the exhaust gas temperature peaks with pure diesel (D) and is minimal for TD and TAD, which is the opposite point of torque that can be seen in Figure 8b and can be justified by looking at the complexity Figure. The reason is that high entropy causes incomplete combustion and high exhaust temperature. Figures 9a and 9b illustrate the complexity of the heat released rate and the experimental results of brake-specific fuel consumption corresponding to different engine speeds, respectively. In Figure 9a, it is observed that the complexity trends follow a distinct pattern (Red dashed line): complexity is high at low speeds, exhibits a downward trend with increasing speed, and then begins to rise again around 2000 rpm. Comparing this pattern with brake-specific fuel consumption reveals a similar trend, with the lowest values occurring at intermediate speeds. Furthermore, it's noteworthy that fuels TD and TAD exhibit the least complexity in heat release rate (HRR), indicating a more orderly heat release process. Interestingly, the specific fuel consumption for these two fuels is also lower compared to the other fuels depicted in Figure 9b. Low entropy and complexity in the combustion process of an engine enhance combustion efficiency and thermal efficiency. Under these conditions, the chemical energy in the fuel is converted more effectively into mechanical work, resulting in reduced brake specific fuel consumption (BSFC). In other words, the engine can produce the same amount of mechanical work with less fuel, indicating optimized energy conversion and reduced losses (Doe & Smith 2020).

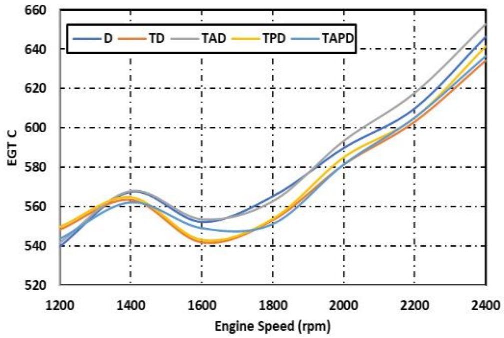
Figure 8

(a) Pressure complexity, (b) torque, and (c) EGT versus engine speed for different fuels.



(a) Simulation

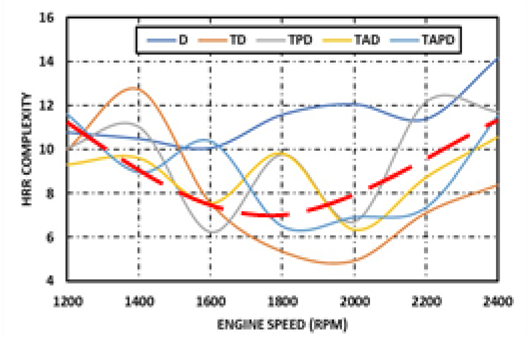


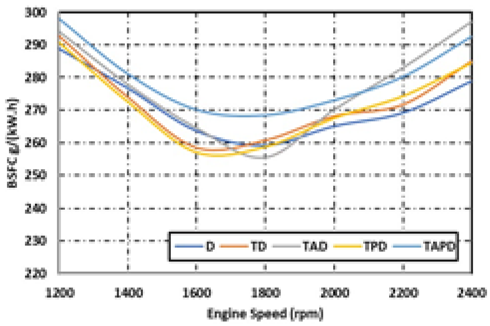


(b) Experimental (c) Experimental

Figure 9

(a) HRR complexity and (b) BSFC versus engine speed for different fuel





(a) Simulation (b) Experimental

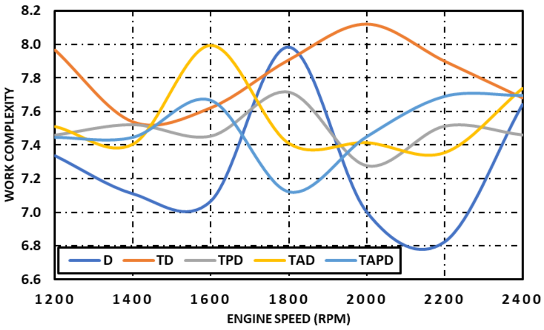
3.4. Exergy and energy analysis

Figure 10a and 10b show the changes in work complexity and experimental output work energy relative to the changes in engine speed, respectively. As can be seen in Figure 10a, the complexity of pure diesel compared to other fuels has the largest fluctuation range compared to other fuels. Now, if this graph is compared with Figure 10b, the lowest work energy is related to pure diesel. Stated otherwise, the mixes of TD, TPD, TAD, and TAPD all exhibited higher thermal efficiency than pure diesel, and they only approached a similar level at high speeds. Simultaneously, the mixes all attain their peak at slower speeds compared to diesel. This can be explained by the fact that biodiesel blends have greater cetane values and shorter ignition delays. Ultimately, TPD, TD, TAD, TAPD, and D attained the best levels of thermal efficiency, with 32.12%, 31.75%, 31.36%, 31.27%, and 30.8%, respectively. This finding suggests that, when compared to pure diesel, the use of binary blends of biodiesel mixtures can increase output complexity, which in turn can lead to improvements in energy or thermal efficiency. These improvements in energy efficiency can also be linked to modifications in fuel specification parameters like viscosity, cetane number, and oxygen content.

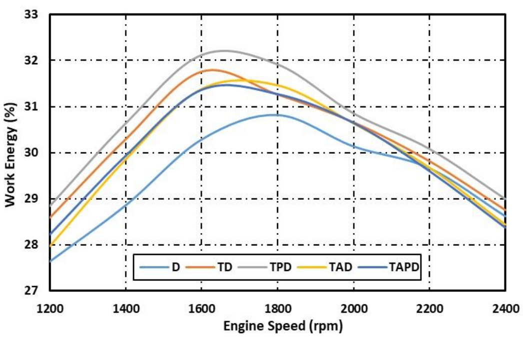
The experimental output exergy work is plotted against engine speed in Figure 10c. The obtained data indicates a similarity between the exergy efficiency and the obtained outcomes. From 1600 rpm to 1800 rpm, exergy efficiency rises with speed before seeing a significant decline. This indicates that energy and exergy efficiency show a similar pattern with varying values for all fuel blends, with exergy efficiency being lower than energy efficiency. Overall, the findings align well with those of other investigators (Hoseinpour et al., 2017). While the binary blend of TPD had the best performance based on exergy efficiency throughout this speed range, those of another binary blend (TAD) and a ternary blend (TAPD) were quite similar to TD, according to the type of fuel evaluated in this study. Notably, all of the fuel blends—TD, TPD, TAD, and TAPD—had exergy efficiencies that are generally higher than of diesel. TPD, TD, TAD, TAPD, and D all had maximum energy efficiency values of 29.63%, 29.08%, 28.97%, 28.94%, and 28.46%, respectively. If the fluctuation range of work complexity is compared in diagram 10a, it is evident that TPD fuel exhibits the lowest range of complexity fluctuations compared to other fuels. As previously mentioned, pure diesel shows the highest complexity fluctuations. This indicates that TPD fuel achieves more stable combustion than other fuels, resulting in better work exergy efficiency. These can be defined that high entropy and complexity during combustion in an engine with high fluctuations can adversely affect the efficiency and exergy output. These conditions lead to less organized and less efficient energy conversion processes, where a significant portion of the available energy is dissipated as waste heat rather than being effectively converted into useful mechanical work. This results in lower overall thermal efficiency and exergy efficiency of the engine (Liu et al., 2020). Additionally, Longer ignition delays are associated with fuels that burn more steadily, which prolongs the fuel combustion process. As a result, diesel engines running at greater speeds have more efficient and consistent combustion. Except for D, which operated at 1800 rpm, these maximum efficiencies happened at 1600 rpm. According to Karagoz et al., (2021) using biodiesel blends and other additives increased a CI engine's energy efficiency.

Figure 10

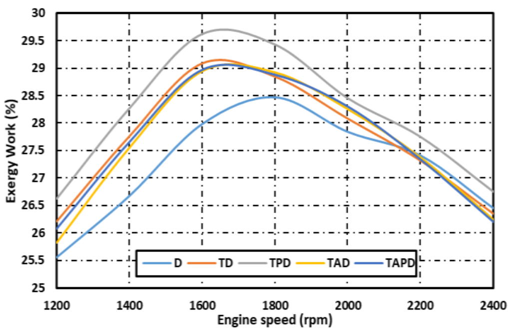
(a) Work complexity, (b) Work Energy and (c) Exergy work versus engine speed for different fuels



(a) Simulation



(b) Experimental



(c) Experimental

4. CONCLUSION

This study investigated the combustion stability, performance, and emissions of a four-cylinder diesel engine using various biodiesel blends and pure diesel, employing multiscale entropy (MSE) to quantify combustion complexity. The results demonstrated that TPD fuel exhibited the lowest fluctuation range in work complexity, indicating more stable combustion, while pure diesel had the highest complexity fluctuations, reflecting less stability. In terms of performance, the biodiesel blends, especially TD and TAD, showed lower combustion complexity, higher torque output, and lower exhaust gas temperatures compared to pure diesel, suggesting more efficient combustion.

Emissions analysis revealed that biodiesel blends generally produce more NOx due to higher combustion temperatures but had more regular combustion patterns, improving air-fuel mixing and reducing CO and CO_2 emissions at certain engine speeds. Furthermore, biodiesel blends achieved higher thermal and exergy efficiencies than pure diesel, particularly at lower engine speeds, with TPD fuel showing the best performance. These findings indicate that biodiesel blends, particularly TPD, offer enhanced combustion stability, improved performance, and reduced emissions, making them viable alternatives for cleaner and more efficient diesel engine operations. Further research could optimize these blends for broader applications, potentially advancing the adoption of biodiesel in various sectors.

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