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Review Article

RISK IDENTIFICATION AND GAP ANALYSIS FOR IMPROVEMENT OF SUSTAINABLE AVIATION FUEL: A SYSTEMATIC LITERATURE REVIEW

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Abstract. The development process of sustainable aviation fuel is observed by economic, technological, and regulatory uncertainties. Therefore, risk identification is essential for comprehending existing barriers and developing feasible strategies. Further, given the diversity in literature, specifying gaps is necessary to determine research orientations and identify priority areas for future research. These two approaches ensure a more comprehensive and target-oriented assessment of research in the field. In this mind, this paper aims to identify the main themes and primary topics, the risks discussed, and the overlooked matters related to Sustainable Aviation Fuel (SAF). A systematic literature review is employed to synthesize relevant papers. The identification process yielded 135 records from WoS and Scopus, which were eventually narrowed down to 14 studies after exclusions. Production and economic subjects are the most common topics discussed on SAF. The academics highlighted the risks regarding financial and natural resources, yet landlessness has not been sufficiently discussed. In addition, the emission-reducing efforts lack holism, and many significant questions remain unanswered. This paper presents a distinctive synthesis of the themes and risks in studies on SAF and highlights some overlooked issues. It is believed that future studies should address the unresolved questions stated to propel green aviation forward.

Keywords: aviation, sustainable aviation fuel, net zero target, risk management, systematic literature review.

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1. Introduction

The aviation industry has been a powerful driver of economic growth, employment, trade and tourism, as well as connectivity and mobility for businesses and citizens. The increase in the industry's products and services contribute significantly to improving inter-country linkages and reducing regional inequalities, especially with peripheral, outermost, sparsely populated and island regions, as well as with third countries (European Commission, 2023). Innovations in fuels (Sustainable Aviation Fuels – SAFs), aircraft design, airlines and airport operations are making significant environmental contributions. Green aviation can be effective when applied with integrated solutions to the industry including operations, materials and manufacturing, structures, energy, propulsion systems, aerodynamics (Afonso et al., 2023). SAF accounts for less than 0.1 per cent of total global jet fuel use. A Virgin Atlantic passenger jet powered by 100% SAF completed a London-New York flight on 28 November 2023, marking the first time a commercial airliner has flown long-haul on SAF, Reuters reported. The flight by a Virgin Boeing (BAN) 787 powered by Rolls-Royce (RR. L) Trent 1000 engines are the first time a commercial aircraft has flown long-haul on 100 per cent SAF. There were no paid passengers or cargo on board (Young & Plucinska, 2023). While there have been experiments with electrifying smaller planes, the batteries are too large for commercial planes, where every ounce of weight matters. This is why SAF is seen as vital in reducing aviation CO_2 emissions (CBC, 2023). Airlines across the world are pinning their hopes on SAF, which uses waste such as cooking oils to reduce emissions by up to 80% compared to fossil fuels, to decarbonize flying before new electric and hydrogen-powered options expected in 2035 (Reuters, 2023). With the impact of globalization in trade, both aviation and maritime activities and passenger numbers have increased, thus increasing the growth momentum of the industries. In addition to the increase in activities and passengers, the increase in trade with emerging economies has also increased travel distances. The number of flights has also increased as low-cost airlines have increased their market share. Aviation activities, including flights as well as the airports themselves, create numerous negative pressures on the environment, including greenhouse gas emissions, air pollution, noise pollution, water demand and waste generation, and emission rates have increased at an accelerated rate (Greer et al., 2020; Lee et al., 2020;

Riley et al., 2021). Carbon emissions accompany the fast-growing aviation market, so exploring the use of SAFs in the European or other region's market is essential (European Commission, 2023). The industry lacks enough alternative and economically viable fuel resources to be environmentally friendly. SAFs or bio jets significantly contribute to a greener aviation footprint (lower carbon footprint and fewer greenhouse emissions). At the same time, they have similar performance characteristics and chemical compositions to conventional kerosene jet fuels (Zhang et al., 2020). Today, there are 11 ASTM-approved SAF pathways (Rosales Calderon et al., 2024). However, the permitted blend ratio ranges from 5% and 50%. The current approved drop-in fuel blending by 50% of SAFs decreases CO_2 emissions by up to 40% and NOx (nitrogen oxides) by 5–10%. However, using 100% SAF or hydrogen, these CO_2 figures can be reduced much further; while hydrogen is a potential competitor of SAFs, and this requires changes in the current aircraft system, in contrast to SAFs, its feedstock is water, a valuable natural resource (Undavalli et al., 2023). Technologies related to producing SAFs and research are in the early stages and require more effort (Undavalli et al., 2023; L. Zhang et al., 2020). Furthermore, even if using 100% SAF that meets sustainability goals is the best option for maximum emissions reduction, the blending limitation is not the sole problem; the necessity to develop operational and safety standards, as well as affordability, are some of the other barriers that come to mind (Kramer et al., 2022). Fuel is the most important cost item in aviation. As increases in fuel prices are reflected in ticket prices, fuel is one of the main factors affecting demand. Sustainable aviation fuels are currently being used only to a certain extent, and it is anticipated that this will gradually increase in the next 10 years. In this respect, a complete transition to SAF 100% use can be considered utopian for the time being. Nevertheless, it is generally accepted that the risk of global warming must be managed, and emissions must be reduced, and sanctions are being implemented to reduce emissions through the development and use of environmentally friendly products. The cost of these sanctions is also high. Therefore, whether to invest in SAF is a multi-criteria decision-making problem that requires risk analysis. Identification risk groups and then prioritized risk are vital to manage risks. For this reason, Systematic Literature Review (SLR) vital to see current situation of academic and scientific research and articles as publication. In recent years, increasing concerns about climate change have been reflected in literature. Accordingly, it is possible to come across various studies regarding sustainability in diverse fields such as tourism (M. R. Khan et al., 2021), education (Kocot et al., 2024), aviation (Proost, 2024), and healthcare (Bian et al., 2023). More narrowly, there is no SLR specifying the key themes and unanswered questions related to SAF to the best of the authors' knowledge. In line with this, the research questions steering this paper are as follows:

1. (RQ 1). What are the main themes and primary topics discussed regarding SAF?
2. (RQ 2). What risks associated with SAF are discussed?
3. (RQ 3). What are the overlooked matters related to SAF?

2. Methodology

This paper employs the SLR to identify the discussed issues and gaps in SAF. The SLR is a transparent and thorough procedure for combining available data regarding a particular topic, which can assist in pinpointing gaps and guiding practice and policy (Üstündağlı Erten et al., 2024). The SLR differs from traditional reviews by being specific to a research question(s) and embracing a scientific and replicable approach (Banomyong et al., 2019; Khan et al., 2022). The eight-step process of SLR was illustrated in Figure 1 (Xiao & Watson, 2019).

Accordingly, researchers should state the research problem and question(s) and design a review protocol in the first step. The process should proceed with searching the literature in databases (e.g., Scopus, Web of Science, etc.), determining the papers that expedient research objectives, checking the accessibility of full text, extracting the data, and synthesizing. As displayed in Figure 2, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) procedure proposed by Page et al. (2021) was adopted. Deciding which database to utilize is important. Pranckutė (2021) stated that academics have yet to reach a consensus on whether Web of Science (WoS) or Scopus is a better bibliographic source, and both remain prominent databases. Thus, both Scopus and WoS were utilized. As of February 14, 2024, a total of 135 records were reached (without filtering) by following search queries and Boolean operators:

Scopus: "sustainable aviation fuel" in title-abstract-keywords AND "risk*" OR "threat*" in all fields.

A similar procedure was applied in Web of Science:

"sustainable aviation fuel" in topic AND "risk*" OR "threat*" in all fields.

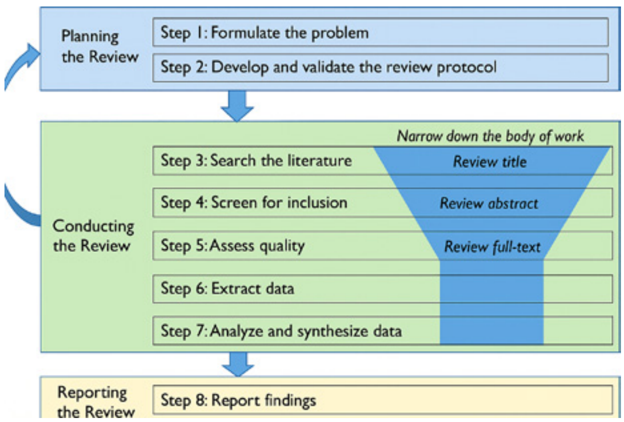

Figure 1. SLR steps (source: Xiao & Watson, 2019)

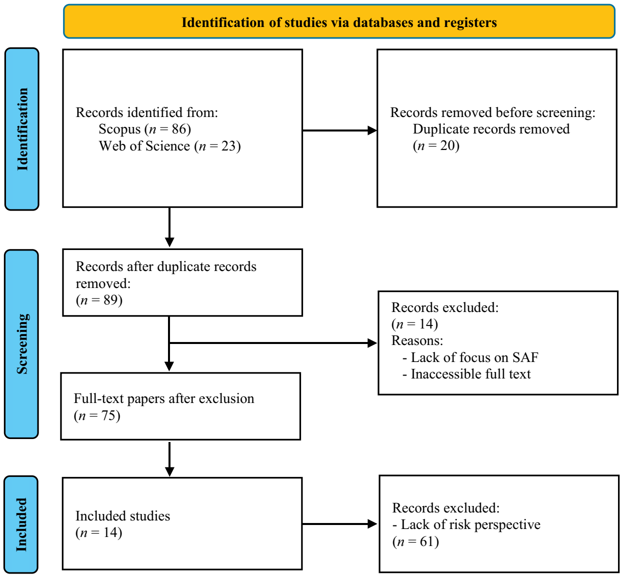

Figure 2. PRISMA procedure (source: adapted by authors)

Subsequently, "article" as document type and "English" as publication language were set (*n* = 109, *n* = 86 from Scopus and *n* = 23 from WoS). The duplicate records were removed using Mendeley Reference Manager, leaving 89 articles. Afterward, studies that did not focus on SAF and whose full texts were not accessible were excluded, leaving 75 articles. The risks and overlooked issues related to SAF were determined based on the studies in the final stage (i.e., *n* = 14). In the final phase, records that did not present a risk perspective directly related to the scope of this study were excluded from the evaluation. Among the reviewed studies, those that did not explicitly define the risk or threat dimension or integrate it into their analysis were assumed not to contain a risk-based assessment. Therefore, 61 out of 75 records lacking these qualities were excluded on the grounds of "lack of risk perspective"; hence ensuring that the final sample reflected the focus of this review and preserved methodological consistency.

3. Results

3.1. Main themes on SAF (RQ1)

The relevant 75 studies reached in the screening phase were meticulously reviewed to determine the main themes (RQ 1). The thematic distribution and the authors addressing the highest themes were presented in Figure 3 and Table 1, respectively. The complete breakdown was presented in the Appendix (Table A1) to enhance readability.

As can be seen in Figure 3, literature approaches SAF in diverse themes, but production is the most common (*n* = 34). The other themes are economic (*n* = 30), environmental (*n* = 20), adoption (*n* = 5), policy (*n* = 7), and other (*n* = 21). In addition, SAF has been addressed from four perspectives in two studies, while four papers covered it from three outlooks (Table 1). Further, while 28 articles covered two themes, 41 articles focused on a single view-

Table 1. Thematic findings (source: created by authors)

Author(s)	Addressed themes
Grim et al. (2022)	4 – Production, Economic, Environmental, Other
Shahriar and Khanal (2022)	4 – Production, Economic, Environmental, Policy
Degirmenci et al. (2023b)	3 – Economic, Environmental, Other
Masum et al. (2023)	3 – Production, Economic, Environmental
Murphy et al. (2015)	3 – Production, Economic, Other
Deng et al. (2023)	3 – Production, Economic, Environmental

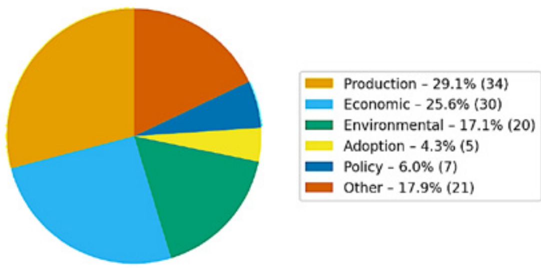

Figure 3. Thematic distribution (source: created by authors)

point (Appendix, Table A1). Therefore, less than half of the papers accessed (i.e., 34 out of 75 studies) have multiple fields. Ahmad et al. (2021) offered a framework based on multi-criteria decision-making for assessing 11 production pathways of SAF. The authors gathered supply chain experts' opinions about 24 criteria under the four groups: environmental (4 criteria), economic (8 criteria), technical (8 criteria), and social (4 criteria). The authors ranked the importance order as environmental impact being the most vital, followed by economic, technical, and social being the least important. According to the ranking results, the highest emission savings were obtained by the process based on Gasification/Fischer-Tropsch. Rubber seed oil was investigated by Baidoo et al. (2022) as a possible source for SAF using the HEFA (hydro processed esters and fatty acids) process. In addition to the technical properties (like density and refractive index), the authors revealed with a feed rate of 100 kg/h of rubber seed oil, the process produced 46% SAF. According to estimates, installing the facility to produce SAF will cost slightly more than $8.5 m in total capital costs and $300k in total operating costs. Moreover, SAF from rubber seed oil has a 1.18% profitability at $4/kg. A similar study without an economic perspective was conducted by Batten et al. (2023) based on corn-sugar-SAF. The mean lifecycle greenhouse gas emissions for the scenario with CCS (carbon capture and storage) of fermentative CO_2 is 5g CO_2e/MJ. The authors indicated that SAF based on corn-to-sugar is promising since it has the potential to replace roughly 12% of the demand for jet fuel by 2030. Another contribution to the literature was made by Field et al. (2022), who examined the potential SAF production from carinata in northern Florida and southern regions of Alabama and Georgia. According to the results of a simulation of cultivating Carinata triennially on a cropland of just over 2 Mha yields enough to produce about 1 billion liters of SAF. Moreover, it was estimated that the croplands' soil greenhouse gas sink varies between 0.24 and 0.32 Mg CO_2e/seed Mg. Gössling and Humpe (2023) approached SAF from a distinct standpoint by modeling the cost of electric and biomass-based fuels combined with several predictors, such as emissions (both CO_2 and non-CO_2), airfare, carbon tax, etc. The scenario findings suggested that the costs per kg of diverse synthetic fuel types are estimated to vary $2.76 to $8.08 by 2050. Compared to fossil fuels costing $0.65, the synthetic fuels remain economically disadvantageous even by the middle of the century. In the lowest-cost scenario, the airfares are projected to increase by 80% in 2050 compared to 2025. Considering the findings and the industry's very low profit margins, the authors proposed implementing an emissions-cost-based carbon tax and highlighted the requirement for a new business model. Kroyan et al. (2022) analyzed the effects of diverse SAF properties on jet engine performance using a mathematical model. The findings indicate that limited improvements in energy efficiency (around 1%) may be possible due to certain properties of SAF (e.g., higher volumetric lower heating value or different atomization characteristics). However, volumetric fuel consumption can increase in many scenarios due to the low fuel density. Therefore, in addition to environmental effects, the study reveals that SAFs can outperform fossil-based fuels in energy consumption. An interview and literature review conducted by Kania et al. (2023) to determine whether ICAO's policy on mitigating climate change is in line with global environmental justice revealed three primary troubles exist: supply of SAF, CORSIA's insufficient scope and features, and uneven improvements in aviation technology. Martinez-Valencia et al. (2021b) classified the supply chain for SAF from the existing literature as product diversification, production growth, risk aversion, efficiency improvements, price parity, and sustainability. The authors, however, pointed out that a novel supply chain design is required.

3.2. SAF related risks (RQ2)

An early effort was made by Lüdeke-Freund et al. (2012). The authors exposed that if an area is utilized for producing feedstock for SAF and demand remains stable, a significant risk might occur that natural resources and ecosystem services, such as soil fertility, biodiversity, and flood prevention, could be affected. Furthermore, the landlessness risk can adversely affect the local community's livelihood and lead to novel social and economic crises. Landlessness risk can bring forward both social and environmental crises. Land rights are one of the main principles in RSB's sustainability framework (Roundtable on Sustainable Biomaterials [RSB], 2024). The regional investigation by RSB (2024) demonstrated that several country-level risks exist, with the most significant being deforestation caused by agricultural expansion. Additional risks varying from low to moderate were stated as water stress, food security, human and labor rights, and governance performance. Therefore, the selection of raw materials to be used in SAF production must be carefully evaluated not only in terms of technical performance but also sustainability indicators such as regional land pressure, agricultural expansion potential, and social vulnerability; since these factors may render certain regions unsustainable for specific SAF pathways, raw material–region compatibility is critical in SAF pathway selection. Ahmad and Xu (2021) explored the opinions of stakeholders concerning SAF by utilizing cognitive maps based on interviews. Accordingly, some stakeholders are worried about SAF pathways, while others are not as worried since numerous chemical processes exist for producing SAF. On the other hand, the issue of which feedstock should be chosen for SAF production is considered the biggest problem among stakeholders. In line with this, it is stated that the local availability of relevant feedstock is significant to reduce production risk. Furthermore, it was also emphasized that traditional fuel companies may face the risk of losing their licenses and that government control in reducing financial risks may harm market dynamics. Parallel research was executed by Dodd and Yengin (2021). The authors interviewed 36 experts, including 11 from airlines, 10 from fuel companies, and 15 policymakers. According to fuel firms, the leadership position should be taken by air carriers since there isn't any mandate to compel them to operate with SAF. On the other hand, air carriers emphasized that single airline leadership will not bring significant results and that the entire SAF supply chain should take joint leadership position. Furthermore, airlines have concerns about the reliability of fuel companies as biofuel companies that do not even have any production standards say they can produce SAF. Policymakers expressed that there are various barriers in such perspectives as technical, political, legislative, environmental, social, and economic. A further difficulty in government-industry joint working is the rareness of humility, knowledge, and collaboration. The obstacles and challenges mentioned above cause possible partners to consider the SAF industry as risky. A similar effort was conducted by Babuder et al. (2024), interviewing stakeholders from government bodies and industry experts to academics. They strived to the outlooks of stakeholders regarding the impact of sustainability attempts, such as hydrogen, electric, and SAF, on operations. The results revealed that SAF is less risky than hydrogen and electricity. Specifically, stakeholders stressed that a high amount of SAF may detrimentally affect some parts of the hydrant refueling system, such as fuel pumps, filters, and engine seals, of older aircraft. This also could reflect on the maintenance process due to further safety checks. In addition, airports may face the extra costs of establishing multiple tanks for different SAFs since diverse blends must be stored apart. Stakeholders share the thought that electric risks safety because of the high voltage. As to hydrogen, some interviewees think that if something goes wrong, the water produced by fuel cells must be dumped onto the surface. It might lead to problems for grounded aircraft, particularly in icy and cold weather. Moreover, Degirmenci et al. (2023b) stressed that hydrogen's self-ignition temperature is more than two times that of kerosene, yet a poorer spark can ignite it. Additionally, transporting it with a compressed hydrogen (CGH_2) truck is riskier than a truck with liquid hydrogen (LH_2). Transporting with a pipeline's capital cost is high, such as ship and truck. Capaz et al. (2021) examined the mitigation costs of diverse pathways of SAF for Brazil. The authors stated the potential risks of novel plants boost the expenses, and hence, the growth factor variable of their model refers to potential risks regarding the startup stage. The results suggested that the HEFA process with palm and soya could be a strategic choice if acquired from certain areas with low risk in terms of land use change. As to mitigating the economic risks, Diniz et al. (2018) examined the financial viability of producing SAF from oilseeds. They assumed the maximum loss probability rate for an investor to bid for a project is 30%. The sensitivity analysis results revealed that fuel prices and feedstocks are the primary drivers of facilities' economic performance. The plant aiming for maximum production of Jatropha, Carinata, and Camelina needs incentives of \$0.61, \$0.39, and \$0.31 per liter SAF to reduce the possibility of loss to around 30%. On the other hand, a parallel paper based on pennycress was authored by Trejo-Pech et al. (2021). The authors estimated the most likely discount rate at 14% with risk adjusted. The findings demonstrated that this rate is economically attractive for the firm, but the maximum buying price paid by crushing firms to farmers is not enough to attract them to produce pennycress. Besides, according to the cash flow model, the firm faces a high financial risk if the rate is lower (11%) or higher (17%) than the optimum rate. The Monte Carlo simulation operated by Carlson et al. (2023) revealed that varying incentives based on the price of crude oil are an effective way to support SAF and lessen the economic risk by reducing up to \$182 per tonne of CO_2e. The risk analysis conducted by Karami et al. (2022) indicated that the highest net present value, \$2,996/ha, can be reached by the rotation of corn-corn soybean with carinata. Further, carinata can decline the crop rotation risk by 8.1% if a contract price of at least \$440.9 per tonne is offered. Farmers may, therefore, want to use the risk-reducing and profitability-enhancing carinata to meet enlarging needs for SAF. Similar findings can be seen in the research conducted by Ullah and Dwivedi (2022), aiming to determine the willingness of farmers to produce carinata. They decided the farmers' decisions for land allocation for producing willingness carinata according to three factors: maximum profit, risk avoidance, and neighborhood farmers' impact. The authors suggested offering a subsidy having a design that considers the risk of declining demand for carinata in the future. Even if there is a substantial interest in the effects of policies on the investment return for assuring the investment for SAF facilities, Martinez-Valencia et al. (2023) concluded that a policy based solely on emission or de-risk is not satisfactory to attract the establishment of a conversion facility. Instead, an incentive based on emission, de-risk, and production can diminish the investment risk by boosting production and decreasing the financial loss probability. Wang et al. (2021) analyzed the influence of policies to lessen economic risk. The authors modeled the loan guarantee as a decline in the debt cost from 8% to 3%. The results meant this policy both reduces the minimum selling price and increases the net present value for all SAF pathways. Grim et al. (2022) presented the risks of electrifying SAF production. Technically, the knowledge about durability, stability, and performance tests of electrolyzers is limited. In addition, the electrolysis based on CO_2 has poorer performance than the counterparts based on H_2O. From a market perspective, high capital costs, the absence of infrastructure for transport, whether there will be a change in resource preference in the future, material sourcing, and competition were considered risky. They also mentioned the risks in integrating systems featuring the shortage of opportunities in modularity and intensification, the requirement of expertise due to complex processes, managing the erratic nature of the electrical input/process shutdowns, and determining the appropriate size for the supporting thermocatalytic and

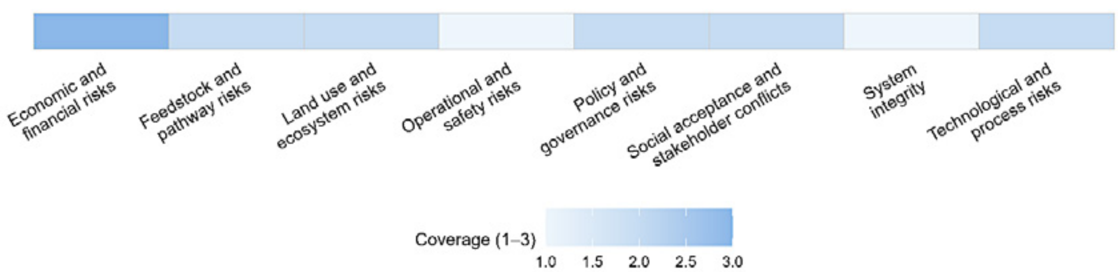

Figure 4. Risk theme coverage (source: created by authors)

biological conversion stages to escalate the capacity. The illustration of the risk theme coverage was presented in Figure 4.

3.3. Overlooked matters related to SAF (RQ3)

As mentioned above, most papers regarding the SAF focus mainly on production with various themes. In addition, the literature has made valuable efforts to spot the potential risks related to SAF. It is believed that the risk of landlessness mentioned in the study by Lüdeke-Freund et al. (2012) has not been sufficiently discussed. This risk could lead to intractable conflicts in many countries. In addition, the risk of existing fuel companies losing licenses, as noted by Ahmad and Xu (2021), will force them to face financing difficulties and business model changes. The risks related to SAF have been tried to address mainly economic aspects, including the supply chain (Degirmenci et al., 2023b), have been discussed, and policy recommendations have been provided (Diniz et al., 2018). An in-depth review by Dodd and Yengin (2021) showed conflicts between stakeholders and that responsibility taken by a single stakeholder is unlikely to provide significant benefits. It is not only field experts who see the SAF industry as risky. Engelmann et al. (2024) found that regular people also view carbon capture and utilization technologies as risky and skeptical. Moreover, Xu et al. (2022) discovered that risk perceptions of people regarding SAF are one of the primary drivers of willingness to pay. Therefore, it is asserted that enlightening and transparent campaigns on SAF are required. Another significant matter neglected is the lack of holism. Many critical questions remain unanswered, including whether the fuel used when delivering SAF to the relevant airports will be environmentally friendly, how to grow and fund the number of airports with ongoing or batch deliveries, and whether all ground vehicles, particularly those transporting SAF from airport fuel depots to aircrafts, will also use environmentally friendly fuel. Is reducing emissions during flight truly sufficient for achieving "net-zero" emissions, or is it more effective to implement measures in both air and ground operations? At this point, the fact that the global aviation industry consumes approximately 300 million tons of conventional fuel annually (World Economic Forum [WEF], 2020) further highlights the importance of these overlooked issues. Meeting demand on this scale with SAF will create much greater pressure on raw material supply, production capacity, supply chain infrastructure, storage and distribution systems, the coordination of ground and air operations, and cost structures. Therefore, these issues, which are not addressed or are only addressed to a limited extent in the existing literature, should be reassessed, considering the true scale of the industry.

The research results from the studies reviewed in this article showed that various SAF derivatives can be obtained from a wide range of raw materials, in varying amounts. However, the agricultural land that could be used for their production is currently being used for other commodities. In the studies reviewed as part of the SLR, no papers were encountered that focused on which raw material or production route is riskier than others in terms of fire or how firefighting procedures differ from one route to another. Besides, no studies were found that addressed whether there is an additional training requirement for SAF, especially for ground handling personnel. The SLR shows that no single measure is sufficient to achieve a net-zero goal. In addition, the possibility that sanctions or decisions taken by governments and/or authorities will lead all aviation stakeholders to be green to the same extent and to continue their activities with the same effectiveness and efficiency with a focus on green aviation is open to debate. As a result of sanction decisions taken by authorities or governments globally, new costs will arise in both production and utilization areas, and it is anticipated that these additional costs will be reflected in ticket prices. Additional costs and new risks have the potential to cause new problems among stakeholders in the aviation industry. An imbalance in the supply and demand balance, especially due to a decrease in demand, may reduce traffic and therefore revenues. This will create the risk of shrinking the sectoral economy. Airports that focus on non-aeronautical revenues as airport cities may also face consequences such as sharply declining or even stagnant demand, just like in COVID times. In addition, it is understood from the review results that airports will face new risks in the storage and fueling of SAF-derived fuels. The potential reduction in traffic will have a negative impact on both the structural and economic efficiency of airports, as well as airports and ground operations. As SAF operation has different characteristics from the current fuel, both safety risk management procedures and policies will need to be revised. The production, supply, and use of SAFs have not yet become a widespread practice. This situation, which is at an experimental stage, also requires consideration of the risks associated with the sustainability of SAF investments. Fuel is one of the biggest cost items in aviation. It is also one of the risk areas in terms of safety and security. Therefore, a change to the SAF foundation has the potential to impact all sectors of the industry – through social, practical and economic implications.

4. Conclusions

Based on all findings, risk management is fundamental to SAF. Investing in and maintaining a politically, economically, operationally, strategic and economically sustainable SAF production, supply and use, and initiating and disseminating its use, without detecting risks, carries many risks. Based on the results of SLR in this regard, it has been concluded that studies on risk detection and analysis should be increased. The first step in the risk management process for achieving the goal of the green aviation industry is to identify potential risks. Once the risks have been identified, management strategies can be developed, and investment decisions can be optimized under the scenarios to be developed. At present, although the sector has a net-zero emissions target for 2050, the result of the ICAO assessment, based on three different scenarios, is that this target cannot be achieved even in 2070. Furthermore, the studies show that the use of SAF alone does not suffice to achieve zero emissions, and that serious economic risks exist. In the aviation industry, which is dominated by economies of scale, it is unlikely that the price of SAFs will become relatively cheap. Incomplete or inaccurate identification of risks will lead to incomplete and inaccurate risk management. Therefore, identifying and managing risks is critical to decision making. In this respect, the risks identified in literature as results of related research will be identified in future research.

Efforts to increase sustainability are evident to varying degrees in every industry. However, this study reveals a lack of holism in SAF. This strict conclusion is led by the following main findings and gaps:

- The literature widely focuses on production, economics, and environmental aspects. However, the operational integration, airport infrastructure, ground handling, safety, and security procedures of SAF have not received sufficient attention.
- Economic and supply-chain related subjects have been discussed. Nevertheless, fire prevention, storage process and conditions, emergency procedures, and compliance with ground handling equipment need further study.
- Social acceptance and public perception are, albeit to a lesser extent, among the topics under discussion. Nonetheless, communication strategies to increase trust among stakeholders are unclear. For instance, how can the trust of environmentally conscious air travelers be regained after greenwashing news?
- Diverse SAF pathways are continuously researched, yet these efforts commonly overlook the interconnected nature of stakeholders.
- Environmental benefits are consistently expressed. However, the impact of SAF on novel infrastructure requirements and its financing, potential changes in operations, and the efficiency estimation of stakeholders are vague.

Accordingly, the following recommendations can be offered to industry and policymakers:

- Holistic models should be designed adopting a systems approach that incorporates the integration of SAF into airport and ground operations.
- Empirical investigations regarding fire precautions, suitable storage processes, and compatibility with ground equipment. Since the chemical properties of SAFs vary, safety and security protocols and risk management procedures should be dynamic.
- SAF-unique comprehensive training programs need to be developed, and mandatory participation by staff should be ensured.
- Efforts should be made to increase social acceptance. Appropriate communication campaigns must be informative and, more crucially, transparent.
- Long-term financial risk modeling regarding SAF investments is required. Since potential incentives that governments may provide also constitute an economic risk, possible price fluctuations in production and supply chains should be simulated, and ways to share the risk should be explored.

In brief, it is necessary to include not only environmental and economic perspectives, but also social, governance, and communication perspectives, among others. Otherwise, in addition to trust issues (e.g., greenwashing), it becomes difficult to create long-term benefits. Focusing on one or a few elements of the system can prevent the identification of successive risks. Therefore, every process from SAF production to its use in flights must be considered, and a suitable framework must be established accordingly. Currently, even the economic drawback of SAF compared to traditional jet fuel remains unresolved, and the lack of a holistic approach means that many issues and risks are not even recognized, making it difficult for the aviation industry to achieve its net-zero target. The existence of multiple feedstock options with similar emission reduction potential leads to strategic uncertainty for governments. Likewise, although subsidies are widely considered an effective policy to cover the currently high costs of SAF, this approach can create a significant long-term financial burden for states. Therefore, rather than solely relying on direct subsidies to reduce SAF costs, broader strategies such as increasing feedstock diversity, scaling up production processes, and developing market mechanisms should be considered.

This paper has some limitations. Only academic articles written in English were included in the analysis. Technical documents and sectoral reports were not incorporated into this review. Besides, the full texts of some studies could not be accessed. This research may contribute to creating social implications such as developing awareness, guiding future work via synthesized literature, and supporting capacity building about green aviation research to both society and adding value beyond operational to practical implementation. Future research should establish integrated models combining technical, economic, operational, and social dimensions to more thoroughly examine the integration of SAF into the aviation ecosystem. Comparative studies investigating different SAF production pathways and combining risk and performance analyses can provide an insightful knowledge ground for industry and policymakers. Further, examining the infrastructure, operational requirements, and supply chain alignment of airports during the transition to SAF through scenario- or simulation-based research will provide valuable contributions to implementation. Considering the impact of SAF's social acceptance and risk perception on its intended use, it is important to increase social science-based research that can guide communication strategies. Furthermore, modeling studies addressing the long-term effects of the transition to SAF on ticket prices, demand changes, and the aviation economy need to be increased. Finally, empirical and field-based research on practical applications such as storage, transportation, fire safety, and operational requirements for field staff will contribute to a clearer understanding of the risks that may arise in practice. Interdisciplinary studies conducted in this context are critical to the safe and sustainable widespread adoption of SAF.

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APPENDIX

Table A1. Complete breakdown of the thematic findings (source: created by authors)

Author(s)	Production	Economic	Environmental	Adoption	Policy	Other
Ahmad and Xu (2021)						X
Ahmad et al. (2021)	X					X
Alam et al. (2021)		X	X			
Amicarelli et al. (2021)				X		
Babuder et al. (2024)						X
Baidoo et al. (2022)	X	X				
Batten et al. (2023)	X		X			
Bergero et al. (2023)		X	X			
Capaz et al. (2021)		X				
Carlson et al. (2023)		X			X	
Changxiong Li and Merkert (2023)		X	X			
Colelli et al. (2023)		X				X
Collis et al. (2022)		X	X			
Cui and Chen (2024)		X	X			
Degirmenci et al. (2023a)						X
Degirmenci et al. (2023b)		X	X			X
Deuber et al. (2023)		X	X			
Diniz et al. (2018)		X				
Dodd and Yengin (2021)				X		
Durand et al. (2021)			X			X
Field et al. (2022)	X					
Gössling and Humpe (2023)		X	X			
Gössling and Lyle (2021)					X	
Grim et al. (2022)	X	X	X			X
Grimme (2023)		X				
Guarenghi et al. (2022)	X	X				
Guo et al. (2023)	X					
Hamdan et al. (2022)		X				X
Hasan et al. (2021)						X
Jie Wu et al. (2023)	X					
Kania et al. (2023)					X	
Karami et al. (2022)	X	X				
Koirala et al. (2023)	X					
Kroyan et al. (2022)			X			X
Liu et al. (2023)	X					
Lüdeke-Freund et al. (2012)	X					
Martinez-Valencia et al. (2023)		X			X	
Martinez-Valencia et al. (2021a)	X					X
Martinez-Valencia et al. (2021b)						X
Masum et al. (2023)	X	X	X			
McCollum et al. (2021)	X			X		
Micheli et al. (2022)			X			
Montoya Sánchez et al. (2022)	X					
Mousavi-Avval et al. (2023)	X					
Murphy et al. (2015)	X	X				X
Oh et al. (2024)						X
Palmeros Parada et al. (2021)						X
Peiffer et al. (2019)						X

End of Table A1

Author(s)	Production	Economic	Environmental	Adoption	Policy	Other
Petersen et al. (2022)	X	X				
Pio et al. (2023)	X					
Przysowa et al. (2021)						X
Puschnigg et al. (2023)	X					
Ram and Salkuti (2023)	X					
Rony et al. (2023)	X					
Rupcic et al. (2023)			X			
Schillaci et al. (2023)	X					
Seber et al. (2022)			X			
Seymour et al. (2024)		X				
Shahriar and Khanal (2022)	X	X	X		X	
Shehab et al. (2023)		X	X			
Su-ungkavatin et al. (2023)	X					X
Trejo-Pech et al. (2019)		X				
Trejo-Pech et al. (2021)	X	X				
Trinh et al. (2021)		X			X	
Ullah and Dwivedi (2022)	X			X		
Ullah et al. (2023)	X					X
Walter et al. (2021)	X					
Wang et al. (2021)		X			X	
Woodroffe and Harvey (2021)	X					
Xu et al. (2022)				X		
Yakovlieva et al. (2023)	X					
Yang et al. (2021)						X
Deng et al. (2023)	X	X	X			
Zhang et al. (2024)			X			
Zhu et al. (2023)	X					