Journal of Turkish

Operations Management

Assessment of sustainable aviation fuel production methods using a hybridized decision-making framework

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Article Info

Article History

Received: 19.12.2023
Revised: 04.03.2024
Accepted: 31.03.2024

Keywords

Aviation
Green fuel
Sustainable Aviation Fuel
PROMETHEE II
Bio Fuels

Abstract

Sustainable aviation fuels (SAF) present a feasible solution to decarbonize modern aviation. Unlike traditional jet fuels, SAFs are produced in a variety of ways, thereby choosing one of these processes is a complicated Multi-Criteria Decision Making (MCDM) challenge that involves conflicting priorities. This study evaluates SAF production processes using a multicriteria methodology, PROMETHEE II. With SAF technology in its nascent stage and limited data, several stakeholders in the aviation sector were enlisted to assist in the collection of data and preferences. The suggested framework's strength lies in its adaptability to suit the subjective opinions of diverse stakeholders, selection of a ranking system, and robustness of outcomes. This research engaged stakeholders in a participatory manner to rank 11 (A1 to A11) SAF production paths based on 24 parameters categorized into social, environmental, economic, and technological evaluation criteria. Industry professionals were given a form to rate SAF production methods according to a performance criterion. Data is validated using fuzzy TOPSIS, fuzzy VIKOR, and PROMETHEE II to reduce professionals' judgmental personal prejudice. Results indicate the optimal feedstock for SAF production is the direct transition process of CO2 to SAF (A11) in the gasification or Fischer-T synthesis group.

1. Introduction

The air transportation sector has grown exponentially in recent years, contributing to substantial economic benefits and increased employment worldwide (IATA, 2019). However, this boon also brings about ecological concerns, primarily due to greenhouse gas emissions (GHG), of which carbon dioxide (CO_2) holds significant responsibility, accounting for approximately 53% of the overall greenhouse gas effect. Even though the airline industry is responsible for just 2%-2.6% of annual global CO_2 emissions, the ramifications of these emissions disproportionately impact the environment (ICAO, 2016; Kivits et al., 2010).

The International Air Transport Association (IATA) foresees that by 2035, global passenger counts will grow substantially. As a result, by 2050, the airline sector may contribute between 4.6% and 20.2% to global fossil fuel CO_2 emissions (O'Connell et al., 2019). Decarbonizing the aviation industry hinges on technological innovations and operational advancements. Potential solutions include refined aviation designs, propulsion systems, and considering the potential of electrifying long-haul planes. However, electric planes might not be commercially viable until around 2050 (Schäfer et al., 2018).

Two of the most important methods for cutting emissions are the use of Sustainable Aviation Fuels (SAF) and planned optimal flight itineraries (Bann et al., 2017). SAF is seen as a calculated method of cutting emissions and decreasing dependency on fossil resources. These fuels play a pivotal role in emission control and reducing dependency on fossil fuels (The Royal Society, 2019). Given the lack of technical preparedness in alternative options, liquid fuels will remain to serve a central role in flight operations. Therefore, the utilization of SAF is viewed as a moderate strategic plan for controlling emissions and lowering reliance on fossil fuels. Thus far, the production of SAF poses significant challenges; ranging from technological hindrances, public perceptions, technological unpredictability, societal attitudes, ecological consequences, financial considerations and environmental implications of production and distribution, to economic barriers (Bann et al., 2017; Wang et al., 2019). Despite the crucial role of SAF in the future of aviation, current literature indicates a lack of research focusing on SAF production techniques (Dožić, 2019). Addressing this gap, the present study introduces a participative model based on a multi-criteria decision framework.

Purpose of the Study

The research aims to delve into the multifaceted realm of sustainable aviation fuel (SAF) production and its implications within the aviation industry. By drawing insights from various feedstock options, production methodologies, economic feasibilities, and environmental impacts of SAF, the study seeks to offer a comprehensive understanding of the potential adoption of biofuels in aviation (Hileman & Stratton, 2014; Lokesh et al., 2015; Wang et al., 2019). Through an exploration of the hydrocarbon composition, thermodynamic properties, and combustion effects of different SAF types in comparison to traditional aviation fuel sources like camelina, jatropha, and microalgae-derived fuels, the research endeavours to shed light on the viability and performance characteristics of biofuels (Moore et al., 2017).

Furthermore, the investigation may encompass an analysis of stakeholder attitudes towards biofuels, an assessment of the socioeconomic ramifications of aviation biofuel production, an evaluation of life cycle greenhouse gas emissions, and an exploration of the feasibility and profitability of diverse biofuel supply chains (Bann et al., 2017; Zemanek et al., 2020). By synthesizing findings from a spectrum of studies on biofuels, feedstocks, production techniques, and stakeholder perceptions, the research aspires to address pivotal challenges in transitioning towards sustainable aviation practices, encompassing technological advancements, policy implications, economic considerations, and environmental sustainability (Kolosz et al., 2020; Zhang, Fang, et al., 2020). Ultimately, the study aims to contribute valuable insights to propel the utilization of bio-aviation fuels and advocate for a more sustainable trajectory for the aviation sector (Chiaramonti, 2019).

By combining a literature review with industry insights, a framework has been developed to prioritize sustainable aviation fuel production paths based on social, environmental, economic, and technological criteria (Shahabuddin et al., 2020). The study aims to bridge the gap in research by offering a comprehensive assessment approach for sustainable aviation fuel production methods, utilizing a multi-criteria decision framework to inform decision-making in the industry (Gegg & Wells, 2017). This model incorporates insights from aviation industry experts regarding low-carbon aviation fuel production. Moreover, expert opinions were harnessed to ascertain each criterion's relative importance and rank alternative SAF production methods. Employing this data, the study simulated professional preferences to prioritize SAF production pathways. Notably, the research also juxtaposed the multi-criteria ranking results using various Multi-Criteria Decision Making (MCDM) techniques.

The remaining of this study is organized as follows. Section 2 provides a literature review on SAF while Section 3 briefly addresses different production methods. Next, the research methodology is introduced in Section 4. Section 5 presents the main findings of the research and provides an analysis of the results. Finally, Section 6 culminates with conclusive remarks.

2. Literature review

The literature review is structured according to research examining societal, environmental, economic, and technological aspects. Chiaramonti, (2019) underlined the challenges and prospects for sustainable fuel adoption while. Kivits et al., (2010) studied the significance of airports in aiding cleaner aviation. Wang et al., (2019) examined the production impacts of airline fuels in a Brazilian economic system and found favorable socioeconomic outcomes for employment and Gross domestic product on balance. O'Connell et al., (2019) prioritized energy efficiency and reduced greenhouse gas (GHG) emissions as the two important factors and found that some Sustainable aviation fuel conversion methods are more energy-intensive than others, excluding those that utilize trash and leftovers as feedstock.

Moreover, Staples et al., (2018) examined emission reductions resulting from the manufacture of SAF using non-food feedstocks via several conversion methods across their whole life cycle. It revealed that annual investments of approx. 12B USD will be required to reduce it by at least 50% by 2050. Besides, Ganguly et al., (2018) performed a Life Cycle Assessment (LCA) on a wood-related feedstock for SAF manufacturing. It was discovered that this type of SAF can reduce global warming by 78% as compared to traditional aviation fuel. Seber et al., (2014) utilized LCA to determine the GHG discharge reductions and manufacturing expenses related to Hydro-processed Esters and Fatty Acids (HEFA). It was discovered that LCA of green fuel derived from yellow grease created fewer GHG emissions than sustainable aviation fuel derived from tallow when compared with aviation fuel derived from petroleum.

Furthermore, Bann et al., (2017) used a financial technique to determine the most suited SAF production process from an economic standpoint. They employed stochastic modelling focused on a net current value computation for six alternative approaches to defining the minimal selling price of sustainable aviation fuels. In addition, it was found that SAF produced using vegetable oil-based feedstocks is more comparable in price to standard aviation fuel than SAF derived from non-food feedstocks. Trivedi et al., (2015) found that the gasification or FT production method is more financially feasible when compared to the hybrid method by focusing on energy investment return analysis intended for Fischer-Tropsch, hydro-processed ester, and fatty acids, & improved fermentation procedures utilizing various feedstock.

Neuling & Kaltschmitt, (2018) found that the FT procedure with switchgrass yielded the highest energy ROI at 9.8% through a techno-economic assessment, including environmental factors for SAF production paths, concluding that such operations use the mass and energy balance method. Achieving technological, economic, and environmental objectives concurrently for a single method is not possible. Li et al., (2018) found that the production parameters analyzed, the minimum selling price (MSP) of sustainable aviation fuel ranged from \$0.40 to \$0.17 per liter, with feedstock expenditure being the most sensitive factor. Michailos, (2018) also conducted a thorough production design and cost evaluation of sustainable aviation fuel from sugar cane residual (bagasse). It was discovered that one kilogram of dry bagasse may create 0.121 kilograms of sustainable aviation fuel at a rate of \$2.78 per liter.

Furthermore, Lokesh et al., (2015) explored the effects of sustainable aviation fuel hydrocarbon composition, thermodynamic characteristics, & fuel combustion on airplane performances studied three alternative SAFs and compared them to standard aviation fuel, including camelina, jatropha, as well as microalgae. Hileman & Stratton, (2014) focused on many criteria to evaluate the viability of various sources of fuels for the airline industry and showed that the fuels obtained from the Fischer Tropsh & HEFA procedures were shown to be practical for supplementing the existing aviation fuel supplies. However, hydrogen is deemed impracticable because of airplanes' existing engine technology. None of the studies employs the multi-criteria decision-making conceptual approach, which is gradually being introduced into the Life cycle assessment or techno-economic assessment toolbox as a definitive endpoint approach, notwithstanding the issue reasoning reflecting a multi-criteria dilemma.

This research intends to address this disparity by presenting an investors' participative Multi criteria decision structure that addresses the opinions of airline-experienced professionals on lower-carbon aviation energy production approaches.

Importance and Contribution of the Study

In the academic literature on sustainable aviation fuel (SAF) production and its effects on the aviation sector, the current research study is highly significant. Through the integration of perspectives from many feedstock alternatives, manufacturing techniques, financial viability, and ecological consequences of SAF, the research advances a comprehensive comprehension of the possible integration of biofuels in aviation. In contrast to conventional aviation fuel, the study explores the hydrocarbon composition, thermodynamic characteristics, and combustion impacts of several SAF types, including camelina, jatropha, and microalgae-derived fuels. In addition, the study might examine how stakeholders feel about biofuels, evaluate the socioeconomic effects of aviation biofuel production, analyze greenhouse gas emissions from the fuel's life cycle, and look at the viability and economics of various biofuel supply chains.

The research provides valuable insights to advance the use of bio-aviation fuels and promote a more sustainable future for the aviation industry by addressing key challenges in the shift towards sustainable aviation practices, such as technological advancements, policy implications, economic considerations, and environmental sustainability. The study stands out as a significant contribution to the literature because of its thorough methodology and in-depth examination of numerous aspects connected to SAF manufacturing and adoption. By filling in knowledge gaps and laying the groundwork for future study in the area, it presents a comprehensive picture of the challenges and opportunities present in the field of sustainable aviation fuel. The investigation of stakeholder perceptions, economic viability, and environmental implications by the research adds richness to the corpus of literature already available on aviation biofuels.

The study adds to the continuing conversation on sustainable energy sources in the aviation industry by illuminating the difficulties and possible solutions in making the switch to sustainable aviation practices. All things considered, the research study makes a substantial contribution to the literature by providing information that can guide industrial practices, technological developments, and regulatory choices regarding the use of bio-aviation fuels. Table 1 presents the summaries of some important articles related to aviation fuel.

Table 1. Summary of Articles Related to Sustainable Aviation Fuel

Author	Contribution to the Sustainable Aviation Fuel Literature
Chiaramonti (2019)	Underlined the challenges and prospects for sustainable fuel adoption.
Kivits et al. (2010)	Studied the significance of airports in aiding cleaner aviation
Wang et al. (2019)	Examined the production impacts of airline fuels in a Brazilian economic system and found favourable socioeconomic outcomes for employment and Gross domestic product on balance.
O'Connell et al. (2019)	Prioritized energy efficiency and reduced greenhouse gas (GHG) emissions as the two important factors and found that some sustainable aviation fuel conversion methods are more energy intensive than others, excluding those that utilize trash and leftovers as feedstock.
Staples et al. (2018)	Examined emission reductions resulting from the manufacture of SAF using non-food feedstocks via several conversion methods across their whole life cycle. It revealed that annual investments of 12B USD will be required to reduce emissions by at least 50% by 2050.
Ganguly et al. (2018)	Performed a Life Cycle Assessment on a wood-related feedstock for SAF manufacturing. It was discovered that this type of SAF can reduce global warming by 78% as compared to traditional aviation fuel.
Seber et al. (2014)	Utilized LCA to determine the GHG discharge reductions and manufacturing expenses related to HEFA. It was discovered that LCA of green fuel derived from yellow grease created fewer GHG emissions than sustainable aviation fuel derived from tallow when compared with aviation fuel derived from petroleum.
Bann et al. (2017)	Used a financial technique to determine the most suited SAF production process from an economic standpoint. They employed a stochastic model focused on a net current value computation for six alternative approaches to defining the minimal selling price of sustainable aviation fuels.
Trivedi et al. (2015)	Found that the gasification or FT production method is more financially feasible when compared to the hybrid method by focusing on energy investment return analysis intended for Fischer Tropsch, Hydro processed ester, and fatty acids, & improved fermentation procedures utilizing various feedstock.
Neuling & Kaltschmitt (2018)	Found that the FT procedure with switchgrass yielded the highest energy ROI at 9.8% through a techno-economic assessment, including environmental factors for SAF production paths, concluding that such operations use the mass and

.	energy balance method. Achieving technological, economic, and environmental objectives concurrently for a single method is not possible.
Li et al. (2018)	Discover that the production parameters analysed, the MSP of sustainable aviation fuel ranged from \$0.40 to \$0.17 per Liter, with feedstock expenditure being the most sensitive factor.
Michailos (2018)	Conducted a thorough production design and cost evaluation of sustainable aviation fuel from sugar cane residual (bagasse). It was discovered that one kilogram of dry bagasse may create 0.121 kilograms of sustainable aviation fuel at a rate of \$2.78 per Liter
Lokesh et al. (2015)	Explored the effects of sustainable aviation fuel hydrocarbon composition, thermodynamic characteristics, & fuel combust on airplane performances studied three alternative SAFs and compared them to standard aviation fuel, including camelina, jatropha, as well as microalgae.
Hileman & Stratton (2014)	Focused on many criteria to evaluate the viability of various sources of fuels for the airline industry and showed that the fuels obtained from the Fischer Tropsh & HEFA procedures were shown to be practical for supplementing the existing aviation fuel supplies. However, hydrogen is deemed impracticable because of airplanes' existing engine technology.

2.1. Sustainable aviation fuel production pathways

2.1.1. Aviation Industry at Present

The aviation industry plays a significant role in contributing to global warming, accounting for approximately 3.5% of global warming when considering non-CO_2 emissions and around 2.5% of global CO_2 emissions in 2018 (Ritchie, 2020). Despite its environmental impact, aviation is perceived as a challenging sector to decarbonize both technologically and economically. In 2019, emissions from jet fuel combustion reached 1027 Metric tons of CO_2, constituting 12% of the CO_2 emissions from the overall transportation industry (Atag.org, 2022; IEA, 2022).

"The UN Climate Change Conference" set a target to limit the average global temperature rise to below 2˚C above pre-industrial levels, with an aspiration for 1.5˚C (United Nations., 2015). Governments worldwide have been making efforts to develop strategies to achieve these goals, but many existing initiatives have fallen short. The transportation sector, including aviation, lags behind other industries in its decarbonization efforts, and the European Union has pointed out that it is not on track to meet its climate goals. Criticism has been directed at the aviation sector's short-term carbon reduction plans as insufficient in the face of the current climate crisis (Reuters., 2021).

ICAO (International Civil Aviation Organization) member nations endorsed the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) in 2016, a market-based framework aimed at achieving net-zero growth in global aviation emissions from 2020 onwards. However, most of these plans and initiatives were based on assumptions of significant corporate air traffic growth and did not account for the sudden disruption caused by the COVID-19 pandemic, resulting in a historic decline in global aviation passengers (International Civil Aviation Organization, 2021). While aviation traffic has partially rebounded in 2021, it remains lower than pre-pandemic levels.

The pandemic's impact on aviation is considered temporary, and long-term projections suggest that passenger traffic in 2050 may still be 8% lower than pre-pandemic estimates. Despite this, the need for mitigation strategies remains, and some existing carbon reduction strategies have had to adapt to the changing circumstances (International Civil Aviation Organization., 2022). Various strategies can reduce the aviation sector's greenhouse gas (GHG) emissions, but their effectiveness varies. Optimizing flight routes for minimal emissions, improving maintenance schedules and other operational initiatives, and developing new weight management resources and related technologies are all important contributors to emissions reduction. However, these efforts alone are insufficient given the growing aviation traffic and emissions (Timperley, 2021).

While the current generation of aircraft is more energy-efficient than previous generations, the rate of improvement is slowing, and it is unlikely to keep up with the expected growth in aviation traffic (International

Civil Aviation Organization., 2019). Additionally, emissions during the takeoff and climb phases, as well as ignition and warm-up emissions, are significant. Some argue for halting aviation industry expansion, but this is impractical given industry competition. To achieve meaningful emissions reductions, commercial aviation must reduce its reliance on fossil fuels (Alkema, B., 2022; Fortier et al., 2014).

Hydrogen-powered and battery-powered aircraft are potential alternatives for the future, but they require substantial changes to aircraft design and face delays in new deliveries and high short-term costs (Scheelhaase et al., 2019). For short and medium-range flights, "drop-in" SAF offer a viable alternative to traditional jet kerosene. Various pathways to produce SAF have been licensed for commercial use, with bioactive feedstocks being the most common. However, sustainability remains a challenge for larger-scale operations, and power-to-liquid options may be a more suitable solution, albeit at higher costs (aviationbenefits.org, 2022).

2.1.2. Green Fuels Used in the Aviation Industry

SAF refer to drop-in kerosene alternatives made from various feedstocks. The ICAO defines SAF as alternative fuels that meet specific sustainability criteria (ICAO, 2022). Although SAF research initially focused on economic and supply concerns, it has gained momentum due to environmental factors. By 2019, over 45 airlines had flown more than a quarter million SAF flights, albeit representing less than 0.1% of total jet fuel usage (IEA, 2022). One challenge for SAF adoption is the existing restrictions on blending ratios. SAF can significantly reduce CO_2 emissions and other pollutants, but blending ratios are typically limited to 5-50%, depending on the production process. Early SAF formulations did not meet the aromatic component requirements, but recent advancements in SAF transfer techniques and O-ring technology may lead to regulatory changes. United Airlines successfully operated an aircraft with 100% SAF in 2021 (Palmer, 2021).

2.1.3. Certification Procedure for Sustainable Aviation Fuels

SAF must meet the same characteristics as conventional jet fuel, ensuring that it is "drop-in ready." The global standard for classifying kerosene fuel in commercial aviation is the American Society for Testing and Materials (ASTM) D1655, which applies to both Jet A and A-1 fuels. Jet A-1 is preferred for long-distance flights using arctic routes due to its low freezing point, but it comes at a higher production cost (Chevron Products Company, 2004). ASTM D45054 established a three-stage, four-tiered testing method, which is a mandatory procedure for qualifying and certification of new airline turbine fuels and extracts, which is required for a novel aircraft fuel to be licensed for business use.

In summary, the aviation industry faces significant challenges in reducing its greenhouse gas emissions, and various strategies are being explored. SAF represent a promising option, but there are obstacles to their widespread adoption, including blending restrictions. Certification processes like ASTM D4054 are essential to ensure the quality and safety of SAF for aviation use.

2.1.4. Biofuels Utilized in the Aviation Sector

SAF must meet stringent criteria and undergo certification processes before they can be used in commercial aviation. ASTM D4054 outlines a comprehensive testing procedure that requires various fuel quantities at each level. This process, lasting 3 to 5 years, imposes a minimum cost of $5 million on prospective fuel manufacturers (Heyne et al., 2021).

To accelerate research and development, ASTM introduced a fast-track annex for D4054 in January 2020, although SAFs certified through this method are limited to a blending ratio of 10% (US Dept. Of Energy, 2020).

2.1.5. Renewable Feedstocks for Biofuels

Biofuels can be produced from renewable feedstocks, which are carbon-based materials capable of renewal. The production of biofuels from plants involves processes that reduce carbon life-cycle emissions, as some of the CO_2 released during production is absorbed by the next crop generation. A comparison of carbon life-cycle emissions between fossil-based aviation fuel and bio SAF is shown in Figure 1. Some frequent feedstocks used for biofuels are listed below.

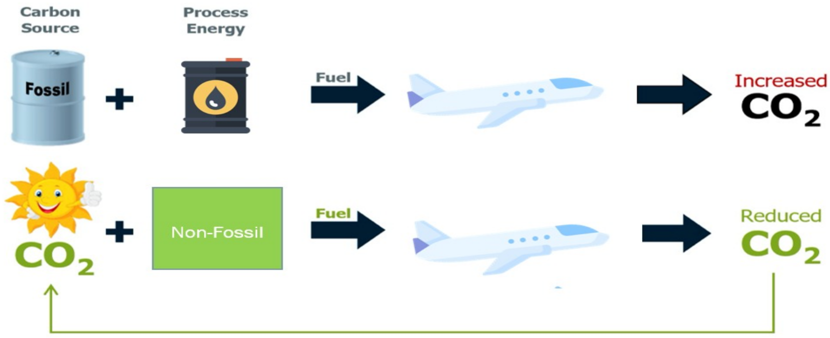

Figure 1. LCA of carbon for fossil aviation fuels (b) sustainable biofuels (VDOCUMENT, 2017)

Camelina: Camelina sativa is a non-edible fuel crop with a high fatty oil content, making it a valuable raw material for biofuel production. The byproduct of oil extraction can also be used as supplemental feed for livestock. Camelina is employed as a cover crop, contributing to soil quality improvement and reducing erosion (World Economic Forum., 2020).

Jatropha: Jatropha Curcas is another potential source of lipid oil for biofuel production. It can thrive in marginal or unproductive environments, making it a promising candidate for biofuel production. However, challenges such as low seed production, vulnerability to diseases, and extraction complexity need to be addressed (Moniruzzaman et al., 2017).

Halophyte: Halophytes are salt-tolerant plants that show potential as feedstocks for biofuels, both oil and lignocellulosic. They can grow in harsh environments and have adaptability for use in fuel production. Their growth may also contribute to desalinizing arable land (CAAFI, 2019).

Algae: Algae, often referred to as "algae fuels," are considered third-generation biofuels. They have rapid growth rates, require less land, and excel in carbon sequestration. Algae can be farmed in marginal sites and offer significant potential for biofuel production (Chisti, 2007).

Waste Oil: Various waste materials can be converted into SAFs, including residual cooking oil, livestock fats, tall and fish oils, and other leftover lipids. Forest and agricultural residues, as well as municipal solid waste, also have potential as eco-friendly fuel sources (O'Malley, J., Pavlenko, N., and Searle, 2021).

2.1.6. Accredited Paths for Biofuel Production

ASTM has validated eight technological systems or conversion methods for producing SAFs, which are outlined in annexes to standards like D7566. Fischer-Tropsch (FT) synthesis is one such method, with two variants: FT-SPK and FT-SPK/A. FT-SPK has a maximum allowable mix percentage of 50%. It involves a reactor using a cobalt/iron compound to catalyze a thermochemical reaction, resulting in synthetic paraffinic kerosene (SPK) that is functionally equivalent to conventional aviation fuel. FT-SPK/A includes benzene to increase the aromatic content of the final hydrocarbon, improving compatibility with modern engines (CAAFI, n.d.; SkyNRG., 2020).

2.1.7. Challenges Faced in Biofuel Adoption

Several challenges hinder the development and widespread use of alternative fuels, including:

- Insufficient Maturity of Fuel Approaches: Many alternative fuel approaches are not fully mature, limiting their practicality.
- Lack of Raw Material: Adequate quantities of raw materials for fuel production, particularly for biofuels, can be scarce.
- Sustainability Concerns: The sustainability of feedstock generation, especially for biofuels, raises environmental and ethical concerns.
- Lack of International Support: The absence of support from international bodies and governments for transitioning from fossil fuels to alternative fuels hampers progress.

These challenges impact the cost-efficiency of SAFs and may hinder the aviation industry's efforts to reduce emissions and achieve sustainability goals. While SAFs have made progress in recent years, achieving ultimate technical ease on demand remains a challenge (Ricardo Energy and Environment., 2020). In conclusion, biofuels hold promise as a sustainable alternative to traditional aviation fuels, with various feedstocks and production methods under consideration. However, significant challenges, such as feedstock availability and sustainability concerns, must be addressed to ensure the successful adoption of these fuels in the aviation industry.

2.2. Approaches to Producing Sustainable Aviation Fuels (SAFs)

SAF can be produced through various methods, each with its unique technological, economic, societal, and environmental characteristics. These methods can be broadly categorized into biochemical and thermochemical routes, as depicted in Figure 2.

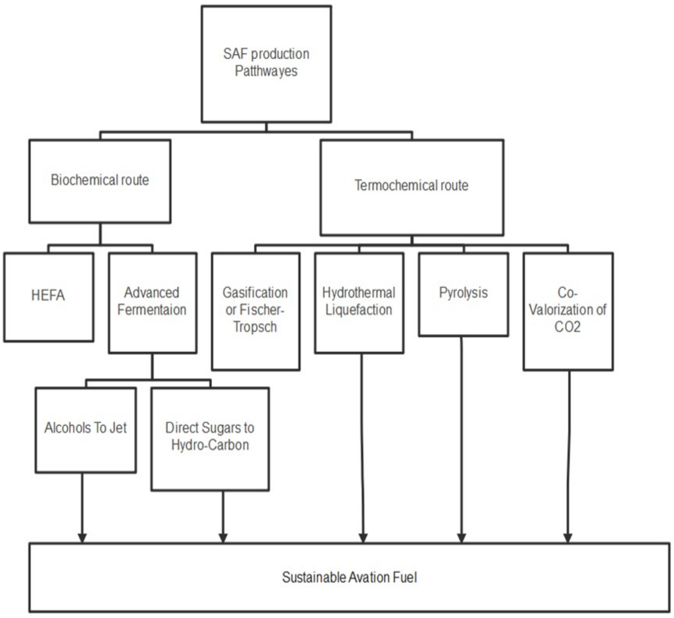

Figure 2 Process classification on SAF production paths (Shahabuddin et al., 2020)

HEFA is a process that produces long-chain hydrocarbons through hydrogenation and isomerization of oils, including animal fat, vegetable oil, residual grease, and algae oil. The resulting SAFs have high energy content, good thermal stability, and lower tailpipe emissions. ASTM has approved HEFA fuels for use in blends with regular aviation fuel, with a maximum blending limit of 50%. Several airlines, such as KLM, Lufthansa, and Etihad, have conducted successful test flights using HEFA-based mixtures (Dayton & Foust, 2020).

Advanced fermentation includes two processes. Alcohols To Jet (ATJ): This process produces long-chain hydrocarbons similar to traditional Jet-A1 fuel from alcohols like ethanol, methanol, or n-butanol. The alcohol can be generated from sugar fermentation, catalytic transformation of biomasses, or direct carbohydrate conversion into hydrocarbons. The ATJ process consists of four steps: dehydration, oligomerization, hydrogenation, and distillation. It has reached an advanced stage of development but involves higher infrastructure costs compared to FT(Geleynse et al., 2020).

Direct Sugars to Hydro-Carbon (DSHC) does not require alcohol generation. Concentrated carbohydrates are converted into hydrocarbons using anaerobic fermentation. The process includes phase separation to produce aviation fuel (Zhang, Wang, et al., 2020). The FT production involves the conversion of syngas (carbon monoxide and hydrogen) from carbon-rich biomass into liquid fuel through a catalytic process. Various biomass resources, such as wood wastes, poplar, willow, and agricultural wastes like corn stover and wheat straws, can be used to create carbon-free aviation fuel. The FT process requires high temperatures and pressures, making it a costly method (Dayton & Foust, 2020).

Pyrolysis produces gas, charcoal, and bio-oil as its primary products. Bio-oil contains a wide range of organic molecules but has a high oxygen concentration. To make it suitable for use as aviation fuel, oxygen molecules must be removed through hydrotreating in the presence of high-pressure hydrogen. After purification, a variety of hydrocarbons, including aviation fuels, can be obtained (Chen et al., 2020).

HTL (Hydrothermal Liquefaction) employs high temperatures and pressurized water to convert biomass into liquid fuel sources. Feedstocks for HTL include algae, composts, wastewater sludge, and lignocellulosic materials like corn stover. The resulting bio-crude has a high oxygen concentration, which is eliminated during hydrotreating. Distillation is then used to separate the refined hydrocarbons into aviation fuel, diesel, and other byproducts (Castello et al., 2019).

Co-Valorization of Carbon Dioxide and Waste Biomass approach, waste biomass is gasified to produce syngas rich in carbon monoxide (CO), while syngas rich in hydrogen (H2) are generated through the co-electrolysis of CO_2 and water. These gases serve as dual feedstocks for FT processes (Zhang, Fang, et al., 2020).

2.3. Policy and Support for SAFs

To encourage the transition from fossil fuels to renewable energy sources, policies and financial assistance systems play a crucial role. Examples include newly authorized tax breaks in the United States and direct project finance. Legislation, like the European Commission's Refuel EU Aviation directive, sets individual objectives for sustainable aviation fuel integration in European Union airports. Such policies set targets for the incorporation of biofuels and e-fuels in aviation fuel mixes, providing a regulatory framework for SAF adoption (Dyk, 2021).

In conclusion, various methods are employed to produce sustainable aviation fuels, each with its advantages and challenges. These approaches are essential for reducing greenhouse gas emissions and promoting the use of renewable energy sources in the aviation industry.

3. Research methodology

In this research, the methodology used to evaluate the effectiveness of SAF production methods is presented. The approach involves an MCDM framework designed to be adaptable and flexible to meet the needs of various stakeholders in the airline sector. The initial stage comprises a PROMETHEE-based criteria selection stage, while the next step evaluates the alternatives (see Figure 3).

The initial phase involved identifying performance standards and measurements for SAF production techniques. Fifteen different production paths for SAF were found in the literature review. Additionally, a list of 45 performance indicators related to social, economic, environmental, and technological aspects of sustainable transport fuels was compiled. To refine the criteria, a value tree approach integrated into the Delphi technique was employed. Experts and stakeholders participated in an online survey, and a consensus level was established. The final model included 24 criteria and 11 SAF production paths, which were evaluated based on various parameters. Criterion and codes for final evaluation are illustrated in Table 2 and sustainable aviation fuel production paths evaluated in this research are given in Table 3. The references that used the same or similar evaluation criteria are listed in the Appendix (see Table A2).

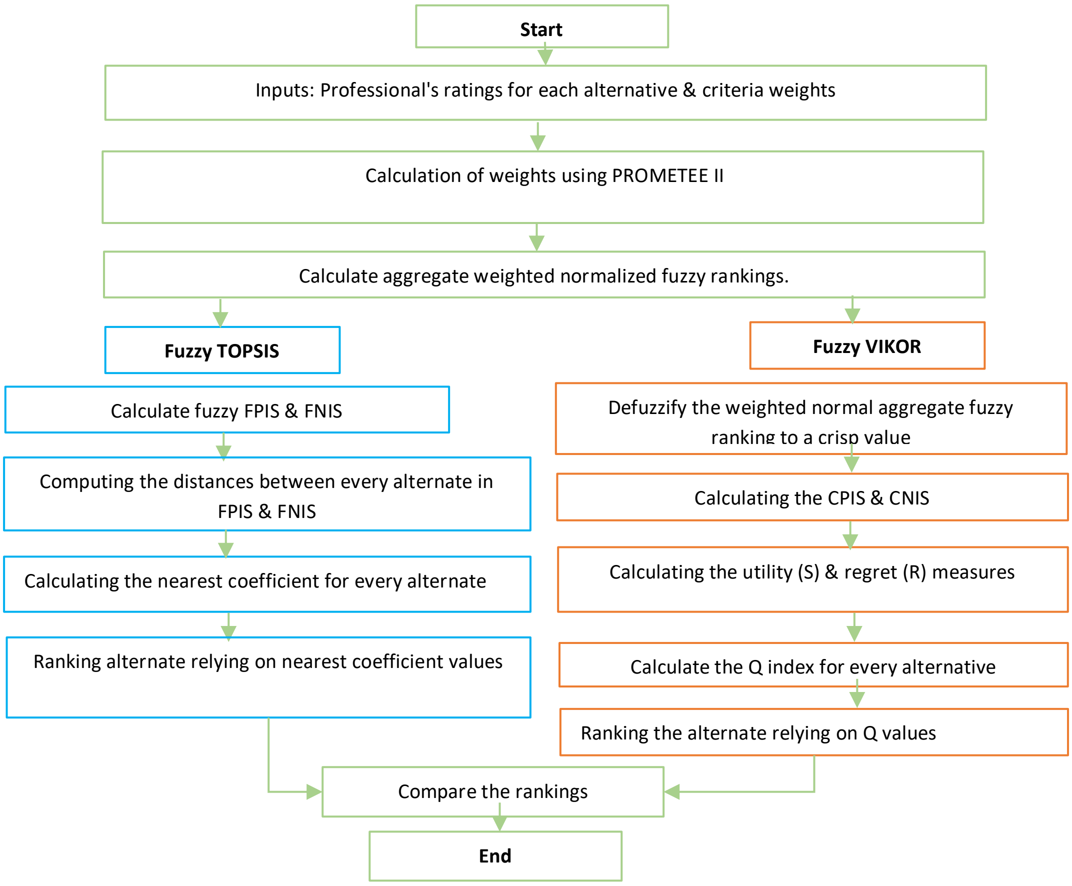

Figure 3. The flowchart on the fuzzy multicriteria decision method

Table 2. Final Evaluation of Criterion and Codes

Category	Code	Criterion	Description
Social	Socl1	Traceability	Transparency of the whole manufacturing procedure from the raw materials to the finished products (Lanzini et al., 2016).
	Socl2	Economical contribution	This signifies the establishment of new businesses, industrial areas, rural growth, etc. (Wang et al., 2019).
	Socl3	Food safety	The effect of feedstock utilized to produce green fuel on food availability (Sikarwar et al., 2017).
	Socl4	Social acceptance	Public opinion towards SAF production and utilization (Gegg & Wells, 2017).
Environmental	Envt1	Sustainability on feedstock	It signifies the continued availability of feedstock for green fuel production (Chiaramonti, 2019).
	Envt2	Savings on GHG emissions	CO_2 discharge levels compared to jet fuels (Zemanek et al., 2020).
	Envt3	The impact caused by a change in land usage	SAF production changes land use directly and indirectly (Lanzini et al., 2016).

	Envt4	Water and Soil pollution	Impact of using fertilizers and pesticides to produce biomass (Efroymson et al., 2017).
Economic	Econ1	Alternative uses with feedstock	Other potential feedstock applications besides SAF production like electricity and biomethane (Hileman & Stratton, 2014).
	Econ2	Profitability of feedstock	Monetary benefits in generating a particular feedstock (Klein et al., 2018).
	Econ3	Minimal price for selling	Minimum selling price estimated for the SAF (Ribeiro et al., 2017).
	Econ4	Input energy usage	Energy consumption during SAF manufacture (Baudry et al., 2018).
	Econ5	Productivity of Land	Incorporation of short crop rotations or intensive farming methods (Li et al., 2018).
	Econ6	Operational and maintenance costs	Operational and maintenance costs related to the SAF production plant (Diederichs et al., 2016).
	Econ7	Cost on feedstock	Costs of acquiring raw materials required for manufacturing of fuel (de Jong et al., 2015).
	Econ8	Cost of plant capital	Construction-related costs of production and associated services (Moore et al., 2017).
Technical	Tech1	Blending limits	Amount of authorized alternative fuel that can be blended with standard jet fuels (Cheng & Brewer, 2017).
	Tech2	Compatibility with Standard jet fuels	Fuel characteristics, such as flashpoint, viscosity, density, and energy content, closely resemble those of conventional jet fuel (Hileman & Stratton, 2014).
	Tech3	Local technical capability	The availability of locally accessible production technologies (Neuling & Kaltschmitt, 2018).
	Tech4	Integration process	The capability of a production method to be integrated with established jet-fuel refinery infrastructures (Ahmad et al., 2017).
	Tech5	Maturity of process technology	The current stage of development for a workflow is either initial, demo, or commercialized (Bann et al., 2017).
	Tech6	Method yield	Quantity of sustainable aviation fuel acquired via conversion method (Schillo et al., 2017).
	Tech7	Scalability on production volume	Capability for future expansion of sustainable aviation fuel processing facilities (Atsonios et al., 2015).
	Tech8	Composition and quality of feedstock	Quality of SAF batch (Fiorese et al., 2013).

Table 3. Sustainable Aviation Fuel Production Paths Evaluated in this Research

Production method	Feedstocks	Code
	Algae and microalgae	A 1

Hydro processed Esters and Fatty Acids (HEFA)	Used cooking oils and animal fats	A 2
	Oilseeds	A 3
Fischer-Tropsch synthesis or gasification	Municipal solid wastes	A 4
	Wood residues and agricultural wastes	A 5
Devolatilization or Pyrolysis	Algae and microalgae	A 6
	Wood residues and agricultural wastes	A 7
Hydrothermal liquefaction (HTL)	Algae and microalgae	A 8
	Wood residues and agricultural wastes	A 9
Advanced fermentation	Wood residues and agricultural wastes	A 10
CO_2 co-valorization and biomass waste	Combination of industrial waste gases CO_2 and wood residues	A 11

To understand the relative importance of criteria, interviews were conducted with 22 European aviation fuel supply chain experts. The summary of the expert pool is given in Table A1. These experts, each with more than five years of experience, ranked four significant criteria (social, environmental, economic, and technological) concerning one another. This ranking system provided a total score out of 100 for each criterion.

Airline industry professionals were surveyed to rate SAF production paths based on different criteria. Due to the limited availability of data, a numerical scale was introduced, ranging from 1 to 9, with corresponding descriptions like extremely poor, poor, average, good, and excellent. These values were then converted to a score out of 100. The PROMETHEE-II approach (Brans & Vincke, 1985), known for handling both qualitative and quantitative data, was chosen for the analysis. This approach helps address conflicting objectives and trade-offs, making it suitable for decision problems involving multiple criteria. PROMETHEE-II approach is especially useful when there are conflicting objectives and trade-offs to consider, making it applicable to a wide range of decision problems. It can help decision-makers better understand the relationships between criteria and alternatives. This means that subjective judgments and expert opinions can be integrated into the model.

PROMETHEE-II can be conceptualized as a modeling and key paradigm for MCDA difficulties in which the difficulty in deciding is modeled as a fully connected system where nodes are alternative and the arc reflects preferences relations among node pairs or alternatives (a, b), like $\pi(a, b)$.

The alternative or node's strength a, which is called the net outranking flow, is written as $\emptyset(a)$ or $\emptyset_{net}(a)$, and it is calculated by deducting outward outranking flow $\emptyset^{+}(a)$ from inward outranking flow $\emptyset^{+}(a)$ i.e., $\emptyset_{net}(a) = \emptyset^{+}(a) - \emptyset^{-}(a)$. The answer to the question of rating a group of alternatives according to the MCDM approach is provided by arranging alternatives as per their strength in descending order as calculated through net outranking flows, $\emptyset_s$. Following is a breakdown of the method in detail.

Input: Weighting scheme and the decision matrix

In PROMETHEE II, the data is integrated into a decision matrix as depicted in Eq. 1 below.

$$DM = \begin{bmatrix} c_1(a_1) & \cdots & c_n(a_1) \\ \vdots & \ddots & \vdots \\ c_1(a_m) & \cdots & c_n(a_m) \end{bmatrix} \qquad (1)$$

Where the alternative set is denoted as A= $\{a_1, a_2, \ldots, a_i, \ldots, a_m\}$, and the performance criteria set is considered as C=$\{c_1, c_2, \ldots, c_j, \ldots, c_n\}$. The alternative $a_i's\ performance$ on criterion *j* is indicated by $c_j(a_1)$ where; i = 1, ..., m, and j = 1, …., n. After that, we obtain the comparative importance weight (w_j), of n^{th} performance criterion. w_j = (w_1, w_2, …, w_n), where j= 1, …, n, it includes non-negative weights with $\sum_{j=1}^{n} w_j = 1$.

Step 1: For every alternative pair (a, b) on criteria *j*, we calculate the difference of opinion in criterion *j* performance concerning alternative a and b, represented as $D_j(a, b)$, (Eq. 2):

$$D_j(a,b) = c_j(a) - c_j(b), \ j = 1, \dots, n \ \forall a, b \in A \tag{2}$$

Step 2: To find every alternative pair (a,b) for criterion j, the method calculates a local preference index $P_j(a,b)$, that considers the difference of opinion in the performance of criterion j concerning alternative a and b that is calculated previously using step 1. Brans and Vince (1985) highlighted the different preference index functions. This study adopts the type 1 general preference as given in Eq. 3.

$$P(D)= \{0, \text{ if } D \leq 0 \ \& \ 1, \text{ if } D > 0\} \tag{3}$$

Output: The concluding rating of each of the alternatives is determined based on the net ranking, $\emptyset_{net}(.)$. That is, the higher the net ranking, the more desirable the alternative is. The study by Shahmardan & Hendijani Zadeh, (2013) provides more insight into the application of the net ratio (∅_net (.)) in the framework of multi-criteria decision-making (MCDM). Insights into the use of fuzzy sets and fuzzy entropy in decision-making processes are provided by combining fuzzy logic and PROMETHEE techniques. This improves knowledge of how the net ratio can be successfully included in MCDM analyses.

To compare the results of the ranking, this study utilized two alternative MCDM methodologies: TOPSIS and VIKOR. To account for the unpredictability of professional preferences, the research adopts the fuzzy version of the TOPSIS and VIKOR approaches (Awasthi et al., 2018). A summary of detailed implementation information for the formulations of fuzzy TOPSIS and VIKOR analysis is discussed here.

Inputs: The ranking done by the K professionals of m alternatives with n criteria is denoted with x_{ij}^k; where $i = 1, \dots, m$, and $j = 1, \dots, n$, and $k = 1, \dots, K$ and every professional's given weight for every criterion is w_j^k; where $j = 1, \dots, n$, *and* $k = 1, \dots, K$.

Step 1*:* Choosing a proper modelling context and computing the aggregated fuzzy rankings for every alternative and weights on every criterion. Utilizing fuzzy triangular numbers to develop the fuzzy data is easier and more common, whereas this study relates to the rankings. Hence, for every alternative "i" (i = 1, …, m) and criteria "j" (j = 1, …, n), the rankings by K professionals are combined to singular triangle fuzzy rankings, assume $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$, like:

$$a_{ij} = \min_k \{x_{ij}^k\}; \ b_{ij} = \frac{1}{K} \sum_k x_{ij}^k; \ c_{ij} = \max_k \{x_{ij}^k\} \tag{4}$$

Likewise, compute the aggregated fuzzy weights for all criteria j (j = 1, …, n), assume $\tilde{w}_{j,1} = w_{j,1}, w_{j,2}, w_{j,3}$, like:

$$w_{i,1} = \min_k \{w_j^k\}; \ w_{j,2} = \frac{1}{K} \sum_k w_j^k; \ w_{j,3} = \max_k \{w_j^k\} \tag{5}$$

Summarize aggregate fuzzy rankings as a decision matrix and fuzzy weight as a vector criterion.

Step 2: Computing weighted normal aggregate fuzzy rankings, assume $\tilde{n}_{ij}$ where i = 1, …, m and j = 1, …, n, like*:*

$$\tilde{n}_{ij} = \tilde{w}_j \otimes \left(\frac{a_{ij}}{\max_i}, \frac{b_{ij}}{\max_i}, \frac{c_{ij}}{\max_i} \right) = \left(w_{i,1} \frac{a_{ij}}{\max_i}, w_{i,2} \frac{b_{ij}}{\max_i}, w_{i,3} \frac{c_{ij}}{\max_i} \right); \text{ where, } i = 1, \dots, m \text{ and } j \in C^+ \tag{6}$$

$$\tilde{n}_{ij} = \tilde{w}_j \otimes \left(\frac{\min_i}{a_{ij}}, \frac{\min_i}{b_{ij}}, \frac{\min_i}{c_{ij}} \right) = \left(w_{i,1} \frac{\min_i}{a_{ij}}, w_{i,2} \frac{\min_i}{b_{ij}}, w_{i,3} \frac{\min_i}{c_{ij}} \right); \text{ where, } i = 1, \dots, m \text{ and } j \in C^- \tag{7}$$

where C^-(respective C^+) indicates the cost criterion set (respective benefit criterion) in which low values (respective high values) are better. Based on the values obtained at this step, fuzzy TOPSIS follows the steps below.

***Step 3**:* Computing the Fuzzy positive and Negative ideal solutions (FPIS and FNIS) accordingly assuming $\tilde{n}^+$ and $\tilde{n}^-$, like:

$$\tilde{n}_j^+ = \{ \min_{i=1,\dots,m} \tilde{n}_{ij} \ IF \ j \in C^- \ \max_{i=1,\dots,m} \tilde{n}_{ij} IF \ j \in C^+ \ ; j = 1, \dots, n \tag{8}$$

$\tilde{n}_j^- = \{ \max_{i=1,\ldots,m} \tilde{n}_{ij} \; IF \; j \in C^- \; mix_{i=1,\ldots,m} \tilde{n}_{ij} IF \; j \in C^+ \;\; ; j = 1, \ldots, n$ (9)

Step 4*:* Computing the distances i.e., $d(i, \tilde{n}^+)$ and $d(i, \tilde{n}^-)$ between every alternate i in FPIS ($\tilde{n}^+$)and FNIS ($\tilde{n}^-$), where $i = 1, \ldots, m$:

$$d_i^+ = \left\{ \frac{1}{n} \sum_j^n \left(\tilde{n}_{ij} - \tilde{n}_j^+ \right)^2 \right\}^{\frac{1}{2}} \quad (10)$$

$$d_i^- = \left\{ \frac{1}{n} \sum_j^n \left(\tilde{n}_{ij} - \tilde{n}_j^- \right)^2 \right\}^{\frac{1}{2}} \quad (11)$$

Step 5*:* Choosing similar scores, which is also known to be the closest coefficient for every alternate i ($i = 1, \ldots, m$) as shown below:

$$S_i^- = d(i, \tilde{n}^-)/(d(i, \tilde{n}^-) + d(i, \tilde{n}^+)) \quad (12)$$

Step 6*:* Ranking the alternate in ascending order concerning their similarities in the ranks. Hence, the effective alternate method is distanced from FNIS and nearest to the FPIS.

Alternatively, fuzzy VIKOR determines the optimal ranking based on the following procedure, where Steps-3-6 are redefined as follows.

Step 3: Defuzzification of the weighted normal aggregate fuzzy rankings, i.e., $\tilde{n}_{ij}$ ($i = 1, \ldots, m$; $j = 1, \ldots, n$) as crisp value by considering n_{ij}, as shown below:

$$n_{ij} = \frac{1}{6} \left(w_{j,1} \frac{a_{ij}}{\max_i}, 4w_{j,2} \frac{b_{ij}}{\max_i}, w_{j,3} \frac{c_{ij}}{\max_i} \right); where, i = 1, \ldots, m; and \; j \in C^+ \quad (13)$$

$$n_{ij} = \frac{1}{6} \left(w_{j,1} \frac{\min_i}{a_{ij}}, w_{j,2} \frac{\min_i}{b_{ij}}, w_{j,3} \frac{\min_i}{c_{ij}} \right); where, i = 1, \ldots, m \; and \; j \in C^- \quad (14)$$

Step 4: *Computing the crisp positive ideal solution (CPIS) considering* n^+ *Moreover, calculating the rating as shown below:*

$$n_j^+ = \{ \min_{i=1,\ldots,m} n_{ij} \; IF \; j \in C^- \; \max_{i=1,\ldots,m} n_{ij} IF \; j \in C^+ \;\; ; where, j = 1, \ldots, n \quad (15)$$

Step 5*: Calculate the performance marks i.e.,* Q_i *for every alternate* i, $where$; $(i = 1, \ldots, m)$*:* $Q_i = \alpha \left(\frac{S_i - S^+}{S^- - S^+} \right) + (1 - \alpha) \left(\frac{R_i - R^+}{R^- - R^+} \right); 0 \leq \alpha \leq 1$

where,

$$S_i = \sum_{j=1}^m \left(n_j^+ - n_{ij} \right); \; R_i = \max_j \left\{ \left(n_j^+ - n_{ij} \right) \right\} \quad (16)$$

$$S^+ = \min_i S_i; S^- = \max_i S_i; R^+ = \min_i R_i; R^- = \max_i R_i \quad (17)$$

Consider α = 0.5

Step 6: Ranking the alternate methods according to their performance in descending order. Hence, the superior alternate method holds the lowest value.

4. Research findings and analysis

This section discusses the weights assigned to criteria, ranks based on broader implications, and PROMETHEE-II ratings. After gathering expert opinions, geometric means are used to derive criteria weights. Economic and environmental criteria carry the most weight, at 31% and 28%, respectively. Technological criteria account for 25%, while social criteria are the least significant at 16%. Local weights highlight the importance of specific criteria within each category. For example, food security and social acceptance are crucial in societal impact, with weights of 29.8% and 26.9%, respectively. Among environmental concerns, reducing greenhouse gas emissions is a top priority at 36.6% (see Figure 4).

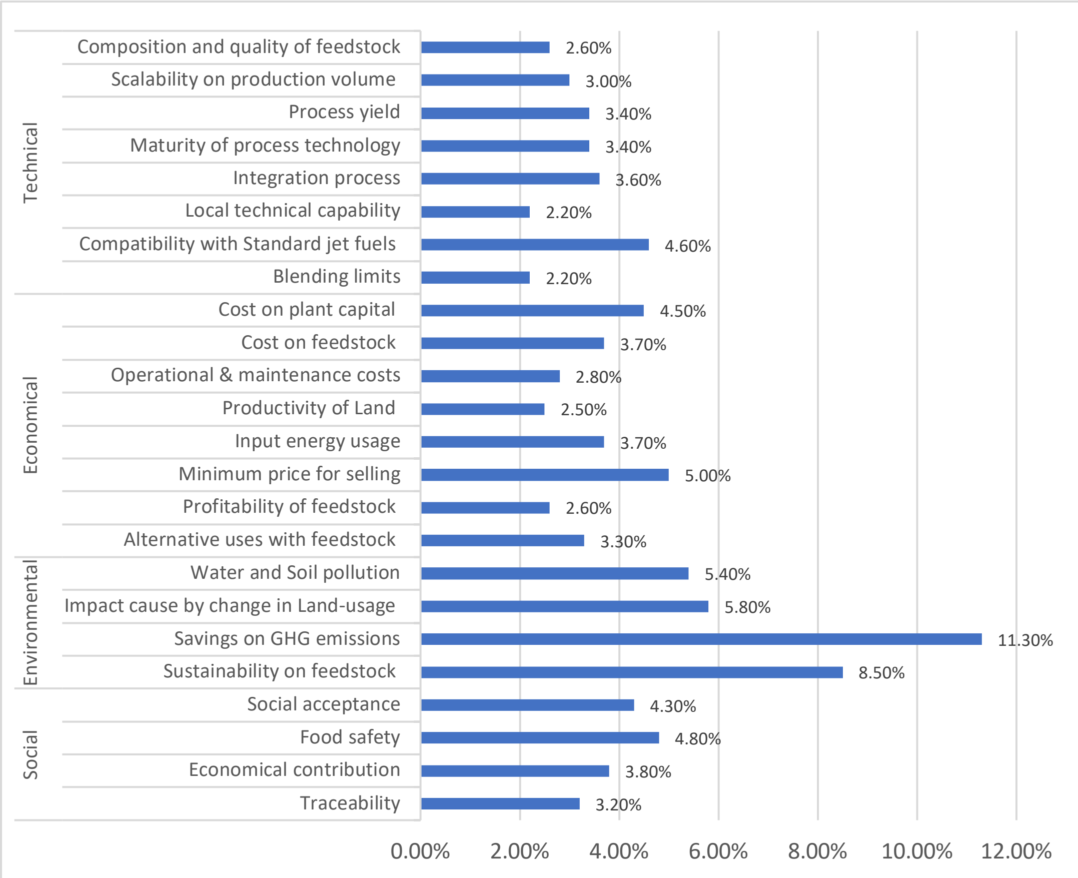

Figure 4. Global weight of selected criteria Source

Principal Components Analysis (PCA) yielded a 2D GAIA plot (see Figure 5), showing relationships and conflicts between criteria. This plot helped identify criteria with competing values, such as the profitability of feedstock conflicting with minimum selling price and capital costs. Utilizing the GAIA model, disagreement, commonalities, and interdependencies between criteria are evaluated. As the length of a criterion vector increases, it becomes more discriminatory. In this instance, a 24-D criterion is predicted, with 67.1 percent.

This shows that the information offered by the group of professionals is reliable. Criteria indicating competing values can be seen in Figure 5. For instance, the profitability of feedstock (Econ2) and productivity of land (Econ5) are incompatible with alternate feedstock usage (Econ1), Minimum selling price (Econ3), and capital costs of the plant (Econ8). Identical preferences are indicated by vectors pointing toward the same direction.

Sustainability of feedstock (Envt1) and Greenhouse gas emission saving (Envt2) from environmental effect, whereas standard aviation fuel compatibility (Tech2), local technical capabilities (Tech3), and integration process (Tech4) have similar views. The most important factors to consider are food security (Socl3), the effect of land use changes (Envt3), the operating costs and maintenance (Econ6), as well as the level of technological maturation in the procedure (Tech5). Tech5 is the only differentiating criterion on the decision axis along the vector line (Red).

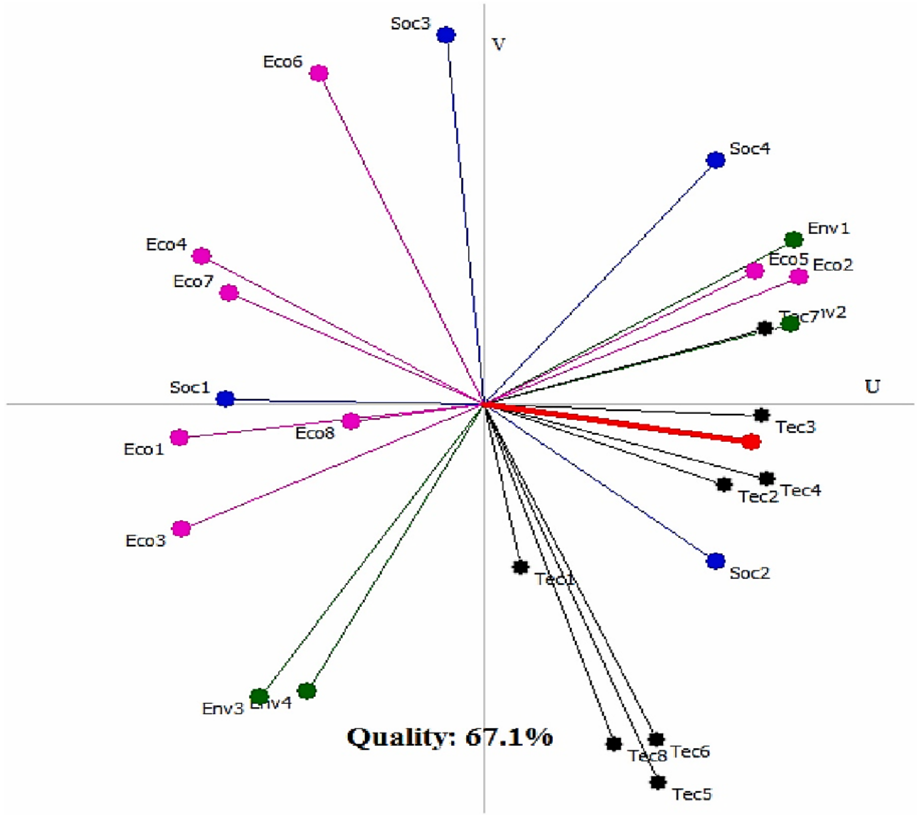

Figure 5. Graphical Representation of GAIA Plan for Selected Criteria

4.1. Analysis of Sensitivity

To confirm the validity of the chosen alternates, it is crucial to evaluate the result's reliability. To do this, a sensitivity study is carried out and the initial rankings of the alternative solutions are verified. Two different strategies were used to achieve this goal:

a. Modify the weight of the criterion, use PROMETHEE to verify the rank, and

b. Compare and confirm the SAF production method ranking using two additional MCDM techniques.

a. Tests on Criteria Weights

To evaluate the impacts of varying criteria weights on alternative rankings, this research considers four scenarios:

i. Pessimistic (considering the weights assigned to each stakeholder's least criteria)

ii. Likely (based upon the average weights of criteria),

iii. Optimistic (considers the highest weight of criteria obtained at the interview)

iv. Neutral (assuming all criteria are equally weighted).

To determine the amount to which decision-makers' preferences will influence the previously stated results, this study assumes that every criterion has equal value and assigns every one of the 24 criteria a weighted sum of 4.2%. This research has been designated as neutral. In all studies reviewed, SAF method A11 obtains the highest rating in all four tests, accompanied by A4 at 2nd position 3 times and A5 at 3rd position 3 times, according to the findings of the sensitivity assessment shown in Figure 6.

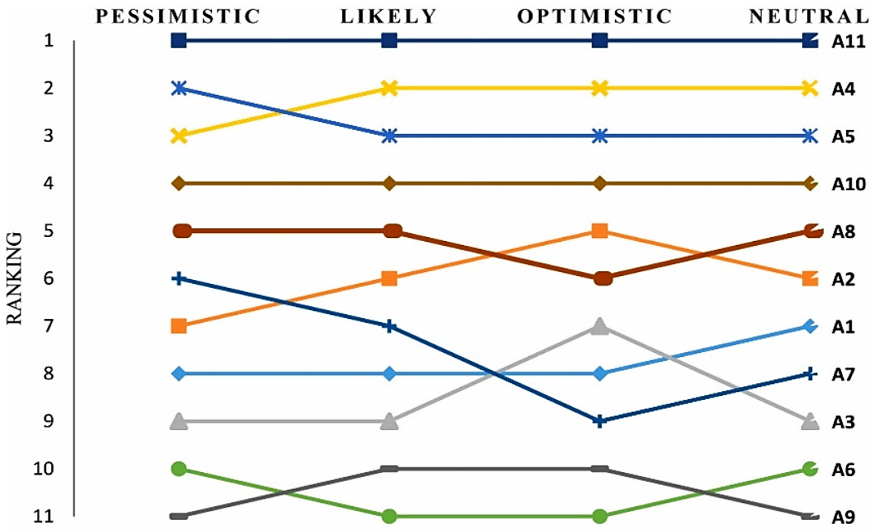

Figure 6 Sensitivity analysis results

Source: Own study

According to the research, the best and poorest-performing production method's ranks did not significantly shift after the weights were changed to an equivalent weighting factor. This indicates that the results are reliable and resistant to changes in the weight of the input criteria. Thereby, the SAF production methods rankings can be trusted.

b. Evaluation Based on Impacting Criteria

SAF production methods have been evaluated based on stakeholders' perspectives, including social, environmental, economic, and technical impacts. Initially, utilizing weight vectors of 0.200, 0.233, 0.289, and 0.269 for social criterion, the study ranked SAF production methods as illustrated in Figure 6.

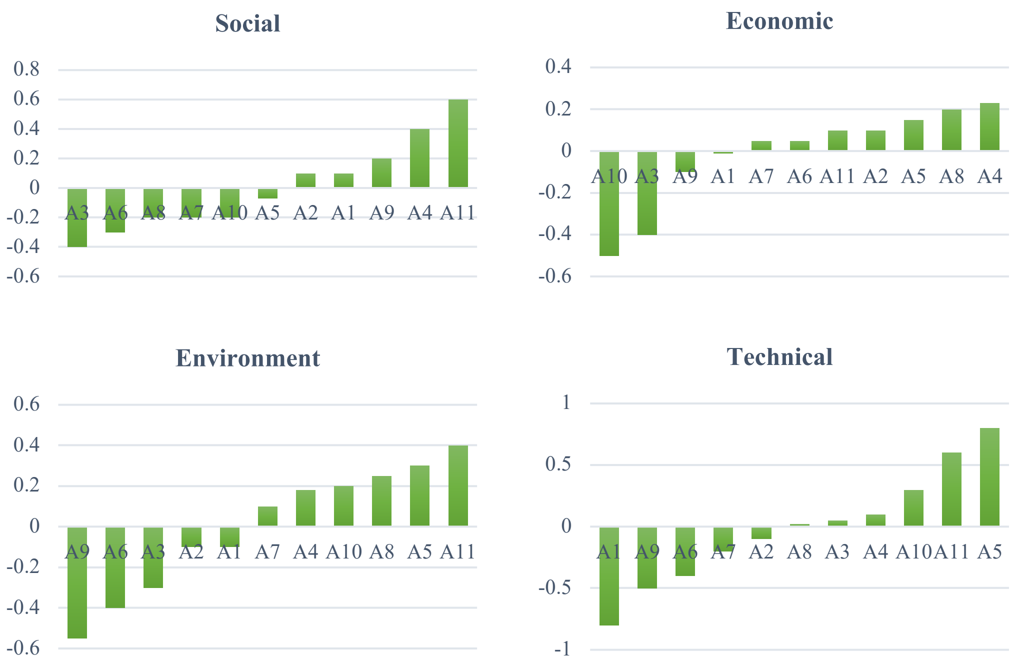

Figure 7. Graphical Representation of GAIA Plan for Selected Criteria

Gasification and Fischer Tropsch synthesis methods (A4 and A11) ranked highest from a social standpoint, as they use wood residue and municipal solid waste as feedstock, which is widely accepted. From an environmental perspective, A11 demonstrated the best performance due to its use of confined CO_2, followed by A5 and A8. A6, A3, and A9 ranked poorly due to environmental drawbacks associated with algae and oilseed production.

Economically, chemical mixing procedures (A4, A5, and A11) were top-rated, while A6 and A7 were middle ranked. HEFA methods (A2 and A3) showed promise due to their lower costs compared to other alternatives. From a technical viewpoint, A5 was the best due to its high SAF yield and development status, while A1, A9, and A6 lagged.

However, regarding technological ability, A1 is the least desirable of the production routes, following A9 and A6. Because of the elevated water and oxygen concentration in the biocrude oil generated, A1 and A6 with algae or microalgae have a reduced sustainable aviation fuel yield. According to research data, A6 has a superior production method than A9. Figure 7 shows the graphical representation of the GAIA plan for selected criteria.

4.2. SAF Production Methods and Global Ratings

PROMETHEE-II was used to evaluate SAF production methods based on 24 criteria. A11 consistently ranked the highest, followed by A4 and A5. These methods were favored for their cost-effective use of feedstock like wood residue and municipal solid waste. Table 4 illustrates the inflow and outflow in sustainable aviation fuel production methods while Figure 8 shows the ranking of the alternatives.

Figure 8 shows that Method A6 has the lowest outranking flow of all Sustainable aviation fuel production methods, with a value of 0.207, and A9 and A3 are the next two extremes, with values of 0.2045 and 0.111 accordingly. The A11 production method has a total outranking flow of 0.240, greater than all other methods. The fact that the highest-ranked production methods, A4, A5, and A11, are gasification or Fischer-T synthesis procedures demonstrates that professionals acknowledge that they are the most appropriate methods for Sustainable aviation fuel production. Syngas, the primary constituent of gasify or Fischer Tropsch synthesis, is produced from Municipal Solid wastes, wood residues, and Agri wastes, all of which are inexpensive feedstock. This offers gasification or Fischer-T synthesis-related production methods a strategic benefit by offsetting its higher capital costs and smaller production scale in comparison to HEFA methods (Neuling & Kaltschmitt, 2018).

Besides gasification or Fischer-T synthesis, the study indicates that A10, which is advanced fermenting, is the second-best method. In contrast to the existing research, which claims that advanced fermenting (DSHC and ATJ) related methods are constrained in feedstock sustainability and incapable of reaching the commercial development stage, the results presented here appear plausible. Nevertheless, it might be challenging to scale up the advanced fermented production process. Figure 8. illustrates that A10 ranks comparatively higher because of its superior overall technical and environmental attributes.

Although A8 (HTL methods with algae or microalgae) scored higher than A2 (HEFA using waste cooking oils or animal fat), this production method's possible capacity expansion is constrained by the availability of inputs. Eventually, other options outperform A6 and A9 (production method using pyrolysis and HTL, respectively). These outcomes are constant with relevant research on biofuel generation technologies (Fiorese et al., 2013). According to their study of industry professionals, gasification or Fischer-T synthesis and oil-based methods, including HEFA, Pyrolysis, and HTL, were the most common production methods.

The optimal feedstock for SAF production is the direct transition process of CO2 to SAF (A11) in the gasification or Fischer-T synthesis group. This might be the case since experts believe that CO2 extraction from industrial technologies is a more direct way than employing MSW (A4), wood residues, and agricultural waste (A5). The reduction in Greenhouse gas emissions by using landfill gas to counterbalance the use of fossil fuels has been dropped even though converting MSW into biofuel prevents Greenhouse gas emission that derives waste in landfills and incinerating processes (Staples et al., 2018).

Table 4. Inflow and outflow in sustainable aviation fuel production methods

Production method	Code	Feedstocks	Inflow	Outflow	Net Phi
Hydro processed Esters and Fatty Acids (HEFA)	A 1	Algae and Microalgae	0.442	0.518	-0.077
	A 2	Animal fats or Used cooking oils	0.487	0.465	0.023
	A 3	Oilseeds	0.423	0.534	-0.112
FT synthesis or gasification	A 4	Municipal solid wastes	0.583	0.386	0.198
	A 5	Wood residues and Agri wastes	0.552	0.423	0.130
Devolatilization or Pyrolysis	A 6	Algae and Microalgae	0.375	0.582	-0.208
	A 7	Wood residues and Agri wastes	0.446	0.517	-0.072
Hydrothermal liquefaction (HTL)	A 8	Algae and Microalgae	0.483	0.464	0.020
	A 9	Wood residues and Agri wastes	0.380	0.584	-0.205
Advanced fermentation	A 10	Wood residues and Agri wastes	0.509	0.447	0.063
CO_2 co-valorization and biomass waste	A 11	Combination of Industrial waste gases CO_2 and wood residues	0.605	0.365	0.25

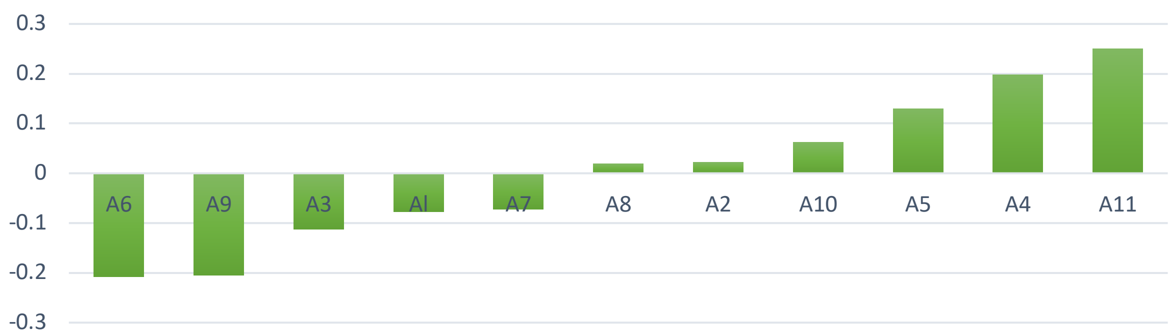

Figure 8. MCDM Ranks Sustainable Aviation Fuel Production Methods

4.3. Comparison of MCDM Methodologies

The rank order produced with TOPSIS and VIKOR using fuzzy methodologies is shown in Table 5. Here, A4 and A5 were consistently placed in the highest 3 by both techniques. However, A6 and A9 were consistently ranked in the lowest three. Nevertheless, due to variations in the theoretical basis of both methods, the ranks given to A3 and A11 in both methodologies are distinct.

Table 5 Fuzzy VIKOR and TOPSIS for Sustainable Fuel Production Method Ranking Source

		Alternate rank order Poor										Strong
	VIKOR	A3	A9	A6	A8	A7	A11	A10	A1	A2	A5	A4
	TOPSIS	A9	A6	A7	A8	A3	A10	A2	A1	A5	A4	A11

5. Conclusions

The airline industry's efforts to reduce CO_2 emissions and find new sources of jet fuel have the chance to benefit significantly when using sustainable fuels in aviation. SAF could be produced in various methods, making choosing a particular route a challenging strategic choice. Utilizing TEA or LCA research, the existing literature compares the effectiveness of one or more methods. This study proposed a comprehensive assessment approach for the SAF selection problem.

5.1. Implications

This research used a stakeholder engagement strategy to collaborate with professionals to create a comprehensive structure based on evaluation criteria including societal, environmental, economic, and technological factors. To determine the most important factors for investment/production/purchase/usage of SAF, this study created a questionnaire to obtain stakeholders' opinions. In-depth conversations with industry professionals confirmed the criterion. Industry professionals were given another form to rate SAF production methods according to a performance criterion. Data is validated using fuzzy TOPSIS and fuzzy VIKOR and PROMETHEE to reduce professionals' judgmental personal prejudice.

The analysis concluded that economic and environmental considerations outweigh technological and social considerations. The focus on these two groups is logical given that SAFs are marketed as having less harmful environmental consequences than normal Jet-A fuel yet, serve as a more expensive alternative. Greenhouse gas reductions, sustainability on feedstocks, minimum selling price, compatibility of jet fuel, and traceability of sustainable aviation fuel are the essential performance factors for rating their production methods. A comparison of sustainable production methods based solely on one criterion reveals that no single production method dominates the 24 assessment criteria. In addition, various results are observed when examining each effect category separately in mono-criteria rankings. HEFA-based output scores highest in economic effects. This conclusion should be interpreted cautiously, as HEFA appears to be a viable opportunity among the remaining 3 impact categories. According to global rankings, gasification or Fischer-T synthesis, advanced fermentation, and hydrothermal liquefaction are the top conversion processes for SAFs. Although technologically developed and frequently used commercially, HEFA-based procedures are less desirable. It is noticeable that collected waste from gas, wood, and farms is superior feedstock when compared to algae or microalgae and purpose-grown seeds that are non-edible for oil extraction.

Animal fats or used cooking oil varieties are additional enticing options, but their restricted availability prevents them from increasing SAF production. The findings suggest integrating/designing/modifying the waste gases and leftovers supply chain for SAF production. The SAF production method analysis and ranking approach aid policymaking. A nation's technical, feedstock, and economic conditions must guide SAF production methods.

Some countries, like Brazil, make SAF from sugarcane, whereas the United Kingdom has found that municipal solid waste and agricultural waste make the best feedstock for making SAF. To secure a consistent supply of raw materials to produce SAF, feedstock suppliers might receive monetary benefits. An improved feedstock supply chain will assist in minimizing the unpredictability in the production of SAF and ensure commercial stability for both feedstock providers and the SAF production companies. Technology-wise, strengthening SAF production paths and R&D capacities will boost economic competitiveness and the bioeconomy. These competencies would be sold to other countries.

In addition, as indicated in the research, the plant capital investment of the SAF production method is a critical factor. In this regard, it is recommended to simplify and underwrite debt or equity funding by state governments. This scenario will increase the trust of private capitalists, allowing new investors and establishing refineries providing biofuel for road transportation to incorporate SAF into their business models. The results of this research may also be used to develop policy choices such as production or buying quotas from a particular SAF production method, taxes on standard jet fuel (creating a comparable environment for that SAF production method), including subsidies for sustainable production of aviation fuels.

Conclusively, as indicated by Trejo-Pech et al., (2019) SAF production can be regarded as a catalyst for creating national climate change policies. In conclusion, it is anticipated that policymakers and decision-makers will consider the research results when investing or making a policy decision about SAF production methods. These findings raise new research questions. For instance, it could be intriguing to examine conflicts across all the societal, economic, technological, and environmental criteria. It is also intended to integrate more synthetic methods for SAF production and a range-based technique to investigate ranking distribution.

Contribution of Researchers

Ibrahim Temam Ibrahim: Methodology, Conceptualization, Analysis, Data collection and curation**. Ali Osman Kusakci:** Supervision, Validation, Formal analysis**. Amna Abdullah:** Writing, Reviewing and Editing.

Conflicts of Interest

The authors declared that there is no conflict of interest.

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APPENDIX

Table A1: Details of the Expert Pool

Participants	Years of Expertise	Department	Job Role	Company
Participant 1	5+	Supply chain	Supply Chain Executive	Shell Aviation
Participant 2	5+	Supply chain	Supply Chain Assistant	BP Aviation
Participant 3	10+	Supply chain	Supply Chain Operations Manager	Total Energies
Participant 4	6	Supply chain	Supply Chain Coordinator	Lufthansa Aviation Fuel
Participant 5	8	Supply chain	Supply Chain Assistant	Sky tanking
Participant 6	5	Supply chain	Supply Chain Administrator	Air BP
Participant 7	6	Supply chain	Supply Chain Specialist	World Fuel Services
Participant 8	5	Supply chain	Downstream Purchasing Assistant	CEPSA
Participant 9	12	Supply chain	Supply Chain Manager	ExxonMobil Aviation
Participant 10	7	Supply chain	Supply Chain Executive	Gazpromneft-Aero.
Participant 11	6	Supply chain	Supply Chain Analyst	Shell Aviation
Participant 12	9	Supply chain	Supply Chain Coordinator	BP Aviation
Participant 13	14	Supply chain	Supply Chain Assistant Manager	TotalEnergies
Participant 14	10+	Supply chain	Supply Chain Manager	Lufthansa Aviation Fuel
Participant 15	8+	Supply chain	Supply Chain Operations Coordinator	Sky tanking
Participant 16	6	Supply chain	Supply Chain Specialist	Air BP
Participant 17	7	Supply chain	Fuel Supply Coordinator	ExxonMobil Aviation
Participant 18	5	Supply chain	Supply Chain Coordinator	ExxonMobil Aviation
Participant 19	17	Supply chain	Supply Chain Manager	Gazpromneft-Aero
Participant 20	8+	Supply chain	Downstream Procurement Manager	CEPSA
Participant 21	7+	Supply chain	Supply Chain Coordinator	Air BP

Participant 22	12+	Supply chain	Fuel Supply Executive	World Fuel Services

Table A2: References to the Evaluation Criterion

Category	Selected Criterion	Citation
Social	Traceability	(Lanzini et al., 2016).
	Economical contribution	(Wang et al., 2019).
	Food safety	(Sikarwar et al., 2017) .
	Social acceptance	(Gegg & Wells, 2017).
Environmental	Sustainability on feedstock	(Chiaramonti, 2019).
	Savings on GHG emissions	(Zemanek et al., 2020).
	The impact caused by a change in land usage	(Lanzini et al., 2016).
	Water and Soil pollution	(Efroymson et al., 2017).
Economic	Alternative uses with feedstock	(Hileman & Stratton, 2014).
	Profitability of feedstock	(Klein et al., 2018).
	Minimal price for selling	(Ribeiro et al., 2017).
	Input energy usage	(Baudry et al., 2018).
	Productivity of Land	(Li et al., 2018).
	Operational and maintenance costs	(Diederichs et al., 2016).
	Cost on feedstock	(de Jong et al., 2015).
	Cost of plant capital	(Moore et al., 2017).
Technical	Blending limits	(Cheng & Brewer, 2017).
	Compatibility with Standard jet fuels	(Hileman & Stratton, 2014).
	Local technical capability	(Neuling & Kaltschmitt, 2018).
	Integration process	(Ahmad et al., 2017).
	Maturity of process technology	(Bann et al., 2017).
	Method yield	(Schillo et al., 2017).
	Scalability on production volume	(Atsonios et al., 2015).
	Composition and quality of feedstock	(Fiorese et al., 2013).