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Sustainable aviation fuel as a pathway to mitigate global warming in the aviation industry

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Abstract. The extensive utilization of fossil fuels by humanity has led to notable ecological degradation alongside a surge in productivity. The ensuing climate change, a result of global warming, poses a grave threat to human survival. A significant contributor to global warming is the emission of abundant greenhouse gases, with carbon dioxide being the most prevalent. Addressing global warming necessitates the identification and adoption of cleaner, alternative fuels to diminish carbon dioxide emissions. Sustainable Aviation Fuel (SAF) emerges as a prime alternative in this context. Chemically akin to conventional and fossil fuels, SAF originates from cleaner sources, offering a reduction in carbon dioxide emissions upon combustion. This paper highlights the importance of SAF as a viable strategy to mitigate CO_2 emissions resulting from fossil fuel combustion. The paper also examines different SAF synthesis approaches, such as Fischer-Tropsch, Hydrogenated fatty acid esters and fatty acids (HEFA), and Alcohol-to-Jet (ATJ) processes. In summary, challenges such as high production costs, raw material price fluctuations, and the need for supportive policies hinder SAF's widespread adoption. To address climate change and reduce aviation emissions, further research, technological advancements, government incentives, and collaborative efforts within the aviation industry are crucial.

Keywords: Sustainable aviation fuel; Emission Reduction; Alternative Energy Resources

1. Introduction

In recent years, global warming has become a popular subject of research and discussion and has gradually received a high degree of public attention. Global warming refers to the significant increase in global average temperature, which is not only a meteorological activity but also a complex environmental phenomenon involving a wide range of multiple factors. According to John Houghton, the main driver of global warming is the large amount of carbon dioxide emissions, which mainly come from the large-scale burning of fossil fuels and excessive cutting down of trees [1]. Aviation accounts for about 2.5% of global carbon dioxide (CO_2) emissions, which have doubled since the mid-1980s, but its share of total global emissions has remained relatively stable in the range of 2% to 2.5%. However, aviation's impact on climate change is not limited to CO_2 emissions. It affects the atmosphere through a variety of complex mechanisms, and its overall contribution to global warming is about 3.5%, taking into account ozone changes, methane reduction, water vapor, soot, sulfur aerosols, and condensation trails [2]. While CO_2 remains a significant component, two-thirds of the warming comes from non-CO_2 factors, with water condensation being the most important contributor. Finding effective ways to decarbonize air travel is challenging, as current emission reduction solutions for other applications are not readily applicable to aviation. Although innovative concepts such as hydrogen-fueled and electric airplanes are emerging, they are still in the early stages of development, making the transition to low-emission aviation a long way off. Figure 1, which clearly presents CO emissions current trends and expected future growth.

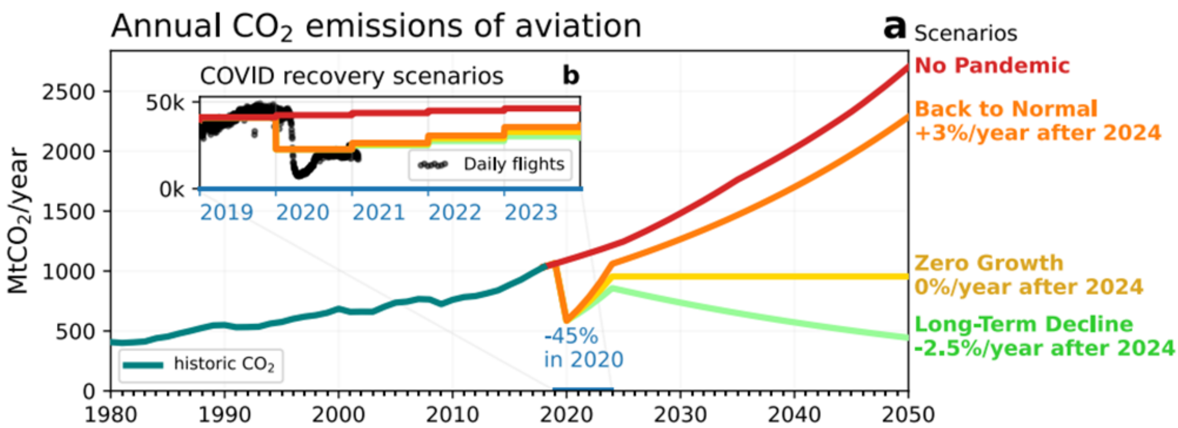

Figure 1. CO_2 emissions of aviation in time domain [3].

As is evident from Figure 1, the red line indicates the growing trend in CO_2 emissions. In 2020, global CO_2 emissions are already approaching 10 million tons per year. Without the impact of major diseases such as COVID-19 on human activities, it is projected that this figure could rise dramatically to 25 million tons per year by 2050, a level that is unsustainable for humans and the Earth's environment. Currently, high levels of carbon dioxide emissions have led to a number of environmental disasters, including melting glaciers, rising sea levels and frequent flooding events. If the uncontrolled burning of fossil fuels continues, its impact on the global environment will be unpredictable and irreversible.

In order to avoid such catastrophic results, mankind must seek greener, sustainable energy solutions, such as Sustainable Aviation Fuel (SAF), to reduce carbon dioxide emissions and curb the process of global warming. SAF is a type of aviation fuel designed to minimize carbon emissions and environmental impacts and is usually converted from renewable resources or waste. SAF is chemically similar to traditional fossil fuels. However, compared to conventional fossil fuels, SAF is very important for environmental protection. SAF is essentially sourced from biological resources, such as various edible oils and plant and animal oils, and can also come from a variety of industrial solid wastes, such as packaging, paper, and even food scraps, which have potential environmental benefits in terms of reducing carbon emissions, lowering the emission of pollutants, and decreasing the dependence on non-renewable resources. This paper focuses on the importance of SAF fuels in mitigating the problem of global warming, with special emphasis on addressing the large amount of carbon dioxide emissions resulting from the combustion of fossil fuels.

2. Raw materials for SAF production

In the pursuit of more sustainable aviation fuels (SAF), it is important to recognize that not all biofuels are suitable for aviation. Biodiesel, for example, cannot meet the performance criteria required for aircraft use, primarily because of its lower energy density and higher freezing point compared to conventional jet-A fuels. In contrast, some bioalcohols, such as bioethanol, have shown the potential to reduce diesel emissions, particularly during the start-up and warm-up phases. Feedstocks suitable for SAF production fall into four categories: oil, sugar, starch and lignocellulosic feedstocks. These categories require different pretreatment methods and are compatible with various conversion processes.

First, oil and grease feedstocks, including used frying oil, animal and vegetable fats, and waste cooking oils, can be converted to SAF through chemical treatments such as esterification and hydrogenation, which not only helps to reduce waste disposal and carbon emissions but also reduces dependence on fossil fuels. Secondly, energy crops such as sugarcane and sugar beet are also important sources of feedstock for SAF. These crops can be converted into bioethanol or biodiesel through fermentation and chemical processing, among other things, thus providing a more environmentally friendly fuel option for the aviation industry. For example, Brazil and some European countries have successfully utilized these crops to produce biofuels for use in reducing carbon emissions from the aviation industry. Meanwhile, wood fiber and waste are also important sources of feedstock for SAF. These materials can be converted to biodiesel or bio-jet fuel through biomass conversion technologies, such as gasification or liquefaction, to provide a greener fuel option for the aviation industry. Some countries have already made significant progress in this area. Finally, microalgae and other microorganisms are also one of the key feedstock sources for SAF. These microorganisms can convert organic materials into SAF through biotransformation processes, such as fat esterification and fermentation. These methods not only help reduce carbon emissions but also promote the production and application of greener SAFs.

In exploring sustainable aviation fuel (SAF), research has identified several promising feedstocks, each with unique properties and potential benefits. Linum usitatissimum, a second-generation biofuel, is a non-edible crop with a high oil content that offers a viable pathway for fuel production and rotational agriculture. Jatropha curcas, which is able to grow on degraded land, offers another option despite challenges in seed yield and oil extraction processes. Saline plants are able to adapt to harsh environments, and their potential for oil and lignocellulose production is being explored, with promising trials already underway at Etihad Airways. Algae-based fuels, known for their rapid growth and carbon sequestration capacity, are emerging as a promising third-generation biofuel that is particularly well suited to growing on marginal lands. In addition, researchers are exploring SAF production from waste products, including used cooking oil and municipal solid waste, demonstrating the potential to reduce emissions and enhance sustainability and even holding promise for converting plastic waste into energy. Together, these feedstocks represent a cutting-edge effort to develop greener, more efficient alternatives to traditional aviation fuels [4]. In the pursuit of more sustainable aviation fuels (SAF), it is important to recognize that not all biofuels are suitable for aviation. For example, biodiesel is unable to meet the performance criteria required for aircraft use, primarily due to its lower energy density and higher freezing point compared to conventional jet-A fuels. In contrast, some bioalcohols, such as bioethanol, have shown the potential to reduce diesel emissions, particularly during the start-up and warm-up phases. Feedstocks suitable for SAF production fall into four categories: oil, sugar, starch and lignocellulosic feedstocks. These categories require different pretreatment methods and are compatible with various conversion processes.

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3. Synthesis Approaches of SAF

There are currently five internationally approved routes to produce fuel for blending with fossil jet fuel.

They are: 1. Fischer-Tropsch synthetic isoparaffinic kerosene (FT-SPK), 2. Hydrogenated fatty acid esters and fatty acids (HEFA), 3. Synthetic isoparaffinic chain (SIP), 4. Fischer-Tropsch synthetic kerosene with aromatic hydrocarbons (FT-SPK/A), and 5. Alcohol-tojet (ATJ). Currently, only the HEFA and FT-SPK approaches have been matured and commercialized. It is expected that HEFA-SPK will be the main biofuel for aviation in the short-term future. HEFA is a process for the hydrotreating of triglycerides and wastewater from vegetable oils, waste food and beverage fats and animal fats and oils. There are four main processes: 1.) Hydrotreating the source material by means of a catalyst. 2.) After treatment, the non-adsorbed medium and triglycerides are converted to soil medium. The triglycerides in the feedstock are removed by the β-hydrogen removal reaction to produce the culture medium. 3.) The soil medium is converted to C15 -C18 straight-chain alkanes by hydrodeoxygenation and deacetylation using zeolite or oxide-loaded precious metal catalysts. However, due to the catalyst, it is easy to be poisoned and deactivated, causing the generation of azo products and other problems, which leads to the high cost of hydrogenation. Later, transition metals such as Ni, Mo and co-unloaded bimetallic catalysts were gradually used. 4.) Pt-loaded Al_2O_3, zeolite molecular sieves, etc., are used as catalysts for cracking and coupling reactions to further selective hydrocracking and deepening of deoxygenated straight-chain alkanes to highly branched alkanes. 5.) Separation of blended liquid fuels into light gases, naphtha, and bio-aviation coals through the process of fractional distillation. The main product produced by HEFA is biodiesel, and the jet fuel accounts for about 15% of the total product. To increase the share of bio-jet fuel, it is necessary to change the temperature of fractional distillation or further cracking. The jet fuel produced by HEFA has the advantages of high thermal stability, good cold fluidity, high cetane number and low exhaust emissions, but the low aromatic content tends to lead to low lubrication of fuel and fuel emission problems. [5] In addition to HEFA, Alcohol to jet fuel (ATJ) is also a good way to prepare SAF fuel. The technical approach of ATJ has two main processes: the first is the production of alcohol, and the second is the conversion of alcohol. In industry, we often use fermentation of sugars to prepare alcohols, and the sugars that can be used include (cellulose, polysaccharides, etc.). There are many complex steps involved in this process. The second process is the catalysis of alcohols. Alcohols are changed into long-chain hydrocarbons through a catalytic process. The process is usually divided into four steps: the alcohols are removed to produce a catalyst and then catalyzed by the catalyst to oligomerize into middle distillates, which are then hydrotreated. Finally, the jet fuel is distilled. Zeolites are often chosen as the catalyst for this step in the oligomerization process, but the volatile activity of zeolites is often difficult to resolve. Fischer-Tropsch synthesis, on the other hand, produces hydrocarbon fuels from syngas. Syngas can be produced from coal, natural gas, biomass, and municipal solid waste. Of these, biomass and municipal solid waste are more environmentally friendly feedstocks. The process of Fischer-Tropsch synthesis to make bioaviation coal can be divided into six steps: collection of feedstock, biomass gasification, gas conditioning, acid gas removal, FT

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synthesis, and synthetic crude oil refining. However, Fischer-Tropsch synthesis requires extremely high-quality syngas, and the harsh experimental conditions are often not a reliable method for preparing SAF fuel. There are basically two major processes involved in the preparation of SAF fuel, regardless of which process is used. The first is deoxygenation, which removes a large amount of oxygen from the organic matter. The second is reforming to catalyze and hydrogenate the feedstock. Finally, the SAF fuel is fractionated and purified. However, due to the limitations of catalysts and the harshness of fuel preparation experiments, it is often difficult to produce SAF fuels, with low production efficiency and high preparation costs. Raw materials are also a major problem in the preparation of SAF fuels, and the price of raw materials for the HEFA process varies in different seasons and at different times of the year, which greatly affects the price of SAF fuels. Therefore, the preparation technology of SAF fuel is still far from being able to produce large quantities to meet the demand for people's use.

4. Economical and Environmental Impact Analysis of SAF

Sustainable Aviation Fuel (SAF) is a cleaner and more readily available alternative to traditional fossil fuels and is derived from biomaterials such as vegetable oils, animal oils, industrial waste oils, paper, and everyday food scraps. As shown in Figure 2, SAF comes from three main sources: used oil, household waste and industrial waste. These materials are collected and processed into aviation liquid fuels, which are then blended with conventional fossil fuels for use in aircraft. This method not only facilitates the recycling of waste materials that would otherwise be buried in the ground, but it also provides a more sustainable solution than fossil fuels, which take thousands of years to naturally occur.

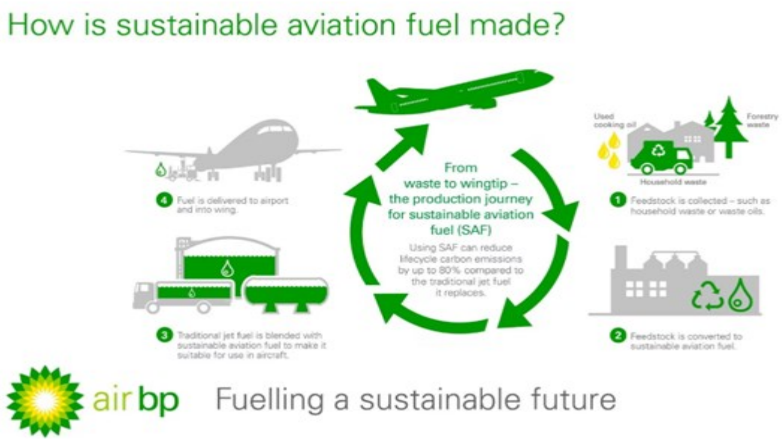

Figure 2. Fabrication Process of SAF [6].

In addition, as shown in Figure 3, SAFs offer the advantage of greater ease of use, especially in the context of global warming mitigation efforts that require reductions in CO_2 emissions. Addressing this issue from the perspective of aircraft engine efficiency, it is clear that increasing the energy output per unit of fossil fuel may require significant changes to the structure and shape of the engine, which can be costly. However, SAFs, due to their similar chemical properties to conventional fossil fuels, are a better option and can be seamlessly integrated without any structural modifications to aircraft engines, thus saving significant costs for engine redesign and retrofitting.

Figure 3. Turbofan jet engine [7].

In terms of economic cost analysis, as shown in Figure 4, the life cycle of SAFs suggests an important role in closing the CO_2 cycle. Emissions from the combustion process are reabsorbed by the bioresources used in SAF production, thus preventing the release of additional CO_2 into the atmosphere and reducing environmental stress. This cycle demonstrates SAF's potential to contribute to a greener, more sustainable aviation industry, emphasizing its role as a cost-effective and environmentally responsible alternative to traditional fossil fuels.

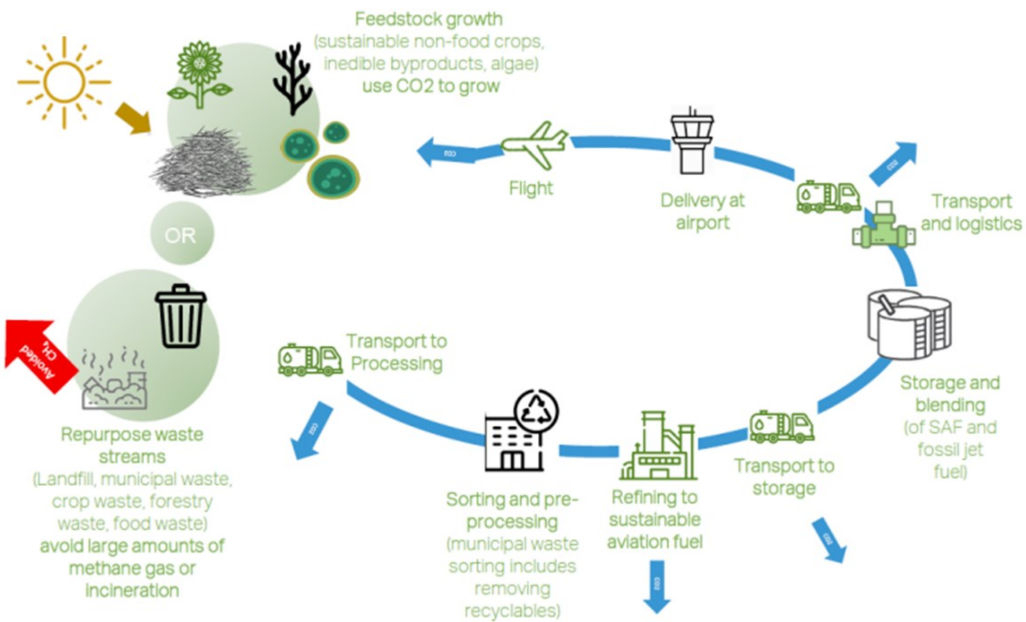

Figure 4. The life cycle of SAF [8].

At the same time, as can be seen in Figure 4, the combustion of aircraft fuel emits a large amount of carbon dioxide. However, this carbon dioxide can be fixed again in biological resources through photosynthesis in plants. However, the source of SAF is mainly biological, which means that if SAF is used as an airplane fuel, then the cycle of carbon dioxide input and output is closed, which makes sense for the environment. This means that when SAF is used as a fuel, there is no excess carbon dioxide being released into the air. This will reduce the pressure on the environment. Biomass is a unique carbon-containing renewable energy source. It produces organic matter and recycles carbon dioxide. And is

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widely distributed and produced [9]. The large amount of biological resources is a good helper for us to recover carbon dioxide. At the same time, they are one of the main sources of SAF feedstock. The cost of SAF fuel preparation is still high, and the construction of a large HEFA-SPK refinery capable of supplying one-thousandth of the annual fuel demand of international aviation would require an investment of about $500 million with current technology. Aviation fuel prices are typically in the range of $1.50 to $3.00 per gallon through 2019, but this depends on geographic location and crude oil prices. In 2020, both oil prices and aviation fuel prices have fallen significantly due to the impact of the COVID-19 pandemic. By the end of 2021, jet fuel prices will begin to recover as the economy recovers and aviation demand gradually picks up. The price of SAF, however, is affected by a number of factors, including the scale of production, raw material costs, technological advances, and government incentives. The price of SAF is typically higher than that of conventional jet fuel. SAF is essentially more than twice the cost of conventional jet fuel. Raw material cost accounts for 80% of the total cost of HEFA jet fuel [10]. Since the price of raw materials varies quite a lot, even for the same raw material, the price varies a lot from season to season and from location to location, which leads to a great fluctuation in the price of HEFA jet fuel. The price of ATJ jet fuel is determined by the production process of the alcohols, and the different alcohol production processes and raw materials used to produce the alcohols have a great impact on the price of ATJ. Therefore, due to high raw material prices and immature production processes, SAF fuels are often more expensive than conventional fuels.

5. Prospects and Future Developments of SAF

The problem of climate change is more serious due to the extreme greenhouse gas emissions and high human dependence on fossil fuels. Nowadays, there is a growing concern that the global average temperature is likely to rise by 4 °C or more than the pre-industrial level if emissions are not reduced [11]. Humans are beginning to look for alternative renewable energy sources to replace traditional fossil fuels such as SAF, even though SAF fuels have this great significance for combating global warming. However, due to the limitations of technology and policy at this stage, the development of SAF fuel does not meet the expected requirements. Most airlines have already formulated their own SAF development plans. For example, in 2023, Airbus has set a target to develop SAF fuel. They want to make SAF fuel ten percent of all their fuel. It is also proposed to replace all conventional fuels with SAF fuels by 2050. The airlines seem confident that SAF can be used to solve the problem of global warming caused by fossil fuels. However, it seems that the pace of research and development by the companies involved is not commensurate with the seriousness of the current climate change problem. SAF has great environmental advantages, but the current production cost of SAF is not economically competitive with that of conventional fuels. If the relevant laboratories can shorten the preparation process of SAF fuel, make it less difficult to make, and find low-cost, durable, chemical catalysts to solve the problem of deoxygenation of organic matter. If the laboratories can shorten the preparation process of SAF fuel and reduce the difficulty of production, find a low-cost and durable chemical catalyst to solve the problem of deoxygenation of organic matter, and have a stable source of high-quality organic material, the production cost of SAF fuel can be greatly reduced, and it can have a competitive advantage. In addition to this, the popularity of SAF is quite worrying. Only five international airports (Brisbane, Australia; Los Angeles, USA; Bergen, Norway; Oslo, Norway; Stockholm, Sweden) provide biofuels on a continuous basis, while the rest of the airports provide them occasionally. Many airlines have entered into offtake agreements with biofuel producers, some of which have invested directly in aviation biofuel refining programs. Nonetheless, the production of aviation biofuels in 2018 was less than one-thousandth of the total amount of aviation fuel consumed. For the aviation industry, a number of organizational activities, government incentives, and effective legislation are necessary to encourage the widespread adoption of SAFE in the aviation industry. In order for biofuels to compete with fossil fuels, incentives also need to be used to facilitate the SAF production process, to examine supply chain requirements, and to reduce the uncertainties and risks associated with initiating commercial-scale biorefinery projects [11]. In the current context, there is a great potential and urgent need to reduce CO2 emissions from the aviation industry by replacing conventional fossil fuels with SAF fuels.

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6. Conclusion

As science and technology continue to advance, the burning of fossil fuels emits large amounts of carbon dioxide, posing a serious climate challenge to human survival. If human beings control the use of fossil fuels, natural disasters such as tsunamis can be caused. Therefore, it makes sense to replace conventional fossil fuels with SAF, which is cleaner than conventional fuels. SAF is cleaner than conventional fuels and can also be used to recycle waste and fix carbon dioxide in the biosphere. SAF is chemically very similar to conventional fuels, and because it can almost completely replace conventional fossil fuels, it can be used in all existing airplanes, which saves a lot of money in the development of aircraft engines. Of course, the use of SAF has great limitations due to the immaturity of the existing preparation process, the mismatch of the current policy system and other issues. The cost of SAF fuel is extremely expensive. However, in the near future, through government encouragement and laboratory research and development to fill the policy loopholes and process deficiencies after the use of renewable bioresources to produce aviation fuel to reduce the aviation industry's dependence on fossil fuels, to achieve the goal of zero carbon emissions is a promising way.

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