REDIN Revista Facultad de Ingeniería Universidad de Antioquia

No.114, pp. 95-111, Jan-Mar 2025

Methodologies for alternative jet fuels testing on small-scale reaction engines

Metodologías para pruebas de combustibles jet alternativos en motores a reacción a pequeña escala

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CITE THIS ARTICLE AS:

A. Turizo-Donado, S. López-Zapata, S. Arias and J. R. Agudelo. "Methodologies for alternative jet fuels testing on small-scale reaction engines", *Revista Facultad de Ingeniería Universidad de Antioquia*, no. 114, pp. 95-111, Jan-Mar 2025. [Online]. Available: `https://www.doi.org/10.17533/udea.redin.20240836`

ARTICLE INFO:

Received: March 06, 2024
Accepted: August 30, 2024
Available online: August 30, 2024

KEYWORDS:

Alternative fuels; micro-turbines; gaseous emissions; engine performance; testing techniques

Combustibles alternativos; micro-turbinas; emisiones gaseosas; rendimiento de motor; técnicas experimentales

ABSTRACT: The aviation industry increasingly recognizes that achieving climate neutrality is evolving into a fundamental and enduring asset for long-term competitiveness. In light of this, this paper provides a comprehensive review of the methodologies used to test alternative jet fuels (AJF) for aviation, which are renewable energy sources with the potential to replace conventional petroleum-derived fuels. It presents the types of AJF tested, focusing on the distinction between drop-in fuels and others. The article encapsulates the results from these tests, particularly concerning the performance and emissions aspects of the biojets, and their impact on engine materials and components. It outlines the equipment and techniques utilized in these tests, highlighting the advantages of using assemblies with miniature engines or combustors for a faster, easier, and more cost-effective preliminary assessment of biojet fuels. The paper also addresses future research directions, such as investigating the long-term impacts on engine lifespan and maintenance, and the potential to increase the blending ratio with conventional fuel. Lastly, it provides an overview of the situation in Colombia, where palm oil biodiesel has been tested, and points out the need for further research on other types of biojets for aviation.

RESUMEN: La industria de la aviación reconoce cada vez más que lograr la neutralidad climática se está convirtiendo en un activo fundamental para la competitividad a largo plazo. A la luz de esto, este documento proporciona una revisión exhaustiva de las metodologías utilizadas para probar combustibles jet alternativos (AJF) en la aviación, que son fuentes de energía renovable con el potencial de reemplazar los combustibles derivados del petróleo. Se presentan los tipos de AJF probados, con un enfoque en la distinción entre los combustibles 'drop-in' y otros. El artículo encapsula los resultados de estas pruebas, particularmente en lo que respecta a los aspectos de rendimiento y emisiones de los biojets, y su impacto en los materiales y componentes del motor. Se describe el equipo y las técnicas utilizadas en estas pruebas, destacando las ventajas de usar ensambles con motores o combustores en miniatura para una evaluación preliminar más rápida, fácil y rentable de los combustibles biojet. El artículo también aborda futuras direcciones de investigación, como investigar los impactos a largo plazo en la vida útil y el mantenimiento del motor, y la posibilidad de aumentar la proporción de mezcla con el combustible convencional. Por último, proporciona una visión general de la situación en Colombia, donde se ha probado el biodiésel de aceite de palma, y señala la necesidad de realizar más investigaciones sobre otros tipos de biojets para la aviación.

1. Introduction

Energy production, use, and availability are critical to the progress of modern society. The source of this energy is a significant consideration, especially in light of the global goal to achieve carbon neutrality by 2050 [1]. This objective

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ISSN 0120-6230
e-ISSN 2422-2844

DOI: 10.17533/udea.redin.20240836

requires the adoption of innovative technologies across various industries, without undermining the profitability of established economies. The aviation industry, responsible for a substantial portion of greenhouse gas emissions (GHG), is actively exploring alternative energy solutions.

Historically, the expansion of air travel has been powered exclusively by petroleum-derived jet fuels. Unlike other sectors, aviation heavily depends on this high-energy-density fuel. Petroleum-based jet fuels possess the highest chemical energy per unit volume and weight among all liquid fuels, making them ideal for minimizing onboard fuel storage space and weight, thereby directly influencing payload capacity and range [2].

The aviation industry currently contributes to 2% of global CO_2 emissions [3], a figure expected to increase both proportionally and in gross volume as other industries, such as the automotive and maritime sectors, transition more rapidly to sustainable technologies [4]. Carbon emissions from the transport sector are projected to rise by up to 80% by 2030 [5].

There are several approaches to achieving carbon neutrality in aviation, and the three options are Alternative Jet Fuels (AJF), Hydrogen propulsion, and a solution in between, ammonia [6]. This paper aims to review the ground concerning AJF solutions.

AJF are also known as biojets, bio-aviation fuels, or Alternative Aviation Fuels when uncertified. Once certified, they are referred to as Sustainable Aviation Fuels (SAF). These fuels, derived from renewable resources such as biomass, algae, and waste materials, offer a potential solution to reduce fossil fuel dependence [7] and decrease the fuel's life cycle emissions by $\sim 84\%$. In recent years, the aviation industry has made significant efforts to explore and develop alternative jet fuels that are both environmentally friendly and economically viable.

The certification of these fuels is governed by the International Civil Aviation Organization (ICAO) through its Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) eligibility criteria [8]. This scheme evaluates the true sustainability of new fuels, considering economic, social, and environmental aspects. Additionally, new fuels must meet the standards set by the American Society of Mechanical Engineers (ASTM), specifically ASTM D7566 [9] and D1655 [10]. These stringent standards limit the number of certified production processes and feedstock, as detailed in Table 1.

Table 1 SAF production routes by ASTM D7566 [9]

ASTM D7566	Route
Annex A1	*Fischer Tropsch - Synthetic Parafinitic Kerosene* (FT-SPK)
Annex A2	*Hydroprocessed Esters and Fatty Acid* (HEFA SPK)
Annex A3	*Sugar-to-jet* (SIP)
Annex A4	*Fischer Tropsch Aromatics* (SPK/A)
Annex A5	*Alcohol-to-jet* (ATJ)
Annex A6	*Catalytic Hydrothermolysis Jet* (CHJ)
Annex A7	*Hydroprocessed Hydrocarbons* (HC-HEFA SPK)
Annex A8	*Alcohol-to-jet Synthetic Paraffinic Kerosene Aromatics* (ATJ-SKA)

The certification process for new fuels, as outlined in ASTM D4054 [11] and detailed in the specifications of ASTM D2880 [12], is essential for approving the fuel as a new certified path in ASTM D7566. This comprehensive evaluation involves first qualifying the fuel's specification and Fit-For-Purpose properties (Tier 1 and 2) before it is assessed in full-scale engines (Tier 3 and 4). However, the path to certifying new aviation fuels under these standards is often a costly and time-intensive venture. The ASTM D7566 currently includes seven approved synthesized paraffinic kerosene (SPK) blendstocks, each described in one of its seven annexes(Table 1).

Most studies on these alternative fuels are carried out in combustors and have focused on emissions and performance, while other researchers have studied these variables in small research engines as an approach to full-scale engines [13].

In this context, conducting preliminary research using small-scale reaction aero-engines presents a pragmatic approach. Such a method allows for initial assessments of fuel performance and compatibility in a more controlled and cost-effective environment. By utilizing smaller engines, researchers might gain valuable insights into the fuel's behavior and potential issues before proceeding to the extensive testing required for ASTM certification. This step not only reduces initial costs but also helps in refining the fuel production process to better meet the stringent criteria set by the aforementioned standards[14].

Both tests in real aviation and small-scale engines have their advantages and limitations: In the first ones, the real-world application is used and qualified, ensuring valid data for the certification process, but the amount of fuel required prohibits these tests for new and expensive technologies. For those using small engines, the data may not extrapolate, and further tests may be needed on bigger engines, but it can be an inexpensive manner for validating and finding potential areas of improvement for new fuels earlier in the process. The scope of this work is to evaluate how the latter tests can be performed and what they have achieved in the past.

This paper aims to address the research that has been conducted in the field prospectives of biojet fuels using small-scale facilities as a screening process. In the first section, there is a review of the biojet fuels that have been tested and their characteristics, then, the main methodologies for testing these models are explained. Later on, the Colombian context in the development of new biojet fuels is explored, and finally, the challenges and work ahead for this topic are discussed.

2. Biojet fuels tested

The main classification of AJF includes pathways such as sugar-to-jet, gas-to-jet, alcohol-to-jet, and oil-to-jet. The following subsections will discuss the efforts made in testing these fuels and also in other AJFs not complying with this classification [15, 16]. There are a significant amount of initiatives to develop optimal alternative jet fuels that can be used in aviation. The already approved paths involve different sources of biomass, conversion processes, and blending ratios, each with its advantages and challenges [3, 17].

The drop-in technologies are the ones with the most promising outlook [5], [4] due to their seamless integration into the aircraft, airports, and supply chains without changing the structure to any of the current components, reducing the costs and risks associated with the transition to alternative fuels [4]. These fuels are already being used by airlines in small blending ratios in Europe and the EEUU, as they offer economic and marketing benefits.

The research of such fuels is an active field of investigation [18], [19], [20], and their holistic implementation [21] and suitability for different contexts has to be assessed. For instance, the availability and sustainability of the biomass feedstock, the environmental and social impacts of the production and use of the fuels, and the economic and regulatory barriers and incentives are some of the factors that need to be considered [22], [23], [24].

Taking this into account, in the following subsections, the drop-in and no drop-in fuels tests are discussed. These tests aim to evaluate the performance and emissions of different types of alternative aviation fuels in various test rigs and engines, ranging from combustors to small-scale and full-scale reaction aero-engines. The results of these tests provide valuable information and feedback for the development and improvement of alternative fuels, as well as for the certification and standardization processes [18], [20]. The tests also help identify the potential benefits and challenges of using alternative fuels in the aviation sector, such as the reduction of greenhouse gas emissions, the improvement of fuel efficiency, and the compatibility and durability of the engine components.

2.1 Oil-to-jet

One category of alternative fuels is based on the Hydroprocessed Esters and Fatty Acids (HEFA) process, which is a hydroprocessing route that can use vegetable oils and animal fats as feedstock. For example, [25] used six different bio-jet fuel blends (Jatropha oil, UOP SPK Camelina-based, Van-SOL 53 aromatic compound added) with Jet-A1 in a combustor test rig to measure their properties at two different conditions. Further, [13], [26], and [27] used two different feedstocks processed with the HEFA pipeline: camelina oil and used cooking oil (UCO). They called them HEFA CAM and HEFA UCO, respectively. They tested these fuels in a small-scale turbojet engine and measured the performance and emissions of the engine.

2.2 Gas-to-jet

Another category of alternative fuels is based on the Fischer-Tropsch (FT) process, which converts coal or biomass into synthetic gas and then into liquid fuels. [28] was one of the first researchers to compare the FT synthetic paraffinic kerosene (FT-SPK) with JP-8 fuel on a combustor. In 2010, [29] investigated the effect of FT-SPK on helicopter engines and measured the emissions characteristics of this fuel. [30] completed their tests using hydroprocessed renewable jet (HRJ) and FT from different sources, as compared with JP-8. They used a small-scale turbojet engine to measure the performance and emissions of the fuels.

2.3 Alcohol-to-jet and sugar-to-jet

A third category of alternative fuels is based on the alcohol-to-jet (ATJ) process, which converts alcohols, such as ethanol or isobutanol, into jet fuel through a process that involves three reactive stages: dehydration of alcohol, oligomerization, and hydrogenation, along with the separation stage to purify biojet fuel [31]. [32] evaluated the soot formation of three alternative fuels: FT-SPK, HEFA from camelina oil, and ATJ, with a maximum blending ratio of 50/50 with Jet A-1. They used a laminar co-flow diffusion flame burner to measure their soot volume fraction and particle size distribution. [33] predicted the global combustion behaviors of Shell SPK, Sasol IPK, HRJ Carmelina, HRJ Tallow, and Gevo ATJ by simple fuel properties measurement. They used a surrogate fuel model and a chemical kinetic mechanism to simulate the ignition delay, laminar flame speed, and adiabatic flame temperature of the fuels.

Besides testing alternative fuels in test rigs and engines, some studies have also used numerical models and simulations to address their performance and emissions. [34] evaluated the gaseous emissions performance of Jatropha and Camelina synthetic paraffinic kerosene (JSPK and CSPK, respectively) in their software, HEPHAESTUS. They used a one-dimensional engine model and a chemical kinetic mechanism to simulate the combustion and emissions of the fuels.

Some studies have also investigated the effects of the fuels on the engine components, such as the combustion chamber and the fuel system. [35] studied the characteristics of deposits of a combustion chamber section rig using GTL FT, algae oil HRJ, and camelina oil. They used a scanning electron microscope and an energy-dispersive X-ray spectrometer to analyze the morphology and composition of the deposits. [36] performed an experimental and numerical activity regarding the influence of synthetic Gas-To-Liquid (GTL) kerosene produced by Sasol and Jatopha oil Methyl Ester (JME) on the fuel system of a small-scale turbojet engine. They measured the fuel flow rate, pressure drop, and temperature of the fuels in the fuel system.

2.4 Other AJF

These fuels are not in the standards but are promising technologies being investigated. One category of alternative fuels for aviation is based on vegetable oils, which are extracted from various plants and can be processed into biodiesel or bio-jet fuel. Several studies have investigated the performance and emissions of different types of vegetable oils and their blends with conventional jet fuel in various test rigs and engines. The usage of biodiesel is not feasible for most aviation applications due mainly to its high freezing point, viscosity limitations, o-rings damage, poor atomization, and the preheating requirement, among others. The objective of this section is to present the results of the fuels not currently included in the certification processes.

One feedstock of vegetable oils is rapeseed, which is a common oilseed crop that can be converted into rapeseed methyl ester (RME) or rapeseed synthetic paraffinic kerosene (RSPK). [37] investigated the gaseous and particulate emissions using a turbine fuelled with rapeseed and sunflower oil. [38] were interested in the spray flame structure of RME in a burner facility. They measured the droplet size, velocity, and temperature of the fuel spray and the flame temperature and luminosity of the combustion.

Another feedstock of vegetable oils is based on the soybean, which is a widely cultivated oilseed crop that can be converted into soy methyl ester (SME) or soy synthetic paraffinic kerosene (SSPK). [39] measured the gaseous emissions of a gas turbine operating with SME and canola methyl ester (CME) blended with Jet-A1. [40] studied refined, bleached, and deodorized (RBD) soybean oil (SBO) in physical properties and behavior in a SR30 engine model.

A third feedstock of vegetable oils is based on the jatropha, which is a non-edible oilseed crop that can be converted into jatropha methyl ester (JME) or jatropha synthetic paraffinic kerosene (JSPK). [41] presented a different fuel: fast pyrolysis bio-oil (FPBO), and tested its emissions in a small-scale gas turbine rig. They also designed a new combustor for the required combustion characteristics. [42] measured the fundamental combustion characteristics of JME and jatropha pure oil (JPO).

A fourth feedstock of vegetable oils is based on the camelina, which is a non-edible oilseed crop that can be converted into camelina methyl ester (CME) or camelina synthetic paraffinic kerosene (CSPK). [43] explored the use of camelina oil and kerosene blends in a multi-fuel burner. [44] tested F-34 and the 50/50 volume mixed camelina-based hydro-processed renewable jet fuel with F-34 (C-HEFA blend) in a T56-A-15 turboprop.

Besides testing the processed vegetable oils and their blends in test rigs and engines, some studies have also used other types of alternative fuels or methods to evaluate their performance and emissions. [45] studied the technical feasibility of the implementation of straight vegetable oil (SVO) in a Micro-Gas Turbine (MGT). [46] examined the emissions and particulate matter (PM) of a combustor using butyl butyrate and ethanol blends. [14] investigated the toxic impact of the gas mixture on exposed living cells. The experiments were carried out on a small-scale turbojet engine running on biobutanol, produced through fermentation of C5 and C6 sugars from renewable feedstocks. [47] utilized in a gas turbine some interesting blends: R20E (70% Jet-A fuel, 20% rapeseed, and 10% ethanol), CS20E (Jet-A 70% fuel, 20% canola-sunflower, and 10% ethanol), R20P (70% Jet-A fuel, 20% rapeseed, and 10% pentanol) and CS20P (70% Jet-A fuel, 20% canola-sunflower, and 10% pentanol). [48] started adding some biodiesel as an additive to JP-8, in 2%, 10%, and 20% blended ratios to study the impact on the emissions of a T63 engine. [49] completed tests of blends of bioethanol and biodiesel in a microturbine. [50] investigated the performance and emissions of corn methyl ester (CRME) and cotton methyl ester (CTME) in blends of B10, B20, and B50 with Jet A-1. [51] presented the results of a MGT operating with Liquefied Wood (LW) produced via solvolysis of lignocellulosic biomass in acidified glycols.

The results and techniques used in these tests are shown at the end of the document.

3. Small-scale reaction performance measurements

3.1 Static thrust

Apart from in-flight tests and computational simulations, which are beyond the scope of this paper, the engine tests discussed here are limited to on-ground testing. This involves the use of a static test rig to measure static thrust. It is expected that this thrust would remain consistent when adding biojet fuel to the blend, as [30] observed comparable static thrust with four alternative aviation fuel blends to JP-8. However, some results have indicated a slight detriment to this static thrust. [39] attribute this to non-aviation fuel having a lower energy content, which reduced the available energy for producing thrust. In the case of [50], the same throttle valve opening resulted in a lower mass flow rate for the biojet fuel blends, leading to a reduction in engine output power and consequently, the measured static thrust.

3.2 Fuel consumption

This parameter refers to the amount of fuel consumed per unit of time, and it is often given in mass units to be independent of the density variations in different types and batches of fuel. The total fuel consumption by the engine to produce a unit of thrust is called Thrust Specific Fuel Consumption (TSFC) [47]. In the literature, it has been found that fuels with lower calorific values tend to exhibit slightly higher fuel consumption and specific fuel consumption. For example, [52] tested blends with butanol and concluded that these blends resulted in higher fuel consumption. But another study by the same researcher shows an opposite result as lower fuel consumption values obtained for HEFA fuel were directly associated with its higher heat of combustion and lower density compared to Jet A-1 fuel [27].

3.3 Air-flow

Another important variable, which is not a direct performance index but is essential for calculating thermal and combustion efficiencies, is the airflow at the intake of the compressor. Combined with the fuel flow, it determines the air-fuel ratio. Typically, engines have this flow characterized in the compressor maps, thus making it a known value. However, in cases where data is unavailable, researchers have resorted to several methods to measure this variable. For instance, [30] measured the air mass flowing through the engine in a separate experiment by equipping the engine with an automotive-type hot wire sensor at the compressor inlet. Another valid approach involves adding an elongated intake before the compressor, where measuring pressure and temperature can quantify the airflow. This setup is exemplified in the GTM 140 JETPOL, part of the test rig described by [53]. Traditional methods like Pitot tubes have limited applications due to their sensitivity to low air speeds. Instead, calibrated nozzles emerge as the optimal choice for high accuracy, while digital manometers offer a viable alternative. Using the resources available, [54] utilized the measurement of O2 content to infer the stoichiometric air-fuel ratio.

3.4 Emission measurements

Generally, the increase or decrease in exhaust emissions and engine performance parameters depends on the composition of the biojet fuel and the jet fuel used in the blend [55]. Based on the results available in the existing literature, it is not possible to generalize the trends, and these results should be interpreted with caution [55]. For this reason, the review of the experiments was conducted individually, and the findings are summarized in Annex A. This table indicates whether the gas emissions decrease (↓), increase (↑), or do not undergo a significant change (=). It should be noted that this information is generalized across all regimes and blends, so there could be exceptions that must be verified in the corresponding reference. When not mentioned assume results concerning base fuel, in most cases Jet A-1 and some diesel.

4. Testing methodologies

The use of reaction aero-engines testing devices in static benches poses a difficulty, because the natural condition of air-breathing engines is its high-speed movement and different operating load conditions, it is a common practice to characterize the aero engine and test rig before testing alternative fuels [56] [57]. This characterization serves a dual purpose: it allows for the measurement of stabilization times, which are essential for defining the specific engine test profile, and it aids in the calculation of uncertainties.

In this section, the small-scale reaction engines and combustors used for testing, their working conditions or so-called test profiles, and gas analyzers commonly used are described.

4.1 Gas turbines

Different approaches exist for testing experimental biojet fuels intended for use in aviation. Firstly, the basic chemical and physical properties are measured. This is the first filter, as described by the ASTM D4054 standard [58]. Then, the prospective fuels can be tested in the Fit-for-purpose tests and later on, emissions and performance characteristics can be investigated in gas turbine engines or combustor rigs in Tier 3 and 4 investigations.

In this section, the different reaction engines used in the literature review are presented in Table 2.

One of the main benefits of using gas turbine technology in the tests of alternative fuels for aviation is that the results can be directly applied to an actual machine that uses the same technology. This means that the performance and emissions of the AJF can be evaluated in realistic conditions and compared with conventional jet fuel. This can help to identify the potential advantages and challenges of using alternative fuels in the aviation sector, such as the reduction of greenhouse gas emissions, the improvement of fuel efficiency, and the compatibility and durability of the engine components.

Since using real-world scale gas reaction turbine engines in the tests is expensive in terms of time, fuel, and other resources, it can be an issue in the early stages of development when the AJF are not widely available and their production processes are complex and costly, therefore, using small-scale engines, such as miniature turbojets, can be a more feasible and affordable option. SSR engines have several advantages, such as low cost, fast operation, and less fuel consumption. They can also provide useful information and feedback for the development and improvement of AJF, such as their properties, combustion characteristics, and emission levels.

4.2 Combustor rigs

Some studies have used rapid compression machines or burner facilities to measure the ignition behavior, flame structure, and soot formation of AJF. For example, [59] studied the ignition behavior of camelina and tallow HRJ using a rapid compression machine. [38] carried out studies on the spray flame structure of RME in a burner test rig. They measured the droplet size, velocity, and temperature of the fuel spray and the flame temperature and luminosity of the combustion. [32] used a counterflow burner facility to study the soot formation of FT-SPK, HEFA-Camelina, and ATJ. [60] performed studies in combustor and injection assemblies using vegetable oil (VO) to measure its physical properties and emissions. In Figure 1, a general description of a combustion testing bench is displayed, some basic elements are shown, as reviewed in the references contained in this section.

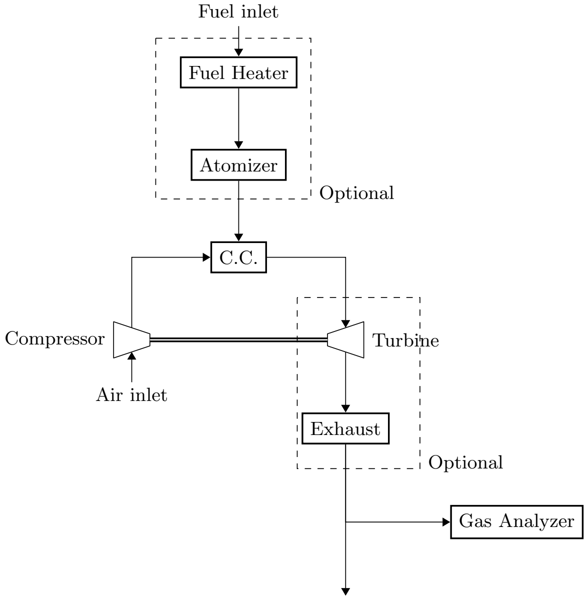

Figure 1 General schematic for combustion testing

[25] investigated some combustion and emission characteristics of several biojet in a high entropy combustion testing rig. [46] performed an experimental study on butyl butyrate and ethanol blends gaseous and particulate matter emissions in a gas turbine combustor test rig. [42] used a combustion chamber test rig to investigate the fundamental combustion characteristics of JME and JPO. [35] used a can-annular combustion chamber from a T56 engine to study the characteristics of deposits of GTL, HRJ, NRC, and Camelina fuels. [43] investigated camelina oil using a multi-fuel burner.

4.3 Test profile

The operating conditions may change depending on whether a test is conducted in a jet engine or a combustor. In the case of a jet engine, it is engineered to function under a variety of conditions, considering that an aircraft must undergo stages of take-off, climb, cruise, descent, and landing. On the other hand, a combustor or burner rig is meticulously designed to maintain a stable regime and should be operated in line with this design. Certain combustor test rigs can function under desired pressures, flow rates, and temperatures. These rigs can accurately emulate the operating conditions of a real-scale engine combustion chamber.

Table 2 Engines used in literature

Engine	Reference	Use	Thrust/Power
IS/60	[61]	Miniature Gas Turbine	44 kW
Solar T-62T-32	[45]	Miniature Gas Turbine	50 kW
Capstone C30	[37], [39], [62], [49]	Miniature Gas Turbine	30 kW
General Electric CF-700-2D-2	[63]	Turbojet	20 kN
TF33	[48]	Turbojet	80 kN
JT8D-9A	[48]	Turbojet	62 kN
T63	[48], [28], [64], [29]	Turboshaft	250 kW
PT6A-61A	[65]	Turboprop	1400 kW
T56-A-15	[35], [44]	Turboprop	3500 kW
GTP 30–67	[66], [41], [54]	APU	-
GTM-140	[26], [56], [14], [27]	Miniature Turbojet	70 N
SR30	[40], [36], [57]	Miniature Turbojet	40 N
-	[47]	Miniature Turbojet	178 N
Olympus E-start HP	[50]	Miniature Turbojet	230 N
JetCat P-200	[30]	Miniature Turbojet	200 N

The goal of these tests is to emulate the operating conditions of aircraft using the fuels. In the work by [13], the typical flight conditions are displayed and emulated in the engine. In [14], different RPM levels are tested with their corresponding stabilization times in an ascending manner. In Figure 2, the engine is tested in "conventional" flight conditions: taxi, take-off, climb, cruise, go-around (slam), descent, and landing.

Some authors also consider the possibility of supplying multiple fuels to the test rig during one testing procedure. This is to ensure the purge of the fuel system and emulate the conditions where airports have the availability of different fuels, as shown in Figure 2.

4.4 Gas analyzers

The emissions determination methodology must be improved. Section 4.4 should be expanded since it provides little information.

In Table Annex A the reference of the analyzer used in each experiment is listed, some of them did not report the commercial reference or specification but mention the method for analyzing each gas.

There are cases, where two independent analyzers were used for double checking [54]. There is a still-going discussion about which is the correct method for each gas emission, for one side the Society of Automotive Engineers (SAE) in their ARP1256 standard [67], guide the most acceptable practice for the continued measurement of exhaust emissions from gas turbines, recommends the use of a non-dispersive infrared analyzer for the determination of NO and a non-dispersive ultraviolet analyzer for NO_2. The EPA departs from this recommended practice in that it specifies the use of a chemiluminescence analyzer with an ancillary thermal converter for the measurement of NO plus NO_2 [68].

5. Colombian context

In the Colombian context, [69] outlined the challenges and uncertainties for the implementation of sustainable aviation fuel (SAF) in Colombia, such as the availability of feedstocks, production technologies, regulatory framework, and market conditions. They suggested that Colombia develop a roadmap and a deployment plan for SAF production, considering the best practices and experiences of other countries. They also recommended that Colombia promote collaboration and coordination among public and private stakeholders, as well as international cooperation and support. Several studies have been conducted to evaluate the sustainability of palm oil biodiesel in Colombia, using different methods and perspectives. For example, [70] performed a life cycle analysis of biodiesel blends, comparing their environmental impacts with those of conventional diesel.[22] and [71] performed a system dynamics approach to the sustainability assessment of biodiesel production in Colombia, considering the economic, social, and environmental dimensions. [72] reported the basic properties of palm oil biodiesel blends, such as density, viscosity, cetane number, flash point, and cloud point.

Several studies have also been conducted to evaluate the performance and emissions of palm oil biodiesel in different types of engines, using experimental and numerical methods. For example, [73] and [74] used a J69 turbine engine to evaluate the performance and emissions

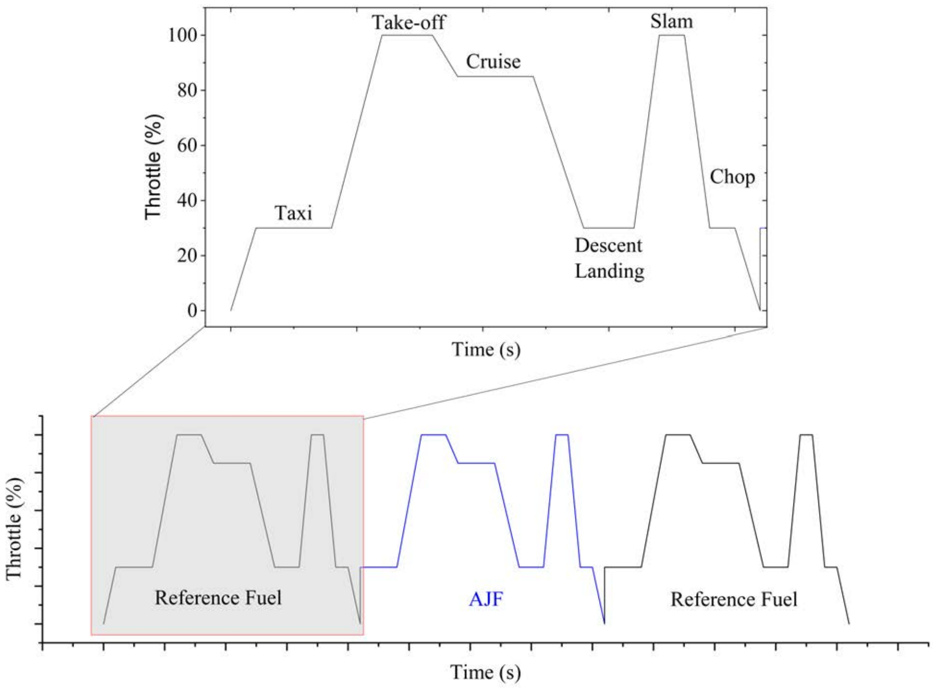

Figure 2 Testing Profile. Adapted from [63].

of Colombian palm oil biodiesel. [65] investigated the mechanical and thermal behavior of a PT6A-61A turboprop engine using the same biodiesel.

In addition to biodiesel, Colombia has also explored the potential of green hydrogen as an alternative fuel for aviation and other sectors. Green hydrogen is produced from renewable energy sources, such as solar or wind, and can be used to produce synthetic fuels or power fuel cells. [75] estimated the green hydrogen potential in Colombia, considering the availability of renewable resources, the demand for hydrogen, and the costs of production and transportation. They found that Colombia had a high potential for green hydrogen production, especially in the regions of La Guajira, Antioquia, and Valle del Cauca. They also found that green hydrogen could be competitive with conventional hydrogen and fossil fuels for some applications, such as heavy-duty transport, industry, and power generation.

According to this panorama, there is still a need for testing facilities of aviation alternative fuels in the territory to evaluate their performance. Furthermore, because of the particular environmental characteristics of this tropical zone, it would be important to test them under these ambient conditions as it is known that changes in the ambient conditions impact both the engine performance and combustion process emissions[27].

At Universidad de Antioquia (UdeA), the Department of Mechanical and Aerospace Engineering has a test rig of a mini jet engine for the research of alternative fuels. The advantage as mentioned before is the cost-effective operation of this equipment. Research on this field in the country is just starting, as reviewed in the literature the few facilities available today are real engine testing and it is needed as an in-between step for preliminary testing.

The specifications of our test rig instrumentation are shown in Table 3, it can be seen in Figure 3 and its schematic is shown in Figure 4.

6. Challenges and future work

Aviation Alternative Fuels can have different compositions and properties than conventional jet fuel, which can result in different emissions of harmful pollutants, including regulated and unregulated. These pollutants can have negative effects on the health of the crew, passengers, and the environment. Therefore, it is necessary to measure the toxicity level of the exhaust gases using appropriate methods and instruments, and to compare them with the regulatory standards and limits. [14] suggested that more time is needed to measure the toxicity levels of AJF, as they can vary depending on the engine operating conditions and the fuel blending ratio.

Table 3 Test bench equipment at Universidad de Antioquia

Component	Reference	Description
Miniature turbojet	JetMunts M210TS	RC engine Produces 210N of thrust Provides EGT and RPM
Universal Pancake Load Cell	Model LCF300	High-performance tension and compression load cell Utilizes metal foil strain gauge technology
Gas Analyzer	parSYNC Flex (3DATX, USA)	Provides gaseous and nanoparticle measurements Capture multiple, dissimilar "images" of particles using Ionization, Scattering, and Opacity sensors in addition to outputs for Particle Number (PN) and Particulate Mass (PM) Measure NO, NO_2, CO and CO_2 gases concentration Use the electrochemical for NO and NO_2. A NDIR Spectrometer for CO_2, CO, and HC. An electro-galvanic for O2
Thermocouple	Type K	Located at the exit of the microturbine to measure exhaust gas temperature Temperature range: –270 to 1260C
Balance	Shimadzu	Measures fuel consumption through the tank mass differential TX4202L platform scale with a maximum capacity of 4.2 kg and a minimum display of 0.01 g. Included are: UniBloc technology, a menu operation key, easy configuration, backlight, Windows Direct capability, an RS-232C interface, weight control, counting pieces, carat measurement and a mode of formulation.
Supervisory Control and Data Acquisition (SCADA)	PLC AS200 of 64K	Collects and transmits data through a Programmable Logic Controller (PLC) Local and remote expansion Receive up to six (6) digital inputs

Another variable that should be measured is the wear of the engine components. Alternative Aviation Fuels can have different effects on the friction and wear of the fuel system materials and the hot components of the turbine, such as the combustor, the nozzle, and the blades. These effects can depend on the lubricity, viscosity, thermal stability, and corrosivity of the AJF, as well as the temperature, pressure, and flow rate of the engine. The wear of the engine components can reduce the engine efficiency, performance, and reliability, and increase the maintenance costs and downtime. [62] investigated the effects of long-term operation on fuel system materials and hot components of the turbine using AJF, and found that some fuels caused more wear and damage than others.

A possible solution to reduce the wear of the engine components is to add a stand-alone oiling system that is completely separated from the fuel system in the Miniature turbojet engines because this oil can also interfere with emissions measurements in the exhaust. This system would provide lubrication and cooling to the engine components, without mixing with the fuel or entering into the exhaust flow. This way, the effects of alternative fuels on the lubricity and thermal stability of the oil would be minimized, and the oil consumption and contamination would be reduced. [30] proposed the possibility of adding a stand-alone oiling system to a small-scale turbojet engine, and discussed the advantages and challenges of this solution.

The behavior of these fuels during extended storage periods warrants further investigation, as demonstrated by [76]. A particular area of interest is the growth of deteriogenic fungi. These microorganisms can significantly impact fuel quality, especially considering the stringent purity requirements set by aviation standards. Moreover, the implications of microbial growth in

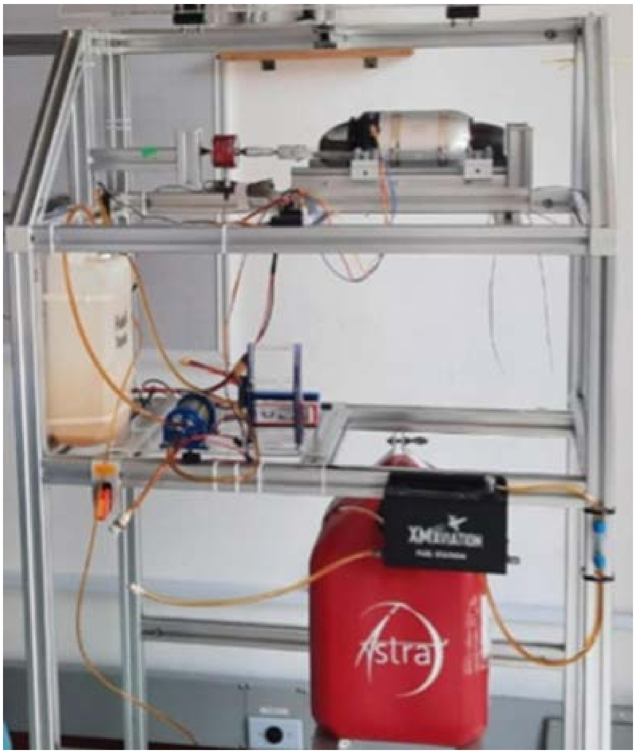

Figure 3 Test bench at Aerospace Engineering Dpt. from Universidad de Antioquia

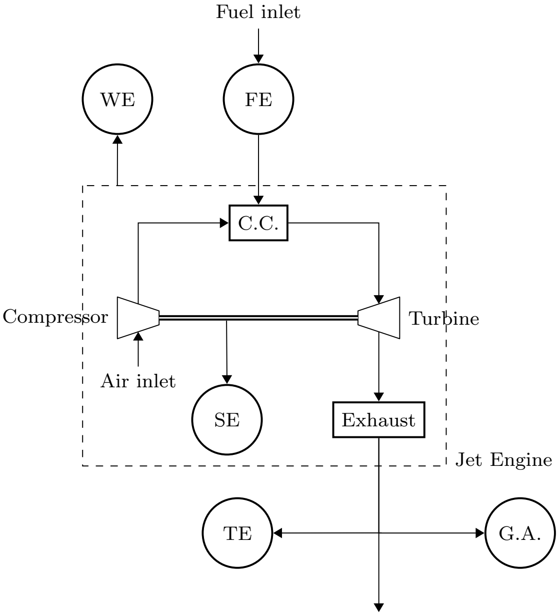

Figure 4 UdeA Bench Instrumentation.

commercial fuels are potentially serious. Microbial activity in jet fuel can cause problems related to fuel deterioration, decreased surface tension, clogging of fuel filters, and microorganism-induced corrosion.

Another possible solution to reduce emissions and improve the combustion of alternative fuels is to increase the blending ratio of the alternative fuel with conventional jet fuel. This would increase the proportion of renewable components in the fuel, and reduce the dependence on fossil fuels. However, increasing the blending ratio can also affect the fuel properties, such as density, viscosity, and flash point, and the combustion characteristics, such as ignition delay, flame speed, and soot formation. Therefore, it is necessary to measure and optimize the blending ratio of the alternative fuel to achieve the best performance and emissions. [32] studied the soot formation of different alternative fuels, and suggested that increasing the blending ratio could reduce the soot formation, approaching eventually 100%.

7. Conclusions

In conclusion, this paper has meticulously investigated and presented the methodologies for testing alternative jet fuels (AJF) in small-scale reaction engines. The critical insights derived from this comprehensive review highlight the significant potential of AJFs as sustainable substitutes for conventional aviation fuels. Importantly, the findings shed light on the technical feasibility and environmental benefits of AJFs, especially when assessed through innovative small-scale testing methods. This research not only advances our understanding of AJFs but also opens up new avenues for their practical application in aviation.

The strategic importance of this study lies in its ability to guide future endeavors in sustainable aviation fuel development. By pinpointing the effectiveness and limitations of various testing methodologies, this paper sets the stage for more focused and practical approaches in AJF research and application. It underscores the necessity for the aviation industry to adopt more sustainable practices, not only in fuel usage but also in the overall approach to environmental stewardship. As the aviation sector moves towards a greener future, the insights from this study will be instrumental in navigating the complexities of implementing sustainable fuel solutions on a larger scale.

8. Appendices

Gas emmisions in literature

Table 4 Gas emissions results in literature

Ref.	Test equipment	Analyzer	Fuels tested	Results
[59]	Rapid compression machine (RCM)	-	Jet fuel (JP-8) with Camelina and tallow hydrotreated renewable jet (HRJ) blends	HRJ fuels ignite more readily than JP-8
[77]	Rover gas turbine IS/60 test rig	AVL exhaust gas analyzer	Diesel and Biodiesel (Jatropha oil) blends	NO$_x$ ↑ (b1 / b2) BSFC↑ at lower loads BSFC↓ for medium loads, with respect to diesel.
[54]	Optical swirl burner	Two systems: (1) FID for THCs, chemiluminescence analyser (Signal 4000VM) for NO$_x$, infrared cell for CO, paramagnetic O$_2$ sensor (2) Standalone Rosemount NGA 2000 multi-gas analyser	Jet A-1 and blends of HRJ (Hydrotreated Renewable Jet fuel) from used cooking oil	Air required for combustion ↑ Jet A-1/HRJ 80/20%vol: CO ↓, NO$_x$ ↓, THC ↓. Higher HRJ concentrations: CO ↑, NO$_x$ ↑, Soot formation ↓, with respect to Jet A-1.
[63]	General Electric CF-700-2D-2 turbofan engine	SEMTECH-DS analyzer	CH-SKA, 100% FT-SPK and a Jet A-1 50% HEFA-SPK	CO$_2$ ↓ at idle. Order of produced CO$_2$: Jet A-1 > 100% CHSKA > 50% HEFA-SPK > 100% FT-SPK. In general, NO ↑ and NO$_x$ ↑ with increasing engine load, but no correlation with change of fuel.
[66]	APU model Garrett GTP 30–67	On-line gas analyser	Diesel and Biodiesel (BD): mixture of Fatty Acid Ethyl (FAEE) or methyl esters (FAME) (25%, 50% and 75% blends)	Non-heated VO: CO ↑. Preheated VO: CO = at standard conditions. MGT could not always run on pure vegetable oil at idle. NO$_x$ = and fuel consumption ↑ with respect to diesel
[37]	Capstone Micro Gas Turbine, model C30	Portable flue gas analyzer (TESTO 350 S)	Commercial kerosene Jet-A1 and four blends with Straight Vegetable Oils from sunflower and rapeseed (SVO) (10% v/v - 20% v/v each)	Global behavior = , CO ↑ and NO$_x$ ↑ soot emission ↑ at part load. 10% v/v of SVO with kerosene: PM emissions↑. However, the PM level appears to be independent of the SVO concentration.
[25]	Compressed air is supplied from a screw type compressor	NDIR absorption method (Fuji ZRE Type analyser), Paramagnetic Sensing (Parox 1200), Heated Vacuum Chemiluminescence (Signal 4000 VM), FID (Signal 3000 HM)	Jet A1 with Biofuels (BF) from Jatropha and Camelina blends	Camelina: CO↓, UHC↓, soot↓, NO$_x$ ↑, with respect to Jet A-1. Jatropha-based fuels show a mixed trend.
[26]	GTM-140 miniature turbojet engine	-	Jet A-1 and blends of HEFA from camelina (HEFA CAM) and UCO (HEFA UCO)	No significant variations in the turbine temperature and CO$_2$ emissions. NO$_x$ ↑ for both blends with respect Jet A-1.

Table 4

Ref.	Engine	Analyzer	Fuels tested	Results
[41]	APU or GPU model GTP 30–67	Greenline 8000 and Sensors Semtech DS analyzer (with NDIR for CO/CO_2 and NDUV for NO/NO_2)	Pure Fast Pyrolysis Bio-Oil (FPBO), denatured ethanol, two FPBO/ethanol blends at different volume fractions (20/80% and 50/50%), and commercial diesel fuel as benchmark fuel	By increasing the FPBO content in the blend, CO ↑ and NO_x ↑. For ethanol and PO/EtOH, electrical efficiency ↑
[28]	T63 turboshaft and a swirl-stabilized combustor	Fourier Transform Infrared analyzer, Planar laser-induced fluorescence and laser-induced incandescence techniques	Jet fuel (JP-8) and Fischer-Tropsch synthetic jet fuel blends	PN ↓, smoke number↓, sulfur oxide emissions ↓, water vapor↑
[29]	General Electric T701C and T700 engines	MKS MultiGas 2030 Fourier transform infrared (FTIR)-based gas analyzer and NDIR analyzer	JP-8 fuel and natural-gas-derived Fischer– Tropsch synthetic paraffinic kerosene jet fuel.	PM emissions ↓, NO_x ↑ and CO↓, soot emissions ↓
[39]	Turbo jet engine lab from Turbine Technologies	Infrared analyzer(%CO_2, %O_2, CO ppm, NO ppm) chemiluminescent analyzer (NO ppm)	Jet A, soy methyl ester, canola methyl ester and their blends in Jet A (50% by volume).	CO ↓ and NO ↓ while still producing high static thrust
[51]	APU-derived small scale turbine (GTP 30-67) with re-designed combustor	Portable on-board exhaust gas analyzer (Sensors Semtech DS) NDIR for CO/CO_2 - FID for THC - NDUV for NO/NO_2, and a portable on-line gas analyzer (Greenline 8000) for double check	Liquefied wood (LW) produced via solvolysis of lignocellulosic biomass in acidified glycols	Evaporation rate↓, solid residue after evaporation ↑ CO ↑ and NO_x ↑
[40]	SR-30 microturbine.	-	Blends of up to 75% by volume soybean oil with No. 2 Ultra-Low-Sulfur-Diesel (ULSD).	-
[45]	Solar T-62T-32 micro gas turbine	Emission analyzer with one catalytical and four electrochemical transducers (for CO and NO_x)	Blends of diesel and Straight vegetable oil (SVO) up to 100%	LHV↓ , rotational speed ↓, fuel injection pressure ↑
[46]	Gas turbine combustor	SIEMENS ULTRAMAC 6 OXYMAT 6 (CO/O_2/CO_2), CAI Model 600 CLD (NO_x), BASELINE 9000 (UHC)	Butyl butyrate and ethanol blends.	CO↑, NO_x ↓, UHC ↓ except for pure butyl butyrate. The emission index of total PN concentrations ↓
[78]	Small two-spool turbofan (computer model)	-	FT-SPK, HEFA-SPK, CH, ATJ-SPK, ATJ-SKA, SIP, HDO-SK, HEFA	In general, NO_x and CO ↓ depending on the fuel and operating conditions, UHC ↑, soot ↓,
[79]	1S/60 Rover gas turbine	SPTC Autocheck gas analyzer	Jet A-1 and Soap-derived biokerosene (SBK) blends	Performance parameters =, CO ↑ and HC ↑ emissions slightly, however as brake power increases CO , NO_x = insignificant differences

Table 4

Ref.	Engine	Analyzer	Fuels tested	Results
[52]	GTM-140 miniature turbine jet engine	Portable exhaust analyser - electrochemical (CO,NO,NO_2) and infrared (CO_2)	Jet A-1/butanol blend	Fuel consumption ↑ and SFC ↑ slightly CO , CO_2 and NO_x slightly.
[42]	Air-assist pressure swirl atomizer	NDIR method (CO), chemiluminescence method (NO_x), paramagnetic method(O2), flame ionization method (THC)	Jatropha pure oil (JPO) and Jatropha methyl ester (JME)	CO emissions: JPO> JME and diesel fuel at a low adiabatic flame temperature. The NO_x emission = when change in the fuel flow rate or fuel viscosity. Flame radiation intensity
[64]	T63-A-700 turbo shaft engine	MKS Multi Gas 2030 FTIR based analyzer, CAI 600 Heated Flame Ionization Detector for UHC and NDIR analyzer for CO_2 diluted samples	Blends of JP-8 and HRJ from camelina and tallow feedstocks	Soot and sulfur oxide , hazardous air pollutants (HAPS) except for formaldehyde and acetaldehyde.
[27]	Miniature turbojet GTM 140 series	portable exhaust analyser - electrochemical (CO,NO,NO_2) and infrared (CO_2)	Jet A-1/HEFA blend	Fuel consumption ↓. CO↓, CO_2 ↓ and NO_x ↓
[47]	178 N mini gas turbine engine	AVL DiGas exhaust gas analyzer	JET-A fuel with Additives (ethanol and pentanol) blend and biofuel (rapeseed and canola-sunflower oil)	NO_x ↓, CO ↓, and HC ↓
[48]	CF-700-2D-2	Horiba FIA-510 THC analyzer, an M&C PMA-10 oxygen analyzer, and an MKS MultiGas 2030 FTIR-based gas analyzer	JP-8 and JP-8/biodiesel blends.	Particle number density emissions↓ at higher power settings. Particulate and THC emissions ↑ at idle
[62]	Capstone oil fired microturbine (C30)	(1) Beckman model 955 chemi-luminescent NO_x analyzer and Fuji Electric Type ZFU 21MY3 Infrared CO analyzer. (2) A Testo 350 portable analyzer (O_2, CO, NO_x, and SO_2).	Fuel blends with biodiesel from soy oil	CO↓. NO_x ↓ under low power conditions. NO_x = at high power conditions
[60]	Swirl -combustor	Electrochemical analyzers to measure concentrations of CO and NO_x	Biodiesel and diesel-VO blends from vegetable oil soybean and animal fat chicken	CO ↓ and NO_x ↓. For constant Q, the CO emissions for both biodiesels and 70–30 diesel-VO blend =, CO ↑ slightly than diesel.
[49]	Micro turbine - Capstone Model C30	continuous emission monitoring system (CEMS)	Bioethanol-diesel-biodiesel blends from palm oil	In general, emissions ↑ from all biodiesel-bioethanol-diesel blend fuels
[50]	Olympus E-start HP turbojet engine	E8500 by E-Instruments analyzer	JetA-1 with biodiesel cotton methyl ester (CTME) and corn methyl ester.	CO_2 ↑ and CO ↓ UHC ↓ and HC emission↓. NO_x ↑. SO_2 ↓
[36]	SR-30 turbojet workbench (Turbine Technologies Ltd)	infrared for CO and UHC and chemical for O2 and NO_x	Jet-A, synthetic Gas To Liquid (GTL) kerosene produced by Sasol and mixture of 70% Jet-A / 30% JME.	CO ↑ slightly. NO_x ↑ at lower loads and NO_x ↓ under higher loads .UHC ↓

Table 4

Ref.	Engine	Analyzer	Fuels tested	Results
[30]	JetCat P-200 mini turbojet	Enerac 700 Micro-Emission Monitoring System. NDIR (CO_2, UHC) and electrochemical sensors (CO, NO, NO_2, O_2)	JP-8, Syntroleum R-8 HRJ, Sasol FT SPK, Swedish Biofuel SB-JP-8, UOP HRJ	NO_x =, CO and UHC not included.

Declaration of competing interest

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

Acknowledgement

We would like to thank Dr. Diego F. Hidalgo for his support and ideas to complement this work. The Efficient Energy Management Group- GIMEL and the Aerospace Science & Technology Research Group - ASTRA, belonging to Universidad de Antioquia, and the professionals that are part of it, for contributing to the development of new knowledge and formation of young researchers.

Funding

This work was supported by project 91914 of Minciencias, Colombia: ”Mejoramiento y escalamiento de prototipo para producción de diésel renovable y biojet a partir de H2 verde, azul o gris y aceites vegetales y/o residuales con visión hacia un contexto real de operación en la transición energética del país.”

Author contributions

Angélica Turizo-Donado: Paper conception, references collection and organization, writing original and edited drafts. S. López-Zapata: Paper conception, reference collection and organization, writing original draft, Information visualization. S. Arias: Conceptualization and methodology. J. R. Agudelo: Conceptualization and methodology.

Data availability statement

For this research, data were collected electronically through the different databases, with the closing date of the search being January 1, 2024.

References

[1] A. World and A. T. Institute, "Integration of sustainable aviation fuels into the air transport system," ACI World and Aerospace Technology Institute, Tech. Rep., 2021. [Online]. Available: https://www.ati.org.uk/wp-content/uploads/2021/10/SAF-Report-2021.pdf

[2] A. Schäfer, "The prospects for biofuels in aviation," in *Biofuels for Aviation*. Elsevier, 2016, pp. 3–16. [Online]. Available: https://doi.org/10.1016/B978-0-12-804568-8.00001-9

[3] C. Gutiérrez-Antonio, F. Gómez-Castro, J. Lira-Flores, and S. Hernández, "A review on the production processes of renewable jet fuel," *Renewable and Sustainable Energy Reviews*, vol. 79, 2017. [Online]. Available: https://doi.org/10.1016/j.rser.2017.05.108

[4] P. Su-ungkavatin, L. Tiruta-Barna, and L. Hamelin, "Biofuels, electrofuels, electric or hydrogen?: A review of current and emerging sustainable aviation systems," *Progress in Energy and Combustion Science*, vol. 96, 2023. [Online]. Available: https//doi.org/10.1016/j.pecs.2023.101073.

[5] T. K. Hari, Z. Yaakob, and N. N. Binitha, "Aviation biofuel from renewable resources: Routes, opportunities and challenges," *Renewable and Sustainable Energy Reviews*, vol. 42, p. 1234–1244, 2020. [Online]. Available: https://doi.org/10.1016/j.rser.2014.10.095

[6] M. Otto, L. Vesely, J. Kapat, M. Stoia, N. D. Applegate, and G. Natsui, "Ammonia as an aircraft fuel: A critical assessment from airport to wake," *ASME Open Journal of Engineering*, vol. 2, 2023. [Online]. Available: https://doi.org/10.1115/1.4062626

[7] J. Yang, Z. Xin, Q. S. He, K. Corscadden, and H. Niu, "An overview on performance characteristics of bio-jet fuels," *Fuel*, vol. 237, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0016236118317927

[8] Icao, "Corsia sustainability criteria for corsia eligible fuels."

[9] A. International, "Standard specification for aviation turbine fuel containing synthesized hydrocarbons," ASTM International, West Conshohocken, PA, Standard ASTM D7566-23b, 2023. [Online]. Available: https://www.astm.org/d7566-23b.html

[10] "Standard specification for aviation turbine fuels," ASTM International, West Conshohocken, PA, Standard ASTM D1655-23a, 2023. [Online]. Available: https://www.astm.org/d1655-23a.html

[11] "Standard practice for evaluation of new aviation turbine fuels and fuel additives," ASTM International, West Conshohocken, PA, Standard ASTM D4054-23, 2023. [Online]. Available: https://www.astm.org/d4054-23.html

[12] "Standard specification for gas turbine fuel oils," ASTM International, West Conshohocken, PA, Standard ASTM D2880-23, 2023. [Online]. Available: https://www.astm.org/d2880-23.html

[13] B. Gawron, T. Białecki, A. Janicka, M. Zawiślak, and A. Górniak, "Exhaust toxicity evaluation in a gas turbine engine fueled by aviation fuel containing synthesized hydrocarbons," *Aircraft engineering and aerospace technology*, vol. 92, no. 1, pp. 60–66, 2020. [Online]. Available: https://doi.org/10.1108/AEAT-11-2018-0277

[14] B. Gawron, T. Białecki, A. Janicka, A. Górniak, and M. Zawiślak, "An innovative method for exhaust gases toxicity evaluation in the miniature turbojet engine," *Aircraft Engineering and Aerospace Technology*, vol. 89, no. 6, pp. 757–763, 2017. [Online]. Available: https://doi.org/10.1108/AEAT-06-2016-0091

[15] A. Yousuf and C. Gonzalez-Fernandez, Eds., *Sustainable Alternatives for Aviation Fuels*. Amsterdam, Netherlands: Elsevier, 2022. [Online]. Available: https://www.elsevier.com/books-and-journals

[16] C. T. Chong and J.-H. Ng, *Biojet Fuel in Aviation Applications: Production, Usage and Impact of Biofuels*. Elsevier Inc., 2021.

[17] C. J. Chuck, Ed., *Biofuels for Aviation: Feedstocks, Technology and Implementation*. London, United Kingdom: Academic Press, 2016.

[18] M. Chiong, "Liquid biofuels production and emissions performance in gas turbines: A review," *Energy Conversion and Management*, vol. 173, p. 640–658, 2018. [Online]. Available: https://doi.org/10.1016/j.enconman.2018.07.082

[19] P. Schmidt, V. Batteiger, A. Roth, W. Weindorf, and T. Raksha, "Power-to-liquids as renewable fuel option for aviation: a review," *Chemie Ingenieur Technik*, vol. 90, no. 1-2, pp. 127–140, 2018. [Online]. Available: https://doi.org/10.1002/cite.201700129

[20] H. Wei, W. Liu, X. Chen, Q. Yang, J. Li, and H. Chen, "Renewable bio-jet fuel production for aviation: A review," *Fuel*, vol. 254, 2019. [Online]. Available: https://doi.org/10.1016/j.fuel.2019.06.007

[21] M. Vásquez, A. Martínez, E. Castillo, and E. Silva, "Holistic approach for sustainability enhancing of hydrotreated aviation biofuels, through life cycle assessment: A brazilian case study," *J Clean Prod*, vol. 237, 2019. [Online]. Available: https://doi.org/10.1016/j.jclepro.2019.117796

[22] A. Espinoza, S. Bautista, P. Narváez, M. Alfaro, and M. Camargo, "Sustainability assessment to support governmental biodiesel policy in colombia: A system dynamics model," *Journal of Cleaner Production*, vol. 141, pp. 1145–1163, 2017. [Online]. Available: https://doi.org/10.1016/j.jclepro.2016.09.168

[23] L. Martinez-Valencia, M. Garcia-Perez, and M. P. Wolcott, "Supply chain configuration of sustainable aviation fuel: Review, challenges, and pathways for including environmental and social benefits," *Renewable and Sustainable Energy Reviews*, vol. 152, 2021. [Online]. Available: https://doi.org/10.1016/j.rser.2021.111680

[24] A. Rodrigues, "Policy, regulation, development and future of biodiesel industry in brazil," *Cleaner Engineering and Technology*, vol. 4, p. 100197, 2021. [Online]. Available: https://doi.org/10.1016/j.clet.2021.100197

[25] R. H. Sundararaj, R. D. Kumar, A. K. Raut, T. C. Sekar, V. Pandey, A. Kushari, and S. Puri, "Combustion and emission characteristics from biojet fuel blends in a gas turbine combustor," *Energy*, vol. 182, pp. 689–705, 2019. [Online]. Available: https://doi.org/10.1016/j.energy.2019.06.060

[26] B. Gawron, T. Białecki, A. Janicka, and T. Suchocki, "Combustion and emissions characteristics of the turbine engine fueled with hefa blends from different feedstocks," *Energies*, vol. 13, no. 5, 2020. [Online]. Available: https://www.mdpi.com/1996-1073/13/5/1277

[27] B. Gawron and T. Białecki, "Impact of a jet a-1/hefa blend on the performance and emission characteristics of a miniature turbojet engine," *International Journal of Environmental Science and Technology*, vol. 15, no. 7, p. 1501–1508, 2018. [Online]. Available: https://doi.org/10.1007/s13762-017-1528-3

[28] E. Corporan, M. J. DeWitt, V. Belovich, R. Pawlik, A. C. Lynch, J. R. Gord, and T. R. Meyer, "Emissions characteristics of a turbine engine and research combustor burning a fischer–tropsch jet fuel," *Energy & Fuels*, vol. 21, no. 5, pp. 2615–2626, 2007. [Online]. Available: https://doi.org/10.1021/ef070015j

[29] E. Corporan, M. J. DeWitt, C. D. Klingshirn, R. Striebich, and M.-D. Cheng, "Emissions characteristics of military helicopter engines with jp-8 and fischer-tropsch fuels," *Journal of Propulsion and Power*, vol. 26, no. 2, pp. 317–324, 2010. [Online]. Available: https://doi.org/10.2514/1.43928

[30] J. Baranski, J. Hoke, P. Litke, and F. Schauer, "Preliminary characterization of bio-fuels using a small scale gas turbine engine," in *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, 2011, p. 694. [Online]. Available: https://doi.org/10.2514/6.2011-694

[31] C. G.-A. S. H. M. E. Araceli Guadalupe Romero-Izquierdo, Fernando Israel Gómez-Castro, "Intensification of the alcohol-to-jet process to produce renewable aviation fuel," *Chemical Engineering and Processing - Process Intensification*, 2021. [Online]. Available: https://doi.org/10.1016/j.cep.2020.108270

[32] X. Xue, X. Hui, P. Singh, and C.-J. Sung, "Soot formation in non-premixed counterflow flames of conventional and alternative jet fuels," *Fuel*, vol. 210, pp. 343–351, 2017. [Online]. Available: https://doi.org/10.1016/j.fuel.2017.08.079

[33] S. H. Won, P. S. Veloo, S. Dooley, J. Santner, F. M. Haas, Y. Ju, and F. L. Dryer, "Predicting the global combustion behaviors of petroleum-derived and alternative jet fuels by simple fuel property measurements," *Fuel*, vol. 168, pp. 34–46, 2016. [Online]. Available: https://doi.org/10.1016/j.fuel.2015.11.026

[34] N. M. Mazlan, M. Savill, and T. Kipouros, "Evaluating nox and co emissions of bio-spk fuel using a simplified engine combustion model: A preliminary study towards sustainable environment," *Proceedings of the Institution of Mechanical Engineers, Part G: Journal*

of Aerospace Engineering, vol. 231, no. 5, pp. 859–865, 2017. [Online]. Available: https://doi.org/10.1177/0954410016643980

[35] G. Pucher, W. Allan, and P. Poitras, "Characteristics of deposits in gas turbine combustion chambers using synthetic and conventional jet fuels," *Journal of engineering for gas turbines and power*, vol. 135, no. 7, p. 071502, 2013. [Online]. Available: https://doi.org/10.1115/1.4023609

[36] M. Badami, P. Nuccio, D. Pastrone, and A. Signoretto, "Performance of a small-scale turbojet engine fed with traditional and alternative fuels," *Energy Convers Manag*, vol. 82, p. 219–228, 2014. [Online]. Available: https://doi.org/10.1016/j.enconman.2014.03.026

[37] F. Chiariello, C. Allouis, F. Reale, and P. Massoli, "Gaseous and particulate emissions of a micro gas turbine fuelled by straight vegetable oil–kerosene blends," *Experimental Thermal and Fluid Science*, vol. 56, pp. 16–22, 2014, eighth Mediterranean Combustion Symposium. [Online]. Available: https://doi.org/10.1016/j.expthermflusci.2013.11.013

[38] C. T. Chong and S. Hochgreb, "Spray flame structure of rapeseed biodiesel and jet-a1 fuel," *Fuel*, vol. 115, pp. 551–558, 2014.

[39] S. G. Zehra Habib, Ramkumar Parthasarathy, *Effects of Biofuel on the Performance and Emissions Characteristics of a Small Scale Gas Turbine*. [Online]. Available: https://doi.org/10.2514/6.2009-827

[40] A. Hoxie and M. Anderson, "Evaluating high volume blends of vegetable oil in micro-gas turbine engines," *Renewable Energy*, vol. 101, pp. 886–893, 2017. [Online]. Available: https://doi.org/10.1016/j.renene.2016.09.054

[41] M. Buffi, A. Cappelletti, A. M. Rizzo, F. Martelli, and D. Chiaramonti, "Combustion of fast pyrolysis bio-oil and blends in a micro gas turbine," *Biomass and Bioenergy*, vol. 115, pp. 174–185, 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0961953418301090

[42] N. Hashimoto, H. Nishida, and Y. Ozawa, "Fundamental combustion characteristics of jatropha oil as alternative fuel for gas turbines," *Fuel*, vol. 126, pp. 194–201, 2014. [Online]. Available: https://doi.org/10.1016/j.fuel.2014.02.057

[43] A. Petcu, F. Florean, I. Porumbel, C. Berbente, and V. Silivestru, "Experiments regarding the combustion of camelina oil/kerosene mixtures on a burner," *Energy for Sustainable Development*, vol. 33, pp. 149–154, 2016. [Online]. Available: https://doi.org/10.1016/j.esd.2016.05.004

[44] T. W. Chan, V. Pham, J. Chalmers, C. Davison, W. Chishty, and P. Poitras, "Immediate impacts on particulate and gaseous emissions from a t56 turbo-prop engine using a biofuel blend," SAE Technical Paper, Tech. Rep., 2013. [Online]. Available: https://doi.org/10.4271/2013-01-2131

[45] A. Cavarzere, M. Morini, M. Pinelli, P. R. Spina, A. Vaccari, and M. Venturini, "Experimental analysis of a micro gas turbine fuelled with vegetable oils from energy crops," *Energy Procedia*, vol. 45, pp. 91–100, 2014, aTI 2013 - 68th Conference of the Italian Thermal Machines Engineering Association. [Online]. Available: https://doi.org/10.1016/j.egypro.2014.01.011

[46] L. Chen, "Experimental study of the gaseous and particulate matter emissions from a gas turbine combustor burning butyl butyrate and ethanol blends," *Appl Energy*, vol. 195, p. 693–701, 2017. [Online]. Available: https://doi.org/10.1016/j.apenergy.2017.03.075

[47] S. Manigandan, A. Atabani, V. K. Ponnusamy, and P. Gunasekar, "Impact of additives in jet-a fuel blends on combustion, emission and exergetic analysis using a micro-gas turbine engine," *Fuel*, vol. 276, p. 118104, 2020. [Online]. Available: https://doi.org/10.1016/j.fuel.2020.118104

[48] E. Corporan, R. Reich, O. Monroig, M. J. DeWitt, V. Larson, T. Aulich, M. Mann, and W. Seames, "Impacts of biodiesel on pollutant emissions of a jp-8–fueled turbine engine," *Journal of the Air & Waste Management Association*, vol. 55, no. 7, pp. 940–949, 2005. [Online]. Available: https://doi.org/10.1080/10473289.2005.10464680

[49] N. Saifuddin, H. Refal, and P. Kumaran, "Performance and emission characteristics of micro gas turbine engine fuelled with bioethanol-diesel-biodiesel blends," *International Journal of Automotive and Mechanical Engineering*, vol. 14, no. 1, p. 4030–4049, 2017. [Online]. Available: https://doi.org/10.15282/ijame.14.1.2017.16.0326.

[50] A. Ali and M. Ibrahim, "Performance and environmental impact of a turbojet engine fueled by blends of biodiesels," *International Journal of Environmental Science and Technology*, vol. 14, no. 6, p. 1253–1266, 2017. [Online]. Available: https://doi.org/10.1007/s13762-016-1228-4

[51] M. Buffi, A. Cappelletti, T. Seljak, T. Katrašnik, A. Valera-Medina, and D. Chiaramonti, "Emissions and combustion performance of a micro gas turbine powered with liquefied wood and its blends," *Energy Procedia*, vol. 142, pp. 297–302, 2017, proceedings of the 9th International Conference on Applied Energy. [Online]. Available: https://doi.org/10.1016/j.egypro.2017.12.047

[52] B. Gawron, T. Białecki, W. Dzięgielewski, and U. Kaźmierczak, "Performance and emission characteristic of miniature turbojet engine fed jet a-1/alcohol blend," *Journal of KONES. Powertrain and Transport*, vol. 23, pp. 123–130, 2016. [Online]. Available: https://api.semanticscholar.org/CorpusID:85548725

[53] B. Gawron and T. Białecki, "The laboratory test rig with miniature jet engine to research aviation fuels combustion process," *Journal of Konbin*, vol. 36, no. 1, p. 79–90, 2015. [Online]. Available: https://doi.org/10.1515/jok-2015-0058

[54] M. Buffi, A. Valera-Medina, R. Marsh, D. Pugh, A. Giles, J. Runyon, and D. Chiaramonti, "Emissions characterization tests for hydrotreated renewable jet fuel from used cooking oil and its blends," *Applied Energy*, vol. 201, pp. 84–93, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261917306050

[55] Y. S. Altarazi, A. R. Abu Talib, J. Yu, E. Gires, M. F. Abdul Ghafir, J. Lucas, and T. Yusaf, "Effects of biofuel on engines performance and emission characteristics: A review," *Energy*, vol. 238, p. 121910, 2022. [Online]. Available: https://doi.org/10.1016/j.energy.2021.121910

[56] B. GAWRON and T. BIAŁECKI, "Measurement of exhaust gas emissions from miniature turbojet engine," *Combustion Engines*, vol. 167, no. 4, pp. 58–63, 2016. [Online]. Available: https://doi.org/10.19206/CE-2016-406

[57] A. Pourmovahed, C. Jeruzal, and K. Brinker, "Development of a jet engine experiment for the energy systems laboratory," in *ASME International Mechanical Engineering Congress and Exposition*, vol. 37084, 2003, pp. 229–247. [Online]. Available: https://doi.org/10.1115/IMECE2003-43638

[58] "D4054-23 Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives," *ASTM*, 5 2023. [Online]. Available: https://doi.org/10.1520/d4054-23

[59] C. Allen, D. Valco, E. Toulson, T. Edwards, and T. Lee, "Ignition behavior and surrogate modeling of jp-8 and of camelina and tallow hydrotreated renewable jet fuels at low temperatures," *Combustion and Flame*, vol. 160, no. 2, 2013. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0010218012002969

[60] H. V. Panchasara, B. M. Simmons, A. K. Agrawal, S. K. Spear, and D. T. Daly, "Combustion Performance of Biodiesel and Diesel-Vegetable Oil Blends in a Simulated Gas Turbine Burner," *Journal of Engineering for Gas Turbines and Power*, vol. 131, no. 3, p. 031503, 02 2009. [Online]. Available: https://doi.org/10.1115/1.2982137

[61] A. Rehman, D. Phalke, and R. Pandey, "Alternative fuel for gas turbine: Esterified jatropha oil-diesel blend," *Renew Energy*, vol. 36, no. 10, p. 2635–2640, 2011. [Online]. Available: https://doi.org/10.1016/j.renene.2010.06.013

[62] C. Krishna, "Performance of the capstone c30 microturbine on biodiesel blends," *Brookhaven National Laboratory*, 2007. [Online]. Available: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=5c5408fe5b11b2bcbb071a1a5a530261a0eeeba7

[63] T. W. Chan, W. A. Chishty, P. Canteenwalla, D. Buote, and C. R. Davison, "Characterization of Emissions From the Use of Alternative Aviation Fuels," *Journal of Engineering for Gas Turbines and Power*, vol. 138, no. 1, p. 011506, 09 2015. [Online]. Available: https://doi.org/10.1115/1.4031226

[64] C. Klingshirn, "Hydroprocessed renewable jet fuel evaluation, performance, and emissions in a t63 turbine engine," *J Eng Gas Turbine Power*, vol. 134, no. 5, 2012. [Online]. Available:

https://doi.org/10.1115/1.4004841.

[65] A. R. Gonzalez Caranton, V. Silva Leal, C. Bayona-Roa, M. A. M. Betancourt, C. Betancourt, D. Cortina, N. J. Acuña, and M. López, "Experimental investigation of the mechanical and thermal behavior of a pt6a-61a engine using mixtures of jeta-1 and biodiesel," *Energies*, vol. 14, no. 11, 2021. [Online]. Available: https://doi.org/10.3390/en14113282

[66] D. Chiaramonti, A. M. Rizzo, A. Spadi, M. Prussi, G. Riccio, and F. Martelli, "Exhaust emissions from liquid fuel micro gas turbine fed with diesel oil, biodiesel and vegetable oil," *Applied Energy*, vol. 101, pp. 349–356, 2013, sustainable Development of Energy, Water and Environment Systems. [Online]. Available: https://doi.org/10.1016/j.apenergy.2012.01.066

[67] "Procedure for the continuous sampling and measurement of gaseous emissions from aircraft turbine engines arp1256e," SAE International, Warrendale, PA, Aeronautical Recommended Practice SAE ARP1256E, 2023. [Online]. Available: https://www.sae.org/standards/content/arp1256e/

[68] J. H. Elwood and R. H. Dieck, "Techniques and procedures for the measurement of aircraft gas turbine engine emissions," *Journal of the Air Pollution Control Association*, vol. 25, no. 8, pp. 839–844, 2012. [Online]. Available: https://doi.org/10.1080/00022470.1975.10470148

[69] M. L. Gómez, J. Posada, V. Silva, L. Martínez, A. Mayorga, and O. Álvarez, "Diagnosis of challenges and uncertainties for implementation of sustainable aviation fuel (saf) in colombia, and recommendations to move forward," *Energies*, vol. 16, no. 15, pp. 1–25, 2023. [Online]. Available: https://doi.org/10.3390/en16155667

[70] W. E. Rodriguez, A. Rodriguez, M. A. Mayorga, J. A. Bonilla, and M. Lopez, "Life cycle analysis of biodiesel blends for aviation," *Tecciencia*, vol. 14, no. 27, 2019. [Online]. Available: https://doi.org/10.18180/tecciencia.2019.27.6

[71] S. Bautista, A. Espinoza, P. Narvaez, M. Camargo, and L. Morel, "A system dynamics approach for sustainability assessment of biodiesel production in colombia. baseline simulation," *Journal of Cleaner Production*, vol. 213, pp. 1–20, 2019. [Online]. Available: https://doi.org/10.1016/j.jclepro.2018.12.111

[72] P. Benjumea, J. Agudelo, and A. Agudelo, "Basic properties of palm oil biodiesel–diesel blends," *Fuel*, vol. 87, no. 10-11, pp. 2069–2075, 2008. [Online]. Available: https://doi.org/10.1016/j.fuel.2007.11.004

[73] G. Talero, C. Bayona-Roa, G. Muñoz, M. Galindo, V. Silva, J. Pava, and M. Lopez, "Experimental methodology and facility for the j69-engine performance and emissions evaluation using jet a1 and biodiesel blends," *Energies*, vol. 12, no. 23, p. 4530, 2019. [Online]. Available: https://doi.org/10.3390/en12234530

[74] G. Talero, C. Bayona-Roa, V. Silva, M. Mayorga, J. Pava, and M. Lopez, "Biodiesel substitution in a j69 aeronautic turbine engine: An experimental assessment of the effects on energy efficiency, technical performance and emissions," *Sustainable Energy Technologies and Assessments*, vol. 40, 2020. [Online]. Available: https://doi.org/10.1016/j.seta.2020.100746.

[75] D. Rodríguez-Fontalvo, E. Quiroga, N. M. Cantillo, N. Sánchez, M. Figueredo, and M. Cobo, "Green hydrogen potential in tropical countries: The colombian case," *International Journal of Hydrogen Energy*, 2023. [Online]. Available: https://doi.org/10.1016/j.ijhydene.2023.03.320

[76] M. R. Lobato, J. C. Cazarolli, R. D. F. Rios, E. B. D' Alessandro, M. T. S. Lutterbach, N. R. A. Filho, V. M. D. Pasa, D. Aranda, P. R. Scorza, and F. M. Bento, "Behavior of deteriogenic fungi in aviation fuels (fossil and biofuel) during simulated storage," *Brazilian Journal of Microbiology*, vol. 54, no. 3, p. 1603 – 1621, 2023. [Online]. Available: https://doi.org/10.1007/s42770-023-01055-6

[77] A. Rehman, D. R. Phalke, and R. Pandey, "Alternative fuel for gas turbine: Esterified jatropha oil–diesel blend," *Renewable Energy*, vol. 36, no. 10, 2011, renewable Energy: Generation Application. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0960148110002697

[78] R. Gaspar and J. Sousa, "Impact of alternative fuels on the operational and environmental performance of a small turbofan engine," *Energy Conversion and Management*, vol. 130, pp. 81–90, 2016. [Online]. Available: https://doi.org/10.1016/j.enconman.2016.10.042

[79] I. K. Reksowardojo, L. H. Duong, T. H. Soerawidjaja, T. T. Nguyen, O. Fujita, and G. F. Neonufa, "Performance and emission characteristics of a gas turbine engine burning soap-derived biokerosene/jet a-1 blends," *SAE International Journal of Fuels and Lubricants*, vol. 13, no. 2, p. 125 – 136, 2020, cited by: 5. [Online]. Available: https://doi.org/10.4271/04-13-02-0007