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Enhancing performance and emission characteristics of palm based biodiesel blends with aeronautical Additives: A comprehensive analysis in a J69 aviation engine

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ABSTRACT

This study investigates the performance of various biofuel blends, including palm kernel biodiesel and palm biodiesel, in comparison to conventional JETA-1 fuel, using an aeronautical additive (ARMOR W7). Biofuels with 5 % and 520 ppm of aeronautic additive, were evaluated in a military J69T-25 aviation engine, with continuous monitoring of engine parameters and emissions across different flow rates. Experimental results demonstrate that a blend comprising 5 % renewable palm kernel biodiesel supplemented with 560 ppm of additive outperforms conventional JETA-1 fuel, delivering a thrust of 698 N at take-off while simultaneously reducing CO and CO_2 emissions by 46 ppm and 29 ppm, respectively. This blend maintains high performance across all operational conditions, achieving a thermal efficiency of 16.1 % and superior parameters compared to conventional JET-A1 fuel. Parameter estimation techniques were applied to refine experimental data, resulting in empirical functions for thrust and thermal efficiency specific to this test bench setup. Furthermore, statistical analysis via principal component analysis (PCA) revealed increased oxygenation of the blend and enhanced emission mitigation, consistent with prior studies on additives of comparable composition. These findings underscore the potential of biofuel blends supplemented with appropriate additives to improve performance and reduce emissions in aviation applications.

1. Introduction

The aviation industry is at a critical juncture, confronted with the pressing challenge of reducing carbon emissions in pursuit of complete decarbonization by 2050 [1]. This challenge is compounded by projections indicating a doubling in passenger demand and a rise in air cargo transportation by 2040. Meeting this objective necessitates a comprehensive transformation, encompassing the advancement and adoption of alternative propulsion technologies like biofuels [2].

This transformation process also entails investments in the essential infrastructure for producing, storing, and distributing alternative fuels, along with the implementation of regulatory frameworks that encourage sustainable practices throughout the industry. Additionally, it's worth noting that airlines under IATA and governments are dedicated to achieving Net Zero in Aviation by 2050 [3]. Despite challenges like the high costs of new technologies and the necessity for a strong commitment from all industry stakeholders, the decarbonization of aviation appears as an achievable and vital objective. Collaboration among governments [4] the private sector, academia, and civil society play a fundamental role in this effort, paving the way toward a more sustainable future for aviation. This collective commitment to innovation and sustainability promises not only to address the environmental responsibility of the sector but also to lead the global transition towards environmentally friendly practices in an efficient and eco-friendly manner [5]. Nowadays the energy systems are the largest contributors of greenhouse gas emissions, which generate multiple effects. Different countries are currently working on energy objectives consolidation and fulfillment agreed at corresponding meetings such as COP 26, these topics involve the energy transition as topic of the international climate agreements, which have allowed the creation of various scenarios where fossil fuels already began to be substituted or replaced by other energy

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Nomenclature

Abbreviations

Symbol	Definition Units
%EA	Percent excess combustion air [% g/g]
P_f	Fuel pressure [kPa]
m˙i	Fuel mass flow [g/s]
wBD	Palm biodiesel volume content in fuel blend [% v/v]
wEtOH	anhydrous alcohol volume content in fuel blend [% v/v]
wPalmiste	palm-kernel biodiesel volume content in fuel blend [% v/v]
PCT ωsha ft	Percent main shaft rotational speed [RPM]
AFR	Air/fuel ratio [g/g]
EGT	Exhaust gas temperature [g/g]
HHV	Higher heating value [MJ/kg]
T	Thrust force [N]
OAT	Outside Air Temperature [C]
m_i	Mass Flow for i component [g/s]
W_i	Molecular weight for I component [Kg $Kmol^{-1}$]
Δt	Time delay [s]
X_i	Mas fracción for i component [% (mi/m_T)]
λ	Lambda [None]
V_i	Fluid velocity across different sections of the turboreactor [m/s]
LHV_{blend}	Lower heating value for fuel blends [Kj Kg^{-1}]
V_θ	covariance matrix [None]
S^2	Variance [$(var)^2$]
B_i	Sensitivity matrix [None]
B^T	Transpose sensitivity matrix [None]
ρ_{ij}	Correlation matrix [None]
V_{ij}, v_{ii},v_{jj}	Covariances of parameter estimates [None]
F_{obj}	objective function [None]
λ_{ii}, λ_{ij}	estimated parameters [None]
σ	Variance [(var)]
y^m	Measured variable [None]
y^e	Estimated variable [None]

sources, favoring the decarbonization [6,7]. Several actors are evolving in energy transition, including the transportation sector in its maritime, land and air modalities [8]. Air transport plays a fundamental role in the development and competitiveness of the economies of countries and regions, which are increasingly interconnected in response to the dynamics of globalization and world trade. The commercial air transport sector, including the military, has been one of the fastest growing industries around the world, for instance, it generates an increase in jet fuel demand [9]. Despite the advances and technological developments of aircraft, annual consumption of aeronautical fuels is expected to grow between 2 % and 3 %. This trend would clearly generate an increase in greenhouse gas emissions [10,11]. The aviation industry, responsible for approximately 2–3 % of global carbon dioxide (CO_2) emissions, has been significantly impacted by the COVID-19 pandemic, leading to a temporary reduction in air traffic.

Projections suggest that passenger air traffic volumes may not rebound to pre-pandemic levels until the end of 2022. Furthermore, there is an anticipated 8 % reduction in passenger air traffic volume by 2050 compared to pre-pandemic estimates [12]. Despite this, the International Energy Agency (IEA) estimates a 50 % increase in aviation fuel demand by 2040 compared to 2019 levels [13].

Research has focused on the importance of assessing the use of fatty acid methyl esters (FAME) in aviation engines and on the production of FAME at a laboratory scale, as these are emerging as substantial alternatives to replace fossil aviation fuels fully or partially. The underlying objective of this transition is the mitigation of greenhouse gas emissions [14]. In addition, it is important to mention the research that was undertaken to analyze the production of FAME biodiesel from palm kernel oil in a laboratory setting, exploring variations in temperature, catalyst amount and methanol-oil ratio. The aim of these experiments is to understand how these factors are able to influence methyl ester production performance [15]. The studies analyze the assessment in the use of potential biofuels for aviation engines, highlighting the ground trials that have been conducted to corroborate and present the results of the options explored [16]. This, also highlights the need to investigate the production and adoption of an alternative, renewable and sustainable biofuel, such as fatty acid methyl ester (FAME), with the aim of diversifying the national energy portfolio, especially in the air transport sector [17].

The development of biofuels provides different advantages and benefits over traditional oil-derived fuels like, energy security, environmental impact reduction and positive socioeconomic impacts, among others [18], contributing to the abatement of greenhouse gasses for transportation. In the aeronautical sector, fuels have higher standards and characteristics which contribute to maximize the efficiency of the cycle and guarantee operability at higher altitudes, this necessity has led to the exploration of other sustainable options, promoting decarbonization in the aviation sector [19]. In Previously works, we demonstrated the use of biofuel blends with JETA-1 and we found that 50 % of biodiesel blends for operating turbojet engines. It was found that combustion was inhibited, producing carbonaceous species that affected some components of the combustion chamber without comprising the operating, moreover, the cold properties like freezing point, pour point and flash changed abruptly, making the use of these blends inoperative [20]. It is also necessary to improve the biofuel blends transport properties, based on these previous remarks. In this work fuel blends with Biodiesel, Kernel Biodiesel with aeronautic fuel JETA-1, were evaluated. Besides, a certified additive containing Light aromatics, heavy aromatics, 2-ethylhexyl nitrate, 1,2,4-Trimethylbenzene (See supporting information), in order to adjust the cold properties of the final blends while evaluating the thermal and mechanical performance and comparing the overall efficiency of the cycle.

Previous literature on biofuel blends with jet fuel for aviation has extensively explored the intricate relationship between various components and their impact on the flashpoint (FP) of these blends. The significance of understanding FP in mitigating fire risks, particularly concerning jet fuel, has been underscored [21,22]. Studies have revealed that the FP of FAMEs is directly correlated with carbon chain length, with an inverse relationship observed in the presence of unsaturation within the carbon chain [23]. Furthermore, the addition of ethanol to hydrocarbon mixtures has been shown to significantly reduce FP, highlighting the non-ideality of the system [21]. Interestingly, ideal solution characteristics have been observed in binary systems formed by FAMEs, suggesting the adequacy of ideal estimation models in describing their behavior [23].

Experimental and computational investigations have further elucidated the impact of aromatics on the flashpoint of biofuels and their blends [24]. Aromatic fluids such as A100 and A200 have been identified as suitable candidates for blending with certain biofuels to match the flashpoints of conventional jet fuels [24]. However, the compatibility of bio-jet fuels with existing fueling systems poses challenges, particularly due to the lack of aromatics and polar compounds [22]. This underscores the necessity for further research to tackle compatibility issues and ensure regulatory compliance [22]. Moreover, comprehensive evaluations have been conducted on the performance characteristics of bio-jet fuels, encompassing parameters such as low-temperature fluidity, thermal oxidation stability, combustion properties, and fuel volatility [22]. These evaluations have provided valuable insights into the feasibility of bio-jet fuels production and their potential as promising alternatives to conventional jet fuels [22].

Engine performance is significantly influenced by the carbonaceous species present in the fuel. [25] demonstrated that the energy density of fuel, as well as specific energy, increases with the carbonaceous chain length of the fuel compared to JETA-1. This suggests that increasing the carbonaceous chain length can enhance both variables, thereby increasing the energy content of renewable fuels when used as additives. Moreover, [26] emphasized the importance of additives in aviation fuels, noting that they contribute to an improved flash point for blends and an increased carbon chain length, thereby enhancing the safety of aeronautic operations related to fuel storage and engine performance. Additionally [27] highlighted the superior performance of bio-jet fuels in cold properties when additives such as compounds derived from biomass (e.g., luke, furfural, ketones, and esters) are utilized. These additives, attributed to their carbon chain properties in blends, have the potential to significantly improve the overall performance of aviation fuels.

In selecting the appropriate concentration of additives for the blend of Jet Fuel A-1 and biofuel, adherence to ASTM D-4171 specifications is imperative, which stipulates a maximum allowable concentration of 0.15 % or 1500 ppm for antifreeze additives. Beyond traditional additives like antioxidants and metal deactivators, antifreeze compounds play a crucial role in enhancing aviation fuel performance by lowering freezing points [21]. These antifreeze additives typically consist of solvent-based compounds comprising light and heavy aromatics, which decrease surface tension and subsequently lower the freezing temperature of the fuel mixture [23]. However, while promising, these additives are still undergoing validation to ensure compliance with the stringent ASTM D-1655 standard, which mandates a maximum freezing point reduction to −47 °C. Numerous research endeavors have been undertaken to explore the efficacy of additives with diverse chemical compositions, ranging from ethers and glycols to organic acids and terpenes [24]. The aviation additives market presents a lucrative opportunity for innovation; however, the literature is notably sparse on reports detailing mixtures of Jet Fuel A-1 with biodiesel esters. This gap in research is particularly significant given the distinctive impact of biodiesel esters on freezing points. Biodiesel esters, characterized by linear oxygenated chains, counteract the freezing point reduction facilitated by branched or cyclic hydrocarbon structures typically found in aviation fuels [22]. Therefore, understanding the interplay between biodiesel esters and traditional additives is crucial for optimizing freezing point reduction in aviation fuel blends. In essence, while antifreeze additives hold promise for enhancing the low-temperature performance of aviation fuels, further research is essential to validate their efficacy and compatibility with biodiesel esters. Addressing this knowledge gap will not only advance the development of efficient aviation fuel blends but also contribute to meeting the stringent standards required for safe and reliable aircraft operation in diverse environmental conditions.

Research has demonstrated the development of an aeronautical additive containing diamyl and *iso*-amylene ethers, cyclic elements, and hydrocarbons derived from an industrial residue of ethanol production [28] This additive exhibits superior properties, including a freezing point twice as low as JETA-1 and a flash point. When mixed with commercial JETA-1, it continues to demonstrate superior properties compared to commercial JETA-1 alone, ensuring improved cold properties crucial for high altitudes [28]. The heat emitted in turbojet reactors due convective and radiative effects, increased proportionally with the size of the carbon chains in the fuels, resulting in higher energy release. This increase is reflected in the outlet temperature of the flue gas, thereby reducing combustion efficiency [29]. This phenomenon is directly linked to the oxidation rate of the fuel, which increases with the percentage of additives. Therefore, the use of additives effectively reduces the carbon chains, enhances oxygenation of the molecules when using ethers or alcohols, and improves the transport and cold properties of the final mixture. There is a notable scarcity of studies focusing on the liquid–solid equilibrium of branched hydrocarbons (JET A1) blended with methyl esters (biodiesel). Consequently, the utilization of predictive modeling methods becomes essential to assess and validate the fluid properties of such combustible mixtures. Several researchers have proposed predictive models aimed at estimating the freezing point of multicomponent mixtures. These models rely on the equality of the chemical potential of each species across the respective phases they inhabit. To determine the activity coefficients in both solid and liquid phases, various equations of state are employed, such as the SRK (Soave Redlich Kwong) equation [30] or using an ideal model as an initial approximation, treating the multicomponent mixture as binary [31]. This approach enabled a preliminary assessment of the system's behavior, providing valuable insights into its phase equilibrium characteristics. These studies predominantly entail theoretical analyses. However, the thermodynamic and mechanical behavior can be investigated through statistical analysis, where variables are adjusted to thermodynamic ideal models. The primary goal is to derive empirical models of these variables for test bench applications, which will be instrumental for SCADA programming and future automation endeavors.

In the realm of aeronautical regulations, stringent limitations govern the utilization of high concentrations of renewable fuels derived from fatty acids, as well as the usage of certified additives. Consequently, the selection of fuel mixtures becomes pivotal, not only considering their life cycle but also delineating the logistic chain of supply and storage while ensuring adherence to stringent quality standards. These standards encompass stability, combustion properties, and fluidity, all of which are determined through a battery of tests performed on the mixtures. Once the mixture's suitability for aviation use is confirmed, it undergoes testing and comparison with conventional fuel in terms of efficiency. Despite meeting these criteria, real-world evaluation under flight conditions becomes essential. This entails modifying engine parameters in the cockpit to accurately assess performance. Studies indicate that the addition of certified additives can enhance both the energy and energy efficiency of the engine. This improvement extends to parameters such as the actual usable energy and sustainability indexes, underscoring the importance of additive inclusion in aviation fuel formulations.

Building on previous research, our study focuses on investigating fuel blends composed of JET A-1 fuel from ECOPETROL, Palmist Kernel Biodiesel (PKB), and Palm Biodiesel (PB) obtained from BioD company. Additionally, we incorporate LS Chemical's aeronautic additive, Total Armor W7 (TAW7). Our aim is to compare thermal, mechanical, and emission parameters of these fuel blends with JET-A1. We conduct our analysis using a J69T-25A aviation engine installed on an A/M37T-20B test bench provided by the Colombian Air Force (FAC).

2. Materials and methods

2.1. Engine test bench specifications

The J69T-25A engine was evaluated on a stationary ground test bench A/M37T-20B[14], equipped with a highly adaptable fuel supply system designed to meet diverse operational requirements while upholding manufacturer specifications (See Fig. 1).

This engine configuration comprises both a centrifugal compressor stage and an axial turbine stage, showcasing impressive capabilities with a maximum shaft rotation speed of 21,730 RPM and a peak power output of 640 kW. Our testing setup also included measures for monitoring compressor and turbine vibrations, facilitating exhaust gas sampling, and ensuring optimal lubrication. In our study, precise test batches were prepared within 200-liter containers, blending varying proportions of renewable fuel and additives with Jet A-1. These blends underwent thorough mixing with a recirculation system, outlined in our experimental protocol. Our testing protocol began with idle operations, followed by subsequent adjustments to comprehensively evaluate performance on the stationary test bench A/M37T-20B. The experimental

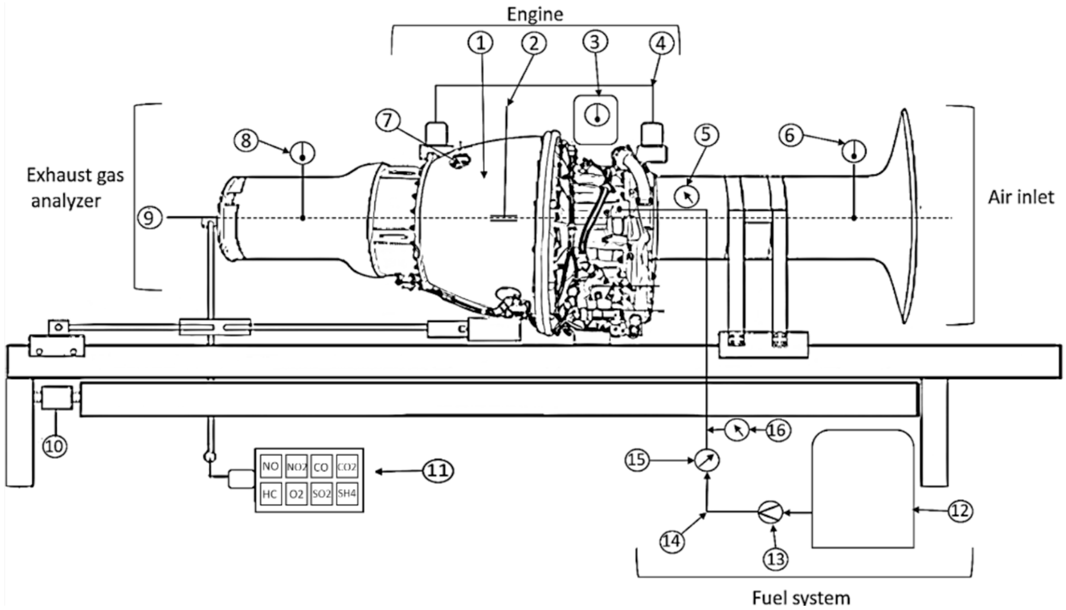

Fig. 1. J69 Engine, instrumentation and detailing peripheral components; (1) Turbojet engine model J69T-25A, (2) Tachometer, (3) Oil temperature thermocouple, (4) Pair of vibration cells, (5) Fuel pressure manometer, (6) Air inlet temperature thermocouple set, (7) PS3, (8) EGT Exhaust gas temperatures thermocouple set, (9) Exhaust gas sampling rake, (10) Thrust force cells, (11) ecom-J2KNpro Series Analyzer, (12) Fuel tank, (13) Fuel pump, (14) fuel line, (15) fuel flow meter, (16) Fuel inlet pressure manometer.

runs were conducted on a A/M37T-20B aviation bench, enabling consideration of additional operational parameters such as fuel inlet pressure, flue flow, and the thrust generated in both the compressor and turbine stages. Table 1 presents the engine specifications including operating parameters and response variables measured [19].

Table 1
J69-T-25th Engine specifications [32,33].

OPERATING PARAMETERS (Take off at 5 min)		
Variable	**Units**	**Value**
Equivalent shaft	HP	902
Jet thrust	Lb	132
Output Delivery	RPM	2000
Mechanical Power	HP	1700
Maximum continuous Power	KW	634
Maximum Interstage Turbine Temperature (ITT)	°C	800

RESPONSE VARIABLES				
Symbol	**Variable**	**Instrument**	**Range**	**Accuracy**
W_{shaft}	Rotational speed	Tachometer AAE. Model MS25038-4	0 RPM – 4200 RPM, speed ratio of 6:1	± 1 %
T_1	Air inlet temperature (OAT)	6Pt termocouples Aircraft Instruments 700,530	−270 °C to 1260 °C	± 1 %
T_7	Exhaust Gas Temperature (EGT)	6Pt termocouples Aircraft Instruments 700,530	−270 °C to 1260 °C	± 1 %
T	Thrust force	2 load cells Toroid model Corp. 3965	0 kg–11,340 kg	± 1 %
O_2	$_i$ (Volume fraction)	ECOM-J2KNpro Series Analyzer	0–21 % vol	± 0.2 % vol
CO			0–10,000 ppm	, ± 2 % Measured
NO			0–5000 ppm	± 5 % Measured
NO_2			0–1000 ppm	± 5 % Measured
SO_2			0–5000 ppm	± 5 % Measured
CO_2			0–20 %	± 5 % Measured
H_2 S			0–1000 ppm	± 5 % Measured

2.2. Fuel blend preparation

The blends were prepared from three essential components: renewable biodiesel derived from palm biodiesel (PB), palm kernel biodiesel (PKB), JET A-1(J_1) and Total Armor W7 (TAW7), an additive provided by LSI Chemical. Table 2 summarizes the main properties of pure components used in the preparation of Blends:

The blends were prepared by briefly mixing the components in 55-gallon drums, utilizing an electrical transfer oil pump with a precision of 1 % and a fuel measuring bucket for biofuel. Subsequently, the blends underwent a re-circulation process using a mobile tank cleaning system ALGAE-X MTC-1000 provided by FAC.

This study investigated three distinct fuel mixtures, all based on the conventional kerosene Jet A-1. Tests on the J69 engine were conducted using various blends, including 94,94 % volume of Jet A-1 and 5 % volume of biofuel, along with Total Armor W7 (0,0540 %). The blends were tagged (See Table 3) as traditional JET A-1 (J_1), blends of palmist kernel biodiesel (PKB) and palm biodiesel (PB), and blends of additive (J_{1Ad}, PKB_{Ad}, PB_{Ad}).

Table 2
Physicochemical properties of pure components.

Fuel	Mass density [(Kg m^{-3}]	HHV [MJ Kg^{-1}]	Molar mass [Kg $Kmol^{-1}$]
J_1	823.35 ± 1.8	45.81 ± 1.8	184,4
PB	873,15 ± 3	39,76 ± 1.8	283,7
PKB	869,75 ± 1.6	38,34 ± 1.8	229,3
TAW7	Not available	Not available	Not available

MEP*	C12:0	C14:0	C16:0	C18:0	C18:1	C18:2	Others
PB	0.12	1,1	44,1	4,4	39	10,5	0,7
PKB	50	14	5,5	6	16	0,5	8

The methyl ester profile (MEP) is shown in Table 3.2 for the two biodiesels used during the tests, which was determined by gas chromatography, described in the next section.

Table 3
Blends designation and main components.

Blend	Main components	Designation
Blend 1	Palmist Kernel Biodiesel (5 %)	PKB
Blend 2	Palmist Kernel Biodiesel (5 %+ 520 ppm additive ppm_additive)	PKB_{Ad}
Blend 3	Palm Biodiesel (5 %)	PB
Blend 4	Palm Biodiesel (5 %+ 520 ppm_additive)	PB_{Ad}
Blend 5	JET A-1 (5 %+520 ppm_additive)	J_{1Ad}
Baseline	JET A-1 Pure	J_1

2.3. Fuel blends characterization

The fuel underwent a robust characterization process following ASTM D1655: Standard Specification for Aviation Turbine Fuels (See Section A.3 from supporting information). Furthermore, additive characterization followed to the ASTM D-4171 standard, specifying a maximum volume of 0.15 % v/v for antifreeze additive, equivalent to 1500 ppm. Various techniques were employed to determine properties including appearance, corrosion to copper foil (D-130), distillation (D-5373), gums (D-4814), Micro-Separometer instrument (D-7261), flash point (D-2386), freezing point (E203-08), total sulfur (D-2622), and aromatics (D-6379). Additionally, measurements encompassed Higher Heating Value (D240-14) and density (D-1298) of both pure fuels and blends. Specifically for fuels tested with the J-69 turbine, elemental analyses were conducted using the Thermo Scientific FLASH 2000 CHNS/O Analyzer, discerning carbon (C), hydrogen (H), nitrogen (N), oxygen (O), and sulfur (S) contents. For chromatographic analysis of methyl esters of fatty acids in biodiesel, a specific procedure was followed. Samples were prepared by combining 5 mg of Tricaprin and 20 mg of biodiesel in an Eppendorf tube, followed by addition of 2 ml hexane, 20 µl silating agent (BSTFA), and 2 drops of pyridine as a catalyst. After a 60-minute wait for derivatization completion, analysis was performed on an Agilent 6820 GC equipped with a FID. The chromatograph comprised a fused silica precolumn (0.3 m x 0.53 mm) and a Supelco SGE HT-5 fused silica capillary column (12 m x 0.53 mm x 0.15 µm). The oven temperature ramped from 140 °C to 380 °C in 12 min (ramp of 20 °C min^{-1}) and held for 10 min. Injector and detector temperatures were 350 °C and 390 °C respectively, with carrier flow rates of 6 cm^3 min^{-1} N_2, 40 cm^3 min^{-1} H_2, and 360 cm^3 min^{-1} dry air.

2.4. Experimental plan design and performance evaluation of blends over J69 test bench

The variables of the considered experimental design were mainly compound in the blend (5 %) and using the same quantity of aeronautical additive provided, it was determined that; the higher level of biofuel content in the blend the more affected the injection systems were, producing blockage in the turbines by the incomplete combustion during the thermal evaluation. Table 4 shows the variables and their respective used levels in the experimental measurement of the performance of fuel blends on A/M37T-20B test bench. Idle conditions were not considered in the analysis due to the required initial time delay necessary to stabilize the main parameters measured on the engine, which is equivalent to the time needed to stabilize idle conditions. Additionally, the cold idle was initiated with a 30-second start-up period. Following this, the engine was allowed to stabilize for 3 min to facilitate data collection.

Table 4
Experimental Planning used for experimental measurements on A/M37T-20B tests bench.

Variable	Levels	Categorical Factors	Specifical levels
Regimen Engine	4	[-1,-2,1,2]	40, 70, 80, 100 % RPM
Blend	4	[-1,-2,1,2]	PB, PKB, PB_{Ad}, PKB_{Ad}
Baseline	J_1	*Not was include Iddle Condition in the analysis	
	J_{1Ad}	Runs = 378	16 replicates for blend and regime engine

2.5. Data processing and thermal calculations

Mass and energy balances are presented according to the following expressions, based on an ideal thermal cycle. The mass balance for these expressions is as follows [34]:

$$\sum (m_i) = m_H + m_O + m_{N_2} + m_{O_2} + m_{H_2O} + m_{CO_2} \tag{1}$$

Then, by assumption of complete combustion:

$$\sum (m_i) = m_{Flue\ Gas} + m_{H_2O} \tag{2}$$

The carbon balance is followed by the main expression:

$$\sum (m_c) = W_{CO_2} m_{CO_2} + W_{CO} m_{CO} \tag{3}$$

Thus:

$$\Delta t / M_{W_c} * [W_{C_f} m_f] = [W_{C_{CO_2}} + W_{C_{CO}}] * m_g \tag{4}$$

Where W_i values represent the experimental values of the percentage of each element in the flue gas to the turbojet outlet, M_{Wc} represents the mass flow for fuel and combustion gases, and dt is the time delay between each measurement in the A/M37T-20B test bench. The complete carbon balance in terms of molecular weight is expressed as follows:

$$[W_{C_f} m_f / M_{W_c}] = W_{C_{CO_2}} m_g / M_{Wc_{CO_2}} + W_{C_{CO}} m_g / M_{Wc_{CO}} \tag{5}$$

So:

$$W_{C_{CO_2}} = X_{CO_2} \left(M_{W_{CO_2}} / M_{W_g} \right) \tag{6}$$

Substituting (6) in (5), the expression resulting is following by:

$$\left[W_{C_f} m_f / M_{W_c} \right] = X_{CO_2} m_g / M_{W_g} + X_{CO} m_g / M_{W_g} \tag{7}$$

Then:

$$m_g = \left[W_{C_f} m_f / M_{W_c} \right] M_{W_g} / (X_{CO_2} + X_{CO}) \tag{8}$$

The mass balance for (N2) in the air inlet and combustion gases is expressed by the following equation: (9):

$$W_{N_{Air}} m_{Air} = W_{N_g} m_g \tag{9}$$

Thus:

$$\Delta t / M_{W_c} [W_{C_f} m_f] = W_{N_{Air}} m_{Air} W_{N_g} m_g \tag{10}$$

Then:

$$m_{Air} / m_{W_{Air}} = m_{Air} \left(M_{W_g} / M_{W_{Air}} \right) \tag{11}$$

making:

$$m_{Air} M_{W_g} / M_{W_{Air}} = m_{Air} / m_f = (W_{c_f}) / M_{W_g} / (X_{CO_2} X_{CO}) \tag{12}$$

Finally, the air–fuel relationship (AFR) is described by expression (13):

$$AFR = m_{Air} / m_f = \left[W_{C_f} / M_{W_c} \right] M_{W_C} / (X_{CO_2} + X_{C0}) \tag{13}$$

The lambda parameter is the ratio between fuel and oxidant and is proportional at AFR according to equation (14):

$$\lambda = AFR\left(M_{W_f}/M_{W_{Air}}\right) \quad (14)$$

The thrust ratio in the turbojet engine is given by the gas velocity differences at the inlet and outlet and is represented by the equation (15)

$$T = AFR\left(M_{W_f}/M_{W_{Air}}\right) \quad (15)$$

The air intake velocity is calculated using Eq. (16), where the ambient air density is determined as an ideal gas mixture with its properties evaluated at the operating environmental conditions, and the cross-sectional area is given as 9,079 m^2. To calculate the exhaust gas velocity, a momentum balance of the engine installed in the testing bench is formulated according to Eq. (18). It is assumed that the pressure of the exhaust gas is approximately equal to the intake air pressure, and that the thrust force is equal to the momentum difference between the intake air and the exhaust gas

$$T = V_{7_{m_{gas}}} - V_{0_{m_{Air}}} \quad (16)$$

$$V_0 = m_{Air}/P_0 A_{T_0} \quad (17)$$

$$V_7 = T + V_0 m_{Air}/m_{gas} \quad (18)$$

Where subindices t_0, i_o corresponding to inlet conditions in nozzle of turbojet reactor expressions (17),18,19) represent mass balance. Thus, the thermodynamic efficiency of operation is given by equation (18)

$$n = \left[TV_0 + 1/2(m_{Air})(1 + AFR^{-1})(V_7 - V_0)^2\right]/[m_{Air} + LHV_{Blend}] \quad (19)$$

In this expression, thermodynamic efficiency is related to the energy provided by the propulsion in fluid dynamic terms, between the inlet and outlet conditions for the air, and the energy when it comes to terms of heat load provided by the air and the calorific value of blends.

3. Results and discussion

3.1. Physicochemical characterization of fuel blends

Table 5 shows the physical and chemical properties of fuels and fuel blends. For these mixtures, these characterizations are presented both with the absence and presence of the additive used in this case.

The density of palmist kernel Biodiesel is 869.75 ± 2.38 kg m^{-3}, while that of Palm Biodiesel is 873.15 ± 3.00 kg m^{-3}, which are densities greater than 823.35 ± 1.8 kg m^{-3} corresponding to that of Jet Fuel [35]. Then it is to be expected that the densities of the mixtures will have a small increase. At this low concentration (5 % V/V), it was observed that the mixture has ideal behavior. For its part, the additive does not contribute to the change in density of the mixture, since it is in a very low concentration of 0.05 % (V/V) corresponding to 503.24 ppm in it. The flash point for palmist kernel biodiesel and palm oil biodiesel is 136.7 °C and 164.9 °C, respectively. Since Jet Fuel A-1 has a flash point value of 48.6 °C, it is expected that when mixing the biodiesel, the value of the property will increase [36]. The additive generates a slight attenuation of this property both in the jet fuel and in the mixture with palm kernel biodiesel, which is understandable because the additive component has a greater volatility than the methyl esters [37]. Regarding the freezing point, it is observed that for jet A-1, the value of −57.5 °C increases significantly when adding any of the two methyl esters, especially with Palm Biodiesel, which has chains of greater length presents a higher freezing point, leading to an increase of 64.35 % [38]. Meanwhile, palm kernel biodiesel, having shorter methyl ester chains, generates a smaller increase (28.70 %) in the freezing point of the blend. This is verified in the methyl ester profile of each biodiesel: 0.2 % laurate, 1.1 % myristate, 44.1 % palmitate, 4.4 % stearate, 39.0 % oleate, 10.5 % linoleate, and 0.7 % others for palm oil; while 50.0 % laurate, 14.0 % myristate, 5.5 % palmitate, 6.0 % stearate, 15.0 % oleate, 0.5 % linoleate, and 9.0 % others for the palm kernel [39]. The additive has a negative effect on the freezing point since it generates a slight increase, except for the mixture of jet fuel A-1 with palm biodiesel, where there is no change [40]. The higher heating value (HHV), it was expected that in both mixtures with biodiesel, it would be reduced since the calorific value of palm is 39.76 ± 0.25 MJ Kg^{-1} and that of palm is 38.34 ± 0.05 MJ Kg^{-1}, values lower by 13.21 % and 16.31 % than that of Jet Fuel A-1, with a value of 45.81 ± 0.01 MJ kg^{-1} [41] The additive, being so diluted, does not make a significant contribution to the heat value of the mixture. According to the elemental analysis, it is observed that when adding any biodiesel to the mixture in both cases, the presence of oxygen increases because in the methyl esters its proportion is between 10.7 % to 14.9 %, compared to hydrocarbons, in which there is a complete absence [41]. This decrease in the calorific value, since C-O and O–H bonds store less energy than C–C and C–H. Finally, the content of methyl esters: palmitate, oleate, and stearate is lower in the mixture with palm kernel biodiesel since unlike palm biodiesel, it is poor in these esters because it is rich in laurate and myristate.

3.2. Thermal and mechanical analysis

Fig. 2 shows the thermodynamic efficiency calculated with the equation (19) assuming ideal gas behavior (a) and Fuel flow measured on the test Bench (b).

The highest temperature, around 582,2 °C, occurs during engine ignition. Operators watch for anomalies such as unusual noises,

Table 5
Characterization of Jet A1, palm-kernel biodiesel and Palm biodiesel blends with JETA-1 up 5% and additive, used in this study.

Test	ASTM	Units	TAW7*	5 % Renewable			5 % Renewable + additive		
				J_1	PB	PKB	J_{1Ad}	PB_{Ad}	PKB_{Ad}
Density at 15 °C	D-1298	kg/m^3	964	823,35	825,84	825,67	823,35	825,84	825,67
Flash point	D-2386	°C	53	48,6	49,5	50,5	48,5	49,5	49,5
Freezing point	E203-08	°C	−45,6	−57,5	−20,5	−41,0	−57,0	−20,5	−40,5
Copper test	D-130	––	NA	1A	1A	1A	1A	1A	1A
HHV	D240-14	MJ/kg	22,1	45,81	43,71	43,23	45,81	43,71	43,23
AFRst	D-2699	g_{air}/g_{fuel}	NA	62,01	57,68	58,34	62,01	57,68	58,34
C_{ad}	D-5373	% g /gfuel	NA	86,25	83,63	82,75	86,25	83,63	82,75
H_{ad}	D-5373	% g /gfuel	NA	13,59	13,18	13,17	13,59	13,18	13,17
N_{ad}	D-5373	% g /gfuel	NA	0,03	0,07	0,03	0,03	0,07	0,03
O_{ad}	D-5373	% g /gfuel	NA	0,13	3,12	4,05	0,13	3,12	4,05
S_{ad}	D-2622	% g/gfuel	NA	0,001	0,0003	0,0003	0,001	0,0003	0,0003
MP	D-6751	% g/fuel	NA	0	2,33	0,29	0	2,33	0,29
MO	D-6751	% g/fuel	NA	0	2,06	0,79	0	2,06	0,79
MS	D-6751	% g/fuel	NA	0	0,24	0,32	0	0,24	0,32

J = JETA-1, PB = Palm Biodiesel, PKB = Palmist Kernel Biodiesel, ad = additive (J_{Ad}, PB_{Ad}, PKO_{Ad},). * Total ArmorW7 (TAW7). NA = not available. MP = Methyl palmitate, MO = Methyl oleate,MS = Methyl stearate.

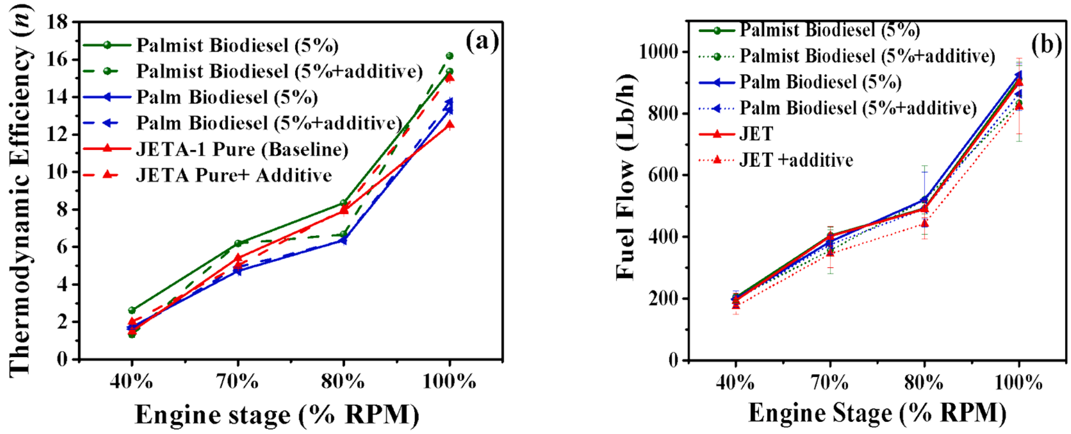

Fig. 2. Efficiency (a) and fuel flow(b) in function of engine stage for Biofuel blends: Continuous lines (only 5 % biofuel), dash lines (included aeronautic additive (20 ppm)). Green line (palmist), blue line (Palm Biodiesel), red line (JET Fuel).

vibrations, or a temperature spike exceeding 780 °C or 900 °C. If so, immediate action is needed. The turbine is then removed from the test bench for inspection. Once in the hot section, the turbine idles at 36–40 % RPM for 5 min, with fuel pressure at 58 PSI and oil pressure at 8 PSI. It progresses to operational modes from 67 % to 80 % RPM, collecting response data. Finally, it reaches standard operational modes of 95 % to 100 % RPM. Oil pressure is monitored at 20–40 PSI, with ± 5 PSI fluctuation. To stop, the turbine is set to 70 % RPM for 30 to 60 s, then returned to minimum RPM, adjusting fuel supply. The accessory box's shutdown time is recorded, usually around one minute. After the engine stops, main fuel and oil solenoid valves are deactivated, and engine oil is collected for analysis.

Fig. 2 shows additives' impact on reducing fuel consumption across engine operational states and increasing efficiency. Solid lines represent pure JET A-1 and biodiesel blends without additives, exhibiting higher fuel flow than dashed lines representing additives. This difference is most notable at 100 % RPM, indicating enhanced combustion efficiency with additives, allowing the engine to generate equivalent power with lower fuel consumption. For instance; Bali [42] observed a 1 % increase in energy efficiency and a 2 % increase in sustainability with biofuel derived from methyl oleate. This improvement was attributed to enhancements in the combustion chamber and combustion behavior, leading to a rise in the sustainability index. Despite increased production of combustion gas outlets, contaminant emissions remained low. Talero [14] reported a 15 % efficiency gain, with 2 % attributed to additives and oxygenated fatty acids like palm biodiesel under optimal conditions. Interestingly, during takeoff, efficiency increased up to 100 % due to improved energy efficiency and combustion kinetics. Biofuel consumption was found comparable to conventional JET A-1 fuel, making it feasible for military aviation. H. Y. Akdeniz and collaborators [43] observed a 2 % efficiency increase, while A. H. H. Ali [44] demonstrated an 8 % efficiency gain using 10 % biofuel blends without additional additives. [45] found slightly higher fuel consumption but comparable performance with reduced emissions using a Jet A-1/butanol blend. Additionally, studies by [46] highlighted improved energy efficiency by 18.18 % and reduced CO_2 emissions by 33.93 % with biofuel utilization compared to Jet A-1 fuel. Fig. 3 illustrates the thrust generated in the turboreactor and the corresponding Air-Fuel Ratio (AFR) for all mixtures across different operating regimes.

In direct comparison with JETA1 and other blends, blends derived from palmist biodiesel have been proved to exhibit superior performance, as depicted by the green line. This superior performance is notably characterized by fuel consumption, serving as a clear indicator of enhanced combustion efficiency, for instance Studies by [46] highlighted reduced thrust and emissions with safflower methyl ester-Jet A1 blends, while [43] reported increased fuel consumption and energy efficiency with biofuel and hydrogen blends. Furthermore, palmist biodiesel demonstrates heightened stability when compared to palm oil-derived fatty acid methyl esters (FAME). This heightened stability extends to excellent transport properties and fluidity. [47] highlighted higher exergy destruction with biofuel, and biodiesel blends led to increased static thrust but also raised CO_2 and NO_x emissions while reducing sulfur dioxide emissions. Studies by [48] emphasized the impact of fuel viscosity and caloric value on combustion characteristics, while microalgae biofuel blends showed improved thrust and reduced emissions. Closely resembling those observed in renewable diesel [49]. Based on experimental observations, it's evident that additives in biodiesel blends don't consistently increase thrust in the J69 engine across

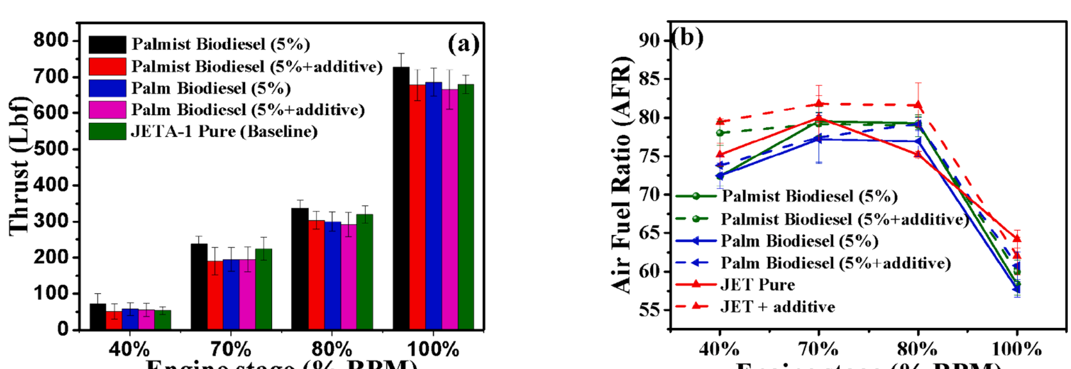

Fig. 3. Thrust(a) and AFR(b) in function of engine stage for Biofuel blends: Continuous lines (only 5 % biofuel), dash lines (included aeronautic additive (20 ppm)). Green line (palmist), blue line (Palm Biodiesel), red line (JET Fuel).

various RPMs significatively, suggests that the efficacy of additives may fluctuate based on operational conditions. For instance, P. Boomadevi and colaborators [50] demonstrate a direct relationship between the percentage of renewable fuel content in JET A-1 and thrust as a function of engine revolutions. This underscores the significance of fuel composition in influencing engine performance, with higher percentages of renewable fuel leading to increased thrust. Furthermore, both passages discuss the role of oxygen in optimizing combustion efficiency and enhancing engine performance [51]. In the experimental observations, the addition of additives to biodiesel blends is suggested to improve combustion efficiency or facilitate better fuel oxygenation [52], leading to higher air–fuel ratios (AFR) and potentially more efficient combustion, increasing in thrust to the enhanced presence of oxygen in the fuel blend [53], which promotes a more efficient combustion process and results in higher thrust output. These additives play a critical role in facilitating the access to hydrocarbon molecules and fatty acids, requiring elevated oxygen levels for optimal combustion [34]. As a result, this process leads to the simultaneous release of greater amounts of usable energy in the form of work [54], for instance [55] assessed turbojet engines using cotton methyl ester, revealing marginal improvements of up to 10 % in both fuel consumption and torque compared to conventional fuel. Thrust values peaked at 230 N, accompanied by elevated combustion temperatures for the renewable fuel. Talib and collaborators found increased thrust and torque alongside improved efficiencies with unspecified fuel blends [56]. Cican and collaborators [57] noted optimal start times and enhanced engine performance with gasoline additives, resulting in reduced CO emissions.

3.3. Emission analysis

Fig. 4 and Fig. 5 displays the levels of exhaust gas emissions CO, O_2 Hydrocarbons not burned (HC) and CO_2.

Answer # 2

The incorporation of additives resulted in a notable decrease in CO emissions by 1000 ppm compared to JET A-1 fuel (Fig. 4a), and a marginal reduction of 0.04 ppm for HC emissions compared to JET A-1 at 100 % RPM (Fig. 5a). Furthermore, the blend's oxygenation was enhanced with the introduction of renewable palm kernel biodiesel and additives, facilitating complete combustion. Thus, this led to a slight increase in CO_2 emissions by 0.2 ppm compared to JET A-1 (Fig. 5b).

Palmist kernel biodiesel has demonstrated superior properties for aviation biofuel blending compared to palm biodiesel, which faces restrictions from IATA and other aviation organizations [58] due to uncontrolled cold properties [59]. The inclusion of esters or alcohols as additives improves these superior properties and enhances cold properties concurrently. For instance, Anderson [60] reported improved thrust and notable reductions in CO, CO_2, and NO_x emissions with the addition of ethanol to fuel blends. Similarly, Devi [61] observed decreased fuel combustion and emissions with microalgae-derived biofuels, though higher substitution percentages correlated with increased emissions levels. Cican and collaborators [62] observed a reduced flame adiabatic temperature, indicating improvements in combustion conditions related to heat and mass transport, attributed to the main effect of Aeroshell 500 additive blended with renewable biodiesel. Subsequently, Cican [63] demonstrated advancements in cold and combustion properties for biofuel blends, showing a reduction in CO and CO_2 emissions with synthetic kerosene, along with additional improvements in thrust [63,64]. Additionally, decreased CO formation was observed with palm biodiesel blends and synthetic kerosene. The addition of the additive results in a significant reduction in the percentage of unburned hydrocarbons, particularly noticeable in the case of palm kernel. Intriguingly, this trend takes an opposite direction from other blends [65,66], revealing an increase in the percentage of unburned hydrocarbons.

3.4. Variability analysis of J69 engine under continuously operation

The thermal and mechanical performance of the J69 engine turbojet varies depending on the type of fuel and the operating regime. Experimental fluctuations are observed in both the parameters measured within the operating turbine and those associated with atmospheric emissions, consequently, a higher correlation between the data obtained on A/M37T-20B test bench is anticipated. In this context, the air–fuel ratio emerges as a pivotal variable with significant relevance to emissions in a turbine. This ratio plays a crucial role in determining combustion behavior and the composition of flue gas. The covariance matrix detailing the variables measured in combustion is presented in Table 6 and Table 7.

The identified significant correlations primarily revolve around the Air-Fuel Ratio (AFR), revealing an inverse correlation of −0.97 concerning CO_2 at high air–fuel ratios. This suggests that the mixture involving renewable fuels demands a higher stoichiometric air requirement compared to the conventional JETA-1 fuel blend. This observation is directly linked to the higher fuel blend flash point. The further use of oil amplifies this required air, explaining the positive correlation of 0.98 for the AFR ratio concerning exhaust air. Additionally, CO_2 levels at the outlet exhibit an increase of gas temperature, elucidating the correlation of 0.87 between these parameters. The overall combustion efficiency is notably improved at lower operating regimes, indicating a kinetics associated with fluid dynamics and determined by the contact between the gas and liquid phases. However, at higher regimes, while combustion velocities are high, there is a noticeable impact on flue gas emissions composition, explaining the correlations found in the AFR ratio (−0.91, 0.92). Conversely, an inverse correlation of −0.6 is observed for unburned hydrocarbons as a function of operating conditions, proportional to the combustion efficiency ETA (0.72). The use of oil introduces unexpected changes in combustion

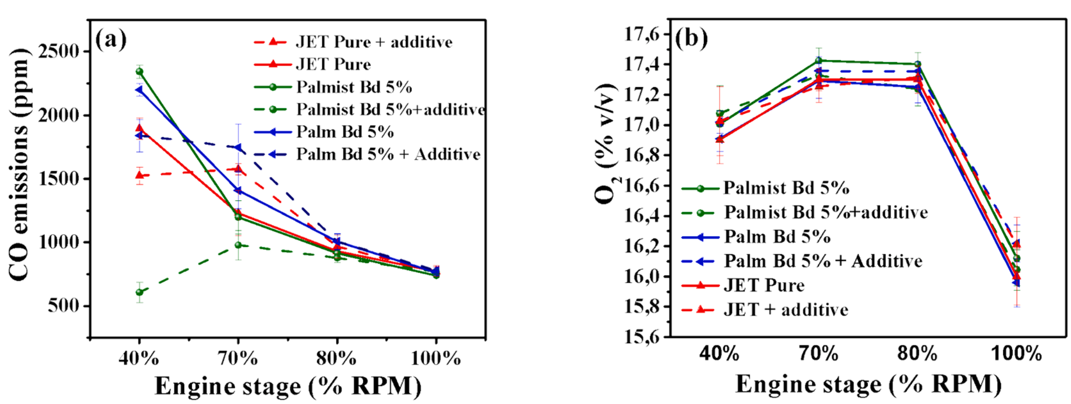

Fig. 4. CO and O_2 in flue gas as function of engine stage for Biofuel blends: Continuous lines (only 5 % biofuel), dash lines (included aeronautic additive (20 ppm)). Green line (palmist), blue line (Palm Biodiesel), red line (JET Fuel).

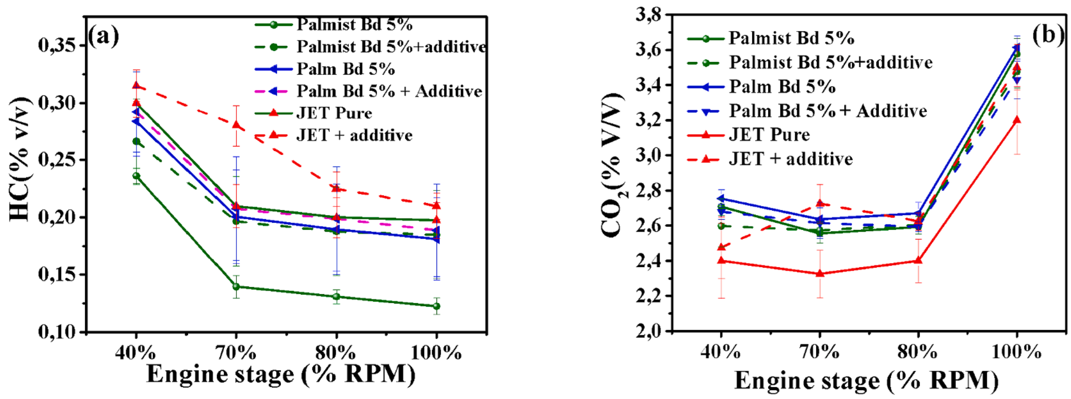

Fig. 5. HC and CO_2 in flue gas as function of engine stage for Biofuel blends: Continuous lines (only 5 % biofuel), dash lines (included aeronautic additive (20 ppm)). Green line (palmist), blue line (Palm Biodiesel), red line (JET Fuel).

Table 6
Correlation matrix of the combustion parameters as a function of the mixture used and the operating regime.

	Engine Stage	$O_2(17,1)$	CO(%)	CO_2 IR (%)	C_xH_y(%)	T_{gas}(°C)	ETA (%)	AFR
Engine Stage	1,00	−0,58	−0,34	0,69	−0,69	**0,91**	**−0,92**	−0,58
O_2(17,1)	−0,58	1,00	0,04	**−0,98**	0,13	−0,79	0,47	**0,98**
CO (%)	−0,34	0,04	1,00	−0,10	0,43	−0,26	0,32	0,04
CO_2 IR (%)	**0,69**	**−0,98**	−0,10	1,00	−0,31	**0,87**	−0,60	**−0,97**
C_xH_y (%)	**−0,69**	0,13	0,43	−0,31	1,00	−0,57	**0,72**	0,15
T_{gas}(°C)	**0,91**	**−0,79**	−0,26	0,87	−0,57	1,00	**−0,91**	−0,82
ETA (%)	**−0,92**	0,47	0,32	−0,60	0,72	**−0,91**	1,00	0,53
AFR	−0,58	**0,98**	0,04	**−0,97**	0,15	−0,82	0,53	1,00

Table 7
Correlation matrix of thermal and mechanical parameters as a function of the blend used and the operating regime.

	Blend	Engine Stage	Thrust	AFR	n	Fuel Flow
Blend	1,00	0,00	−0,05	−0,04	−0,13	−0,01
Engine Stage	0,00	1,00	**0,92**	−0,58	**0,90**	**0,94**
T	−0,05	**0,92**	1,00	**−0,81**	**0,99**	**0,99**
AFR	−0,04	−0,58	−0,81	1,00	**−0,78**	−0,78
n	−0,13	**0,90**	**0,99**	**−0,78**	1,00	**0,97**
Fuel Flow	−0,01	**0,94**	**0,99**	−0,78	**0,97**	1,00

parameters, attributed to the engine's nature and its non-specificity for this type of renewable fuel. Considering the thermal and mechanical behavior of the combustion chamber, an in-depth analysis of correlations between operating parameters, mixtures used, and operating regimes is essential. Table 7 presents the correlation matrix of bench delivery parameters, encompassing calculated parameters based on the proposed thermodynamic model which was outlined in the methodology section.

3.5. Empirical models for engine efficiency and Thrust

The empirical models were obtained from the measured experimental data and the parameter estimation performed in STATISTICA, considering the least weighted squares objective function and the variance. Engine delivery parameters exhibit clear dependencies on the engine operating speed, with positive correlations identified for thrust (0.92) and efficiency (0.90). Notably, fuel consumption shows an upward trend at higher engine speeds (0.94). There are another significant correlation surfaces; the increase in efficiency as a function of thrust; consequently, at lower Air-Fuel Ratio (AFR) values. Higher efficiencies are observed as evidenced by correlations with thrust (−0.81) and efficiency (−0.78). These correlations indicate that, under low operating conditions, a more stoichiometric air–fuel mixture is required to drive the engine until stability is achieved, notably up to 70 % RPM where combustion remains stable; in turn, this stability will result in lower emitted CO_2 levels, contributing to a reduction in system irreversibility. The correlation matrix offers insights into the suitable variables for constructing an empirical model predictively. This model proves to be valuable for understanding the primary trends in engine operation. The initial empirical model focuses on predicting efficiency and thrust under any condition and it's formulated through expressions (20) and (21).

$$T = \lambda_0 + \lambda_1 F_B + \lambda_2 E_S + \lambda_3 E_S F_B + \lambda_4 E_S^2 + \lambda_5 F_B^2 + \lambda_6 E_S^2 F_B^2 \quad (20)$$

$$n = \lambda_7 + \lambda_8 E_S + \lambda_9 T + \lambda_{10} AFR \quad (21)$$

Each parameter was minimized using an objective function previously defined (See Supporting Information), from which the iterative procedure is derived. The parameter estimation procedure yielded the following results. The data to be adjusted with the proposed empirical models is presented in Table 8.

Error was computed using the t-student method and determination of the confidence interval, while also considering the hypothesis that the experiments followed a normal distribution. Statistical evaluation was conducted using empirical models derived from independent variables. The associated error was determined by the arithmetic difference between the two extremes of the confidence interval, employing either the Chi^2 test or the F test for verification (See section A.5 from supporting information). Table 9 shows the parameter estimation and the final parameters respectively; considering if the experiments and their experimental errors follow the normal distribution, we could assume that their residuals also follow a normal distribution.

Fig. 6 displays the normal distribution of the residuals for the two models and the probability of their residuals. This analysis aims to verify whether some experiments are significantly outside the generalized trend observed from the experimental data.

The experimental data showed a normal distribution, indicating that hypothesis related to a well-done experiment will be assumed; with

Table 8
Parameters used in the development of empirical models for thrust and efficiency on J69 engine.

	Categorical variables		Factors*			
Run	E_s	F_B	T (Lbf)	AFR	n (%)	F_F (lbm /b)
1	−2	−2	72,4	72,4	3 %	204,8
2	−1	−2	238,3	79,6	6 %	403,6
3	1	−2	337,0	79,3	8 %	492,3
4	2	−2	728,5	58,3	15 %	911,3
5	−2	−1	51,3	78,0	1 %	201,1
6	−1	−1	190,3	79,2	6 %	356,4
7	1	−1	303,7	79,0	7 %	519,9
8	2	−1	678,3	60,0	16 %	832,3
9	−2	1	57,8	72,4	2 %	198,5
10	−1	1	195,5	77,2	5 %	384,1
11	1	1	300,1	76,9	6 %	520,7
12	2	1	686,3	57,7	13 %	925,5
13	−2	2	55,7	73,8	2 %	196,7
14	−1	2	195,0	77,4	5 %	375,0
15	1	2	291,6	79,2	6 %	491,0
16	2	2	665,4	60,7	14 %	863,1

Table 9
Parameter estimation for the thrust model and efficiency as a function of operating regime and mixture used.

n	λ_7	λ_8	λ_9	λ_{13}	
Estimate	0,065634	−0,00695	0,00028	−5,89127	F_{OBJ}
Std. Err.	0,016482	0,00268	0,00002	1,55511	1,66
t(12)	3,982136	−2,59792	11,27785	−3,78834	**Variance explained**
p-level	0,002151	0,02479	0,00000	0,00300	97,6%

Thrust (T)	λ_0	λ_2	λ_4	
	λ_0	λ_2	λ_4	
Estimate	216,5	140,8	40,2	F_{OBJ}
Std.Err.	38,6	12,5	13,2	169,96
t (13)	5,6	11,2	3,0	**Variance Explained**

constant error and similar experimental fluctuation, this empirical model will be used to made an approximation of N and T from fuel blend type and engine stage, confronting the models that the model and the experimental results show on Fig. 7:

From Fig. 7(a), it can be inferred that for both Palmist Biodiesel blends and Palm Biodiesel blends, the inclusion of additives appears to increase efficiency compared to the non-additive mixtures, particularly at higher RPMs. This suggests that the additive may enhance combustion or the transfer of energy from the fuel to mechanical work in the engine. Furthermore, the model curves closely match the experimental data points, indicating that the model is suitable for predicting efficiency under these conditions. In Fig. 7(b), the empirical model illustrates a non-linear relationship between thrust and engine stages, with thrust increasing exponentially as the engine approaches its maximum capacity (100 % RPM). This is consistent with expectations that at higher RPMs, there is an increase in energy production and, therefore, greater thrust. Table A.6 (See supporting information), presents the principal components that the matrix derived from the analysis of all replicates collected during the measurement of these parameters. According to results of PCA analysis over replicates, showed that the incorporation of additives proved to be advantageous in mitigating experimental noises or fluctuations [67], at least four sources contribute to experimental variability, these are likely linked to the incoming airflow into the combustion chamber, fluctuations in the gearshift between each regime, minor variations in mixture composition, and potential atmospheric changes impacting the system [14]. The principal component analysis for gas emissions can be related to the combustion kinetic and its relationship in the pathway of the reaction inside the combustion chamber. The principal component analysis for emission data is given by Table A.7 (See supporting information). Gas emissions represent the molar balance for combustion chamber [68], typically, indicating the nature of reaction combustion [69] and revealing that employing renewable fuel with a certified additive offers the most effective emission mitigation scenario. This is noticeable from the highlighted values, indicating the characteristic vectors of the output emissions, especially for the palmist kernel Biodiesel blend with JETA-1 and additive (PKB_{Ad}) The values for CO_2 (−0.891), NO_x (−0.953), and T_{gas} (−0.988) suggest a reduction in emissions (See Table A.7 from Supporting Information), as well as a decrease in flue gas temperature, signifying a utilization of enhanced energy in the cycle, this is in agreement with the results found by [62] A comparison with the second mixture (PB_{Ad}) indicates slightly lower values, suggesting a more efficient combustion process with improved heat energy utilization and reduced CO_2 formation. Four significant fluctuations related to the electrochemical emission sensors were found, contributing to the alteration of the dynamic system. Additionally, the impact on HC emissions was shown using aeronautic additives [70], indeed, when additives are used, the fuel blend showed a higher proportion of oxygenated compounds, facilitating combustion of paraffin instead of fatty acids [71].

3.6. Discussion

The measured experimental results and their analysis demonstrate a synergy exists between an appropriate balance in the fuel mix and its mechanical, thermal, and life-cycle behavior associated with emission mitigation factors. There is a strong correlation in the physicochemical properties of the resulting blend. Table 10 presents a comparison of thermal, mechanical, emission analysis and performance for fuel blends with additives for similar engines test bench.

In their study, [61] examined microalgae-derived biofuels as additives blended with JET A1, ranging from 20 % to 100 % substitution. They documented maximum thrust values of 178 N, alongside reduced fuel combustion and emissions. However, higher substitution percentages correlated with increased NOx levels. Similarly, [56] observed increases in thrust and torque, peaking at 230 N, alongside improved air–fuel ratios and efficiencies of 70 %. These findings were consistent with variations in Lower Heating Value (LHV).

developed a testing protocol for a JET CAT P80 engine, integrating 5 % and 10 % gasoline additives with conventional JET A1 during start and cruise phases. Their research revealed that the 5 % additive led to optimal start times and enhanced engine performance, notably increasing turbine combustion temperature (T_3) and facilitating complete combustion, thereby reducing CO emissions. [57] The maximum recorded torque was 45 N with a fuel consumption rate of 27 l/h. Subsequently, [62] examined JET CAT P80 engine tests with blends of up to 30 % biodiesel and a 5 % Aeroshell 500 additive. They observed that higher percentages of renewable fuel correlated with decreased combustion temperatures and increased thrust. Notably, a 10 % blend exhibited optimal emission parameters concerning unburned hydrocarbons. Moving forward, [63] evaluated residual palm biodiesel blends, extending up to 50 %, with synthetic kerosene. Their investigation showcased advancements in the cold properties of the aviation fuel blend, with stability observed at a 10 % blending ratio while maintaining efficiencies comparable to pure conventional fuel. Additionally, the blend displayed reduced CO_2 formation in exhaust gases, suggesting potential environmental benefits. Lastly, [64] investigated blended pork animal fat (10–30 %) with JET A1, incorporating a 5 % Aeroshell 800 additive. Their study highlighted increases in flash point and torque delivery, alongside reduced emissions of CO, CO_2, and SO_x. The optimal blend comprised 10 % animal fat and 5 % Aeroshell 800, boasting an LHV of 44,903 KJ Kg^{-1}.

Upon a thorough examination of energy efficiencies and thrust characteristics of the system, a clear and compelling pattern emerges; there is a notable elevation in thrust levels, accompanied by a

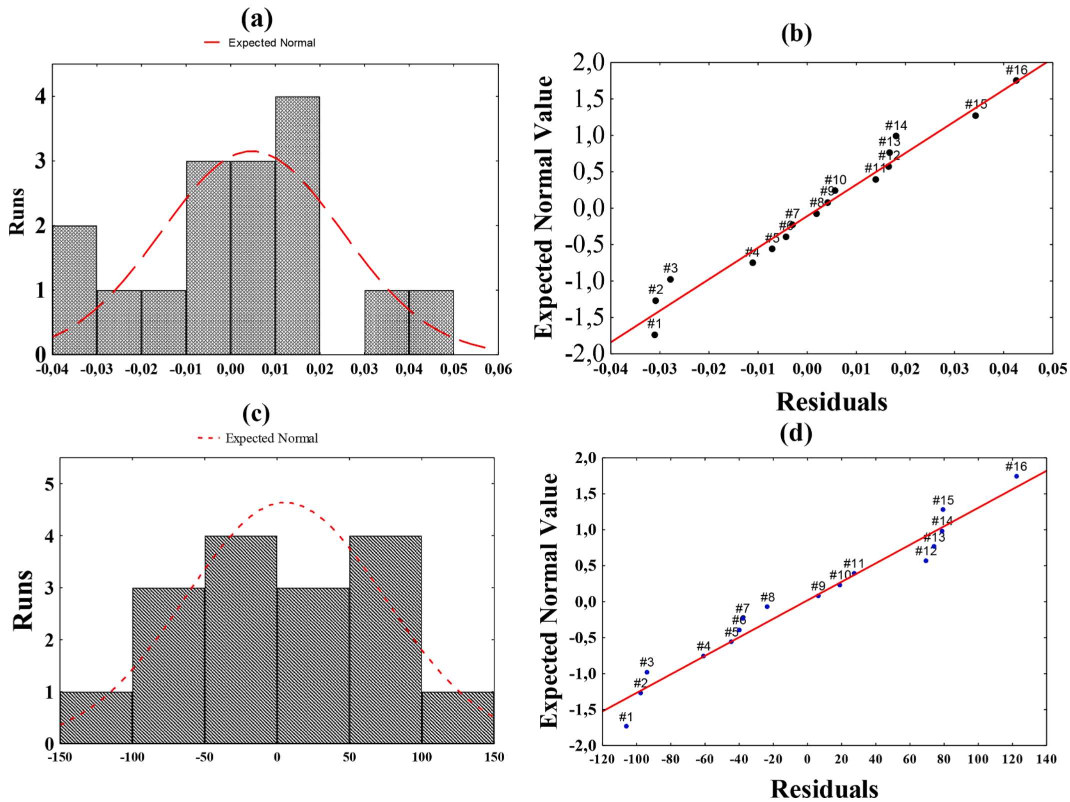

Fig. 6. Behavior and distribution of experimental residual data of empirical model for Thermal Efficiency (a,b) and Thrust (c,d).

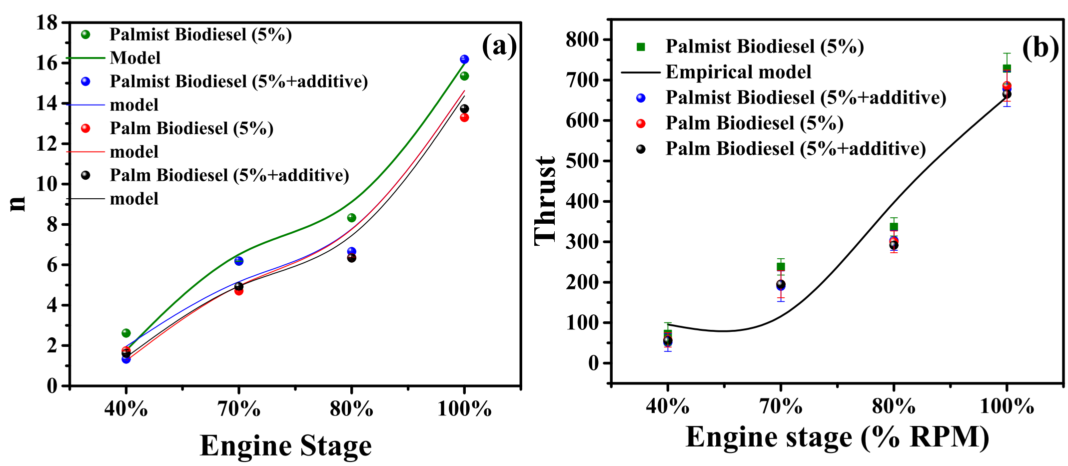

Fig. 7. comparison between Predicted values from empirical model and experimental values: (a) efficiency model (n), Thrust model (b).

simultaneous reduction in emissions. This dual effect highlights the viability and effectiveness of the proposed approach, positioning it as a promising strategy for optimizing energy conversion in the context of reducing environmental impact.

4. Conclusions

Palmist Kernel Biodiesel with additive (PKB_{Ad}) demonstrated exceptional thermodynamic efficiency across the entire range of speeds when operating the J69 engine, outperforming both JET A-1 and biodiesel alternatives. Incorporating an aeronautical additive resulted in a significant reduction in CO, HC, and CO_2 emissions, thereby optimizing combustion within the engine chamber. This improvement in compatibility and oxygenation of the fuel blends resulted in a significant reduction in fuel.

The incorporation of additives has proven to be a valuable strategy for mitigating experimental fluctuations, thereby enhancing the dependability of bench-tested variables. This improvement is particularly noteworthy considering the diverse sources of experimental variability, including airflow dynamics, gearshift fluctuations, mixture composition variations, and atmospheric influences. By effectively addressing these factors, additives contribute to greater precision and robustness in experimental measurements, ultimately advancing the accuracy and reliability of scientific investigations.

The impact of additives on air–fuel ratio (AFR) improvement and emissions reduction, such as CO and CO_2, varies depending on the type of biodiesel and the engine's operational conditions. This variability highlights the need for specific additive formulations tailored to the

Table 10
Comparable works reported on literature using renewable fuels and additives.

Ref	Renewable fuel	Additive	T_{max}	n	CO_2	CO
			N	%	%	%
This work	PKB_{Ad}	TotalArmor	3113	16	3,23	0,07
[14]	10 % BD	None	4450	12,5	3,45	0,07
[37]	5 % PPB	EtOH	178	––	4.2	––
[43]	10 %BD	None	1045	17,10	NR	NR
[47]	30 % BD	None	177	47	NR	NR
[63]	10 % SFB	Aeroshall 500	80	0.8	––	––
[64]	10 % PB	Aeroshell 500	38,8	––	––	––
[72]	10 % EtOH	None	68	10	3,3	0,07
[73]	10 % BD	Aeroshell 500	70	3,2	3	0,02

PKB = Palmist kernel Biodiesel, SFB = Sunflower biodiesel, MDB = Microalgae derived Biodiesel, PPB = Plastic pyrolysis biodiesel, BD = Biodiesel, PB = Pork Biodiesel, RF = Renewable fuel in blend. NR = not reported.

unique characteristics of different biodiesel bases to achieve optimal combustion and environmental benefits, for instance using Palmist kernel Biodiesel blends with additive (503.24 ppm), resulting in enhanced efficiency and reduced CO_2 emissions across various RPM stages, with notable enhancements at 100 % RPM.

The empirical models obtained enable approximations for conducting experiments within the applicable limits for both the percentages of fuels and additives used. This facilitates the preliminary acquisition of prompt responses on the bench, followed by subsequent adjustments and predictions within the SCADA control system currently under development in the project. Additionally, these empirical models prove to be more effective under cruise conditions.

Principal component analysis further highlighted the additive's impact, aiding in the identification of experimental fluctuations and refining readings during aeronautical operations. This effect may be attributed to the additive's role as a coadjutant in enhancing thechemical compatibility of the paraffinic mixture and the mixture of fatty acids. However, it is noteworthy that the concentration of unburned hydrocarbons at the exit of the combustion chamber increased.

A valid strategy for operating military engines involves using a lower percentage of renewable fuel combined with an additive. This approach preserves the mechanical integrity of the engine and addresses concerns related to high FAME percentages, which can compromise the microstructure of the metal components within the system.

In future research on the use of additives in palm kernel biodiesel blends with Jet A1, tested in a J69 engine, a multifaceted approach is proposed to extend the observed benefits beyond bacterial resistance. This includes exploring the additive's potential to enhance fuel stability and durability, potentially extending the biofuel's shelf life. This optimization of logistics and storage in aeronautical applications could significantly enhance operational efficiency.

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CRediT authorship contribution statement

Alberth Renne Gonzalez Caranton: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vladimir Silva:** Investigation, Methodology. **Miguel Galindo:** Conceptualization, Methodology, Formal analysis. **Juan Pava:** Supervision, Investigation. **Mauricio López:** Resources, Funding acquisition. **Andrés Cerón:** Methodology, Conceptualization. **Manuel A. Mayorga:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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