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Strategic Pathways to Aviation Sustainability: Insights from Turkish Experts on Regulatory, Technological, and Market Responses

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Abstract

As the global aviation sector faces increasing pressure to meet decarbonization targets, transitional economies like Türkiye—positioned between emerging and developed markets—must navigate the complex intersection of international environmental mandates, evolving technological capabilities, and domestic implementation challenges. This study investigates the strategic and operational dimensions of sustainable aviation in Türkiye through four key lenses: regulatory adaptation (RQ1), challenges in Sustainable Aviation Fuel (SAF) adoption (RQ2), the role of artificial intelligence (AI) in enhancing operational efficiency (RQ3), and the influence of Corporate Social Responsibility (CSR) and Environmental, Social, and Governance (ESG) practices (RQ4). Based on semi-structured interviews with 14 aviation experts and thematic analysis, the findings reveal that Türkiye's carriers face regulatory asymmetries between ICAO's CORSIA and the EU ETS, limited SAF infrastructure and incentives, fragmented digital systems for AI integration, and inconsistent CSR adoption. The study contributes to the literature by highlighting how sustainability frameworks are adapted within transitional economies, where global mandates must be reconciled with national capabilities. It also provides actionable policy and managerial implications for harmonizing environmental governance, scaling clean energy infrastructure, and fostering digital transformation in aviation. These insights offer value for both domestic policymakers and international stakeholders seeking to enable sustainable transitions in complex regulatory environments.

1. Introduction

The aviation industry plays a pivotal role in facilitating global mobility and economic activity; however, it remains one of the fastest-growing sources of greenhouse gas (GHG) emissions. As concerns over climate change intensify, the environmental implications of air travel-including carbon emissions, noise pollution, and excessive resource consumption-have come under increasing scrutiny (Rupcic et al., 2023; Sher et al., 2021). In response, a combination of global regulatory instruments and technological innovations has emerged to guide the industry's sustainability transformation. Initiatives such as the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and the European Union Emissions Trading System (EU ETS) aim to curb emissions through market-based mechanisms. At the same time, advancements such as Sustainable Aviation Fuels (SAF), artificial intelligence (AI)-enabled fuel optimization, and digitized operational efficiencies are reshaping how airlines approach environmental performance (Amankwah-Amoah, 2020; Wang, Ting, & Zhao, 2024).

However, significant challenges persist. High implementation costs, infrastructure gaps, and regulatory inconsistencies across jurisdictions complicate the effective adoption of sustainable practices (Karaman, Kilic, & Uyar, 2018; Lai et al., 2022). These obstacles are particularly pronounced in emerging aviation markets, such as T√ºrkiye, where regulatory maturity and technological integration vary considerably compared to the European Union. Despite rapid growth in its civil aviation sector over the past two decades, T√ºrkiye continues to face systemic barriers to sustainability. While the country has aligned itself with ICAO's CORSIA and issued emissions monitoring guidelines through the Directorate General of Civil Aviation (DGCA), more robust enforcement mechanisms and integration of advanced solutions like SAF and AI are still in early development stages (DGCA, n.d.-a; n.d.-b). These conditions make Türkiye a compelling context for investigating how regional aviation sectors interpret and operationalize global sustainability mandates. Rather than positioning T√ºrkiye as an outlier, this study presents it as a representative case for exploring how emerging aviation markets contend with evolving international pressures, domestic regulatory capacities, and technological innovations. The European Union's comparatively advanced systems-such as the binding EU ETS framework and national roadmaps from airlines like Lufthansa and Air France-KLM-offer critical reference points for contrast and contextualization (European Commission, 2023).

Existing literature provides substantial coverage of sustainability challenges in aviation, often focusing on either technological advancements (e.g., electric propulsion, SAF) or global policy frameworks (e.g., CORSIA, ETS) in isolation (Kim, Lee, & Ahn, 2019; Pereira, Lohmann, & Houghton, 2021). Few studies integrate these domains or examine how sustainability strategies unfold within specific national contexts. This study addresses this gap by offering a multi-dimensional analysis grounded in the perspectives of aviation experts based in Türkiye. Drawing on insights from sustainability managers, environmental policy advisors, and analysts, it examines how airline sustainability strategies are shaped by international regulation, technological capacity, and stakeholder expectations-including those of passengers, investors, and regulators.

Accordingly, the study seeks to answer the following research questions:

- How do airlines in Türkiye adapt to global and regional sustainability regulations, including CORSIA and the EU ETS?
- What are the challenges and opportunities associated with Sustainable Aviation Fuel (SAF) adoption and other low-emission technologies?
- How do AI and operational efficiency strategies contribute to fuel consumption and emissions reduction in Türkiye?
- What role does corporate social responsibility (CSR) play in shaping sustainability strategies in Türkiye's aviation sector, and how does it influence investor confidence and passenger preferences?

To address these questions, a qualitative research design was employed. Semi-structured interviews were conducted with 14 industry experts in Türkiye, and thematic analysis was performed using NVivo software (Braun & Clarke, 2006; Nowell et al., 2017). Sentiment analysis and word cloud visualizations complemented this process by capturing expert attitudes and highlighting key discussion themes (Liu, 2012; McNaught & Lam, 2010). Secondary data from international and national sources-such as the Air Transport Action Group (2023), airline sustainability reports, the World Economic Forum Net-Zero Tracker (2023), and Türkiye's Directorate General of Civil Aviation-provided additional context.

The remainder of this paper is organized as follows: Section 2 reviews relevant literature on aviation sustainability strategies, including regulatory compliance, SAF development, AI applications, and CSR engagement. Section 3 details the methodology. Section 4 presents findings from the thematic and sentiment analyses. Section 5 discusses implications for policy and practice. Section 6 concludes with recommendations for advancing sustainability in Türkiye's aviation sector while aligning with global objectives.

2. Literature Review

To contextualize Türkiye's position in the broader sustainability landscape, this literature review includes international examples of sustainability strategies from leading global aviation companies. The inclusion of U.S.-based carriers (such as American Airlines and Delta) and European leaders (such as Lufthansa, KLM, and IAG) enables a comparative understanding of how regulatory frameworks, fuel transition efforts, and digital innovations are approached across different policy environments. This comparative lens is especially relevant given that Türkiye operates at the intersection of EU-aligned obligations and ICAO's global frameworks without being fully integrated into either. The review is structured around four key themes reflecting the research questions: (1) global and regional regulatory mechanisms and their implications for airlines, (2) the evolving landscape of Sustainable Aviation Fuel (SAF) and its economic and logistical barriers, (3) the integration of digital technologies, particularly artificial intelligence, in enhancing operational efficiency and emissions reduction, and (4) the role of Corporate Social Responsibility (CSR) and Environmental, Social, and Governance (ESG) initiatives in shaping stakeholder perceptions and sustainability performance. By synthesizing recent studies, regulatory reports, and corporate sustainability disclosures from multiple regions, the literature review establishes a comprehensive foundation for analyzing Türkiye's national responses within the global shift toward sustainable aviation.

2.1. Environmental Impact of the Aviation Industry

Aviation is a significant contributor to global greenhouse gas (GHG) emissions, playing a critical role in climate change and environmental degradation. The industry's environmental footprint extends beyond carbon emissions, encompassing fuel consumption, contrail formation, and noise pollution, which collectively impact air quality, global warming, and community well-being (Rupcic et al., 2023). The aviation sector accounts for approximately 2–3% of global CO_2 emissions, a figure that is expected to rise as demand for air travel continues to grow (Air Transport Action Group, 2023). Despite efforts to introduce carbon-neutral technologies and improve operational efficiency, the industry's reliance on fossil fuels remains a substantial barrier to achieving sustainable aviation (Lai et al., 2022).

Fuel consumption is a central factor in aviation's environmental impact, with kerosene-based jet fuels producing high levels of carbon dioxide, nitrogen oxides, and particulate matter that contribute to climate change and local air pollution (Sher et al., 2021). The increased adoption of alternative energy sources such as sustainable aviation fuels (SAFs) has shown promise, but their large-scale implementation remains hindered by production costs and infrastructure limitations (Wang, Ting, & Zhao, 2024). In response, several leading European airlines have taken concrete steps to advance SAF usage. Lufthansa Group, for instance, has committed to reducing its net CO_2 emissions by 50% by 2030 and achieving net-zero by 2050, in line with the Science Based Targets initiative (SBTi). Lufthansa is one of Europe's largest SAF purchasers and has launched customer-facing initiatives such as the Compensaid platform and Green Fares, which allow passengers to directly fund SAF usage or offset emissions (Lufthansa Group, 2024).

Similarly, KLM Royal Dutch Airlines has been at the forefront of sustainable fuel innovation, operating the world's first commercial flight using synthetic SAF in 2021 and launching partnerships with SkyNRG and Neste to increase fuel availability. The airline also participates in the Destination 2050 coalition, aligning with the EU's climate roadmap (KLM, 2023). Air France, supported by France's SAF blending mandates, has partnered with TotalEnergies for SAF demonstration flights using up to 30% SAF content. These airlines' efforts underscore the growing recognition that sustainability requires long-term strategic investments and multi-stakeholder cooperation.

Contrail effects are another critical environmental concern, as the condensation trails produced by aircraft engines at high altitudes contribute to atmospheric warming by trapping outgoing infrared radiation (Yang & O'Connell, 2020). These contrails can evolve into cirrus clouds that exacerbate radiative forcing, further intensifying aviation's impact on global temperatures. Studies suggest that altering flight altitudes or optimizing air traffic routes can mitigate contrail formation, yet such adjustments often conflict with fuel efficiency goals and airline operational priorities (Lai et al., 2022). Several EU carriers have expressed interest in integrating artificial intelligence (AI) into air traffic optimization to both reduce contrail formation and enhance route efficiency—an area where further investment and regulatory coordination are still needed.

Noise pollution remains a persistent issue, particularly for communities located near airports. Aircraft operations generate substantial noise emissions that can adversely affect human health, leading to sleep disturbances, cognitive impairment, and cardiovascular issues (Torija & Self, 2018). Regulatory efforts have led to technological advancements in quieter engine designs and operational noise abatement strategies, but the rapid expansion of global air traffic continues to challenge mitigation efforts (Kılıç, Uyar, & Karaman, 2019). In the EU, airports such as Charles de Gaulle and Schiphol have adopted operational noise restrictions, nighttime curfews, and collaborative decision-making frameworks with local communities, demonstrating a more inclusive and environmentally responsive airport governance approach (Karaman, Kılıç, & Uyar, 2018).

The aviation industry's commitment to sustainability is increasingly reflected in corporate sustainability reports and environmental policies. Airlines such as American Airlines, Delta Air Lines, and United Airlines have outlined sustainability goals, including carbon neutrality targets and improved fuel efficiency programs (American Airlines, 2023; Delta Air Lines, 2023; United Airlines, 2023). However, this study initially focused more heavily on U.S.-based carriers. To create a more balanced global view, the inclusion of European airlines like Lufthansa, KLM, and Air France offers important comparative insights. These EU carriers have generally shown greater alignment with governmental policies on climate change, especially given the EU's commitment to the 2050 Net-Zero Aviation goal and stronger environmental regulations compared to the U.S., which withdrew from the Paris Agreement between 2017–2021. Consequently, EU airlines appear to have adopted more aggressive sustainability practices, partly driven by mandatory national and EU-level SAF mandates, public scrutiny, and participation in collaborative climate initiatives. Efforts to reduce aviation's environmental footprint also extend to aircraft manufacturing and material recycling. The potential for closed-loop recycling of carbon fiber composites offers an opportunity to minimize waste and improve resource efficiency, but challenges related to cost and technological feasibility remain (Meng et al., 2020). Additionally, energy and environmental assessments of turbofan engines highlight the need for improved fuel efficiency and emissions reductions in future engine designs (Tuzcu, Sohret, & Caliskan, 2021).

Despite ongoing challenges, the aviation industry continues to explore pathways toward sustainability through technological innovation, regulatory adaptation, and corporate responsibility initiatives. The transition to greener aviation will require a combination of policy interventions, financial incentives, and industry-wide collaboration to achieve meaningful reductions in emissions and environmental impact. The development of strategic sustainability plans for airports, such as those implemented at Istanbul Airport, demonstrates the potential for localized solutions that integrate environmental priorities with operational efficiency (Mizrak, Polat, & Tasar, 2024). The push for sustainable aviation remains a complex and evolving challenge, necessitating a holistic approach that balances economic growth with environmental stewardship.

2.2. Global and Regional Environmental Regulations

Global and regional environmental regulations play a crucial role in guiding the aviation industry's sustainability agenda. At the international level, frameworks such as the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), the European Union Emissions Trading System (EU ETS), and sustainability initiatives championed by the International Air Transport Association (IATA) form the backbone of emissions control in global aviation. CORSIA, implemented by ICAO, seeks to cap the net carbon emissions of international flights by mandating that airlines offset excess emissions through certified carbon reduction projects (Baledón & Kosoy, 2018). However, ensuring consistent compliance and standardization across jurisdictions remains a challenge (European Commission, 2023). In parallel, the EU ETS imposes a cap-and-trade mechanism on airlines operating within the European Economic Area, requiring them to purchase carbon allowances proportional to their emissions. This system is designed to incentivize the adoption of low-emission technologies and sustainable aviation fuels (Gudmundsson, 2019). Complementing these regulatory efforts, IATA promotes voluntary industry-wide commitments to carbon neutrality, operational efficiency, and SAF integration, although the actual implementation varies significantly across regions due to disparities in cost, infrastructure, and policy support (Amankwah-Amoah, 2020).

At the national level, regulatory approaches vary across key aviation markets such as the European Union, the United States, and Türkiye. The EU has been at the forefront of aviation sustainability policies, implementing stringent regulations that require airlines to integrate SAFs and adopt emissions monitoring programs (Linden, 2021). The U.S. Federal Aviation Administration (FAA) has prioritized research into hybrid-electric propulsion technologies and air traffic management innovations to reduce fuel consumption and environmental impact (Rendón et al., 2021). However, regulatory enforcement in the U.S. has faced challenges, particularly as airlines resist more aggressive emissions reduction mandates due to financial constraints.

Türkiye, emerging as a strategic aviation hub, has progressively aligned its environmental policies with European standards by implementing sustainability measures across its aviation infrastructure—most notably at Istanbul Airport, which incorporates energy-efficient technologies and green design principles (De Neufville, 2020). The Directorate General of Civil Aviation (Türkiye) has formalized national compliance with international emissions frameworks by integrating ICAO's CORSIA guidelines into domestic regulations, as outlined in the SHT-CORSIA Implementation Guidelines (Directorate General of Civil Aviation, n.d.-b).

Furthermore, Türkiye's "Green Airport" certification program incentivizes airports to reduce carbon emissions, optimize energy use, and improve environmental performance in ground operations, contributing to broader climate goals and signaling a growing commitment to sustainable aviation development (Directorate General of Civil Aviation, n.d.-b).

Despite these advancements, Türkiye faces challenges in integrating SAFs into its fuel supply chain and meeting international emissions reduction targets. While Turkish Airlines (THY) has begun incorporating SAFs into its operations as part of its sustainability strategy, the widespread adoption of these fuels remains limited due to high production costs and inadequate supply infrastructure (Türk Hava Yolları, n.d.). Efforts to expand the SAF market have been supported by national initiatives promoting research and development in sustainable fuel alternatives (Türkiye Yüzyılı, n.d.), yet the country's SAF production capacity remains insufficient to meet long-term demand. The Turkish Standards Institute (TSE) has also introduced ICAO CORSIA verification programs to ensure that airlines adhere to global emissions reporting requirements, further integrating international environmental standards into national policy (Türk Standartları Enstitüsü, n.d.).

Regulatory adaptation continues to be a challenge as governments and industry stakeholders attempt to balance economic growth with environmental sustainability. The aviation sector's transition toward digitalized operations and smart airport technologies is expected to play a critical role in enhancing emissions monitoring and improving air traffic efficiency (Zaharia & Pietreanu, 2018). However, the industry must also address long-term resilience strategies following the disruptions of the COVID-19 pandemic, ensuring that sustainability measures are incorporated into financial recovery plans (Amankwah-Amoah, 2020). The success of these initiatives will depend on the harmonization of international and national regulations, increased investment in SAFs, and the development of comprehensive green aviation policies. While Türkiye has made significant progress in aligning its aviation sector with global environmental standards, continued advancements in regulatory compliance, alternative fuel integration, and emissions monitoring will be necessary to achieve long-term sustainability goals (TFS Akaryakıt Hizmetleri A.Ş., n.d.; Yesil Ekonomi, 2018).

2.3. Sustainability Strategies in Aviation

Sustainability strategies in aviation have become a central focus for the industry as it seeks to mitigate its environmental impact while maintaining operational efficiency. The aviation sector has introduced multiple approaches to achieving sustainability, including fuel efficiency programs, carbon offsetting mechanisms, and technological innovations. These strategies aim to reduce greenhouse gas emissions, optimize resource utilization, and align aviation operations with international sustainability goals.

Fuel efficiency programs have played a crucial role in minimizing the aviation industry's environmental footprint. Airlines have increasingly invested in new-generation aircraft that feature improved aerodynamics, lightweight materials, and more efficient engines designed to reduce fuel consumption (Qiu et al., 2021). Optimized flight routes and advanced air traffic management systems have also contributed to fuel savings, allowing airlines to minimize unnecessary fuel burn by reducing flight times and congestion at airports (Pereira et al., 2021). The introduction of Sustainable Aviation Fuels (SAFs) has been another key element in reducing carbon emissions, offering an alternative to conventional jet fuel with significantly lower life-cycle emissions. However, challenges remain in scaling up SAF production and integrating it into the global aviation fuel supply chain due to cost and infrastructure limitations (Kim, Lee, & Ahn, 2019). Airlines such as Air France-KLM have been actively seeking partnerships to expand SAF production in an effort to align with sustainability commitments, but logistical and economic barriers continue to hinder widespread adoption (Air France-KLM, 2025). Despite these challenges, major carriers like Delta Air Lines, American Airlines, and United Airlines have included SAF as a core component of their sustainability strategies, as reflected in their recent environmental reports (Delta Air Lines, 2023; American Airlines, 2023; United Airlines, 2023).

Carbon offsetting initiatives have emerged as a widely adopted measure for airlines seeking to achieve carbon neutrality. Many carriers have introduced voluntary offset programs that allow passengers to contribute to environmental projects designed to absorb or prevent emissions equivalent to those produced by their flights (Rajiani & Kot, 2018). Airlines have also pledged to participate in global offset mechanisms, such as ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which mandates that airlines compensate for their emissions by investing in carbon reduction projects (Gössling & Lyle, 2021). Despite these efforts, the effectiveness of carbon offsetting remains a subject of debate, as critics argue that it serves as a temporary solution rather than a long-term emissions reduction strategy. The success of these programs depends on their credibility, transparency, and ability to generate verifiable emissions reductions (Jahanger et al., 2024). The World Economic Forum (2023) has tracked progress on aviation net-zero commitments, highlighting that while offsetting is widely used, a shift toward direct emissions reductions through SAFs and technology adoption is essential for long-term sustainability.

Technological innovations have been pivotal in accelerating the transition toward greener aviation. Developments in electric and hydrogen-powered aircraft have the potential to transform the industry by eliminating direct emissions from flight operations (Thummala & Hiremath, 2022). Several manufacturers and research institutions are actively working on hybrid-electric propulsion systems, which combine traditional jet engines with battery-powered electric motors to reduce fuel dependency and emissions (Bridgelall, 2024). Additionally, artificial intelligence (AI) has been leveraged to enhance operational efficiency, particularly in flight planning and route optimization, helping airlines reduce unnecessary fuel consumption and streamline air traffic management (Jayabal, 2024). However, the large-scale deployment of these emerging technologies remains in the early stages, with further research and investment required to overcome technical, regulatory, and financial barriers. Some airlines, including Frontier Airlines and Alaska Airlines, have outlined commitments to researching and piloting new technologies that enhance fuel efficiency and reduce emissions (Frontier Airlines, 2023; Alaska Airlines, 2023).

While these sustainability strategies offer promising pathways to reducing aviation's environmental impact, their successful implementation relies on coordinated efforts between governments, industry stakeholders, and technological innovators. Public awareness and consumer willingness to support greener aviation initiatives have also been identified as key factors in driving sustainability adoption. Studies indicate that passengers who possess a greater understanding of aviation's environmental challenges are more likely to support and pay for sustainable flight options (Ragbir et al., 2021). Moving forward, the aviation industry must continue to balance economic viability with its commitment to sustainability, integrating fuel efficiency measures, carbon offsetting mechanisms, and technological advancements to achieve a more environmentally responsible future. The Air Transport Action Group (2023) has emphasized the importance of international collaboration in addressing aviation's sustainability challenges, noting that airlines, airports, and policymakers must work together to ensure the long-term viability of green aviation. Similarly, recent reports on European aviation emissions stress the need for stronger regulatory frameworks to drive sustainable innovation and reduce reliance on fossil fuels (Transport & Environment, 2023). These efforts highlight the critical role that both corporate sustainability commitments and regulatory action will play in shaping the future of aviation.

2.4. Corporate Social Responsibility (CSR) in Airlines

Corporate social responsibility (CSR) has become an essential component of the airline industry's sustainability strategy, reflecting commitments to environmental protection, social equity, and ethical governance. As airlines navigate increasing regulatory pressures and consumer expectations, CSR initiatives play a crucial role in shaping their corporate image and financial performance. Airlines have progressively integrated CSR policies that emphasize emissions reductions, operational efficiency, and investment in sustainable aviation fuels (SAFs) to mitigate their environmental impact (Kuo, Chen, & Meng, 2021). The implementation of CSR strategies is no longer just a voluntary ethical consideration but a competitive necessity, particularly as stakeholders, including governments, consumers, and investors, demand greater accountability and transparency in airline operations (Streimikiene et al., 2021).

Airlines' commitments to sustainability have expanded beyond environmental efforts to include social initiatives such as diversity and inclusion, community engagement, and fair labor practices. Research indicates that companies with strong CSR programs often experience enhanced corporate reputation and increased customer loyalty, particularly in the highly competitive aviation industry (Vuong et al., 2024). Budget airlines, which historically prioritized cost efficiency over sustainability, have increasingly incorporated CSR into their business models to enhance brand trust and attract environmentally conscious consumers (Streimikiene et al., 2021). Furthermore, strategic CSR initiatives have been linked to improved financial performance, as passengers are more likely to choose airlines with demonstrated commitments to sustainability and corporate responsibility (Phillips, Thai, & Halim, 2019). This shift has encouraged airlines to align their CSR objectives with long-term profitability by integrating green technologies, reducing operational waste, and investing in carbon offsetting programs (Karaman & Akman, 2018).

Public perception and stakeholder pressure have significantly influenced the adoption and expansion of CSR programs in the airline sector. Airlines frequently report their sustainability efforts on corporate websites and annual reports to improve transparency and engage with environmentally conscious stakeholders (Okumus et al., 2020). However, the credibility of such reports has been questioned, as some airlines engage in "greenwashing" practices—exaggerating their environmental contributions while continuing high-emission operations (Peeters et al., 2019). Consumers have become increasingly discerning, expecting airlines to demonstrate tangible sustainability efforts rather than relying on corporate rhetoric. Studies suggest that passengers' willingness to pay for greener flights is contingent upon their trust in an airline's sustainability claims, highlighting the importance of authenticity in CSR communication (Sorsa & Bona-Sánchez, 2024).

CSR trends in the airline industry are also influenced by regulatory frameworks and industry-wide sustainability goals. Green human resource management (HRM) has emerged as a key factor in integrating CSR into airline operations, fostering a sustainability-oriented corporate culture that aligns with passenger expectations (Wang et al., 2024). Additionally, cross-country studies have demonstrated that airports with strong CSR commitments experience higher passenger satisfaction, reinforcing the importance of CSR in enhancing customer experience and brand loyalty (Alam et al., 2024). Case studies of airlines such as Singapore Airlines have shown that both qualitative and quantitative CSR disclosures play a role in shaping investor confidence and industry positioning (Boulesnam et al., 2025).

As the aviation industry continues to evolve, CSR will remain a fundamental driver of corporate sustainability and competitive advantage. Airlines that successfully integrate environmental, social, and governance (ESG) principles into their operations will not only improve their public perception but also ensure long-term financial stability in an era where sustainability is increasingly linked to profitability (Upadhaya et al., 2018). Moving forward, the effectiveness of airline CSR programs will depend on their ability to implement meaningful environmental initiatives, engage with stakeholders transparently, and adapt to evolving consumer and regulatory expectations.

2.5. Technological Innovations in Aviation Sustainability

Technological innovation is emerging as a critical pillar in aviation sustainability, complementing regulatory and market-driven efforts to reduce environmental impact. Central to this transformation are digital technologies and AI-enabled systems that enhance fuel efficiency, optimize route planning, and support predictive maintenance. According to Belobaba, Cooper, and Seabridge (2023), recent advances in aircraft design, engine efficiency, and digital flight operations have the potential to significantly reduce carbon emissions per passenger-kilometer. These innovations include real-time data analytics for load and trajectory optimization, integration of AI for minimizing fuel burn, and the application of machine learning algorithms in air traffic control to mitigate unnecessary holding patterns. However, the authors note that despite the availability of these technologies, their adoption varies widely across regions, often due to infrastructural limitations and inconsistent investment in digital transformation. For emerging markets like Türkiye, the gradual incorporation of such tools offers both opportunity and challenge—providing environmental gains while requiring systemic modernization of aviation infrastructure and governance frameworks.

Parallel to operational advancements, sustainable aviation fuels (SAFs) represent a foundational technological innovation with direct implications for carbon neutrality. As emphasized by Ershov et al. (2023), innovation in SAF production processes—including thermochemical conversion, power-to-liquid synthesis, and algae-based feedstocks—is rapidly evolving to overcome economic and scalability barriers. SAFs are considered a near-term solution to decarbonize aviation without requiring massive changes to aircraft engines or airport fueling infrastructure. However, their broader deployment is hindered by high production costs, limited feedstock availability, and policy uncertainty, especially in countries where state incentives or mandatory blending requirements are absent. Khujamberdiev and Cho (2024) further explore the technical compatibility of SAFs with existing aircraft engines, confirming that drop-in fuels can reduce lifecycle emissions by up to 80%, but they stress the need for regionally tailored policies to support large-scale adoption. In Türkiye's context, experts echo these concerns, pointing to the absence of domestic SAF production facilities and insufficient policy alignment with international sustainability targets as key obstacles to progress.

Aligning SAF research with global sustainability goals has also gained momentum, highlighting the need for multi-dimensional frameworks that consider environmental, economic, and social impacts. A recent thematic analysis by Raman et al. (2024) underscores the evolving research landscape, identifying key clusters related to feedstock optimization, emissions reduction, and integration into existing supply chains. The study emphasizes that to effectively contribute to Sustainable Development Goals (SDGs), SAF research must not only focus on technical feasibility but also engage with questions of equity, access, and global cooperation. This broader systems-level thinking is echoed in Raihan's (2025) critical review, which calls for stronger alignment between technological innovation and long-term policy instruments. Raihan argues that countries with emerging aviation markets—such as Türkiye—must adopt a dual-track strategy: building technical capacity for SAF production and engaging in international policy dialogues to harmonize sustainability benchmarks. These findings suggest that Türkiye's SAF roadmap, while currently underdeveloped, could benefit from collaborative regional efforts and lessons learned from more advanced markets like the EU and the U.S.

Beyond fuel technologies, the digital transformation of aviation enterprises plays a vital role in embedding sustainability into core business models. According to Smerichevskyi et al. (2024), digital technologies such as blockchain, Internet of Things (IoT), and big data analytics are increasingly used to monitor environmental indicators, streamline operations, and enhance transparency in sustainability reporting. The integration of digital dashboards for emissions tracking, AI-driven scheduling tools, and simulation-based carbon forecasting are some of the practices identified to boost the innovative potential of aviation firms. These tools not only contribute to environmental performance but also foster stakeholder trust and institutional readiness for future regulatory shifts. In Türkiye, where digital maturity remains uneven across aviation actors, such technologies offer a path to leapfrog traditional inefficiencies and align more closely with international standards.

Finally, the broader relationship between business sustainability and information technology has become even more prominent in the post-COVID aviation landscape. Trivedi, Negi, and Tiwari (2024) highlight how IT systems can reinforce the triple bottom line—people, planet, and profit—by enabling responsive decision-making, enhancing energy efficiency, and supporting remote operational capabilities. Their findings indicate that IT-driven sustainability strategies not only mitigate environmental risks but also improve long-term financial resilience, particularly during periods of volatility. This intersection of digital resilience and ecological responsibility is particularly salient for Turkish airlines navigating post-pandemic recovery while facing increasing environmental scrutiny from both domestic regulators and international stakeholders. In this regard, the strategic integration of technological tools—from AI to SAF—offers a multifaceted approach to achieving sustainability in aviation that is both operationally viable and ethically aligned.

3. Materials and Methods

3.1. Research Design

This study employs a qualitative research design to investigate sustainability strategies, regulatory adaptation, and technological innovation in the aviation industry, with a particular focus on the Turkish civil aviation context. Qualitative inquiry is well-suited for examining complex, evolving issues such as environmental sustainability in aviation, as it facilitates deep exploration of stakeholder perceptions, strategic responses, and institutional challenges (Creswell & Poth, 2018). By drawing on expert insights, the study captures the nuanced interplay between policy mandates, market pressures, and organizational practices. Figure 1 presents a flowchart of the data collection and analysis process. The flowchart outlines the sequential stages of the research—from expert identification and interview scheduling to transcription, coding, and cross-comparison with secondary sources. It also highlights the tools and procedures used in thematic analysis, including the application of NVivo software for coding and visualization. This structured representation supports methodological rigor and helps readers understand how empirical data were systematically gathered and interpreted within the study.

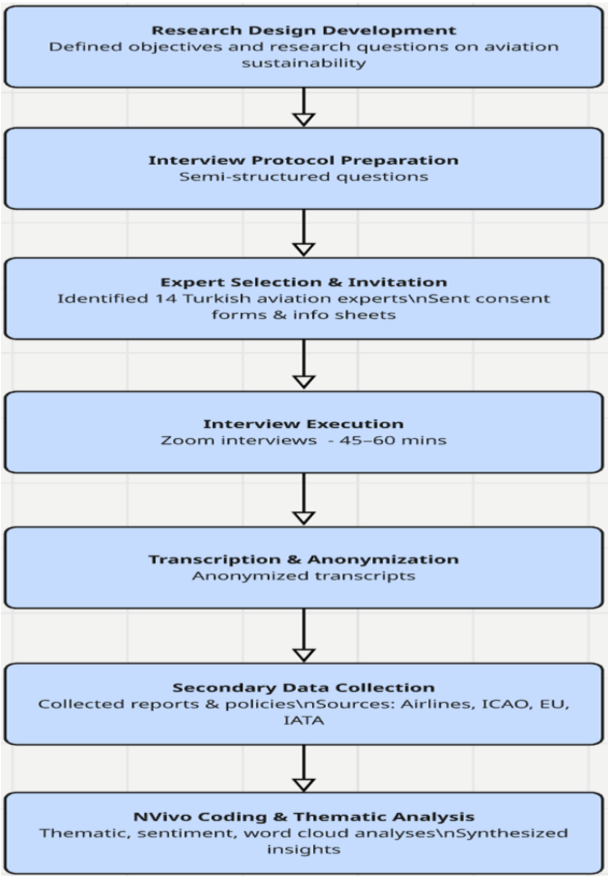

Figure 1. Flowchart of the Data Collection and Analysis Process

3.2. Data Collection Methods

This study adopts a qualitative research design grounded in semi-structured interviews to explore sustainability strategies, regulatory adaptation, and technological innovation within the aviation industry. A total of 14 participants were purposefully selected based on their roles as sustainability managers, environmental policy advisors, aviation analysts, and other experts actively engaged in Türkiye's civil aviation sector. This purposive sampling approach enabled access to individuals with deep, experience-based knowledge of airline sustainability practices and policy engagement (Patton, 2015).

The primary data collection method was semi-structured interviews, which allowed for consistency in addressing core themes while also offering the flexibility to explore unanticipated insights raised by participants (Braun & Clarke, 2006). Interviews were structured around three thematic domains:

(1) Airline sustainability strategies, such as SAF deployment, carbon offsetting efforts, and fuel efficiency initiatives; (2) Regulatory adaptation, with a focus on ICAO's CORSIA, the EU ETS, and national environmental compliance mechanisms; and

(3) Technological innovation, particularly in digital transformation, AI-based optimization, and emerging propulsion systems.

The interview protocol consisted of open-ended questions designed to encourage rich, narrative responses and capture nuanced perspectives on sustainability implementation and policy alignment. This format enabled participants to elaborate on strategic priorities, operational challenges, and future directions in their own words, thereby enhancing the depth of thematic analysis. Interviews were conducted online via Zoom to facilitate logistical accessibility and international scheduling flexibility. Each session lasted between 45 and 60 minutes, was recorded with informed consent, and transcribed using Zoom's built-in transcription feature. All transcripts were carefully reviewed for accuracy and anonymized to ensure ethical compliance and participant confidentiality. Digital recordings and transcripts were securely stored in encrypted research folders.

In parallel with interview data, secondary sources were analyzed to triangulate findings and contextualize expert perspectives. These sources included ESG reports, sustainability disclosures, and regulatory documents from major global airlines—such as Delta Air Lines, United Airlines, and Air France-KLM—as well as publications from international organizations like IATA and the World Economic Forum. Türkiye-specific regulatory documents and environmental guidelines issued by the Directorate General of Civil Aviation were also incorporated to validate national policy references. This dual-layered approach ensured a comprehensive foundation for comparing expert insights with broader policy trends and corporate strategies.

3.3. Sampling Strategy

The study employs purposive sampling to ensure that participants represent airlines with significant sustainability initiatives. Expert selection is based on their professional involvement in aviation sustainability, regulatory compliance, or strategic decision-making. The participant group includes sustainability managers, environmental policy experts, aviation analysts, and industry consultants to capture diverse perspectives on sustainability challenges and best practices in the airline sector.

3.4. Data Analysis

The data collected from the interviews undergoes thematic analysis, a qualitative research method used to identify, analyze, and interpret patterns within the data (Braun & Clarke, 2006). The purpose of thematic analysis in this study is to structure expert insights into recurring patterns, challenges, and strategies related to airline sustainability, facilitating a comparative understanding of regulatory adaptation, technological innovations, and corporate social responsibility (CSR) efforts. This method ensures that both anticipated and emerging themes are captured, allowing for a comprehensive examination of how airlines navigate sustainability challenges (Nowell et al., 2017).

To conduct the thematic analysis, NVivo software is used to organize, code, and interpret the qualitative data systematically. The process begins with data preparation, where all interviews are transcribed verbatim to preserve accuracy and detail. These transcripts are then imported into NVivo, where preliminary readings help identify key discussion points, and memos document early observations. During the coding phase, NVivo's node structure allows for the segmentation of text into meaningful units, ensuring that themes are captured at various levels of granularity. Thematic analysis follows both inductive and deductive approaches. Deductive coding categorizes responses based on predefined themes such as regulatory compliance, sustainable aviation fuels (SAF), and emissions reduction, while inductive coding allows new themes to emerge organically from the expert discussions. As coding progresses, NVivo's hierarchical structure enables the formation of broader categories and sub-

themes, refining the analysis. For example, regulatory adaptation includes sub-themes such as compliance challenges, financial implications, and policy harmonization, reflecting the complexities of adhering to sustainability mandates across different regulatory environments.
To further enhance the thematic analysis, NVivo's Matrix Coding Query tool is used to identify relationships between themes. This enables a comparative analysis of sustainability strategies across airlines, revealing differences and similarities in regulatory responses, SAF adoption strategies, and the integration of technological solutions (Castleberry & Nolen, 2018). The matrix analysis also helps to cross-reference expert responses, ensuring internal consistency and thematic saturation in the findings.
In addition to thematic analysis, sentiment analysis is performed to evaluate experts' perceptions of key sustainability challenges and initiatives. This technique, commonly used in qualitative research, assesses the polarity of responses (positive, neutral, or negative) toward sustainability regulations, SAF adoption, and operational strategies (Liu, 2012). The sentiment analysis is conducted using NVivo's sentiment scoring function, which assigns quantitative sentiment values to qualitative text. For instance, while CORSIA received predominantly positive responses, EU ETS was frequently criticized for its financial burden, providing a quantifiable measure of expert attitudes toward regulatory frameworks. The sentiment scores help contextualize expert feedback, revealing areas where sustainability policies are perceived as effective versus areas where concerns remain prominent.
To complement the analysis, a word cloud visualization is generated using NVivo's word frequency analysis tool. The purpose of the word cloud is to highlight the most frequently mentioned terms in expert discussions, providing a quick visual representation of dominant topics (McNaught & Lam, 2010). Words such as SAF, AI, emissions, fuel efficiency, regulatory compliance, and ESG reporting appear most frequently, reinforcing the key thematic areas identified in the coding process. The word cloud not only validates thematic findings but also reveals which sustainability topics are most emphasized by industry experts, offering additional insight into priority areas for airlines and policymakers.By integrating thematic analysis, sentiment analysis, and word cloud visualization, this study ensures a holistic and structured examination of airline sustainability strategies. The use of NVivo software enhances the efficiency, accuracy, and transparency of qualitative data analysis, allowing for a deeper understanding of expert perspectives and industry trends.

3.5. Ethical Considerations

The study adhered to strict ethical guidelines to safeguard the anonymity, confidentiality, and privacy of all interview participants. Prior to participation, all experts received a detailed informed consent form outlining the purpose of the research, the nature of their involvement, and their rights, including the option to withdraw at any stage without consequences. Their identities remained undisclosed, with all personally identifiable information either anonymized or excluded from the final reporting to protect both their professional reputations and personal interests. The data collection process was conducted in a transparent and ethically responsible manner, ensuring that all interviews were accurately documented, securely stored, and analyzed without bias or misinterpretation. Findings were reported objectively, adhering to rigorous ethical and methodological standards. This study received formal ethical approval from the Ethics Committee of Istanbul Ticaret University, confirming its compliance with institutional and international research ethics standards.

4. Findings

This section presents the key findings derived from thematic analysis, word cloud visualization, and sentiment analysis. These analyses provide insights into how airlines navigate sustainability challenges, implement technological innovations, and respond to regulatory pressures.

4.1. Thematic Analysis

The thematic analysis revealed five key themes aligned directly with the research questions, reflecting core dimensions of sustainability in Türkiye's aviation sector. These themes are: (1) Regulatory Adaptation and Compliance, (2) Sustainable Aviation Fuels (SAF), (3) AI and Operational Efficiency, (4) Corporate Social Responsibility (CSR) and Stakeholder Expectations, and (5) Emerging Technological Innovations. Table 1 summarizes the results.
Sustainable Aviation Fuels (SAF) are widely recognized as essential for decarbonization, yet challenges persist in their adoption. One respondent noted Türkiye's ambition: *"Our airline is committed to achieving a 10% blend of SAF by 2030, though limited supply continues to hinder our efforts."* Another stated, *"There is minimal airport infrastructure to support SAF blending, which complicates operational rollout."* These insights reflect Türkiye's dual status as both a committed participant in SAF dialogues and a nation contending with cost, supply, and infrastructural readiness issues. National programs, including the Türkiye Yüzyılı vision, highlight the state's interest in SAF development, but industry professionals stress that scalable implementation remains a significant hurdle.
Operational efficiency, particularly through AI integration, is also gaining momentum. Turkish experts confirmed that AI applications are actively being adopted for real-time fuel optimization and route planning. As one expert explained, *"We are leveraging AI for real-time route optimization, which significantly reduces fuel burn and enhances efficiency."* Yet, constraints such as airspace congestion were also emphasized: *"Despite advanced technology, congested airspace often forces us into less efficient routing, which increases emissions."* These accounts mirror global trends while emphasizing Türkiye's particular infrastructural bottlenecks, such as regional ATC coordination and older airport logistics systems.

Table 1. Thematic Analysis Results

Theme	Subtheme	Code	Frequency	Example Quotes
Regulatory Adaptation and Compliance(RQ1)	Compliance with ICAO's CORSIA	CORSIA	12	E5: "The CORSIA framework has provided a baseline for our carbon offsetting strategy, but the cost of compliance is a persistent concern."E11: "ICAO's CORSIA program plays a key role in standardizing emissions reduction globally, although its real impact is still debated within the industry."
	Challenges with EU ETS	EU ETS Challenges	9	E3: "The EU ETS introduces financial burdens that complicate our ability to expand sustainability investments."E9: "While carbon pricing via the EU ETS is effective in theory, it puts European airlines at a competitive cost disadvantage."
	National Sustainability Policies	Local Regulations	7	E7: "The inconsistency of national sustainability regulations makes compliance challenging for international airlines."E14: "Incentives for SAF use vary across countries, with some offering strong support and others providing no clear direction."
Sustainable Aviation Fuels (SAF) (RQ2)	Adoption of SAF	SAF Adoption	10	E2: "Our airline is committed to achieving a 10% blend of SAF by 2030, though limited supply continues to hinder our efforts."E12: "SAF represents a revolutionary step forward for aviation sustainability, but we still lack consistent regulatory backing for full-scale integration."
	Cost and Production Barriers	SAF Costs	8	E6: "Currently, SAF is between three to five times more expensive than traditional jet fuel, which slows its broader adoption."E10: "Although investing in SAF production is critical, most airlines cannot compete with fossil fuel pricing structures."
	Infrastructure Challenges	SAF Infrastructure	6	E8: "There is minimal airport infrastructure to support SAF blending, which complicates operational rollout."E13: "Even when SAF is secured, the absence of adequate supply chain infrastructure in key regions restricts its practical use."
AI and Operational Efficiency (RQ3)	Fuel Efficiency Optimization	AI Fuel Optimization	11	E4: "We are leveraging AI for real-time route optimization, which significantly reduces fuel burn and enhances efficiency."E9: "Our smart fuel management systems have achieved an 8% reduction in fuel waste over the past two years."
	Air Traffic Constraints	Congested Airspace	7	E1: "Despite advanced technology, congested airspace often forces us into less efficient routing, which increases emissions."E14: "Enhanced coordination among air traffic control agencies would allow for much more efficient routing and energy savings."
	Fleet Modernization	Fleet Renewal	8	E3: "Renewing our fleet with next-generation aircraft is currently our most effective approach to reducing emissions."E12: "Although fleet modernization is essential, the capital required for it is not available to every airline."
CSR and Stakeholder Expectations(RQ4)	Stakeholder Pressure	Investor Expectations	10	E6: "We are increasingly pressured by institutional investors who demand stronger ESG policies and measurable commitments."E11: "Clients now evaluate us based on the strength and transparency of our sustainability reporting."
	Passenger Engagement	Carbon Offsetting Programs	6	E7: "Passengers are making choices based on whether we offer carbon offsetting as part of our ticketing."E13: "Our brand loyalty is being influenced by the visibility and credibility of our sustainability programs."
	Transparency in ESG Reporting	ESG Accountability	5	E2: "Being transparent in our ESG reporting is fundamental to maintaining regulatory and consumer trust."E9: "There is a growing concern around greenwashing; our claims must be backed by real, auditable data."
Emerging Technological Innovations(extension of RQ2 & RQ3)	AI for Route Optimization	AI-based Flight Efficiency	9	E4: "AI-driven flight scheduling has led to measurable reductions in fuel usage across our routes."E12: "Our predictive analytics tools allow us to proactively reduce flight delays and emissions simultaneously."
	Hydrogen and Electric Aircraft	Hydrogen Aircraft Development	8	E1: "Hydrogen-powered aircraft offer great promise, but the infrastructure to support them remains severely lacking."E10: "Although we're closely monitoring hydrogen aircraft, making them cost-effective for commercial use is still far off."
	Smart Airport Technologies	AI-Driven Airport Operations	7	E5: "Our smart airport systems use AI automation to streamline ground operations and minimize emissions."E8: "Energy-efficient and intelligent airport infrastructure is fundamental for achieving long-term sustainability targets."

Corporate Social Responsibility (CSR) has become increasingly central in Turkish aviation. Stakeholder expectations are reshaping business models, driven by investor demand and public scrutiny. One expert noted, *"We are increasingly pressured by institutional investors who demand stronger ESG policies and measurable commitments."* Passenger expectations were similarly influential: *"Passengers are making choices based on whether we offer carbon offsetting as part of our ticketing."* These findings demonstrate a clear shift within Turkish aviation—where CSR is no longer an ancillary activity but a strategic priority for competitiveness and stakeholder trust.

Lastly, long-term innovations—including hydrogen-powered aircraft, smart airport systems, and electrification—are being seriously considered by Turkish aviation stakeholders. While these technologies are largely in developmental or trial phases, the ambition is clear. As one participant highlighted, *"Hydrogen-powered aircraft offer great promise, but the infrastructure to support them remains severely lacking."* Despite these limitations, Turkish actors are actively exploring R&D initiatives and participating in global conversations on clean aviation, reinforcing the country's emerging role as a forward-leaning but realistically constrained innovator.

This thematic framework directly addresses each research question by mapping the experiences and reflections of Turkish aviation professionals to global trends and localized challenges. The consistency between expert responses and international benchmarks underscores Türkiye's evolving role in aligning with—and at times diverging from—broader sustainability mandates. The inclusion of direct quotes not only illustrates these dynamics vividly but also anchors the findings in the grounded experiences of industry professionals navigating complex transitions in policy, technology, and stakeholder engagement.

4.2. Word Cloud Analysis

The word cloud (Figure 2) provides a visual representation of the most frequently occurring terms in expert discussions, offering insights into which topics dominate aviation sustainability conversations. The most prominent words include Sustainable Aviation Fuels (SAF), AI, emissions, fuel efficiency, regulatory compliance, passenger engagement, and ESG reporting. The size and frequency of these words indicate their significance in shaping airline sustainability strategies, policy discussions, and technological advancements.

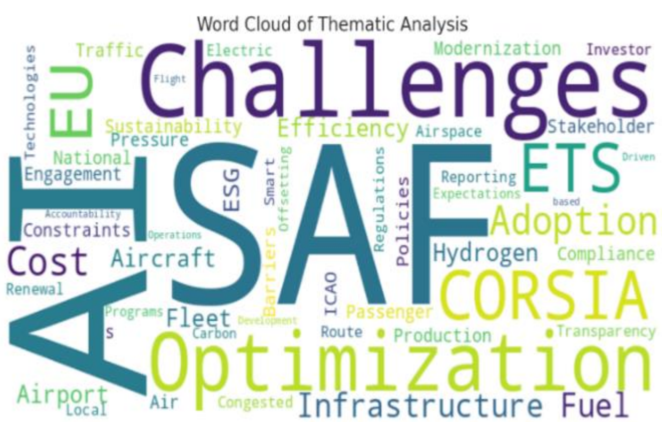

Figure 2. Word Cloud

The frequent appearance of SAF-related terms in the word cloud directly reinforces RQ2: "What are the key enablers and barriers to the adoption of Sustainable Aviation Fuels (SAF) in Türkiye?" Words like "cost," "investment," "supply," and "infrastructure" appear prominently alongside "SAF," underscoring that Turkish aviation professionals perceive SAF not just as a technological solution, but as a complex economic and logistical challenge. For instance, several experts noted the absence of local supply chains and insufficient airport blending infrastructure in Türkiye. This mirrors the thematic finding that while SAF adoption is a strategic goal, national support systems remain underdeveloped. The word cloud thus complements the qualitative data, revealing the emphasis stakeholders place on financial viability and policy support as prerequisites for SAF integration.

The strong presence of AI-related terms corresponds to RQ3: "How are digital technologies, particularly AI, enhancing operational efficiency and sustainability outcomes in Turkish aviation?" Words such as "optimization," "flight planning," and "efficiency" suggest that AI is perceived as a practical and already-in-motion tool. Experts linked AI to real-time route optimization and fuel savings, which aligns with Türkiye's current investments in smart operations. However, the smaller size of AI-related terms compared to financial or regulatory terms hints at ongoing barriers such as scalability and airspace constraints—also reflected in expert interviews. This illustrates that while Türkiye is adopting AI-based solutions, full implementation is limited by external coordination and modernization issues.

"Regulatory compliance," "CORSIA," and "EU ETS" appear as central terms, aligning with RQ1: "How are regulatory frameworks shaping the strategic sustainability priorities of Turkish aviation stakeholders?" The frequent clustering of terms like "carbon pricing," "offsetting," and "penalties" shows that Turkish professionals view compliance not only as an environmental obligation but also a financial challenge. These perceptions reflect Türkiye's dual navigation of global aviation norms and regional economic limitations. For example, experts mentioned competitive imbalances introduced by the EU ETS and uncertainty around local enforcement of international agreements, all of which are reflected in this visual frequency distribution.

The appearance of terms such as "passenger engagement," "investor pressure," "ESG reporting," and "sustainability marketing" strongly supports RQ4: "What role do stakeholder expectations play in shaping aviation sustainability strategies in Türkiye?" These terms reveal how Turkish airlines are increasingly driven by reputational factors and external scrutiny. Notably, words like "carbon offsetting" and "transparency" signal an emerging shift where sustainability is no longer a regulatory checkbox but a strategic business imperative. This is particularly relevant in Türkiye, where several airlines are now aligning branding and CSR initiatives with evolving passenger and investor expectations.

Finally, the word cloud visually captures the intersectionality of sustainability drivers in Türkiye—economic, regulatory, technological, and stakeholder-based. The relative size and proximity of words across these categories reinforce that aviation decarbonization in Türkiye is not led by a single factor but is shaped by the convergence of international standards, domestic capabilities, and market pressures. The word cloud analysis thus enhances the study's thematic insights by offering a frequency-based lens through which the research questions are both visually and conceptually validated.

4.3. Sentiment Analysis

The sentiment analysis (Table 2) reveals mixed perceptions regarding regulatory policies, reflecting both support and criticism from industry experts. CORSIA received predominantly positive responses, with several experts acknowledging its role as a global baseline mechanism for emissions offsetting. One expert emphasized, "ICAO's CORSIA program has significantly shaped our carbon offset strategy" (E1), suggesting that it provides a structured approach to emissions reduction without imposing excessive financial burdens on airlines. Additionally, some experts highlighted that CORSIA allows airlines flexibility by offering carbon offsetting options rather than enforcing direct emission reduction quotas.

Table 2. Sentiment Analysis Results

Theme	Subtheme	Example Quote	Sentiment Score	Sentiment Label
Regulatory Compliance	Compliance with ICAO's CORSIA	E1: "ICAO's CORSIA program has significantly shaped our carbon offset strategy."	0.38	Positive
Regulatory Compliance	Challenges with EU ETS	E2: "The EU ETS has been a financial challenge, requiring airlines to purchase carbon credits."	0.00	Neutral
Regulatory Compliance	National Sustainability Policies	E3: "National sustainability policies vary, making compliance complex for international airlines."	-0.15	Negative
Sustainable Aviation Fuels (SAF)	Adoption of SAF	E4: "Our airline has begun blending SAF with conventional jet fuel on long-haul flights."	-0.14	Negative
Sustainable Aviation Fuels (SAF)	Cost and Production Barriers	E5: "SAFs are still 2-5 times more expensive than conventional jet fuel, making large-scale adoption difficult."	-0.16	Negative
Sustainable Aviation Fuels (SAF)	Infrastructure Challenges	E6: "Limited SAF blending infrastructure at major airports is slowing adoption."	-0.20	Negative
Operational Efficiency	Fuel Efficiency Optimization	E7: "We use AI-driven flight route optimization and real-time weather analytics to improve fuel efficiency."	0.45	Positive
Operational Efficiency	Air Traffic Constraints	E8: "Air traffic congestion sometimes forces inefficient routing, reducing fuel savings from optimization."	-0.12	Negative
Operational Efficiency	Fleet Modernization	E9: "Investing in newer, fuel-efficient aircraft is one of our long-term sustainability strategies."	0.32	Positive
Corporate Social Responsibility (CSR)	Stakeholder Pressure	E10: "Institutional investors increasingly prioritize ESG performance, influencing airline sustainability commitments."	0.28	Positive
Corporate Social Responsibility (CSR)	Passenger Engagement	E11: "Passengers are more likely to fly with airlines that offer carbon offset options."	0.35	Positive
Corporate Social Responsibility (CSR)	Transparency in ESG Reporting	E12: "Transparency in ESG reporting is key to maintaining credibility with stakeholders and regulators."	0.22	Positive
Technological Innovations	AI for Route Optimization	E13: "AI-powered real-time flight scheduling enhances operational efficiency and reduces emissions."	0.40	Positive
Technological Innovations	Hydrogen and Electric Aircraft	E14: "Hydrogen-powered aircraft could eliminate emissions, but infrastructure limitations remain a challenge."	-0.18	Negative

The sentiment analysis complements the thematic findings by providing nuanced insights into how Turkish aviation professionals emotionally and strategically respond to sustainability challenges. These perceptions—ranging from frustration to cautious optimism—offer an important interpretive layer that connects directly to the study's research questions.

For RQ1 (Regulatory Influence), sentiment around the EU ETS and CORSIA reveals a dichotomy. While CORSIA is generally viewed neutrally to positively as a global standard-setting mechanism, the EU ETS elicits predominantly negative sentiment. As one Turkish airline executive (E3) stated, "The EU ETS imposes financial burdens, making it harder for airlines to scale sustainability investments." Another remarked, "Carbon pricing through the EU ETS is effective but places European airlines at a cost disadvantage" (E9). These quotes reflect widespread concern that Türkiye, aiming to harmonize with the EU, risks inheriting cost-intensive policies that may not match its current economic and infrastructural capacity. The negative sentiment indicates that regulatory compliance is not just a procedural hurdle but a strategic and financial risk, particularly when incentives do not offset associated costs.

Additionally, neutral to slightly negative sentiment appeared regarding regulatory fragmentation, with one expert noting: "National sustainability policies vary, making compliance complex for international airlines" (E7). This aligns with Türkiye's current position—straddling international obligations (e.g., ICAO and EU directives) and domestic implementation gaps. These views reinforce the need for regulatory harmonization, a key finding from the thematic analysis, and highlight how sentiment reflects underlying structural issues faced by the country's aviation stakeholders.

With respect to RQ2 (SAF enablers and barriers), sentiment ranged from positive strategic alignment to economic frustration. SAF was described as an "essential component of aviation's decarbonization future," but experts expressed disappointment over high costs, limited local production, and inadequate infrastructure. One professional (E10) commented: "Although investing in SAF production is critical, most airlines cannot compete with fossil fuel pricing structures." This view captures a recurring tension in Turkish aviation: alignment with global green innovation versus domestic feasibility constraints. Positive sentiment toward the concept of SAF exists, but its implementation in Türkiye is clouded by cost and logistical realities.

Regarding RQ3 (digitalization and AI integration), sentiment was generally positive, with several experts expressing enthusiasm about the role of AI in fuel management, predictive analytics, and route optimization. As one stated, "We are leveraging AI for real-time route optimization, which significantly reduces fuel burn" (E4). However, subtle frustrations emerged when discussing external limitations, such as restricted airspace or limited inter-agency coordination, which impede the full impact of these tools. Thus, sentiment here reflects optimism tempered by operational barriers, a theme consistent with Türkiye's current modernization trajectory in aviation infrastructure.

For RQ4 (stakeholder expectations and CSR), sentiment skewed positively but cautiously, particularly around ESG transparency and passenger influence. Experts acknowledged the growing importance of ESG disclosure, with one emphasizing, "Clients now evaluate us based on the strength and transparency of our sustainability reporting" (E11). However, concerns around greenwashing and accountability were evident. This duality reflects the Turkish aviation sector's attempt to balance reputational expectations with meaningful performance, especially as investor scrutiny intensifies. The sentiment analysis validates the shift from voluntary CSR to stakeholder-driven sustainability.

5. Result and Discussion

This study investigated sustainability strategies in global aviation with a particular focus on Türkiye's aviation sector, guided by four research questions: regulatory adaptation (RQ1), SAF challenges and opportunities (RQ2), the role of digital technologies such as AI (RQ3), and the influence of CSR and stakeholder engagement (RQ4). Drawing on thematic analysis of interviews with 14 experts, this section interprets the findings in relation to each research question and compares them to relevant academic literature.

RQ1 – Regulatory Adaptation and Compliance Experts highlighted the tension between international commitments—particularly ICAO's CORSIA—and regional obligations such as the EU ETS. While CORSIA was broadly seen as a baseline for global compliance, it was criticized for depending heavily on offsetting mechanisms rather than real emissions reductions. This reflects concerns from Baledón and Kosoy (2018), who argue that offset-centric policies dilute the transformative potential of sustainability mandates. The EU ETS was perceived more negatively due to its financial burden and perceived inequity for Turkish carriers operating outside the EU bloc, echoing Scheelhaase et al. (2020) regarding non-EU airline disadvantages. Experts emphasized the need for harmonized national policies and clearer long-term roadmaps, including domestic carbon pricing strategies and SAF-related incentives, to bridge the gap between ambition and implementation.

RQ2 – Sustainable Aviation Fuels (SAF) SAF was seen as both a necessary and highly constrained solution for decarbonizing aviation. While major Turkish carriers have initiated SAF trials, cost barriers, limited production, and inadequate infrastructure continue to inhibit meaningful scale-up. These concerns align with studies by Gegg et al. (2020) and Wang et al. (2024), which argue that supportive ecosystems—including feedstock logistics, blending mandates, and economic incentives—are essential for SAF viability. Unlike the EU's ReFuelEU strategy, Türkiye lacks structured policy tools and dedicated SAF development zones. Experts recommended exploring regional SAF production near agricultural hubs and aligning infrastructure investment with airport capacity expansion, resonating with suggestions from Pavlenko and Searle (2021) and IRENA (2023).

RQ3 – AI and Digital Operational Efficiency Participants expressed cautious optimism about the growing use of AI in sustainability efforts. AI applications in predictive routing, fuel optimization, and fleet management are gaining momentum, mirroring global practices (Tu et al., 2022; Schäfer et al., 2023). However, implementation in Türkiye is impeded by airspace congestion, fragmented data systems, and outdated traffic management infrastructure. These limitations correspond with Liu et al. (2021), who argue that digital aviation innovation requires strong institutional coordination. Türkiye's lack of a national AI strategy for aviation stands in contrast to digital leaders such as Singapore and Germany, underscoring the need for cross-agency collaboration and public-private partnerships to fully leverage AI's potential.

RQ4 – CSR and Stakeholder Expectations CSR and ESG frameworks are becoming more influential in Türkiye's aviation sector, with investor expectations, passenger behavior, and global reporting norms driving adoption. Larger airlines are aligning with international ESG frameworks and tapping into green finance instruments, consistent with Kolk and Pinkse (2020) and Eccles et al. (2014), who highlight finance-sector pressure as a catalyst for CSR. However, the absence of a standardized national ESG reporting requirement creates disparities in implementation and opens the door to greenwashing. Smaller carriers and service providers struggle to keep pace, lacking the financial and organizational resources to execute robust CSR policies. Experts called for clear regulatory frameworks and third-party audits to enhance credibility and stakeholder trust, echoing findings from Alonso-Almeida et al. (2015).

Collectively, the findings indicate that Türkiye's aviation sector is increasingly attuned to global sustainability priorities, but it faces significant gaps in policy coherence, technological integration, and resource allocation. The insights from this study suggest that progress depends not only on technical innovation but also on systemic reforms and strategic alignment. Compared to leading countries with integrated aviation sustainability frameworks, Türkiye's approach remains fragmented. However, its willingness to engage in SAF trials, invest in digital solutions, and respond to ESG pressures reflects a growing maturity.

6. Conclusion

The transition toward sustainable aviation is an urgent and global undertaking, yet its implementation unfolds unevenly across national contexts. This study contributes to the growing literature by examining how Türkiye's aviation sector navigates regulatory mandates, SAF limitations, digital transformation, and CSR engagement. By drawing on expert insights, the research provided a comprehensive view of the opportunities and constraints faced by the sector as it strives to align with global sustainability norms. Regulatory asymmetries—particularly between ICAO's CORSIA and the

EU ETS—illustrate the challenges Turkish carriers face in reconciling international frameworks with limited national policy support. These disparities highlight the urgent need for harmonized domestic strategies to reduce compliance burdens and ensure coherence in environmental governance.

From a practical standpoint, the findings suggest several targeted interventions that can enhance the sustainability performance of Türkiye's aviation sector. First, the government should develop a comprehensive national aviation sustainability roadmap that includes binding targets, sector-specific emissions guidelines, and financial instruments aligned with international mechanisms like the EU ETS and ICAO's CORSIA. This roadmap must address SAF barriers by incentivizing production through tax breaks, feedstock subsidies, and infrastructure investments at major airports. Policymakers could explore creating regional SAF innovation clusters, particularly near agricultural and industrial byproduct zones, leveraging Türkiye's geographical diversity for localized fuel sourcing. Moreover, aviation authorities and digital transformation agencies in Türkiye must collaborate to create a unified strategy for AI deployment in air traffic management, route planning, and fuel optimization. Public-private partnerships could support technology infrastructure modernization, while funding mechanisms like green aviation grants or AI innovation funds could encourage airline and airport investment. Strengthening ESG regulations through mandatory disclosure standards and independent audits would also raise accountability and trust among consumers and investors. Such reforms would empower not only flag carriers but also smaller service providers to adopt meaningful sustainability and CSR strategies.

At the global level, these insights underline the importance of harmonizing international regulatory frameworks to avoid competitive imbalances—particularly for countries like Türkiye that operate across both EU and non-EU airspaces. Global aviation authorities should work toward integrating CORSIA, EU ETS, and other carbon pricing schemes into a more cohesive model that accounts for varying national capabilities. Similarly, international cooperation on SAF R&D, technology transfer, and blended finance solutions could enable developing and transitional economies to contribute to decarbonization without facing prohibitive entry barriers. Finally, global aviation actors—whether regulators, technology providers, or international carriers—must recognize the role of contextual adaptation. The lessons from Türkiye underscore that sustainability strategies cannot be one-size-fits-all. Instead, they require flexible frameworks that accommodate national infrastructure realities, governance capacities, and socio-economic conditions. Only through coordinated but adaptive implementation can the aviation sector globally meet its emissions reduction targets and deliver on its sustainability promise.

Limitations of the study include the scope of participants, which was limited to 14 experts operating primarily in Türkiye. This scope may not fully reflect the experiences of all stakeholders, particularly low-cost carriers, regional airports, or global regulators. Moreover, while word clouds and sentiment analysis supplemented the findings, the absence of statistical modeling or longitudinal data restricts the generalizability and depth of the insights. Future research should integrate cross-national comparisons and quantitative modeling of sustainability impacts to validate and deepen these qualitative findings. Areas such as lifecycle emissions of SAF, financial returns on digital investment, and public perception of ESG in aviation remain ripe for further exploration.

In conclusion, Türkiye stands at a pivotal crossroads in the global push toward aviation sustainability. With targeted policy reform, technological investment, and stakeholder coordination, the country can move from fragmented compliance to proactive leadership. Achieving this requires a multi-dimensional strategy—one that unites regulation, innovation, finance, and social accountability into a cohesive sustainability agenda for aviation. By embracing such an integrated approach, Türkiye has the potential to shape not only its national aviation trajectory but also contribute meaningfully to the global effort in achieving climate-resilient air transport systems.

Ethical approval

Approval for this research was authorized by İstanbul Ticaret University Ethics Committee under decision number 02-09 and dated 28.02.2025.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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