



ANÁLISE DE PATENTES EM COMBUSTÍVEIS SUSTENTÁVEIS DE AVIAÇÃO: DINÂMICAS GLOBAIS, PRINCIPAIS ATORES E OS CAMINHOS PARA O PROTAGONISMO DO BRASIL **PATENT ANALYSIS IN SUSTAINABLE AVIATION FUELS: GLOBAL DYNAMICS, KEY ACTORS, AND BRAZIL'S PATH TO PROTAGONISM**

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Resumo

Este trabalho analisa a atividade inventiva global relacionada aos Combustíveis Sustentáveis para Aviação (SAFs), utilizando dados de patentes como proxy para o desenvolvimento científico e tecnológico. O estudo buscou caracterizar a evolução temporal do patenteamento, identificar os principais detentores de patentes, mapear a distribuição geográfica dos depósitos e analisar as principais rotas tecnológicas associadas aos SAFs. A metodologia incluiu uma busca abrangente na plataforma Questel Orbit IP Business Intelligence em julho de 2025, resultando na identificação de 972 famílias de patentes, das quais 220 foram publicadas apenas em 2023. Os resultados indicam que a atividade inventiva é recente e vem crescendo de forma expressiva desde 2021, refletindo pressões regulatórias e a abertura de mercados. Observou-se elevada concentração das patentes em poucas empresas, principalmente fabricantes de motores aeronáuticos e companhias dos setores de petróleo e químicos. Estados Unidos, China e Europa concentram a maior parte dos depósitos, mas o Brasil destaca-se na América Latina pela intensidade de depósitos realizados, embora sem participação relevante de empresas, universidades ou institutos de pesquisa nacionais. Conclui-se que o setor de SAFs ainda está em formação, com múltiplas rotas tecnológicas competindo e janelas abertas para novos entrantes. Para o Brasil, país com histórico em biocombustíveis, a construção de um papel protagonista depende de políticas públicas direcionadas, investimentos empresariais em P&D e da articulação estratégica entre indústria, governo e academia.

Palavras-chave: combustíveis sustentáveis para aviação; patentes; desenvolvimento tecnológico; Brasil; biocombustíveis

Abstract

This paper analyzes global inventive activity related to Sustainable Aviation Fuels (SAFs), using patent data as a proxy for scientific and technological development. The study sought to characterize the temporal evolution of patenting, identify the leading patent holders, map the geographical distribution of filings, and analyze the main technological pathways associated with SAFs. The methodology involved a comprehensive search on the Questel Orbit IP Business Intelligence platform in July 2025, resulting in the identification of 972 patent families, with 220 published in 2023 alone. The results show that inventive activity is recent and has been growing significantly since 2021, driven by regulatory pressures and market-opening measures. Patent ownership is highly concentrated among a few companies, primarily aircraft engine manufacturers and oil and chemical companies. The United States, China, and Europe account for most filings, but Brazil stands out in Latin America for its filing intensity, although with little participation from domestic companies, universities, or research institutes. The study concludes that the SAF sector is still emerging, with multiple competing technological pathways and open windows of opportunity for new entrants. For Brazil, a country with a strong biofuels tradition, building a leading role will require targeted public policies, corporate investment in R&D, and strategic coordination among industry, government, and academia.

Keywords: sustainable aviation fuels; patents; technological development; Brazil; biofuels.

1. INTRODUCTION

Sustainable Aviation Fuels (SAFs) are renewable or low-carbon fuels specifically designed to replace conventional fossil-based jet fuels in the aviation sector (ICAO, 2025). They can be derived from a variety of feedstocks and processes, including biological oils and fats, lignocellulosic biomass, alcohols, and even renewable electricity combined with captured carbon. SAFs are widely recognized as one of the most promising pathways to decarbonize aviation, a sector that is particularly difficult to abate due to its high energy intensity, long asset lifecycles, and the limited feasibility of direct electrification for long-haul flights (ICAO, 2025; US DEPARTMENT OF ENERGY, 2025). Despite their strategic importance, SAFs face significant challenges that hinder large-scale deployment. Current production costs are substantially higher than those of conventional jet fuel, creating a cost penalty that constrains market adoption. Moreover, the SAF landscape is characterized by multiple competing technological pathways, such as Hydroprocessed Esters and Fatty Acids (HEFA), Alcohol-to-Jet (ATJ), Fischer-Tropsch (FT) synthesis, and Power-to-Liquid (PtL) processes. Each pathway has distinct technological requirements, feedstock needs, and scalability prospects, and there is still no clear dominant design. This technological fluidity is consistent with the theoretical framework of



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Dominant Design, which characterizes early innovation phases as an "era of ferment" where multiple technological trajectories coexist before a dominant configuration emerges (Abernathy & Utterback, 1978; Anderson & Tushman, 1990). Situating SAFs within this perspective highlights their systemic uncertainty and the importance of intellectual property in shaping future trajectories.

In such a context of uncertainty, understanding the intensity and direction of inventive activity becomes essential. Patent data, in particular, provide valuable insights into how technological development is unfolding, which actors are leading innovation, and where investments in research and development (R&D) are being concentrated (Flamand, 2016). Tracking the evolution of patenting activity can also help identify collaboration networks and technological niches that may overcome existing barriers and mitigate the high costs associated with SAF production.

The objective of this study lies in the identification, description, and analysis of global inventive activity in SAFs using patenting as a proxy for technological development. The central question driving this work is: how is SAF-related patenting activity characterized worldwide? We aim to map the evolution of patent filings over the last two decades, identify leading companies and institutions, analyze cooperation networks, and assess geographical distribution. By providing a global overview of inventive activity, this work offers critical evidence to inform investments and policy design in Brazil, enabling the country to better position itself in the SAF innovation landscape and to develop strategies aligned with international technological trends.

2. METHODOLOGY

The theoretical framework guiding this article draws on the literature of Innovation Systems, with a particular emphasis on Technological Innovation Systems (TIS). This perspective highlights that the development and diffusion of new technologies are not solely the result of individual firm strategies, but rather emerge from the interaction of multiple actors, institutions, and infrastructures that collectively shape the innovation process (Bergek *et al.*, 2008; Carlsson; Stankiewicz, 1991; Hekkert, Marko; Heimeriks, Gaston; Harmsen, 2011). Within this framework, patents are not merely instruments of legal protection but act as endogenous institutional elements of the system, influencing knowledge creation, market formation, entrepreneurial experimentation, and the coordination of resources. Thus, the analysis of patents offers an entry point to assess how SAF-related technologies are evolving within a broader systemic and institutional context. In this sense, the use of patent data in this study is not restricted to a descriptive mapping of inventive activity but is positioned within the repertoire of the Economics of Innovation as an established indicator of scientific and technological development (Griliches, 1990). Patents provide codified signals of technological trajectories and, when analyzed in terms of their distribution, citation networks, and ownership concentration, reveal the underlying dynamics of systemic innovation. This theoretical anchoring allows the empirical results presented here to be interpreted not only in terms of trends in inventive activity but also in relation to the functions and governance mechanisms of the emerging SAF Technological Innovation System.

In the Industrial Property domain, patents constitute one of the primary mechanisms for granting exclusive rights over inventions. According to the World Intellectual Property Organization (WIPO, 2025), *"A patent is an exclusive right granted for an invention. Patents benefit inventors by providing them with legal protection of their inventions.."*

Patent holders enjoy the right to control the use of their inventions during the period of protection, including the possibility to license or transfer rights to third parties (WIPO, 2025a). Once the exclusivity period ends, patents enter the public domain, allowing unrestricted use by society. This feature underlines the public interest of patent systems as a mechanism for disseminating technological knowledge (Griliches, 1990).

The use of patent data has gained increasing attention in innovation and technology management studies (Barassa, Edgar, Consoni, 2015; Pilkington; Dyerson, 2006). Patents provide valuable information that can be used to analyze technological evolution over time and across sectors. Beyond their role as legal appropriation mechanisms, patents can also be understood as endogenous institutional components of Technological Innovation Systems (TIS). They not only codify knowledge but also function as governance instruments, shaping trajectories, coordinating actors, and signaling resource allocation (Teece, 1986; Cohen *et al.*, 2000; Hsu & Ziedonis, 2013). This broader view strengthens the rationale for using patent data as proxies of systemic innovation dynamics.

Although not all technological developments are captured through patenting—given the use of trade secrets, know-how, and other non-formal mechanisms of protection—patent data remains a powerful tool for mapping technological trajectories and identifying the leading players involved. This methodological approach is particularly relevant for sectors such as Sustainable Aviation Fuels (SAFs), which are characterized by multiple competing technological pathways and significant cost and scale-up challenges.



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This article employs patent analysis to identify the global actors engaged in SAF innovation, as well as the possible technological routes currently under development. The patent search was conducted on July 30, 2025, using the Questel Orbit IP Business Intelligence platform¹. The following Boolean command was adopted:

((SUSTAINABLE AVIATION FUEL OR SYNTHETIC PARAFFINIC KEROSENE OR RENEWABLE AVIATION FUEL OR LOW-CARBON AVIATION FUEL OR JET BIOFUEL OR GREEN AVIATION FUEL OR ECO-FRIENDLY AVIATION FUEL OR BIOJET FUEL OR BIO-AVIATION FUEL OR ALTERNATIVE AVIATION FUEL OR ADVANCED BIOFUELS FOR AVIATION)/TI/AB/CLMS/DESC/ODES/OBJ/ADB/ICLM/KEYW/TX AND (STATE/ACT=ALIVE))

This search equation targeted active patent families that explicitly reference SAF-related keywords in their title, abstract, claims, or other descriptive fields. The time frame of the search extended up to July 2025.

To ensure robustness and comparability, the retrieved patent publications were organized into patent families, defined by the OECD Patent Statistics Manual as “*the set of patents (or applications) filed in several countries which are related to each other by one or several common priority filings*” (Organisation for Economic Co-operation and Development, 2009).

In order to accurately capture the inventive dynamics of the sector, the analysis considered the priority dates of the patent families as the primary temporal reference. The priority date represents the earliest filing date of a patent application within its family and is generally the closest indicator of when the inventive activity actually occurred. By using priority dates rather than publication or grant dates, the study provides a clearer and more precise visualization of the temporal evolution of SAF-related inventive activity, minimizing distortions caused by processing delays in different patent offices.

It is important to recognize the inherent limitations of using patent data as an indicator of technological development. Not all innovative activities result in patent filings; companies may instead rely on alternative mechanisms such as trade secrets, lead-time advantages, or know-how. Additionally, patenting practices and the propensity to seek protection vary significantly across industries and countries, which may bias the representation of actors or geographies. There is also an intrinsic delay between patent filing and publication, typically around 18 months, which can obscure the most recent developments.

Finally, the SAF sector itself presents additional complexity: many technologies are still in early research or pilot phases, which may reduce the volume of patents filed, while others are embedded in broader chemical or energy technologies, making it challenging to isolate SAF-specific inventions. For these reasons, the results presented here should be interpreted as a proxy of inventive activity rather than a comprehensive measure of all technological advances in the SAF field.

3. RESULTS AND DISCUSSION

This section presents a comprehensive analysis of the global patent landscape related to Sustainable Aviation Fuels (SAFs), combining the presentation of results with an integrated analytical and strategic discussion. All subsequent analyses are based on primary data extracted from the Questel Orbit IP Business Intelligence platform, which provides one of the most comprehensive global patent databases. The discussion is structured into six interconnected sub-sections, each focusing on a key dimension of the inventive activity mapped in this study.

3.1. Temporal evolution of patent publications

The analysis of patent families related to Sustainable Aviation Fuels (SAFs) shows a clear upward trajectory over the last decade, with a pronounced acceleration beginning in 2020 and continuing through 2021 and 2022. This growth culminates in a peak in 2023, when 220 patent families were published, contributing to a total of 972 patent families mapped globally in the database. This pattern reflects the combined effect of mounting regulatory pressures—such as the strengthening of ICAO’s Carbon Offsetting Reduction Scheme for International Aviation (CORSIA); renewable energy directives in the European Union—and the progressive opening of markets for SAFs through mandates and voluntary corporate commitments. These external drivers have created a strong incentive for companies to invest in Research and Development (R&D), resulting in an expansion of inventive activity across multiple technological pathways. It is important to note that patent publication data inherently underestimates the most recent period. Due to the standard 18-month confidentiality period between patent filing and publication, the data for 2024 and 2025 likely does not capture the full extent of inventive activity underway. Nevertheless, the trend observed through 2023 provides robust evidence of increasing interest and strategic investment in SAF technologies.

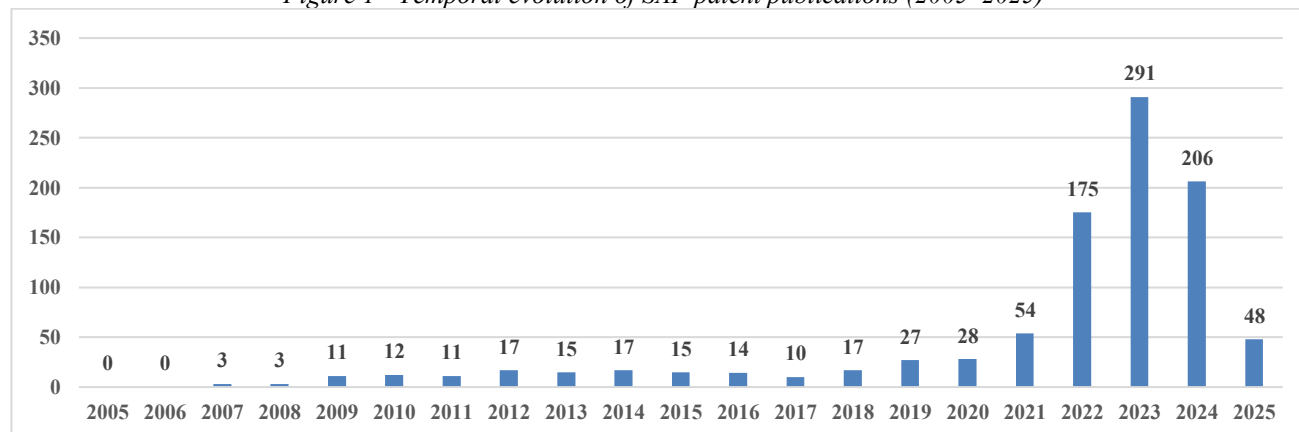
¹ The analysis presented in this article was conducted using the **Questel Orbit IP Business Intelligence** platform, recognized as one of the largest and most comprehensive intellectual property databases in the world. The platform covers more than 96 national and regional patent offices, including USPTO (United States), EPO (Europe), WIPO (International), CNIPA (China), JPO (Japan), and others, allowing the integration of global data on publications, legal status, patent families, and international classifications (IPC/CPC). This broad coverage makes Questel Orbit a strategic tool for technology intelligence studies and for analyzing trends in inventive activity (Questel, 2025).



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Figure 1 - Temporal evolution of SAF patent publications (2005–2025)

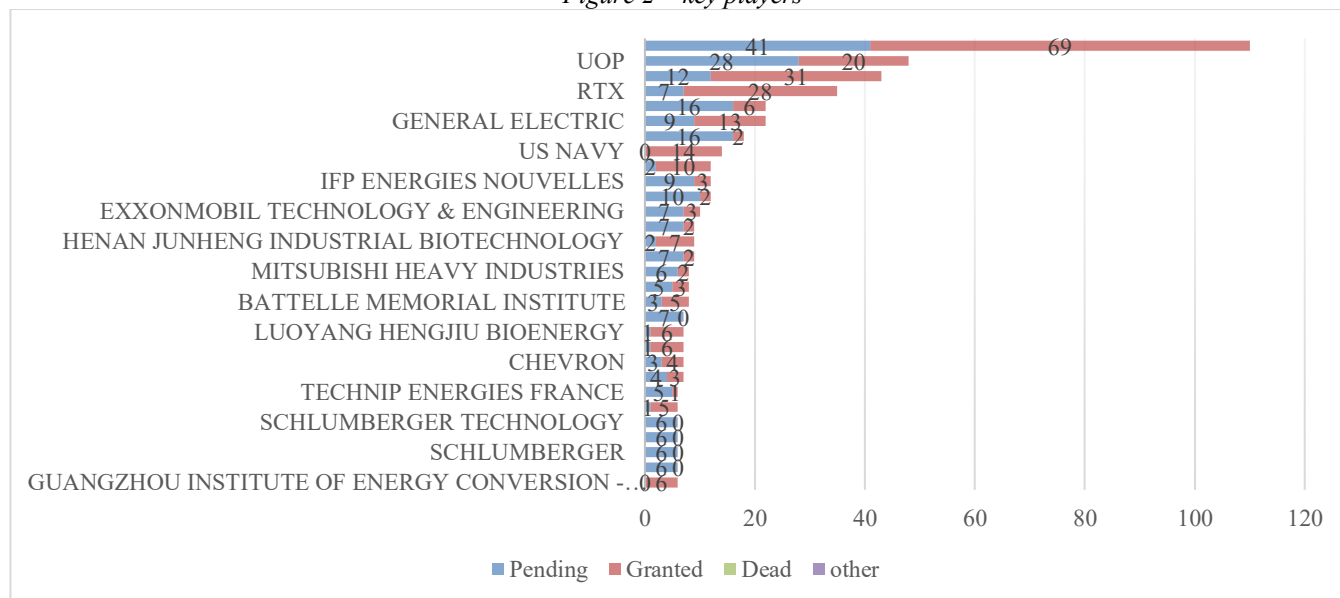


This significant growth underscores the global relevance of SAFs, which are emerging as a critical pillar in the decarbonization of aviation. Although the number of patents remains modest compared to more mature technological fields, the intensity of recent inventive activity highlights the sector's incipient and still emerging nature. Each patent family represents not only a potential technological advance but also a deliberate financial commitment by the applicant, reflecting confidence in the commercial prospects of the underlying innovation. As such, the sharp growth in patent activity can be interpreted as a proxy for the broader momentum of SAF development, signaling a sector that is rapidly gaining strategic importance within the global energy transition.

3.2. Leading applicants and collaborative networks

The analysis of patent ownership reveals a marked concentration among a small number of actors, underscoring the strategic relevance of Sustainable Aviation Fuels (SAFs) for a core group of organizations. A prominent feature of this landscape is the presence of aircraft engine manufacturers, most notably Rolls-Royce, the world's largest producer of aircraft engines. Rolls-Royce stands out as the leading applicant in the SAF patent landscape, reflecting its clear interest in understanding how SAFs will affect the performance and evolution of its propulsion technologies. Beyond simply anticipating technical requirements, the company appears to be leveraging patenting as a way to capture potential benefits in terms of enhanced products, optimized equipment, and new services linked to SAF adoption.

Figure 2 – key players





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Following Rolls-Royce, the dataset highlights the active participation of chemical companies and oil and gas majors, for whom SAFs represent a natural extension of their existing businesses. These companies, including UOP, Neste Oil, TotalEnergies, and others, have both the industrial infrastructure and the feedstock supply chains to support large-scale fuel production. Their engagement in SAF-related patenting suggests a deliberate strategy to secure a competitive position in what is expected to be a significant future market. However, the concentration of portfolios in a few incumbents also raises the possibility of patent thickets, that is, dense webs of overlapping IP rights that increase litigation risks and transaction costs (Shapiro, 2001). Such strategic patenting behavior is consistent with the so-called "patent paradox," where firms accumulate patents less to exclude rivals than to secure bargaining power and freedom to operate (Hall & Ziedonis, 2001).

3.3. Legal status of patents

The legal status analysis of SAF-related patent families (Figure 2) demonstrates a sector that is highly active and still in its formative stages. The majority of patent families identified in the dataset are either granted or pending examination, while virtually no cases of abandoned, lapsed, or expired patents were observed. This finding reinforces the conclusion that SAFs represent an emerging technological field, with most innovations still within their period of exclusivity.

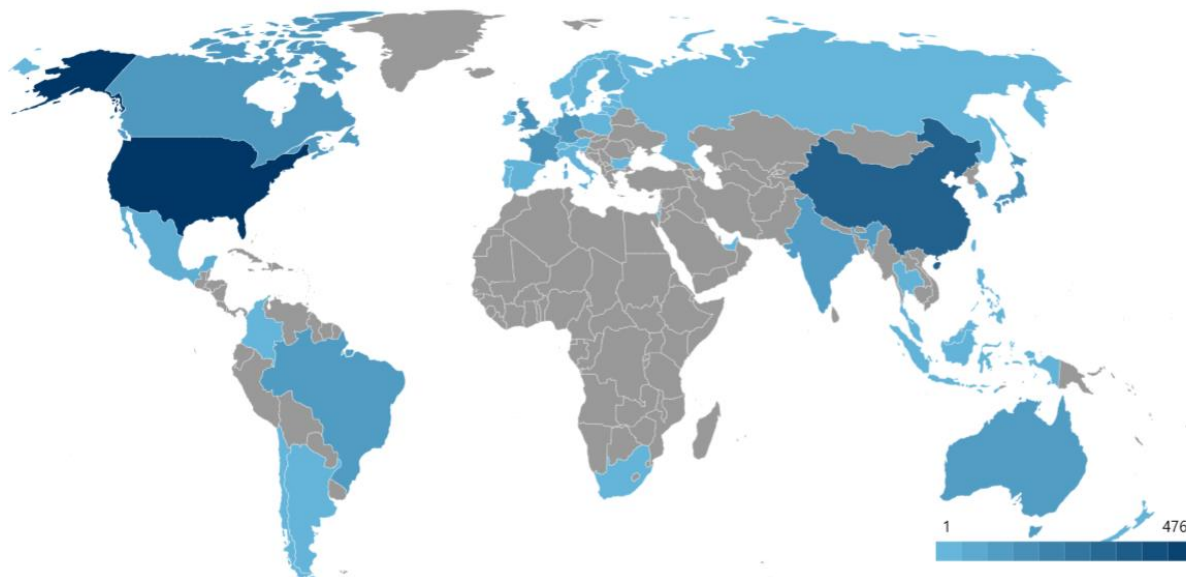
The predominance of active patents has several strategic implications. First, it indicates that companies and institutions are continuing to invest in maintaining and defending their intellectual property portfolios, which reflects confidence in the long-term commercial prospects of SAF technologies. Second, the relative novelty of the field means that future litigation is likely to be a significant issue, particularly given that many patent families have been filed simultaneously in multiple jurisdictions. This pattern of parallel filings across strategic markets increases the potential for disputes over overlapping claims and could shape competitive dynamics as the sector matures.

In short, the current legal status profile underscores that the SAF patent landscape is not only expanding but also consolidating, as applicants seek to secure strong and defensible intellectual property positions in anticipation of future market growth. This is consistent with the broader finding that SAFs are an emerging, high-stakes technological domain, where the resolution of intellectual property rights is likely to play a decisive role in determining leadership.

3.4. Geographical distribution of patent filings

The geographical distribution of SAF-related patent families (Figure 3) reveals a clear concentration in a limited number of jurisdictions, primarily the United States and China, followed by the European Patent Office (EPO) and selected European national offices. This distribution reflects the alignment between inventive activity and the world's largest current or prospective markets for SAFs, which are also home to the major industrial players and supportive regulatory frameworks. The presence of parallel filings across these jurisdictions suggests deliberate strategies to secure intellectual property rights in regions critical for commercialization.

Figure 3 – Geographical distribution of SAF patent families





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An important finding is the moderate-to-high intensity of patent filings in Brazil, which distinguishes the country from most of its Latin American peers, as well as from other emerging economies in Africa and parts of Asia. This pattern underscores Brazil's strategic relevance as a target for intellectual property protection, likely driven by its well-established biofuels sector, robust agricultural base, and longstanding industrial capabilities in feedstock production and processing. The country's positioning as a locus for inventive activity and protection suggests that applicants perceive Brazil not only as a potential manufacturing hub but also as a future market for SAF technologies.

This observation carries significant implications for the domestic innovation ecosystem. The presence of foreign and potentially domestic applicants filing SAF patents in Brazil signals opportunities for the development of local competencies, technology transfer, and industrial partnerships. Moreover, it reflects an acknowledgment of Brazil's unique competitive advantages—including its abundant biomass resources and extensive experience in biofuel production—as strategic assets in the emerging global SAF landscape.

By contrast, other Latin American countries, as well as African economies, exhibit low to negligible levels of patenting activity in this domain. This disparity highlights the differentiated attractiveness of Brazil within the Global South and reinforces the country's potential to consolidate a leadership position in SAF development and commercialization. Yet, the limited participation of Brazilian assignees underscores a structural misalignment within the domestic TIS. While Brazil's biomass advantages are evident, the lack of local proprietary positions in midstream and downstream SAF technologies suggests a risk of technological dependency, leaving the country confined to lower value-added segments of the global value chain (Lee & Lim, 2001; Dang & Motohashi, 2015).

3.5. Technological domains and pathways (IPC analysis)

The analysis of the International Patent Classification (IPC) codes associated with SAF-related patent families demonstrates a high degree of technological dispersion, reflecting the fact that this is still an emerging field without a dominant design. Patents are distributed across a variety of pathways for SAF production, including Hydroprocessed Esters and Fatty Acids (HEFA), Alcohol-to-Jet (ATJ), Fischer-Tropsch (FT) synthesis, and Power-to-Liquid (PtL) routes, among others. Each pathway carries distinct feedstock requirements, technological challenges, and cost profiles, which helps explain the absence of a single prevailing approach.

Despite this diversity, the data reveals the presence of two major technological axes. The first is centered on chemical and biochemical processes related to the production of SAF, which are heavily represented in the IPC codes for chemical engineering, catalysis, feedstock conversion, and fuel upgrading. This domain is dominated by companies in the oil and chemical sectors, which are leveraging their infrastructure and know-how to scale fuel production.

The second axis encompasses technologies related to the application of SAF in aviation engines, covering aspects such as fuel compatibility, combustion optimization, emissions control, and long-term engine performance. This cluster of patenting activity is particularly associated with the major engine manufacturers, most notably Rolls-Royce, which seek to ensure that new fuels can be integrated effectively into existing and future propulsion systems.

The existence of these two complementary yet distinct domains reflects the dual nature of SAF development: innovation must occur simultaneously in fuel production technologies and in the systems that will utilize these fuels. The interdependence between these axes is further reinforced by the observed patterns of citations and collaborative filings among applicants from both domains, which highlight the importance of cross-sectoral partnerships.

In sum, the IPC analysis underscores that the SAF technological landscape remains fragmented but highly dynamic, with multiple production pathways and applications advancing in parallel. This configuration creates both opportunities and risks: while diversity fosters experimentation and innovation, it also raises the possibility of future consolidation around a subset of winning technologies. From the perspective of TIS functions, this pattern reflects the predominance of entrepreneurial experimentation and knowledge development (Bergek et al., 2008). The absence of convergence reinforces the notion that the SAF sector is still in a formative phase, aligned with the dynamics described in Dominant Design theory. The ability of actors to navigate this uncertainty—and to position themselves effectively across these two major technological fronts—will be a key determinant of competitive advantage as the SAF sector matures.

3.6. Cross-citations among patent portfolios

The analysis of cross-citations among SAF-related patent families provides valuable insight into the pioneering and strategically important players in the field. In patent landscapes, the frequency with which a portfolio is cited by others is a strong indicator of its relevance as prior art and as a potential foundation for subsequent technological developments. Conversely, heavily cited portfolios can also act as blocking positions, given that their claims may restrict competitors' ability to operate freely in certain technological domains.



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The citation network for SAF patents reveals a small group of highly connected nodes that exert disproportionate influence over the innovation ecosystem. Among these, Rolls-Royce stands out as a central hub, frequently cited by other applicants and simultaneously referencing a wide range of external portfolios. This pattern reinforces the company's central role in shaping the technological direction of SAFs, particularly in areas related to engine compatibility and performance optimization.

Similarly, Neste Oil, ExxonMobil, UOP, AIRBUS, and General Electric appear as key nodes in the citation network. These organizations occupy influential positions either because their patents are foundational to core SAF production processes or because they actively engage in the development of enabling technologies. Their portfolios are widely referenced, suggesting that competitors must build upon—or carefully design around—these existing patents when pursuing new innovations.

The presence of dense citation links among these top players also reflects the interconnected nature of SAF technological development. Engine manufacturers, oil and chemical companies, and research institutions rely on one another's advances, resulting in an intricate web of technological dependencies. This configuration underscores both the opportunities for strategic collaboration and the potential for future litigation, as overlapping claims may become points of contention as the SAF market expands. Citation networks can be interpreted as indicators of knowledge flows within TIS, where highly cited patents act as focal points delineating emerging technological cores (Hummon & Doreian, 1989; Martinelli, 2012). In this sense, the SAF patent landscape illustrates not only technological interdependencies but also potential early signals of convergence toward dominant trajectories.

In sum, the cross-citation analysis identifies a set of actors whose portfolios represent the state-of-the-art in SAF-related technologies. Their patents serve both as essential building blocks for ongoing innovation and as strategic assets that can shape competitive dynamics. Applicants entering the SAF domain must therefore consider the positioning of these portfolios carefully, whether to pursue alliances, negotiate licenses, or design alternative technological solutions.

4. CONCLUSIONS

This study sets out to characterize the global inventive activity related to Sustainable Aviation Fuels (SAFs) by analyzing patent data as a proxy for technological development. The findings demonstrate a genuine and growing interest in SAF technologies, as evidenced by the upward trajectory in patenting activity observed particularly after 2021, with a sharp incline in 2022 and a peak in 2023. This trend underscores the emergence of SAFs as a strategic technological domain within the broader aviation decarbonization agenda.

The analysis also revealed that patent ownership is highly concentrated among a small number of companies, predominantly in the oil, chemical, and aerospace sectors. In particular, engine manufacturers such as Rolls-Royce and large fuel producers like Neste Oil and TotalEnergies are central to the patent landscape, reflecting both the critical role of fuel production technologies and the need to ensure compatibility with aircraft propulsion systems. It is important to acknowledge that this study does not capture other forms of intellectual property protection, such as trade secrets, which may influence the broader innovation dynamics. Nevertheless, the patent-based evidence points to a landscape dominated by a few key actors.

Geographically, the United States, China, and Europe remain the primary markets for patent filings, consistent with their industrial capabilities and regulatory environments. A notable finding, however, is the moderate-to-high intensity of SAF patenting in Brazil, which distinguishes the country from other Latin American and emerging economies. This reflects the country's strategic importance as a market and as a potential hub for future SAF production, given its extensive agricultural base and long-standing expertise in biofuels.

Despite this strategic positioning, the analysis found no significant participation of Brazilian companies, universities, or research institutes in SAF-related patenting. The patents filed in Brazil largely originate from foreign entities with commercial or industrial presence in the country, but without evidence of local R&D. While this highlights a current gap in domestic innovation capabilities, it should also be interpreted as a window of opportunity. Given that the SAF sector is still at an early stage of development, there is ample room for new entrants—both companies and research institutions—to position themselves in this technological domain.

For Brazil, which has a historical vocation for biofuels and sustainable energy, establishing a leading role in SAF development is a natural progression. Achieving this, however, will require targeted public policies, strategic corporate investments, and a coordinated innovation agenda to leverage the country's unique competitive advantages. Strengthening R&D capabilities and fostering partnerships with international leaders will be essential for Brazil not only to participate in the global SAF market but also to help shape its technological direction. In TIS terms, policy interventions should explicitly target critical bottlenecks in conversion technologies and certification processes, while also fostering institutional coordination through patent pools or FRAND-based licensing mechanisms (Henkel, 2022; Baron & Pohlmann, 2013). By moving from static comparative advantages (biomass supply) to dynamic competitive advantages (proprietary technological capabilities), Brazil can avoid technological lock-in and establish itself as a leading actor in the global SAF transition.



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