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BIOFUELS FOR GAS TURBINES: A SURVEY OF COMBUSTION TECHNOLOGIES AND THEIR IMPACT ON POWER GENERATION

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Abstract

The prospects in the use of biofuels include the ability to reduce dependence on imported oil, enhance the levels of energy self-sufficiency and thus enhance energy security through the use of biofuels as a replacement for fossil fuels. This paper surveys the integration of biofuels in gas turbines, focusing on advanced combustion technologies and their impact on power generation. Biofuel is divided into four categories, including the process of making it, feedstock used, benefits and even the associated drawbacks of each generation. The work examines some of the combustion technologies like lean-premixed, catalytic, and micro-mixing systems in their applications with biofuels and the feasibility of attaining ultra-LOW NOx and particulate matter emissions. Specific conclusions highlight environmental, economic, and operational advantages of biofuel-powered turbines, such as the feasibility of supply, their compatibility with the existing turbine systems. However, problems like fuel variability, relatively low energy density and cost of manufacturing are effectively dealt with, stressing the need for improved technologies and strategies for improving the combustion quality and reducing emissions. This paper also identifies the policy factors, research partnerships, and technology that could enhance the use of biofuels in gas turbines to support efficient, clean, and sustainable power systems. Contributing to worldwide efforts towards sustainable and decarbonized energy solutions, the insights seek to allow future breakthroughs in biofuel utilization.

Keywords: Biofuel, Power Generation, Combustion Process, Gas Turbines, Energy Sources, Combustion Technologies.

I. INTRODUCTION

There may be creatures like microalgae, plants and bacteria in the animals, which may be used to make biofuels which are simply an energy-dense material. The demand for renewable energy sources has increased tremendously in combination with the increasing global population. Biofuels have recently become more popular as a greener alternative to fossil fuels, the burning of which dramatically worsens the state of the environment. In addition to reducing emissions of dangerous greenhouse gases, biofuels and other forms of renewable energy may assist in meeting the growing need for energy [1].

New advances in microbial biofuel generation and growth techniques, including the use of biofilm for microalgae and cyanobacteria growth, have enhanced the efficiency of processing biofuels.

Among them, algal biomass has received the greatest attention for its high growth rates and the capacity to use carbon dioxide photosynthetically from the atmosphere to produce sugars. Spirulina maxima, Porphyra cruentum, Schizochytrium capable of yielding lipids, carbohydrates and proteins when applied as raw materials for biofuel production under proper conditions [2].

One great way to use biofuels for greener, more sustainable electricity is in gas turbines, which are crucial to contemporary power production and propulsion systems. However, the direct use of biofuels in gas turbines involves such issues as variability of fuel quality, fuel combustion efficiency, and emissions. If biofuels are to replace fossil fuels in gas turbines efficiently while being environmentally friendly, new forms of combustion, such as lean-premixed and catalytic combustion, are beneficial. This paper reviews the application of biofuels in gas turbines with an emphasis on combustion technologies and their effects on power generation efficiency, sustainability and cost[3].

A. Motivation of the Study

The rapid increase in energy demand across the globe, together with the threats posed by pollution from the residual products of fossil fuels, has occasioned a search for renewable energy sources. Gas turbines selected for electricity generation and industrial uses are ideal equipment in which biofuels can be incorporated as an environmentally friendly and renewable energy option. In addition to lowering emissions of greenhouse gases, biofuels improve energy security by making better use of locally available resources and lessening reliance on fossil fuels imported from other countries.

B. Structure of the Study

The paper is structured as follows: Section II covers the Fundamentals of Biofuels. Section III discusses Combustion Technologies for Gas Turbines and their compatibility with biofuels. Section IV examines the Impact of Biofuels on Power Generation, focusing on efficiency, environment, and economy. Section V Highlights Advantages and Challenges of Biofuel Combustion. Section VI presents the literature review, while Section VII presents the findings and suggestions for further study.

II. BIOFUELS FOR GAS TURBINES

Biofuels application in gas turbines has in the recent past been adopted for use as a more sustainable option as compared to fossil based fuels. The use of biofuels, which are produced from renewable biological materials such as plants, algae or agricultural residues, reduces the emission of greenhouse gasses and the reliance on non-renewable fossil fuels. Its use in gas turbines is particularly desirable due to its compatibility with the existing combustion system, low modification needs, and the availability of a stable and dispatch able power output. To improve combustion efficiency and reductions of NOx or other emissions biofuel powered turbines incorporate Lean Premixed and catalytic combustion systems. With a growing need for renewable energy all over the globe, bio fuels have to be used in place of fossil fuels to drive gas turbines to provide power to the globe in a more reliable manner.

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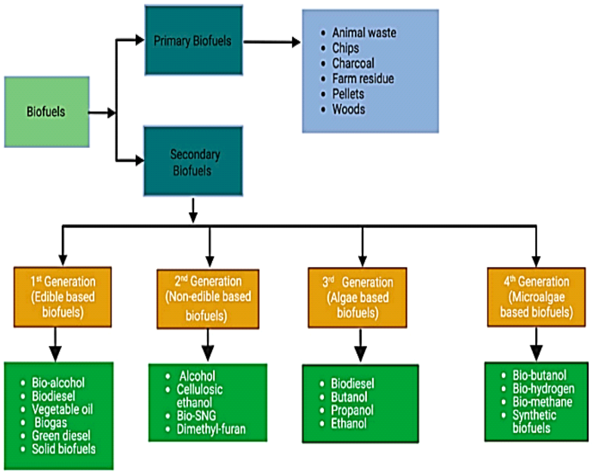
Types and Generation of Biofuels

Based on the origins and manufacturing of different biomaterials, biofuels are divided into four generations: the first, second, third, and fourth. The following highlights a quick summary of each generation.

1. First-Generation Biofuels

In the first generation of conventional biofuels, the main ingredients were starch-rich foods (potatoes, maise, barley, and wheat) and sugar-rich foods (sugarcane and sugar beets) [4][5]. The main advantages of first-generation raw materials are their crop availability and relatively straightforward conversion processes. On the other hand, food prices might rise if edible crops are used to make biodiesel, as this reduces the food supply[6]. Different conventional biofuels are characterised by the different technological processes that go into making them (Figure 1).



Types and generations of Biofuel [4].

A. Bio Alcohols

Bio alcohols are produced by fermenting sugars such as cellulose, glucose, starches, carbs, and others with the aid of microbes and enzymes. Three other types of bio alcohols are bio propanol, bio butanol, and bioethanol [26].

B. Biodiesels

Diesel fuels that are produced from environmentally friendly sources, including lignocellulosic biomass, which includes long-chain fatty acid esters, are known as biodiesels. Biodiesels are chemically produced by reacting lipids (e.g., tallow, soybean oil, or other vegetable oils) with alcohol to make an ester (ethyl, propyl, or methyl) [27]. Use of sodium hydroxide or potassium hydroxide as a catalyst is common in biodiesel production [28].

C. Vegetable Oil

Vegetable oils are made from a variety of plant sources, including fat, olive oil, castor oil, turmeric, and sunflower oil. Vegetable oil fuels are both environmentally friendly and cost-effective. In some specific contexts, recent research has shown that cooking and vegetable oils may be used as diesel engine alternatives [29].

D. **Green Diesel**

Green diesel is made from hydrotreated triglycerides in vegetable oils. Decarbonylation (DCO), hydrodeoxygenation (HDO), and decarboxylation (DCO2) are the three primary processes that occur during the process [30].

E. **Biogas**

The process of anaerobic digestion, which involves a microbial consortia and does not use oxygen, results in a production of biogas and dig estate, a by-product that is rich in nutrients [7]. Biogas is a by-product of this process that is composed of around 60%CH_4, 35%CO_2, and 5%volatile amines, a combination of H_2, N_2, CO, NH_3, andO_2 [8]. Potential uses for biogas include power generation in industrial settings, cooking in rural areas, and combined heat and power (CHP) systems [9][10].

F. **Solid Biofuels**

Wood, wood chips, leaves, sawdust, charcoal, and even animal excrement are some of the raw materials that are frequently utilised as solid biofuels. In the energy industry, solid biofuels are only used in specific markets [4]. One typical method of producing bioenergy that may be utilised for cooking is firewood [11].

2. Second-Generation Biofuels

Using non-edible feedstocks that do not compete with agricultural land, the transition from first-generation biofuels to second-generation biofuels, including lignocellulosic biomass, tackles the food vs. energy problem. Lignocellulosic biomass, which includes cellulose, lignin, and hemicellulose, provides an eco-friendly option that helps with energy stability, economic development, and lowering emissions of greenhouse gases [12]. Agricultural leftovers, woods, and grasses have the potential to be valuable resources for advanced biofuels, and technical improvements in the US can create 1.3 billion tonnes of dry biomass per year without affecting food supplies [13].

A. **Cellulosic Ethanol**

Cellulosic ethanol is made by fermenting sugars that come from cellulose components and polyose. Cellulosic biofuels have the potential to improve the economic situation in rural communities while also making agricultural landscapes more environmentally friendly [14][15].

B. **Algae-Based Biofuels**

Algae have quickly surpassed more conventional biofuel extraction techniques as the industry's most exciting and promising new raw resource. To isolate and concentrate algal biomass, many methods are employed, including centrifugation, aggregation, flotation, purification, and flocculation [16][17]. Producing biodiesel, biogas, and hydrogen, among other biofuels, from algae is now possible thanks to the innovative feature [18].

C. **Alcohol**

By using targeted microbes in the fermentation process, syngas may be converted into alcohol [19].

D. **Dimethylfuran**

Dimethylfuran has 17% oxygen by weight, making it an oxygenated hydrocarbon. It is a component of diesel fuel. Compared to other methods, this one is quite effective in lowering engine emissions [20].

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E. **Biosynthetic Natural Gas (Bio-SNG)**

Anaerobic digestion may be enhanced with the aid of bacteria to provide biogas. Compressed and liquid bio-SNG are utilised in vehicles and for refilling natural gas cylinders [21].

3. Third-Generation Biofuels

Third-generation biofuels are derived from algal biomass and waste oils, offering benefits like high productivity, no need for agricultural land, and reduced food supply impact[22]. Some examples of these sources are microalgae, animal fat, fish oil, and used cooking oil. Though it's expensive to collect and extract, algal biomass generates 10-100 times more biofuel per unit area [23]. Seaweed, with its high carbohydrate and lipid content, is another promising resource[24]. Algal biofuels include biodiesel, bioethanol, and biohydrogen, though they can emit higher NOx due to algae's nitrogen content [25]. Waste cooking oil is also used, but variations in feedstock quality and impurities limit scalability. Recent examples include waste coffee grounds and Bardawil Lagoon oils [26][27].

4. Fourth-Generation Biofuels

Fourth-generation biofuels utilise genetic engineering, such as CRISPR/Cas9, to enhance biofuel yields[28]. These biofuels are made from cyanobacteria and genetically engineered algae that are rich in carbohydrates and lipids [29]. For example, modifications in algae and cyanobacteria have shown significant improvements in biofuel production, such as a 10-fold increase in triacylglycerol (TAG) or direct butanol production from CO2[30]. This advanced approach integrates molecular biology to optimise biofuel production efficiency and sustainability[31].

Advantages and disadvantages of biofuel combustion

Their CO2 neutrality and the fact that they can be produced locally are the two biggest benefits of biofuels. Biofuels have the dual benefit of reducing a country's or region's reliance on imported fuels and increasing local revenue. Fuelling MSW and other organic waste reduces harmful effluents and helps with the ever-increasing waste disposal problem.

The recommended approach for managing municipal solid waste is controlled incineration. About 20% to 25% of municipal solid waste (MSW) weight, or 10% of MSW volume (because of greater densities), consists of ash and flue gas treatment leftovers. Assuming efficient energy conversion technologies are in place, producing power from MSW on a large scale might account for 3–5% of the total power consumption in developed nations.

The LHV or HHV of a fuel is the standard measure of its energy content. When dry ash-free, raw biofuels have heating values of approximately 20 MJ/kg, equivalent to mid-quality coal. The fuel's elemental composition, ash, and moisture content affect its heating value and combustion qualities. Biomass has a high oxygen content, which lowers its heating value, reduces the air needed for stoichiometric burning, and increases fuel volatility. Combustion changes the physical properties of ash-forming chemicals, which impacts biofuel combustion chamber design, performance, and maintenance.

Unsorted MSW isn't CO2-neutral. While largely biological, some of its components come from fossil sources. The quantity of energy contained in unsorted MSW is mostly attributable to plastics

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despite the fact that they only account for a small portion of the total mass. Results from a full life cycle assessment of MSW power units in Japan show that MSW incineration lowers net CO_2 emissions even at extremely low electrical efficiencies, all because the supporting activities—including MSW collection, materials, utility construction, and maintenance—have a fossil carbon intensity of less than 1g fossil carbon per MJ HHV, and that's before we even get into the MSW's fossil content. These emissions are half those of coal and half that of natural gas, despite the fact that unsorted MSW contains 8 grams of fossil carbon per MJ LHV.

III. COMBUSTION TECHNOLOGIES FOR GAS TURBINES

This section provides an overview of the principles of gas turbine combustion, explores advanced combustion technologies, and examines the challenges associated with implementing these technologies.

A. Principles of Gas Turbine Combustion

Gas turbine combustion is a fundamental process in power generation and propulsion systems, wherein the chemical energy stored in fuel is converted into thermal energy by burning it with compressed air in a meticulously designed combustion chamber. This thermal energy is then transformed into mechanical energy as high-temperature, high-pressure gases expand through a turbine, driving a generator, mechanical load, or propulsion system[32]. Combustion is a versatile process with many uses, such as transportation, industrial power generation, and marine propulsion, because of its high power-to-weight ratio, quick start-up capabilities, and versatility.

The performance in terms of the efficiency and emissions of this process depends on the composition and quality of fuel and combustion chamber configuration, operation parameters and the condition of the environment. The combustion chamber should provide stable flame front combustion, reduced pressure drop and efficient heat release coupled with good thermal stability at high temperatures. Advances in turbine materials, cooling technologies, and flame stabilisation techniques have significantly improved combustion performance and reduced emissions of pollutants such as nitrogen oxides (NOx), carbon monoxide (CO), and unburned hydrocarbons (UHC). Additionally, the application of advanced technologies of lean-premixed and catalytic combustion has improved the environmental effectiveness of gas turbines, and they have become an integral part of modern, efficient energy networks.

B. Combustion Technologies and Their Compatibility with Biofuels

1. Conventional Combustion Chambers

Conventional combustion chambers designed for natural gas or liquid fuels are often annular or can-annular. These chambers may only need a few modifications to hold biofuels but could likely need changes to the fuel injectors to guarantee suitable atomisation and burning. The primary challenge is maintaining stable operation while managing higher viscosities or impurities in biofuels [33].

2. Lean Premixed Combustion

Lean premixed combustion reduces emissions of nitrogen oxides by creating a homogeneous flame by combining fuel and air before ignition. Because of its reduced pollutant production and ability to work at lower temperatures, this technique is very beneficial for biofuels. Nevertheless, when using biofuels with changing calorific values, lean flames are more unstable and need sophisticated management techniques.

3. Catalytic Combustion

In catalytic combustion, the temperature is reduced using catalysts to help it undergo combustion wherever it is incomplete due to high temperatures. It is compatible with biofuels because it solves problems that arise from soot formation and high NOx emissions. Catalysts also shield biofuels from early combustion, thus suitable where very low emission is required.

4. Micro-Mixing and Advanced Techniques

Micro-mixing strategies help to introduce fuel and air at a molecular level and thus promotes improved and stabile combustion. The Mike Horn version gets biofuel compatibility benefits from the meeting of swirl stabilisation and staged combustion, which reduces hotspots and assists flame spread [34]. These methods address the challenges of fuel variability and maximise combustion efficiency.

C. Challenges of Biofuel Combustion in Gas Turbines

1. Combustion Efficiency

Biofuels contain less energy compared to fossil fuels, contain high moisture content and affect the combustion rate. For full combustion, one must design combustors more effectively and efficient control systems to address varying fuel characteristics [35].

2. Emission Characteristics

According to this, while biofuels decrease overall greenhouse gas emissions, they may release more NOx because of nitrogen. These emissions require combustor modifications in the form of water injection or selective catalytic reduction (SCR) in order to prevent them.

3. Fuel Stability and Handling

Biofuels like waste or algae-based fuels will inevitably have some levels of impurities and varying viscosity, and hence, storage, transportation, and combustion are problematic. Some of the preconditioning treatments, which may include filtration and heating, may be necessary to check on the stability of the fuel, and atomisation within turbines.

IV. IMPACT OF BIOFUELS AND COMBUSTION ON POWER GENERATION

A. Impact of biofuels on power generations

1. Efficiency and Performance Implications

Bio-fuels are renewable resource that can replace or be blended with fossil fuels but the design and use of gas turbines involve certain modifications because of the lower energy content of bio-fuels. Lean-premixed and catalytic technologies enhance biofuel-based turbines as they facilitate accurate fuel and air mixing while minimising energy losses. Biofuels also increase operating adaptability by providing prime mover versatility achieved through dual-fuel arrangements that can change between biofuels and other traditional fuels to ensure energy availability and reliability. However, the differences in chemical composition, such as higher oxygen and moisture content, may slightly affect thermal efficiency compared to fossil fuels.

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B. Environmental Impacts

1. Carbon Footprint Reduction

The net effect of the carbon dioxide removed from the atmosphere by burning biofuels is the same as the net effect of cultivating their feedstocks, making them carbon neutral. Their use in gas turbines significantly reduces emissions of greenhouse gases in comparison to fossil fuels, which is in accordance with global climate goals. Waste-derived biofuels, such as those from municipal solid waste (MSW) or agricultural residues, provide additional environmental benefits by addressing waste disposal challenges and reducing methane emissions from landfills.

2. NOx and Other Pollutants

Despite their carbon neutrality, some biofuels, such as algae-based ones, can increase NOx emissions due to higher nitrogen content. Advanced emission control technologies, including selective catalytic reduction (SCR) and water injection, are essential to mitigate these emissions. However, biofuels produce fewer particulate matter (PM) and sulfur oxides (SOx) compared to fossil fuels, contributing to improved air quality and reducing environmental health impacts.

C. Economic Considerations

1. Cost of Production and Transportation

The price of biofuels is also influenced by feedstock type, scale of production and available processing technologies. Initially generated biofuels, for instance, corn ethanol, are cheaper but are a competitor to foods. Second generation bio fuels for instance the lignocellulosic and algal biofuels are more costly to produce and are not as easily scalable as the first generation bio fuels. Transportation costs are also higher because of lower energy density of biofuels; quantity required to yield the same energy is greater [36].

D. Impact on Levelized Cost of Electricity (LCOE)

Biofuel leads to a higher LCOE because of higher production cost and cost involved in changing the infrastructure. These costs can however be systematically lowered through technical advancements, technological incentives, and experience. From a longer term economic perspective biofuels translate into such positive effects like reduced reliance on foreign oil, support of domestic industries and compliance with goals of the green economy. At start, using biofuels leads to a higher LCOE because the costs of production and infrastructure conversion are higher first. However, through time policy support, enabling technologies, and increased scale of production can bring these cost down[37]. Biofuels are a renewable and achievable type of energy as they stimulate local industry does not increase the demand for importing of fossil fuels, and supports renewable energy strategies.

E. Impact of Combustion Technologies on Power Generation

Biofuels concerning gas turbines studied in the survey of combustion technologies are influential not only in environmental but also in operational aspects. Here are the key impacts discussed below:

1. **Reduction in Greenhouse Gas Emissions:**

The incorporation of biofuels in the gas turbines mean that greenhouse emission is much lower than that of the fossil fuels. This facilitates the reduction of climate change because green energy varies from other energies in a number of ways [38].

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2. **Sustainability and Renewable Energy**:

Biofuels are relatively environmentally friendly, and they can be manufactured from a great many biomass resources. It provides energy security and decreases use of an exhaustible source of energy that is fossil fuel [39].

3. **Improved Efficiency and Flexibility:**

Biofuels can improve the performance of gas turbines with regard to combustion profiles, especially in the new generation DLE turbines. Another advantage of the biofuels is operational since they can be used in both new and current Turbine systems [40].

4. **Reduced Dependency on Fossil Fuels:**

The application of biofuels in gas turbines minimises the use of the familiar conventional gases such as natural gas and oil; this tends to wane dependency on foreign natural resources, hence leading to energy security for the farmland-producing bio-feed stocks [41].

5. **Supporting Clean Power Generation:**

The use of biofuels in gas turbines helps in clean power generation in that levels of particulate matter, NOx and CO in turbines that use biofuels are reduced, making biofuel-powered turbines some of the key technologies in clean power generation [42].

6. **Energy Grid Stability:**

Biofuels therefore when blended with renewables such as wind or solar energy can provide stability to the energy grid. Because biofuels are dispatchable based on the intermittency of renewable resources such as wind, solar, and hydropower, they can be used as a source of backup to these renewable sources [43].

7. **Cost-Effectiveness:**

Even if at times, biofuels are slightly more expensive than fossil fuels, improvements in availing production technologies, investment in economies of scale, along with the rising demands of emissions conformity and higher global concerns for renewable energy could lead the way to increased usage of biofuels.

8. **Innovation and Technological Advancements:**

Advancements and improvements in technologies of biofuels for use in the gas turbine provide opportunities for the improvement of combustion technologies, fuel, and emission. This promulgates improvements in gas turbine efficiency and characteristics crucial in the sustainability quest [44].

V. LITERATURE OF REVIEW

This section presents a review of studies on Biofuels for Gas Turbines with combustion technologies and their Impact on power generation. A summary of the reviewed studies is provided in Table I for a concise overview.

In this study, Vijay Kumar, Veeresh Babu and Ravi Kumar, (2018) article presents the results of a comparative research that aimed to determine the impact of biodiesel fuel additives on combustion performance, emissions, and recovery efforts. There are a number of drawbacks to utilising biodiesel, including its increased density, decreased heating value, increased fuel use, and increased oxides of nitrogen. Fuel additives play a crucial part in reducing biodiesel's negative aspects and keeping it up to par with international fuel regulations, which helps to prevent the problems listed above. Consider adding additives to your fuel mix to boost combustion, save gas mileage, and cut down on pollutants[45].

This study, Alrashidi et al. (2022) evaluate how a micro-GTE that runs on biodiesel fuel made from animal fat may be improved in terms of performance, fuel efficiency, and greenhouse gas emissions by using plasma combustion technology. The Public Authority for Applied Education and Training in Kuwait oversaw the whole laboratory process, from design to manufacture, assembly, testing, and assessment of findings. The results show that the biodiesel mixed fuels had the lowest levels of sulphur, nitrogen oxide (NO), NO2, and CO harmful emissions. The engine's combustion efficiency is enhanced by the increased amount of hydrogen plasma fed into GTE biodiesel, which leads to better thermal efficiency[46].

This study, Kiehbadroudinezhad et al. (2023) found that biofuels might achieve Net Zero Emissions by 2050 Scenario (NZE) targets and capture the lion's share of the world's power-generating sector if the economic and technological hurdles associated with their use are removed. As a result of technological advancements, the globe is now seeing a surge in electricity consumption. There has been an uptick in the worldwide usage of fossil fuels and environmental deterioration due to the fact that the majority of power plants' fuel is derived from these sources[47].

This study, Al-Mamoori et al. (2019) kept in mind that biofuel has been touted as a possible alternative to natural gas for powering gas turbines. The fuel system of the micro-gas turbine is designed and tested in MATLAB Simulink to guarantee the project's dependability and reliability in a complex multi-domain system, such as a gas turbine. This model represents the nominal operating conditions of a gas turbine in both its transient and steady-state forms. There is strong agreement between the results of the simulation and the field data, according to the evaluations. The experimental data is also used to optimise the fuel system in the micro-gas turbine simulation model. Nowadays, gas turbines play a crucial role in maritime propulsion and power generation[48].

In this study, Banihabib and Assadi (2022) summarise the features of tiny gas turbines that support their potential use in future systems for generating heat and electricity. This paper provides a high-level summary of the difficulties associated with enhancing the operational availability, dependability, and flexibility of MGTs while reducing their costs and environmental effect. An AI-based model for a micro gas turbine active monitoring and control system is suggested, with the potential to increase the grid's tolerance for MGT operating dependability[49].

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Presents the comparison table on biofuels for gas turbines with combustion technologies.

Study	Focus	Objectives	Limitations	Challenges	Future Scope
[45]	Effects of additives on biodiesel fuel	Improve combustion, fuel economy, and reduce emissions using biodiesel additives; evaluate the impact of various additive types like metal-based and cetane additives.	Limited to second-generation biodiesel; does not address the impact on advanced generation fuels or hybrid systems.	Ensuring compatibility of additives with diverse biodiesel sources and varying international standards.	Research novel additives with multifunctional properties to further improve emission control and fuel performance.
[46]	Plasma combustion technology in micro-GTEs using biodiesel	Assess the impact of hydrogen plasma injection on performance, fuel consumption, and GHG emissions of biodiesel-powered micro-GTEs.	Requires advanced plasma equipment; insufficient scalability for large industrial systems; limited focus on cost reduction during plasma implementation.	Overcoming high initial costs and adapting plasma technology to varied engine types and conditions.	Develop scalable plasma systems and optimise technology for larger gas turbines and diverse biodiesel blends.
[47]	Impact of biofuels on power generation and microgrids	Evaluate biofuels as alternatives to fossil fuels for microgrids; analyse their potential for carbon neutrality and energy sustainability.	Technical and economic hurdles for biofuel adoption; limited real-world implementation data for diverse microgrid setups.	Overcoming biofuel production costs and addressing efficiency losses in microgrid systems.	Explore hybrid systems combining biofuels with renewable energy to achieve stable, efficient, and cost-effective energy supply.
[48]	Biofuel usage in micro-gas turbines (MGTs)	Simulate and optimise fuel systems in micro-gas turbines using MATLAB; assess biofuels as substitutes for natural gas in power generation.	Focuses mainly on simulation rather than real-world implementation; lacks consideration of diverse biofuel types and hybrid fuel systems.	Bridging the gap between simulation models and real-world deployment with experimental validation.	Conduct large-scale pilot projects to validate MGT performance with biofuels and enhance fuel system efficiency.
[49]	Characteristics and potential of micro-gas turbines (MGTs) for future power systems	Improve MGT operational flexibility, reliability, and low environmental impact; propose AI-based monitoring and control systems for grid integration.	Limited scalability and applicability to larger power systems; lack of integration with hybrid renewable systems.	Developing AI algorithms for adaptive MGT control and ensuring compatibility with hybrid renewable grids.	Create advanced AI-driven MGT monitoring systems for efficient operation in hybrid and decentralised energy markets.

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VI. CONCLUSION AND FUTURE WORK

Biofuels offer a viable path toward sustainable energy generation in gas turbines, reducing dependence on fossil fuels while addressing global environmental challenges. This study highlights the potential of advanced combustion technologies to enhance the efficiency and performance of biofuel-powered turbines, with significant reductions in greenhouse gas emissions and pollutants such as NOx. However, challenges related to fuel variability, combustion stability, and economic feasibility remain, requiring further research and innovation.

Future work should focus on developing cost-effective production methods for advanced biofuels, improving emission control technologies, and designing adaptable gas turbines to accommodate diverse biofuels. Collaborative efforts in research, policy support, and industry adoption will be essential for maximising the potential of biofuels as a cornerstone of sustainable power generation.

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