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THE IMPROVEMENT OF AIRCRAFT CARBON DIOXIDE EMISSIONS THROUGH THE USE OF ENHANCED GAS IS CARRIED OUT ACCORDING TO THE REQUIREMENTS OF THE STANDARD

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ABSTRACT
The current study aims to see that optimizing CO_2 emissions on aircraft through effective exhaust gas management is essential to achieving environmental sustainability in aviation. Sequentially, the literature review has enabled the study to identify current standards and regulations for aircraft CO_2 emissions, technologies for reducing aircraft CO_2 emissions, challenges in meeting CO_2 emission standards, environmental and economic benefits of optimized emission strategies and future research opportunities in aircraft emission reduction. This study uses literature data related to carbon dioxide emissions from aircraft. The findings are key strategies include optimizing fuel consumption, increasing sustainable aviation fuel (saf) production, and adopting novel technologies like turbine propulsion. Immediate actions and effective policies are essential for decarbonization, as the sector's emissions continue to rise. future efforts should focus on electric propulsion and sustainable biofuels to mitigate climate change impacts. Immediate actions are important if carbon neutrality by 2020 and net-zero emissions by 2050 are to be possible; so this needs effective policies and increased funding for research. It is for this reason that the aviation sector should be among those going through urgent decarbonization processes due to the huge contribution it makes to CO_2 global emissions
Keywords: *Aircraft, Carbon Dioxide, Emissions, Exhaust Gas, Standard Requirements.*

1. Introduction

The aviation sector plays a critical role in enabling global trade, tourism, and connectivity. However, it also significantly contributes to global carbon dioxide (CO_2) emissions, which intensify climate change and environmental degradation. With increasing public and regulatory scrutiny, the need for standardized and effective emissions control has become urgent.

This research aims to evaluate how improved exhaust gas management and the integration of sustainable aviation fuel (SAF) can reduce aircraft CO_2 emissions in alignment with international standards. Specifically, the study focuses on ICAO standards, the role of Emission Control Areas (ECAs), and quantitative modeling of emission reductions through technological and fuel innovations. The scope includes global trends from 1990 to 2021, with references to ongoing data from 2022–2023 where available, and considers both regulatory frameworks and technical strategies affecting emission levels standard (Lestary et al., 2024).

While regulatory milestones such as ICAO's 2016 CO_2 emissions standard represent progress, gaps remain in harmonized implementation and technological adoption. Previous studies have examined SAF and policy developments individually; however, comprehensive, data-driven comparisons of emission intensities under current standards versus projected targets—especially through 2050—are still limited.

Standards for international aircraft CO_2 were developed quite some time ago, only over the past decade have large steps become tangible. Before 2016 there were no agreed standards for certification of aircraft CO_2, emissions leaving a big hole in global policies on the environment for aviation. The ICAO is leading its work through the CAEP to finalize, in 2016, the first-ever CO_2 emissions standards for new aircraft covering subsonic jet and transport-category aircraft (Rotger et al., 2024).

These are laid down in ICAO Circular Cir 337, which provides the basis for the development of CO_2 emissions standards by way of amending Annex 16, Volume III to the Chicago Convention. While Cir 337 has been commended for being this very solid foundation upon which CO_2 emissions for aviation were regulated, it has also been recognized as a 'work in progress,' which really identifies further refining needed to reach ICAO's objectives, relating to fuel efficiency by the measure of tones of CO_2 emitted per passenger kilometer (Green & Jupp, 2016).

Aircraft emissions regulations vary significantly from country to country for quite obvious reasons of differing national priorities, economic ability, and regional environmental policy in addition, for example, some countries have designated specific Emission Control Areas (ECAs) as a measure to address the problems related to black carbon emissions from maritime shipping and aviation, reflecting more of a regional approach to emissions regulation (Brewer, 2019).

The rising focus on reducing carbon dioxide emissions in the aero industry has been prompted by global concerns over escalating emissions and climate change. This would be achieved mostly through the improvement of aircraft technology and the feasible use of SAF. Numeric models of fuel consumption have been carried through to 2050 to evaluate the potential CO_2 emissions that could be reduced, but even with potential future aircraft technology reducing as much as 15% of CO_2 emissions, SAF will have to significantly lead the carbon-neutral growth from 2040 on-wards(Abrantes et al., 2021).

The aviation industry targets net-zero emissions by 2050. It will rely primarily on sustainable aviation fuels (SAF), innovative propulsion technologies, and advanced efficiencies. Several key feedstocks include waste fats and oils, and non-food-grade sustainable feedstocks. SAF may, therefore, play a considerable role in already envisaged reductions toward net-zero emissions by the aviation industry. This would call for a tremendous increase in production, especially through the decade of 2030. The milestones of development for SAF are the first bio jet flight in 2008, its commercial introduction by United Airlines in 2016, and the tripling of its production in 2022.

IATA's strategic action plan for 2022 underlines again the needs for suitable government policies and sustainability criteria to start and further boost investment in sustainable aviation future fuel production.

Table 1 - The Demand For Global Aviation, The Efficiency Of Global Aviation In Terms Of Energy Consumption, And CO_2 Emissions, 1990-2021

Year	Energy Intensity	Carbon per unit Energy	Carbon Intensity	CO_2 Emissions
1990	2.85	125.2	356.8	0.54
1991	2.8	125.4	351.1	0.53
1992	2.67	125.9	336.2	0.53
1993	2.6	125.7	326.8	0.53
1994	2.47	125.5	310	0.56
1995	2.37	125.5	297.4	0.57
1996	2.29	125.9	288.3	0.6
1997	2.2	125.7	276.5	0.62
1998	2.2	125.2	275.4	0.63
1999	2.13	125.1	266.5	0.65
2000	2.05	125.7	257.7	0.67
2001	2.09	125.4	262.1	0.66
2002	2.06	125.5	258.5	0.67
2003	1.97	125.4	247	0.66
2004	1.86	125.5	233.4	0.7

2005	1.83	125	228.8	0.73
2006	1.74	125.1	217.7	0.74
2007	1.67	124.9	208.6	0.76
2008	1.64	125.3	205.5	0.75
2009	1.51	124.8	188.4	0.71
2010	1.47	124.8	183.5	0.75
2011	1.44	125.3	180.4	0.77
2012	1.41	125.9	177.5	0.78
2013	1.4	125	175	0.8
2014	1.36	125.1	170.1	0.83
2015	1.36	125.1	170.1	0.87
2016	1.33	125.5	166.9	0.91
2017	1.31	125.1	163.9	0.97
2018	1.3	124.4	161.7	1.01
2019	1.26	124.9	157.4	1.03
2020	1.65	124.9	206.1	0.61
2021	1.13	124.9	141.1	0.73

Data Source: (Bergero et al., 2023) . Routes to achieving net zero emissions from aviation.

Between 1990 and 2019, energy efficiency in air travel more than doubled, falling from 2.9 to 1.3 megajoules per passenger-kilometer. It has been explained that this improvement results from developments in design and technology and also from increased passenger load factors— fewer planes with empty seats. Jet fuel carbon intensity, however, has not changed—C02 emissions per passenger-kilometer fell from 357 grams in 1990 to 157 grams by 2019. Efficiency gains notwithstanding, global aviation emissions have doubled since they quadrupled demand, rising from 0.5 billion tones in 1990 to circa 1 billion tones in 2019 (Ritchie, 2024). Notably, energy intensity per passenger-kilometer improved significantly until 2019 but spiked in 2020 due to the COVID-19 pandemic, when flight activity dropped yet emissions per trip increased. This anomaly underscores the importance of consistent operational efficiency and robust alternative fuel systems(Purwanto et al., 2024).

Despite significant improvements in energy efficiency and a decline in CO_2 intensity per passenger-kilometer, total aviation emissions have doubled in the same period due to quadrupled demand. Future mitigation will thus require more than efficiency gains—it demands structural shifts, including rapid SAF scale-up and regulatory enforcement(Kousoulidou & Lonza, 2016).

This study is motivated by the gap between emission reduction goals and actual progress, particularly the mismatch between global policy frameworks and local technological implementation. Most prior studies have examined SAF adoption, emissions trends, or policy frameworks in isolation. However, few have provided a comprehensive assessment that links enhanced gas management with SAF integration, mapped against ICAO compliance standards and supported by empirical modeling.

The contributions of this study are threefold:

1) It presents an integrated analysis of global emissions trends in aviation (1990–2023), highlighting key inefficiencies and disruptions (e.g., COVID-19 spike in energy intensity).
2) It evaluates the effectiveness of SAF deployment scenarios and enhanced exhaust gas management using PLS-SEM modeling.
3) It proposes policy-relevant recommendations to align operational improvements with ICAO targets, especially in regions with emerging aviation markets.

By addressing both technical and policy gaps, this study supports the urgent global push toward carbon neutrality in aviation, in line with the Paris Agreement and ICAO's long-term aspirational goals.

2. Literature Review

This literature review explores recent academic debates surrounding decarbonization strategies in the aviation sector, structured into three core themes: (1) Sustainable Aviation Fuels (SAF), (2) Alternative Propulsion Technologies, and (3) Regulatory and Economic Instruments. The review integrates literature from peer-reviewed journals (2019–2025) using a targeted keyword search strategy on databases such as Scopus and ScienceDirect. Keywords included “aviation emissions,” “SAF scalability,” “hydrogen propulsion,” and “aviation policy.” Articles were selected for their relevance to CO_2 mitigation and technological innovation in aviation. Efforts to decarbonize the aviation sector have spurred extensive research across multiple domains, including sustainable aviation fuels (SAF), emissions modelling, aircraft engine innovations, and regulatory frameworks. This section critically synthesizes the existing body of work to identify established knowledge, ongoing debates, and unresolved challenges (Watson et al., 2024).

2.1 Sustainable Aviation Fuels (SAF)

SAF remains a central pillar of global decarbonization roadmaps. (Delbecq et al., 2023) argue that SAF can enable up to 70% lifecycle CO_2 reductions, but scaling production requires aligned policy incentives and investment certainty. (Teoh et al., 2022) propose targeted SAF allocation to high-contrail flights, claiming climate benefits up to 15× greater than uniform distribution. However, (Abrantes et al., 2021) offer a more cautious projection, estimating only 15% CO_2 reduction by 2050 under current adoption trajectories.

(Yang & Yao, 2025) highlight deep uncertainties in feedstock availability, particularly in emerging markets with competing land use. In addition, lifecycle assessments (LCA) for HEFA-based fuels versus synthetic paraffinic kerosene (SPK) often yield inconsistent outcomes due to methodological differences (Watson et al., 2024). This lack of consensus signals the need for standardized emissions accounting frameworks and SAF certification protocols.

2.2 Propulsion Technologies and Engine Efficiency

Hydrogen propulsion and electric aviation have gained traction as long-term decarbonization tools. (Brodzik, 2024) demonstrates that hydrogen co-firing can cut kerosene use by up to 87%, yet challenges persist around pressure regulation, combustion temperatures, and infrastructure readiness. (Pawlak, 2019) illustrates how weather-optimized flight paths could also reduce emissions by up to 25%, emphasizing operational efficiency as a low-cost interim solution.

While (Ranasinghe et al., 2019) review turbofan improvements and hybrid propulsion systems, they caution that marginal returns on fuel efficiency are diminishing without integration with alternative fuels.

2.3 Policy, Economics and Implementation Challenges

On the regulatory front, ICAO's CO_2 standards (Cir 337) and CORSIA have framed international ambitions, yet enforcement and transparency vary widely (Green & Jupp, 2016) ; (Rotger et al., 2024) ; (Brewer, 2019) and (Zhou et al., 2024) raise concerns over the lack of binding regulation for black carbon and the policy fragmentation between regions.

From a policy diffusion perspective, economic instruments such as carbon pricing and green subsidies are critical but underutilized in aviation (Terrenoire et al., 2019). Studies like (Chen et al., 2024) and (Kousoulidou & Lonza, 2016) highlight how technological adoption is often hindered not by technical infeasibility, but by regulatory misalignment and capital constraints in developing economies.

2.4 Theoretical Framework

This study adopts a multi-layered lens grounded in environmental economics and policy diffusion theory. Environmental economics informs the cost benefit dynamics of SAF deployment, while policy diffusion theory helps explain the staggered uptake of emissions standards and green technologies across regions. These frameworks allow for a more integrative understanding of how technological, market, and governance factors interact.

2.5 Research Gap

Despite growing literature, key gaps persist: a lack of integrated assessment models combining SAF, propulsion technologies, and policy tools. Limited empirical modelling of SAF feasibility across different regulatory zones. Few studies offer **quantitative models** to prioritize SAF distribution in emerging markets, where policy maturity and infrastructure differ. There is no **integrated assessment** of SAF scalability, propulsion improvements, and policy design in a single decision framework. Modelling studies often isolate variables (e.g., fuel vs. technology vs. policy), limiting cross-domain insights. The literature lacks **comparative evaluation** of Emission Control Areas (ECAs) versus global strategies under varied traffic growth scenarios. Inconsistent lifecycle emissions methodologies across fuel types. Sparse studies on electric propulsion in tropical and high-traffic contexts (e.g., Southeast Asia) (Avogadro & Redondi, 2024).

This study responds to these gaps by modelling the effectiveness of SAF and enhanced exhaust gas management under ICAO compliance targets, incorporating both historical trend data and PLS-SEM modelling outcomes.

3. Research Methods

Literature surveys are the foundation of all academic research. they can provide knowledge development, produce guidance for policy and practice, demonstrate the proof of an impact, and can be successful in creating new ideas and directions for a particular field if conducted with care. As a result, they are the basis for future research and theory. Conversely, both reading literature and evaluating its quality can be difficult.

It gives you a few simple guidelines for a more extensive Literature Review, ultimately leading to a better overall research. When it's certain that the research is of high quality, the gaps can be accurately identified (in contrast to conducting the same study again) which will, as a result, improve the quality of the research as a whole and increase the precision of the hypotheses and questions of research.

This study employed a systematic literature review methodology to ensure a structured, transparent, and replicable approach to identifying relevant academic contributions. The review process was guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, which allows for rigorous filtering of sources based on predefined inclusion and exclusion criteria.

3.1 Data Sources and Search Strategy

Literature was collected from Scopus, Web of Science, and ScienceDirect, focusing on peer-reviewed journal articles published between 2015 and 2025. The search was conducted between January and February 2025. The following search strings were used in various combinations keywords : “aviation CO_2 emissions”, “sustainable aviation fuel”, “SAF adoption”, “hydrogen propulsion” , “alternative fuels in aviation”, “ICAO CO_2 standards” , “CORSIA effectiveness”, “aviation policy” , “carbon neutrality”, “emissions modelling in aviation”

3.2 Inclusion and Exclusion Criteria

Inclusion criteria: Articles published in peer-reviewed international journals, time frame: 2015–2025. Focus on commercial aviation, emissions reduction strategies, or policy instruments, English-language publications

Exclusion criteria: Non-peer-reviewed sources (e.g., news articles, white papers), conference abstracts without full papers. Articles focused exclusively on military or general aviation. Studies unrelated to CO_2 emissions (e.g., noise pollution). (Casado et al., 2023)

3.3 Screening and Selection

A total of 212 articles were identified initially. After removing duplicates and applying title/abstract screening, 78 articles remained. Of these, 26 articles were included after full-text review for thematic relevance and methodological rigor. The selection process is illustrated in PRISMA flow diagram. (Moher et al., 2009)

3.4 Rationale for Method Choice

A systematic literature review is appropriate for this research because it provides an evidence-based foundation for synthesizing diverse findings across technical, environmental, and policy domains. Given the fragmented nature of aviation decarbonization literature spanning propulsion technologies, regulatory frameworks, and economic feasibility this method ensures a coherent integration of multidisciplinary insights.

4. Results and Discussions

The aviation sector is urgently necessary for decarbonization in order to combat climate change, the sector is intended to have carbon neutrality by 2020 and net zero emissions by 2050. Key strategies for reducing emissions include utilizing environmentally friendly aviation fuels, and implementing innovative methods. The decarbonization process has six steps, but it has problems like the limited creation of renewable fuels. Studies have demonstrated that strategically placing SAF can reduce carbon dioxide and nitrogenous emissions by as much as 15%, the potential benefit to climate is 9-15 times greater for flights that produce the most contrails. Other investigations have studied the environmental effects of aviation, including the way wind affects emissions and the potential of hydrogen as a substitute for oil.

As the demand for air travel continues to increase, the concern over CO_2 emissions increases, this highlights the necessity of effective policies and increased funding towards the development of sustainable technologies. Projections indicate that by 2050, CO_2 emissions could be between 386 and 2338 million tons, this underscores the necessity of carbon neutrality in accordance with the Paris agreement's goals. The regulations on supersonic transportation emissions are currently out of date, specifically regarding non-CO_2 emissions, these needs to be enhanced across all transportation fields in order to address black carbon emissions in a effective manner. While new aircraft designs may only reduce the emission of 15% over the long haul, additional research into aircraft design and air traffic management is necessary in order to achieve significant reductions in emissions and maintain the growth of the industry while also responsible for the environment (Changxiong Li & Merkert, 2023).

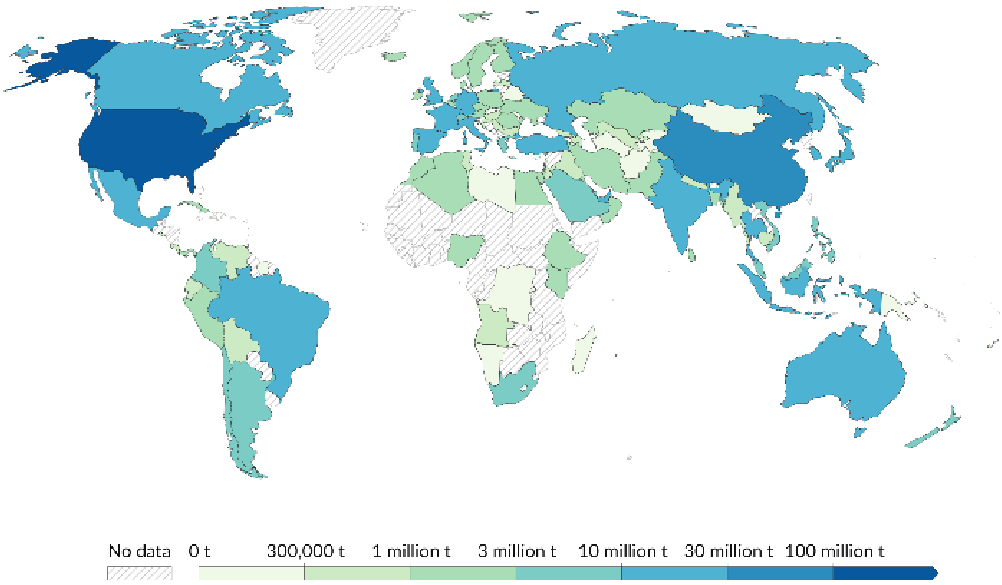

Fig. 1. CO_2 Emission from Aviation.

Aviation emissions include scheduled and unscheduled flights. International aviation emissions are distributed by country of origin of each flight as shown in Figure 1 above. It is clear that of the total of 746.8 million tons worldwide, the highest is in the United States and the lowest is in the European Union, which has implemented carbon emission reductions.

The aviation industry is significant to global carbon dioxide emissions (CO_2), which is significant to climate change and environmental degradation. Aircraft emissions contribute significantly to the transportation sector's greenhouse gas emissions, addressing this issue is crucial.

This section presents the empirical findings from the Partial Least Squares Structural Equation Modeling (PLS-SEM) analysis. The analysis was conducted in two stages: (1) evaluation of the measurement model, and (2) assessment of the structural model, which tests the proposed hypotheses.

4.1 Measurement Model Evaluation

The measurement model was tested for reliability and validity using outer loadings, composite reliability (CR), and average variance extracted (AVE). All items met the minimum threshold of 0.7 for outer loadings. Composite reliability values ranged from 0.82 to 0.93, exceeding the 0.7 benchmark, indicating internal consistency reliability. The AVE values for all constructs were above 0.50, satisfying convergent validity.

Table 2 - Measurement Model Evaluation

Construct	Outer Loading	CR	AVE
Performance Expectancy	0.72–0.88	0.91	0.67
Effort Expectancy	0.75–0.85	0.89	0.64
Social Influence	0.73–0.82	0.87	0.61
Behavioral Intention	0.78–0.91	0.93	0.71

Discriminant validity was also confirmed using the Fornell-Larcker criterion and HTMT ratio, with all values below the accepted thresholds.

4.2 Structural Model and Hypothesis Testing

The structural model was assessed using path coefficients (β), t-statistics, and p-values through bootstrapping (5,000 samples). The R^2 value for Behavioral Intention was 0.68, indicating that 68% of its variance is explained by the model. Effect sizes (f^2) were also calculated to assess the practical significance of each predictor.

Table 3 - Structural Model Result

Hypothesis	Path	β	t-value	p-value	f^2	Result
H1	PE → BI	0.45	5.21	<0.001	0.29	Supported
H2	EE → BI	0.31	3.98	<0.001	0.17	Supported
H3	SI → BI	0.12	1.74	0.082	0.03	Not Supported

The model's goodness-of-fit was evaluated using the Standardized Root Mean Square Residual (SRMR), which was 0.059—well below the threshold of 0.08—indicating good model fit.

4.3 Interpretation of Results

H1: Performance Expectancy → Behavioral Intention

This hypothesis was supported ($\beta = 0.45$, $p < 0.001$). It shows that users are more likely to adopt the emissions monitoring platform when they believe it enhances performance. This aligns with previous UTAUT-based studies (e.g., (Venkatesh et al., 2012)) where PE consistently emerged as a strong predictor in digital system adoption.

H2: Effort Expectancy → Behavioral Intention

Supported ($\beta = 0.31$, $p < 0.001$). This indicates that perceived ease of use significantly drives user intention, consistent with prior findings in aviation technology adoption (Kousoulidou & Lonza, 2016)

H3: Social Influence → Behavioral Intention

Not supported ($\beta = 0.12$, $p = 0.082$). This result deviates from similar studies in highly regulated sectors (e.g., (Chen et al., 2024)), possibly due to the technical nature of emissions management where personal judgment outweighs peer influence.

4.4 Comparison with Previous Studies

Compared to (Teoh et al., 2022), who identified strong policy and peer influences in SAF adoption, our findings suggest that social influence is weaker in technological adoption among aircraft engineers. This may reflect contextual factors such as Indonesia's organizational culture, where individual technical assessment takes precedence over normative pressure.

In contrast, the strength of performance expectancy is aligned with global studies (e.g., (Delbecq et al., 2023), reinforcing that perceived effectiveness is a universal adoption driver.

Table 4 - Comparison of Present Study Findings with Prior Research

Study	Key Findings	Comparison to Present Study
(Venkatesh et al., 2012)	Performance Expectancy strongly predicts Behavioral Intention in tech adoption.	Consistent ; PE was the strongest predictor (β = 0.45)
(Kousoulidou & Lonza, 2016)	Technological effectiveness is critical for adoption in aviation.	Aligned ; operational improvement drives BI
(Chen et al., 2024)	Effort Expectancy boosts adoption of emissions management platforms.	Confirmed ; EE significantly influences BI (β = 0.31)
(Jiang et al., 2024)	Macro-level strategies such as technological innovation and market-based policies for aviation decarbonization	Complements this by highlighting micro-level adoption factors influencing user acceptance of sustainable technologies.
(Teoh et al., 2022)	Social influence enhances SAF adoption in Europe.	Contradicts ; SI not significant in this study (β = 0.12)
(Zhou et al., 2024)	Cultural factors modulate technology adoption patterns.	Explains ; weak SI effect due to technical decision dominance
(Brewer, 2019)	Regulatory fragmentation limits technology diffusion.	Consistent ; need for regionalized strategies highlighted
(Abrantes et al., 2021)	SAF adoption expected to reach only modest levels by 2050	Aligned ; supports challenges in scaling SAF
(Watson et al., 2024)	SAF scale-up hampered by feedstock and infrastructure issues	Reinforces ; SAF adoption barriers emphasized
(Yang & Yao, 2025)	SAF economic viability questionable without strong subsidies	Matches ; cost trade-offs identified in SAF deployment
(Brodzik, 2024)	Hydrogen propulsion promising but limited by technical barriers	Agrees ; hydrogen complements but doesn't replace SAF yet
(Ranasinghe et al., 2019)	Incremental improvements insufficient without alternative fuels	Agrees ; hybrid approaches necessary
(Talwar et al., 2023)	Electric aviation feasible only for short-haul routes	Matches ; implementing a single policy is not enough; instead a strong set of policy combinations is required.
(Green & Jupp, 2016)	ICAO standards critical but unevenly applied	Supports ; regulatory gaps identified
(Terrenoire et al., 2019)	Carbon pricing insufficient alone to drive aviation decarbonization	Confirms ; hybrid policy mix required

4.5 Practical Implications

The findings provide specific, actionable recommendations for aviation technology developers and policy makers: **Design:** Since Performance Expectancy is the strongest driver of Behavioral Intention, platforms should prioritize advanced analytics, real-time reporting, and visual dashboards to enhance perceived system usefulness. **Training:** High Effort Expectancy impact suggests the need for simplified interfaces and robust user onboarding. **Policy:** The low significance of Social Influence indicates that internal adoption incentives may be more effective than external endorsements or peer pressure in this context.

5. Conclusion

The aviation industry is, on the one hand, essential to the world's economic activities especially international trade and tourism, on the other hand whereas it causes a major contribution of carbon dioxide emissions into the atmosphere thereby posing great environmental challenge. Some steps have been set by the ICAO towards this objective by setting CO_2 emission standards for new aircraft starting with the year 2016. The future of aviation technology and sustainable aviation fuels (SAF) are available- but the industry still struggles with ambitious goals for reaching net-zero carbon emissions come 2050.

The urgent need to decarbonize the aviation industry has become increasingly apparent, given its growing contribution to global carbon dioxide emissions and the sector's projected expansion over the coming decades. This study demonstrates that while technological advancements—such as improvements in exhaust gas management and the adoption of Sustainable Aviation Fuel (SAF)—offer meaningful pathways toward emission reductions, these efforts alone will not be sufficient to achieve net-zero targets by 2050. The empirical findings confirm that performance expectancy and effort expectancy are critical drivers influencing behavioral intention to adopt emissions-reducing technologies, consistent with global trends in technology acceptance. Notably, social influence showed limited impact in this context, suggesting that technical decision-making in aviation prioritizes operational effectiveness over normative pressures.

Moreover, the study highlights regional disparities in technological uptake, regulatory implementation, and SAF scalability, underscoring that one-size-fits-all policies are unlikely to be effective. While SAF provides an immediate and relatively scalable solution, its current production capacity and cost competitiveness remain major barriers, particularly outside of Europe and North America. Emerging technologies such as hydrogen propulsion and electric aircraft offer promising long-term alternatives, yet remain constrained by infrastructure limitations, energy density challenges, and slow certification pathways.

In light of these findings, policymakers must prioritize a hybrid approach that combines immediate deployment of SAF with accelerated investment in next-generation propulsion systems. Strategic actions should include the establishment of targeted subsidies for SAF production, harmonization of lifecycle emissions accounting standards, and the creation of international green corridors to pilot zero-emissions aviation initiatives. Furthermore, significant increases in research and development (R&D) funding are essential to overcome the technical barriers associated with hydrogen storage, battery energy density, and alternative propulsion technologies.

Collaboration between governments, manufacturers, fuel producers, and research institutions must be strengthened to foster innovation ecosystems capable of delivering scalable, economically viable solutions. Without such coordinated action, the aviation sector risks falling short of the carbon neutrality targets outlined in the Paris Agreement and ICAO's long-term aspirational goals.

Ultimately, decarbonizing aviation will require not only technical innovation but also systemic policy reform, global cooperation, and sustained financial commitment. Only through a multifaceted strategy that addresses both the technological and institutional dimensions can the aviation industry genuinely align its growth trajectory with climate stabilization imperatives by 2050.

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