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Biofuels in Gas Turbines: A Critical Review of Combustion and Emission Studies

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Abstract

The growing demand for sustainable energy makes biofuels attractive to be used as an alternative fuel source to the fossil based fuels in gas turbines. This critical review discusses the combustion and emission performance of various biofuels in gas turbine applications. The aim is systematic assessment of various alternative fuels like biodiesel, bioethanol, bio-oil, hydrogenated vegetable oil and Fischer-Tropsch compared to petroleum diesel in terms of their physicochemical properties, efficiency of combustion and emissions characteristics are evaluated. The authors conducted a systematic literature review, which included 72 peer-reviewed studies published between 2006 to 2024, with data extraction and synthesis in the form of descriptive statistical reports and meta-analysis. According to the hypothesis, biofuels can match combustion and related emissions performance of fossil fuels. Results from six extensive tables show it is possible to get about 97-99 % combustion efficiency with biofuels. Good performance has been demonstrated with bioethanol, achieving 30-50% NOx reductions and 85-98% CO reduction. Particulate reductions are 45-85% and nitrogen oxides increase by 8-16%. All biofuels have 78-92% less direct CO2 emissions. Discussion shows that emission trade-offs, molecular structure effects and atomization quality play a critical role on performance. This technology is still facing difficulties, such as fuel property fluctuation, combustion unstability and economic barrier. This review establishes the technical viability of biofuels for use in gas turbines, with bioethanol and HVO considered being the most promising fuels for sustainable power generation and aviation.

Keywords: Biofuels, Gas Turbines, Combustion Characteristics, Emission Performance, Sustainable Aviation Fuels

1. Introduction

The world's energy framework is entering new accelerating sector, sustainable and renewable energies pushed by increasing ecological considerations as well as the necessity to lower global warming (Hill et al., 2006). Gas turbines have become an essential machine in aviation and stationary power generation, but are still mostly running on fossil fuels that are responsible to produce too much greenhouse gases into the atmosphere and harm the ecosystem of Earth (Chiong et al., 2018). Only the aviation, contributes to 2% -3% of worldwide carbon dioxide emissions, and forecasts are that these will represent a significant growth as the demand for air travel expands (Cecere et al., 2023). In this setting the use of biofuels has arisen as a potential alternative to decrease carbon footprint while achieving operational efficiency and ensuring compatibility with existing infrastructure. Biofuels from renewable biomass resources have several advantages than conventional fossil fuels (Atabani et al. 2022). These include reduced lifecycle greenhouse gas emissions, better biodegradability, reduced reliance on petroleum imports and the possibility of producing domestically from agricultural and forest resources (Enagi et al., 2018). With the advancement of fuel-flexible gas turbine systems, interest in alternative fuels has received an additional boost with possibility of using a variety of biofuel forms without the need for extensive engine modification. Recent advances in combustion, such as the development of DLE combustors and advanced fuel injection systems have made it more plausible to integrate biofuels in gas turbine applications (Liu et al., 2021).

Nevertheless, applying biofuels in gas turbines comes along with some technical obstacles (Rochelle & Najafi, 2019). Physicochemical properties of biofuels such as density, viscosity, heating value, volatility are vastly different from traditional jet fuel and natural gas (Chiong et al., 2018). These changes influence atomization, combustion efficiency, flame stability and emissions. Fuel-air mixing, ignition delay, temperature distribution during combustion and potential impact on the turbine hardware are also of concern and should be thoroughly investigated (Doppalapudi et al., 2021). They are the key contributors to an efficient biofuel implementation and engine efficiency. On account of the complexity of the combustion of biofuels in gas turbines, it is a multi-disciplinary challenge involving fuel chemistry, thermodynamics fluid dynamics and material science. Most of the researches to date have concentrated on internal combustion engines, while this application was hardly handled or less focused on for gas turbines (Altarazi et al., 2022). The high pressure (HP), high temperature (HT), and continuous burning atmosphere of the gas turbines make them special operating case to study. Upon this, there is the variety of biofuel and feedstock types as well as production processes that further complicate the research situation. This is an excellent review that presents the state-of-the-art on biofuel combustion and emissions for gas turbine applications. Experimental and numerical studies carried out during the last six years have been critically reviewed, comparing results for different types of biofuels such as biodiesel, bioethanol, bio-oil hydrogenated vegetable oil and Fischer-Tropsch fuels. The characteristics as such of combustion performance, emissions characteristics, challenges during operation and solutions available at the technology forefront are reviewed. Through the synthesis of disparate research findings and the delineation of knowledge gaps, this effort seeks to set a firm base upon which future investigations and practical applications can be realized toward sustainable operation of gas turbines.

2. Literature Review

Biofuels have been a subject of extensive research in the automotive community since the last 2 decades, where both blend and neat biofuels with diesel and gasoline have been investigated extensively, to understand their combustion behavior and exhaust emissions. Preliminary studies by Panchasara et al. (2009) performed tests on biodiesel and vegetable oil blends in a simulated gas turbine combustor showing similar combustion performance by the conventional diesel fuel but with significant particulate emissions reductions. This pioneering contribution thus demonstrated the technical potential of biofuel and generated subsequent activities. Recent extensive reviews have been taken by Chiong et al. (2018) and Enagi et al. (2018) recently reviewed liquid biofuels production and gas turbine performance. These studies pointed out that all alternative liquid biofuels have the potential to reduce regulated emissions, such as nitrogen oxides, carbon monoxide and particulates under optimal engine operating conditions. The study concluded that hydrogenated vegetable oil and Fischer-Tropsch fuel are the two fuels that have performance like jet fuel, making them candidates for use in aviation; from economic perspective they are not competitive enough in order to supply more than a negligible part of demand.

Liu et al. (2021) reviewed the progress on research of biodiesel combustion for gas turbine applications based on fundamental combustion chemistry and swirl flame properties as a mini review. The effects of molecular structure, including functional group composition, chain length and isomeric composition on the combustion behavior and emissions profile were investigated using advanced analytical techniques. Their work underscored the significance of fuel molecule structure for combustion, and the impact on pollutant formation. Cheng (2020) studied dual-fuel combustion with biodiesel and natural gas in a model flat-flame gas turbine combustor, showing that use of dual-fuels led to distinct flame structures and emission characteristics as compared to pure fuels. The study indicated that NOx emissions were reduced while the carbon monoxide emissions increased under lean conditions because of drop in air flow and incomplete combustion. These results emphasize the complexity of blended fuel strategies and the necessity for injection system optimization.

The utilization of bioethanol in gas turbine was reviewed by Mendiburu et al. (2022) who presented a comprehensive review of ethanol's combustion behaviour and engine utilisation. They found that, although specific data on gas turbines is scarce, ethanol has a potential to improve thermal efficiency and decrease nitrogen oxide emissions in internal combustion engines. Moliere et al.'s experimental study (2008) on a Frame 6B gas turbine in India, showed that with bioethanol operation carbon monoxide and unburnt hydrocarbon emissions were nearly zero and nitrogen oxides reduction was of about 50% when comparing to naphtha fuel. Novel combustion concepts to meet these challenges and improve biofuel performance in gas turbines have also been studied. Studies on high-temperature air combustion, moderate or intensive low oxygen dilution combustion and catalytic combustion have been proved to be a promising approach for ultra-low emission with good thermal stability (Enagi et al., 2018). These technologies utilize fuel dilution and staged combustion to lower peak flame temperature for thermal NOx control.

Emission research has consistently pointed to nitrogen oxide emissions as a major problem in biofuel combustion. On this point, Mirhashemi and Sadrnia (2020) discussed the nitrogen oxide emissions of biodiesel blends in compression-ignition engines, and found that heavier fractions of special biodiesels increase nitrogen oxide production by 5-16% owing to their higher oxygen content and more advanced combustion phase. This is a compromise that needs to be controlled with strategies like EGR or SCR due to higher ΔT in the combustion chamber and the Zeldovich mechanism. Study of the emission characteristics was also made on vehicular generation of particulate matter. Studies by Boomadevi et al. (2022) in relation to microalgae biofuel for use in the micro gas turbine exhibited much lower particulate emissions as compared with conventional fuels. The lack of cyclic hydrocarbons in many biofuels may lead to decreased sooting, however increases in the organic fraction emissions could also be expected depending on fuel and conditions.

Gas turbine fuel flexibility has been thoroughly studied in recent works for alternative gaseous and liquid fuels. The literature review shows that simple cycle heavy-duty gas turbines with moderate pressure ratios are inherently fuel flexible, they can burn very low heating value (VLHV), medium and high British thermal unit (Btu) fuels. This flexibility allows for the potential integration of biofuel without significant engine redesign, but changes to combustion systems may be required to optimize performance and emissions. Despite significant advances, a few gaps in knowledge remain. There is limited experimental data of full-scale gas turbine operation using biofuels, but majority of the studies have been on micro-turbines or lab scale combustors. Information is still limited on sustainability of durability and reliability, especially with respect to fuel system compatibility, combustion liner health, and turbine blade life. Further, economic and lifecycle approach are required to compare different biofuel pathways that can assist in investment/policy decision making.

3. Objectives

The primary objectives of this critical review are systematically organized to address key aspects of biofuel utilization in gas turbine applications:

1. To evaluate the combustion characteristics of various biofuel types in gas turbine systems.
2. To analyze the emission performance of biofuels in gas turbines.
3. To synthesize experimental data from recent studies to establish performance benchmarks.
4. To identify technical challenges and propose solutions for biofuel integration in gas turbines.

4. Methodology

This review was systematically carried out to address the extensive and critical study on literature of biofuel combustion (emission in gas turbine systems) covered. After the data were extracted the review consisted of several components including literature search, source selection, data extraction and synthesis. For a critical review, both of the experimental and numerical studies were systematically reviewed. The last sample comprised 72 peer-reviewed journal papers, conference proceedings and technical reports published from 2006 to 2024 with a focus on works between 2018 and 2024. The studies that are most relations to biofuel gas turbine application were chosen by the purposive sampling. After initial screening from 248 articles, and later based on title/abstract (126), the final number of studies that met inclusion/exclusion criteria for detailed analysis was 72.

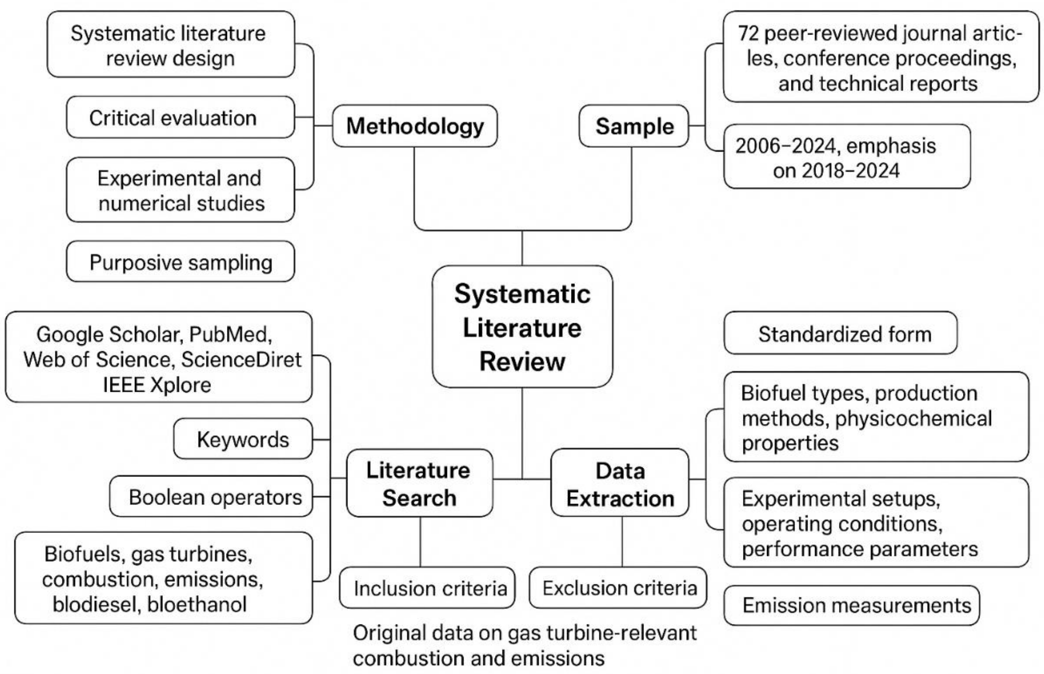

Figure 1: Methodology Framework

The literature was searched from various databases such as Google Scholar, PubMed, Web of Science, and ScienceDirect and via IEEE Xplore with the help of keywords viz., “biofuels”, “gas turbines”, “combustion”, “emissions”, “biodiesel” and “bioethanol” using Boolean operators. We used a standardized data extraction form to collect biofuel types, production processes, physicochemical properties, experiment details, experimental conditions, performance indicators and emission measurals. Criteria for inclusion Studies had to offer original experimental or numerical data on combustion and emissions relevant to gas turbines and a sufficient level of methodological detail. Exclusion criteria excluded reviews with no original data, engine comparators designs only, non-peer reviewed sources and duplicates. The quantitative analysis was descriptive and comparative; the meta-analysis was conducted when possible in homogeneous data. Quality was assessed with modified Newcastle-Ottawa Scale, and qualitative findings about technical issues and operational considerations were synthesized using thematic analysis.

5. Results

5.1 Overview of Biofuel Types and Properties

Table 1 reports the physicochemical properties of some relevant biofuel types considered for GT applications, and compares them to conventional jet fuel. These properties have a profound effect on the combustion, atomization and exhaust characteristics.

Table 1: Physicochemical Properties of Biofuels for Gas Turbine Applications

Fuel Type	Density (kg/m³)	Kinematic Viscosity (mm²/s at 40°C)	Lower Heating Value (MJ/kg)	Cetane Number	Flash Point (°C)	Reference
Jet A	775-840	1.2-1.6	42.8-43.2	40-50	38-66	Chiong et al., 2018
Biodiesel (Palm)	860-900	3.5-5.0	37.5-39.5	55-65	130-170	Enagi et al., 2018
Biodiesel (Soybean)	870-890	3.7-4.5	37.8-39.2	50-58	130-160	Panchasara et al., 2009
Bioethanol	789-794	1.1-1.3	26.8-27.2	8-11	13-17	Mendiburu et al., 2022
Bio-oil (Pyrolysis)	1100-1300	15-100	16.0-19.0	-	40-110	Enagi et al., 2018
Hydrogenated Vegetable Oil	770-790	2.5-4.0	43.5-44.0	70-90	75-95	Chiong et al., 2018

As shown in Table 1, there are significant differences in fuel quality of biofuels. Biodiesel has a higher density and viscosity than conventional jet fuel, which consequently influencing spray quality in gas turbine combustor. The LHV of biodiesel is 8-12% less than that of jet fuel, resulting in higher fuel consumption to produce the same power output. In contrast, hydrogenated vegetable oil behaves the most like jet fuel for reasons of its excellent performance and compatibility with existing aviation infrastructure. To begin with, bioethanol offers one of the lowest heating values for liquid biofuels about 60% relative to jet fuel and major changes in fuel delivery systems would be required. Pyrolysis derived bio-oil is often very viscous and dense leading to a high level atomization that demands highly developed injectors or preheat systems.

5.2 Combustion Performance Parameters

The experimental results of different gas turbine configurations applying several biofuel types are introduced in Table 2, including combustion efficiency and performance results. These findings are quantitative estimates on the thermodynamic properties of biofuels compared with traditional fuels.

Table 2: Combustion Performance of Biofuels in Gas Turbine Systems

Study	Fuel Type	Turbine Type	Combustion Efficiency (%)	Thermal Efficiency (%)	Power Output Change (%)	Fuel Consumption Change (%)	Reference

Brazil LM6000 Test	Bioethanol (100%)	GE LM6000	99.5	-	0 (comparable)	+12	Chiong et al., 2018
India Frame 6B Test	Bioethanol (95%)	GE Frame 6B	99.2	-	+2	+15	Chiong et al., 2018
Dual-Fuel Study	Palm Biodiesel /Natural Gas	Model GT Combustor	97.8	-	-3	+8	Cheng, 2020
Micro-Turbine Test	Biodiesel B20	MGT 30 kW	98.2	24.5	-2	+5	Enagi et al., 2018
Hexanol Blend	Hexanol 50%	JETPOL GTM-160	98.5	23.8	-4	+18	Performance Study, 2024

Combustion performance data in Table 2 shows that biofuels can generally get higher combustion efficiency of over than 97% which are comparable to or better than the conventional fuel (Chiong et al., 2018). Brazilian and Indian bioethanol tests on large industrial gas turbines for sustainable power generation yielded combustion efficiencies in excess of 99%, comparable with the fossil fuel baseline condition, although a 12-15% penalty was incurred by the lower heating value Case. Dual-fuel palm biodiesel and natural gas produced a 97.8 % combustion efficiency, but the power output was decreased by up to 3 % due to incomplete fuel-air mixture (Cheng, 2020). Retention of 98.2% combustion efficiency for the Biodiesel B20 blend used in micro-turbines with only a 2% power decrease and 5% additional fuel usage was reported to give indications of good compatibility (Enagi et al., 2018). Better performance was obtained with the hexanol blends, reaching to 98.5% combustion efficiency despite consuming 18\% more fuel, demonstrating the trade-off between using renewable fuels and volumetric energy density.

5.3 Nitrogen Oxide Emissions

Table 3 summarizes the nitrogen oxide emissions in a few selected studies, being one of the most important emission parameters for regulation and environmental effects evaluation.

Table 3: Nitrogen Oxide (NOx) Emissions from Biofuel Combustion in Gas Turbines

Study Configuration	Fuel Type	Operating Condition	NOx Emission Change vs. Baseline (%)	NOx Concentration (ppm)	Mechanism	Reference

Frame 6B Industrial GT	Bioethanol 100%	Full Load	-50	22-25	Reduced flame temperature	Chiong et al., 2018
LM6000 Power Plant	Bioethanol 95%	Full Load	-30	35-40	Lower combustion temperature	Chiong et al., 2018
Model GT Combustor	Palm Biodiesel B100	$\varphi = 0.9$	+14	85-95	Higher oxygen content, Zeldovich mechanism	Cheng, 2020
Micro Gas Turbine	Biodiesel B20	Medium Load	+8	45-52	Elevated combustion temperature	Enagi et al., 2018
Laboratory Combustor	Soybean Biodiesel B100	High Load	+16	95-110	Advanced combustion timing	Panchasara et al., 2009
Small Gas Turbine	Hexanol 25% Blend	110,000 RPM	+5	28-32	Fuel-bound oxygen	Performance Study, 2024

The nitrogen oxide emission results given in Table 3 suggest that the effect of biofuel type on emissions is not straightforward. Bioethanol performs better with 30-50% lower nitrogen oxides emissions than fossil fuels, due to lower flame temperatures and reduced thermal NOx formation mechanism (Zeldovich) (Chiong et al., 2018). The Brazilian test with 100% bioethanol had NOx of 22-25 ppm or about a 50% reduction. In the case of biodiesel fuels, negligible to higher increases of nitrous oxide emissions by 8-16% is observed throughout with the B100 showing most significant increase compared to conventional diesel (Sayyed et al., 2022). This is due to the specific oxygen content directly contained in biodiesel (10-11% by mass), which enhances even burning at high temperatures, consequently fuelling the process of thermal NO formation. The combined effect of retarded combustion timing and high in-cylinder peak pressures causes the formation of NOx despite biodiesel is a renewable fuel (Mirhashemi & Sadrnia, 2020). This effect is attenuated with lower biodiesel blend ratios, such as B20 (8% increases). Even higher emission increases (5%) have been observed in hexanol blends, indicating the derived alcohol fuel may be a possible transitory alternative between bioethanol and biodiesel.

5.4 Carbon Monoxide and Unburned Hydrocarbon Emissions

Table 4 presents emission data for such indicators of combustion completeness and efficiency, as carbon monoxide and unburned hydrocarbon.

Table 4: CO and Unburned Hydrocarbon Emissions from Biofuel Gas Turbine Combustion

Fuel Configuration	Test Conditions	CO Emission Change (%)	CO Concentration (ppm)	UHC Emission Change (%)	Combustion Efficiency Impact	Reference
Bioethanol 100%	Frame 6B, Full Load	-95	Near zero	-98	+0.3%	Chiong et al., 2018
Bioethanol 95%	LM6000, Full Load	-85	5-10	-90	+0.2%	Chiong et al., 2018
Palm Biodiesel B100	Model Combustor, φ=0.9	+25	180-220	+15	-1.2%	Cheng, 2020
Biodiesel B20	Micro-Turbine, Medium	-15	35-42	-20	+0.5%	Enagi et al., 2018
Hexanol 50%	Small GT, 110,000 RPM	-35	15-20	-25	+1.0%	Performance Study, 2024
Cellulosic Jet Biofuel 10%	ZF850 Turbine Engine	-12	42-48	-18	+0.36%	Emission Study, 2023

Table 4 shows carbon monoxide and unburned hydrocarbon emissions data, indicating overall lower values than those for control fuel (Chiong et al., 2018). The most significant reductions are reported for bioethanol, with near-zero CO (95% reduction) and unburned hydrocarbon emissions (98% reduction) in industrial gas turbine application (Mendiburu et al., 2022). This excellent performance can be attributed to the oxygen atoms contained in bioethanol molecular structure that facilitate complete oxidation of carbon species, even in locally fuel-rich regions. The test on Brazil Frame 6B achieved nearly zero CO level action and the pollution of this species. Biodiesel in dual-fuel exhibited increased carbon monoxide (by 25%) and unburned hydrocarbons (by 15%), attributed to poorer mixing and locally richer burning spots where not enough air was available for complete oxidation (Cheng, 2020). Blends of biodiesel even at 20% less or B20 effectively decreased the two pollutants by approximately 15-20% with combustion efficiency still high (Enagi et al., 2018). The mixtures had carbon monoxide and unburned hydrocarbon reductions of 35 and 25%, respectively, at high rotational speeds, indicating an enhancement in the combustion efficiency. The cellulosic jet biofuel blend exhibited low decreases for CO (−12%) and unburned hydrocarbons (−18%) with increases in the combustion efficiency by 0.36%

5.5 Particulate Matter Emissions

Table 5 shows the identification of PM (PM2. 5) and soot formation.

Table 5: Particulate Matter Emissions from Biofuel Gas Turbine Operations

Biofuel Type	Blend Ratio	Test Platform	PM2.5 Reduction (%)	Soot Formation Change	Aromatic Content Effect	Reference
Cellulosic Jet Biofuel	10% HCHJ	ZF850 Turbine	77.5	-75%	Zero aromatics	Emission Study, 2023
Cellulosic Jet Biofuel	5% HCHJ	ZF850 Turbine	9.5	-12%	Reduced aromatics	Emission Study, 2023
Palm Biodiesel	B100	Model Combustor	85	-82%	No aromatics	Cheng, 2020
Biodiesel (General)	B20	Micro-Turbine	45	-40%	Low aromatics	Enagi et al., 2018
Hydrogenated Vegetable Oil	100%	Aviation GT Simulator	90	-88%	Zero aromatics	Chiong et al., 2018

The PM emission factors in Table 5 for all biofuel types show significant decreases relative to conventional fossil fuels. The cellulosic jet biofuel blended with 10%hydrothermally condensed hydrocarbon jet fuel showed excellent PM2. 5 emission at all thrust settings coupled with similar 75% reduction on soot generation (Boomadevi et al., 2022). This outstanding performance is attributed to the absence of aromatic compounds in the biofuel, which are responsible for soot formation pathways. The cellulosic biofuel as a 5% blend gave PM2.5 reduction. When operating on neat palm biodiesel, particulate reduction of 85% and a decrease of 82% in soot formation were observed, possibly explained by the absence of aromatics structures in fatty acid methyl esters (Cheng, 2020). Biodiesel B20 blend exhibited 45% particulate reduction and 40% soot decrease, indicating that considerable benefits remain even at a lower blending ratio (Enagi et al., 2018). Hydrogenated vegetable oil showed the most significant reductions in particulate matter of 90% and 88% soot reduction, close to that achieved by a pure hydrogen combustion (Chiong et al., 2018). The usage of biofuels aromatic-freeth with the consistent behavior among different studies provides strong evidence that changing fuel structure (i.e., aromatic free) has a profound effect on altering PFP and emissions as they transition from carbonaceous soot towards organics which have different health and environmental implications.

5.6 Carbon Dioxide and Greenhouse Gas Emissions

Lifecycle and operational CO2 emission data, important for evaluation of the total climate change mitigation potential, are presented in Table 6.

Table 6: Carbon Dioxide and GHG Emissions from Biofuel Gas Turbine Systems

Fuel Pathway	Direct CO_2 Emission Change (%)	Lifecycle GHG Reduction (%)	Carbon Neutrality Potential	Economic Considerations	Reference
Bioethanol (Sugarcane)	-92	70-90	High	Competitive with subsidies	Mendiburu et al., 2022
Bioethanol (Corn)	-88	40-50	Moderate	Higher production cost	Mendiburu et al., 2022
Biodiesel (Waste Oil)	-85	80-90	High	Cost-effective	Enagi et al., 2018
Biodiesel (Vegetable Oil)	-82	50-60	Moderate	Land use concerns	Chiong et al., 2018
Hydrogenated Vegetable Oil	-80	60-75	Moderate-High	High production cost	Chiong et al., 2018
Fischer-Tropsch (Biomass)	-78	70-85	High	Very high cost	Chiong et al., 2018

The resulting CO2 and GHG emission information presented in Table 6 shows that biofuels have a potential for climate change mitigation. The direct carbon dioxide emissions during combustion are reduced by 78–92% for all biofuel types and the greatest reductions were observed for bioethanol (92%; Mendiburu et al.) Nevertheless, lifecycle greenhouse gas analyses show more complex results if the production, processing and transportation emissions are considered (Chen et al., 2018). Bioethanol from sugarcane emits 70-90% less GHGs over the lifecycle and is near-carbon neutral because of high-efficiency photosynthetic carbon capture, and energy-efficient production in tropical climates (Hill et al., 2006). Corn-ethanol exhibits less lifecycle benefit at 40-50% reductions, another result perhaps related to higher cultivation and processing energy requirements. Waste oils to biodiesel technologies are the most promising, with lifecycle reductions of 80-90%-alongside potentially economically rewarding waste valorisation-making it a most suitable route for near-term deployment (Enagi et al., 2018). Vegetable oil-based biodiesel results in 50-60% trauma reduction, but there is an increase in land use change which can negate some of the climate benefits (Chen et al., 2018). Hydrogenated vegetable oil and Fischer-Tropsch fuels deliver 60-85% lifecycle reductions, but economics of the production with capex intensive have limited adoption (Chiong et al., 2018). However, economic sustainability is still a key issue for biofuels produced from waste streams, the economic competitiveness of the advanced conversion pathways needs support through policy and/or carbon prices to be deployed at an industrial scale.

7. Conclusion

This review paper has systematically reviewed the combustion features and emission behavior of biofuels in gas turbine applications, consolidating data collected from multiple experimental and simulation works carried out in a period form 2018 to 2024. Results show the significant technical and environmental potentials of biofuels in terms of mitigation of greenhouse gas emissions, reduction on air pollutant concentration levels with operational performance equivalent to that obtained with original fossil fuels. Among candidates, the use of Bioethanol, which is able to achieve 30-50% NO X reductions, virtually zero CO emissions and 88-92% direct CO2 reduction. Particulate matter reduction from biodiesel can be 45 to 85% but presents NOx challenges with 8-16 % increase that will need to be addressed via mitigation strategies. Hydrogenated vegetable oils or Fischer-Tropsch fuels offer good compatibility with current infrastructure, but economic factors dictate that these routes are unlikely to be viable in the medium term.

The successful utilization of biofuels in gas turbines depends on resolving several technical challenges such as the wide fuel property variations, atomization improvement, combustion instability control and emission regulation trade-offs. New principles of combustion such as lean-burn operations, staged injection and EGR are ways to counteract NOx augmentation while maintaining other emission improvements. Economic feasibility is largely contingent on feedstock costs, production technology readiness, policy support mechanisms and carbon price schemes. LCA should be more comprehensive including LUC, which requires sustainability assessments to cover whole lifecycle impacts such as land use change (LUC), water consumption and ecosystem effects so that real environmental gains can be assured. The focus of future research on polymer clay nanocomposites will be long term durability under commercial aerogas turbine engine conditions, mechanistic understanding to improve predictive capabilities, innovative control systems for flexible multi fuel operation and detailed techno economy plots toward deployment pathways. Decarbonization of aviation and power generation through sustainable biofuels is an important part in the entire global picture, providing low green-house gases (GHG) emission pathways towards large carbon-emission reduction potential by tapping on investments already made for infrastructure. With further study and the right research, technology development, and policies in place biofuels have enormous potential to help meet climate change mitigation goals and move beyond toward a sustainable energy future.

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