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Revolutionizing waste management: smart technologies and sustainable aviation fuel integration for environmental sustainability

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Abstract
This manuscript introduces a novel approach integrating smart technologies and sustainable aviation fuel (SAF) production within solid waste management hierarchy to address waste accumulation and aviation emissions. The study demonstrates that approximately 960 Mt of municipal solid waste are available globally for biofuel conversion, with potential to produce 115 MT of SAF through gas/Fischer-Tropsch pathways.
Our analysis reveals SAF production from waste reduces net greenhouse gas emissions by 27–87% compared to conventional jet fuel, with 1000 kg of waste converted yielding a 380 kg CO_2 reduction. The research establishes a revised environmental hierarchy prioritizing composting for biodegradable waste, followed by SAF production for non-compostable materials, with incineration as a last resort, addressing significant air pollutants and emissions from traditional incineration. The integration of smart technologies (digital and automated tools like Internet of Things, artificial intelligence, sensors, and data analytics that improve efficiency, traceability, and decision-making in waste management) boosts operational performance and facilitates waste-to-fuel conversion. Despite environmental benefits, economic challenges persist, with SAF production costs 2–8 times higher than fossil jet fuel. However, the global SAF market is projected to grow at 57.5% Compound Annual Growth Rate from USD 576 million (2022) to USD 15.7 billion (2030), improving viability through policy support and economies of scale. This integrated model addresses dual crises of waste management and aviation decarbonization while supporting the transition toward circular economies and climate-resilient infrastructure.

Keywords Waste management, Smart technologies, Sustainable aviation fuel, Circular economy, Environmental sustainability, Green aviation

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1 Introduction

Solid waste management (SWM) poses a significant global challenge, encompassing the complex processes of waste collection, transportation, treatment, and disposal resulting from human activities [1]. This challenge is shaped by a range of factors including population density, urbanization, economic development, cultural practices, and regulations [2]. Traditional waste management approaches, which emphasize disposal and treatment, have led to considerable environmental and societal consequences [3]. These practices contribute to landfill pollution, greenhouse gas (GHG) emissions, resource depletion, health risks for waste workers and communities, environmental injustice, reduced quality of life, and economic losses.

The volume of global waste generation has been rising significantly over time. In 1965, the total waste produced was 635 Mt, escalating to 1,999 Mt by 2015. Projections indicate that by 2050, global waste generation could reach approximately 3,539 Mt [4]. Traditional methods of waste treatment and disposal, such as incineration and landfilling, have raised environmental concerns [5]. There are over 1,700 thermal Waste-to-Energy (WtE) plants worldwide, with more than 80% located in developed countries [6]. Incineration, while a prevalent waste disposal method, has significant drawbacks. It releases harmful pollutants into the atmosphere, exacerbating air pollution and GHG emissions, and generates hazardous fly and bottom ashes that pose challenges for safe disposal [7, 8]. Furthermore, incineration is energy-intensive and costly, imposing financial burdens on waste management services and impacting local governments and communities [9]. Similarly, landfills contribute to environmental pollution through GHG emissions and toxic leachate, as well as causing air pollution, habitat disruption, and social inequalities [10].

The inefficiency and high costs associated with traditional waste processing underscore the unsustainable nature of conventional waste management practices [11]. Under a business-as-usual scenario, global waste management costs are projected to reach $640.3 billion by 2050, representing an almost doubling of current expenditures [12]. This highlights the urgent need for a paradigm shift away from linear, end-of-pipe solutions toward holistic, resource-efficient, and climate-responsive waste systems.

Recent advances in smart technologies such as Internet of Things (IoT) enabled waste bins, artificial intelligence (AI)-driven waste sorting, data analytics, and real-time route optimization present transformative potential for improving efficiency and sustainability in waste management systems. These tools enhance operational efficiency, reduce emissions and costs, and improve service delivery through real-time decision-making and optimized logistics [13–17]. Moreover, they enable better citizen engagement and transparency, fostering behavioral change and accountability in waste generation and separation.

Parallel to these advancements, SAF has gained global momentum as a critical tool for decarbonizing the aviation industry. SAF can be produced from a range of renewable feedstocks, including MSW, food waste, used cooking oil, and agricultural residues [18]. Compared to conventional jet fuels, SAF can reduce lifecycle GHG emissions by up to 80%, depending on the feedstock and conversion pathway used [19–21]. With aviation emissions on the rise, SAF represents a scalable, near-term solution for aligning air transport with climate goals, especially when derived from waste that would otherwise be incinerated or landfilled [22, 23].

While both smart waste technologies and waste-to-fuel conversion processes have been studied independently, there remains a critical gap in the literature: the lack of integration between digital innovation in waste systems and the valorization (the process of converting waste materials into valuable products or energy sources) of waste through SAF production. Most research addresses these strategies in isolation, without exploring the synergistic benefits of combining them in a single, circular framework. This siloed approach overlooks the opportunity to rethink waste not just as a burden, but as a valuable, traceable, and transformable resource that can contribute to energy security, climate action, and sustainable development.

This manuscript fills that gap by proposing a novel paradigm that links smart technology-driven waste management systems with SAF production. Through an extensive literature review and integration analysis, it evaluates the environmental, economic, and policy implications of this dual approach. The paper also highlights the limitations related to SAF production with incineration, the role of composting in a circular hierarchy, and identifies enabling conditions - technological, regulatory, and economic - for its successful implementation.

By bridging digital transformation and clean energy production, this model advances existing literature by: (i) linking IoT and AI-based waste analytics to feedstock identification and conversion tracking; (ii) redefining the waste hierarchy to prioritize composting and SAF before incineration; and (iii) embedding policy and techno-economic parameters to support large-scale implementation. To further highlight the novelty of this work relative to existing studies, Table 1 summarizes the distinctions between previous research streams and the proposed integrated smart technologies – SAF model.

Table 1 Comparison of previous approaches and the proposed integrated model

Study Focus	Key Features	Identified Gaps	Advancement in this Study
Smart Waste technologies	IoT, route optimization, automated sorting	Lack of integration with energy recovery and carbon mitigation	Connects digital infrastructure with SAF feedstock mapping and tracking
SAF Production Pathways	Thermochemical and biochemical conversion of waste	Absence of digital and policy integration	Embeds smart monitoring and data analytics into SAF supply chain
Policy and Circular	Emphasis on regulatory frameworks	Weak link between urban waste policy and aviation decarbonization	Creates cross-sectoral circular policy model linking waste and aviation sectors
This Study	Smart technologies – SAF integrated model		Introduces a cross-domain digital energy policy framework for waste valorization and low-carbon aviation

2 Materials and methods

This study adopted a conceptual integration approach grounded in empirical data and recent literature to develop a new model for SWM that combines smart technologies with SAF production. Rather than conducting a systematic literature review, the research was designed to construct a novel framework using real-world data, policy insights, and technological case studies. The main objective was to assess how new digital technologies and waste-to-fuel solutions could be strategically incorporated into MSW systems to promote sustainability, lessen environmental impacts, and align with circular economy principles - an economic approach focused on preserving the value of materials and resources through ongoing reuse, recycling, and recovery, rather than the conventional linear take–make–dispose model.

Data was sourced from a wide range of credible publications and databases. Peer-reviewed articles were retrieved from platforms such as Scopus, Web of Science, ScienceDirect, and SpringerLink, focusing on studies published between 2010 and 2024. Supplementary information was drawn from reports and statistical documents published by leading global institutions including the United Nations Environment Programme (UNEP), the International Civil Aviation Organization (ICAO), the International Air Transport Association (IATA), the International Renewable Energy Agency (IRENA), and the European Commission. Additional quantitative data on waste generation, SAF production potential, and carbon emission impacts were compiled from global datasets such as OECD.Stat, the World Economic Forum, and International Energy Agency (IEA) publications. Only English-language documents relevant to MSW, organic and biomass waste streams, smart infrastructure, and SAF technologies were included in the analysis.

The methodology followed a structured integration process. First, relevant concepts and technologies were mapped and classified within the SWM hierarchy, identifying where smart technologies and SAF production could be most effectively implemented. Second, a comparative assessment of traditional waste treatment options - primarily incineration - was carried out against emerging alternatives such as composting and SAF pathways. This assessment relied on life-cycle data, environmental impact metrics (e.g., GHG emissions), and energy recovery efficiency values reported in the literature. Third, a scenario-based framework was developed to illustrate how a revised waste management hierarchy could prioritize waste prevention, composting, recycling, and SAF production before resorting to incineration or landfilling.

Thirdly, the study conducted a policy and feasibility analysis by drawing on case studies from countries that have successfully implemented advanced waste management practices and SAF strategies. Examples from Sweden, South Korea, and the European Union were used to extract policy mechanisms, economic incentives, and infrastructure models that enable integration at scale. The resulting framework is intended not as a theoretical model, but as a practical roadmap for cities and governments seeking to transition to more sustainable and technologically integrated waste systems.

Lastly, to evaluate implementation potential across varying socio-economic contexts, a qualitative Decision-Support Matrix was developed. The matrix assesses integration feasibility across three scenarios, urban developed, urban developing, and rural contexts, based on five criteria: (1) technological readiness, (2) infrastructure maturity, (3) policy and governance alignment, (4) economic cost/benefit, and (5) social acceptance. Each parameter was rated on a 1–5 scale (1 = low feasibility; 5 = high feasibility).

Through this interdisciplinary and data-driven approach, the study proposes a comprehensive strategy to repurpose waste as a resource while simultaneously addressing climate change, energy resilience, and public health. This methodology bridges gaps across environmental science, technology, and policy to support evidence-based decision-making and scalable implementation.

3 Results and discussion

3.1 Evolution of solid waste management

SWM has evolved significantly from unsanitary open dumping to more structured and sustainable strategies. In early stages, waste was often discarded in uncontrolled sites, leading to severe environmental pollution, groundwater contamination, and public health crises [24]. The introduction of engineered landfills marked a modest improvement; however, these still contribute to methane emissions and leachate pollution. The current state of the world's largest landfills, which vary in size and capacity from 0.18 to 4.4 Mt per year highlighted these challenges (Fig. 1) [25]. Although some landfills have adopted green technologies, like methane-to-energy systems, the overall progress remained uneven. The data emphasized the necessity for comprehensive waste management strategies focused on waste reduction, recycling, and resource recovery to minimize the environmental impact of landfills.

As concerns about resource depletion and environmental impact grew, waste reduction and recycling gained prominence [26]. Governments and organizations promoted recycling programs to divert waste from landfills and conserve resources. The emergence of WtE technologies, including incineration and combustion, aimed to recover energy from waste [27]. Approximately 27% of MSW in the European Union (EU-27) is incinerated for electricity and heat generation [28, 29]. Advanced methods, such as incineration with energy recovery, anaerobic digestion, and gasification, have become viable options for converting waste into heat, electricity, or biofuels [30]. Figure 2 illustrates the varying rates of waste incineration across countries [31]. For instance, Denmark, Sweden, and Norway have high incineration proportion, ranging from 52 to 63%, while countries like Chile, Greece, and Portugal have lower proportions. The diverse approaches to waste management reflect different national priorities and strategies.

The concept of smart technologies has gained traction, emphasizing waste minimization, recycling, reuse, and designing products for durability and resource efficiency [32]. This shift in economy closed the resource loop and reduced the environmental impact of waste management.

Incineration, though widely used for solid waste disposal, posed serious environmental challenges. Incineration emits significant air pollutants including particulate matter, nitrogen oxides, sulfur dioxide, furans and dioxins derivatives, and heavy metals that threaten public health and ecosystems. Moreover, incineration contributes to GHG emissions, particularly CO_2, and results in hazardous fly and bottom ashes residues that can contaminate soil and groundwater. From a resource efficiency perspective, incineration is inherently wasteful, as it destroys materials that could otherwise be recovered or recycled, undermining circular economy efforts.

In contrast, SAF production offers a cleaner and more sustainable alternative for managing waste. By converting organic and MSW into low-carbon fuel, SAF production reduces pollutant emissions and supports climate goals through significantly lower life-cycle GHG emissions. These technologies operate under controlled conditions, minimizing toxic by-products and promoting resource recovery. Integrating SAF production into waste management systems not only helps decarbonize aviation but also reduces the environmental and health impacts associated with traditional incineration, supporting a more circular and sustainable economy (Fig. 3).

This innovative model leverages advanced technologies to optimize waste management processes, reduce environmental impacts, and support the decarbonization of the aviation sector. Key elements and advantages of this paradigm are summarized in Table 2.

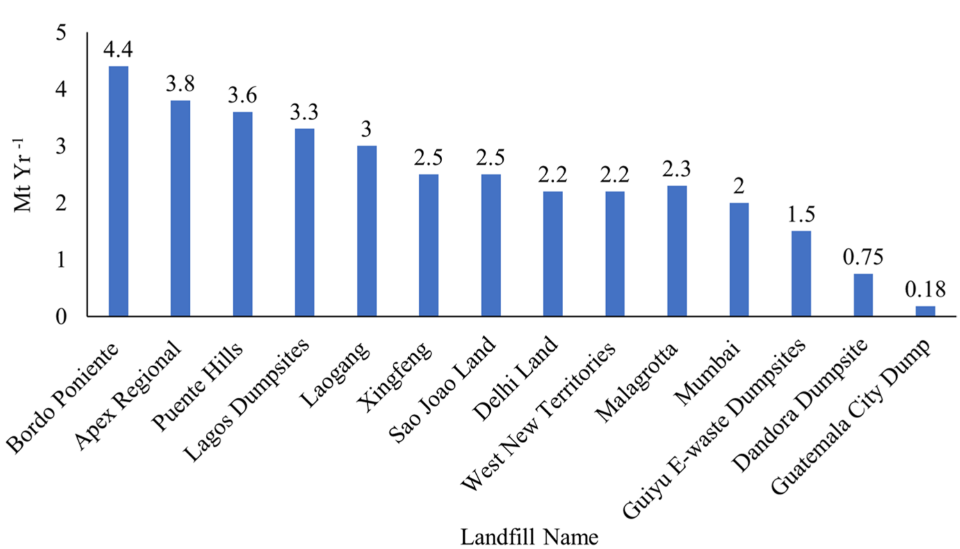

Fig. 1 The 15 largest landfills in the world [25]

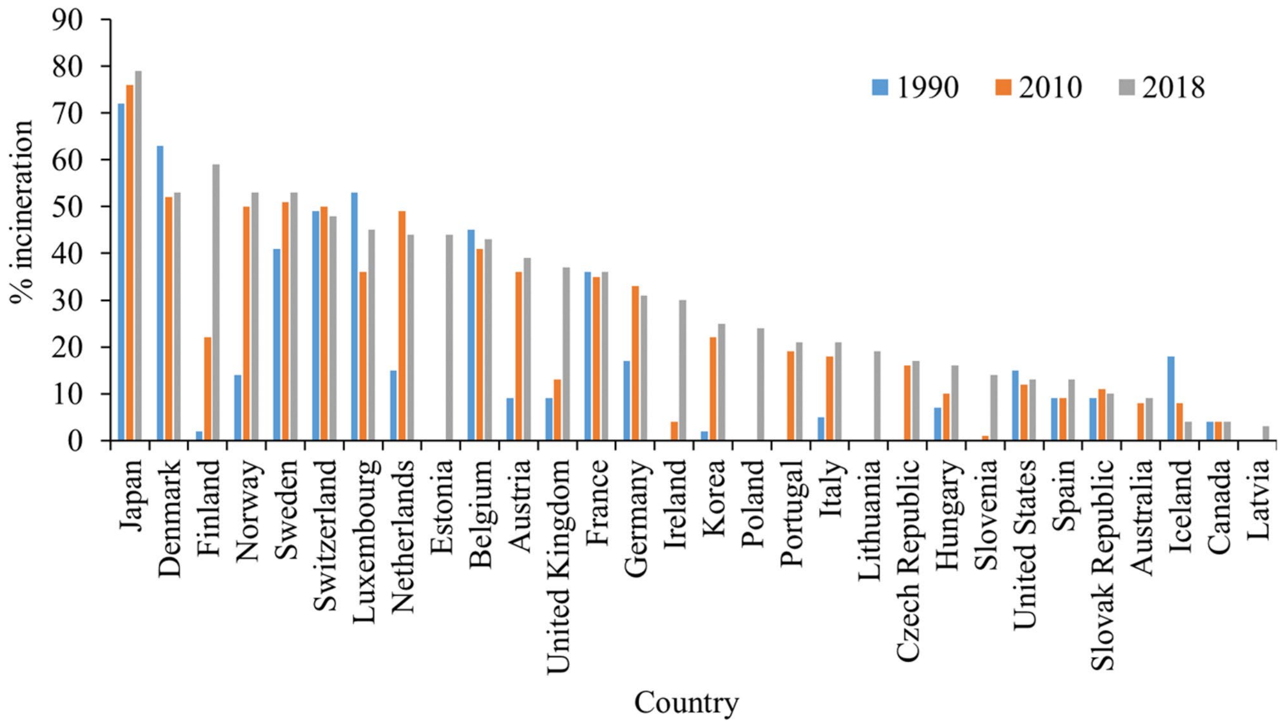

Fig. 2 Proportion of waste incineration across different countries

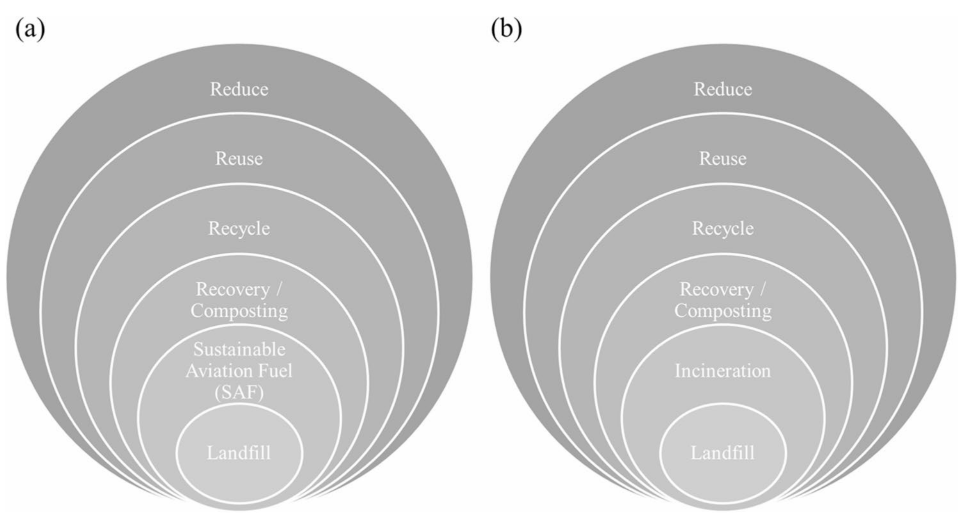

Fig. 3 Proposed (**a**) and Current (**b**) solid waste management hierarchy

3.2 Integration of SAF production in SWM hierarchy

Approximately 2.0 Bt of MSW are generated globally each year, with about half consisting of organic materials like food and garden waste [33]. Non-reusable plastics also present a viable feedstock with minimal sustainability concerns. This results in roughly 960 Mt of MSW being available for conversion into biofuels. Utilizing the gas/Fischer-Tropsch pathway, this quantity of waste could potentially produce around 115 Mt of SAF [34].

Several factors influence the production capacity of SAF. The availability and volume of feedstocks, including agricultural residues and MSW, vary regionally based on local waste management practices, recycling rates, and regulations. Additionally, the choice of waste-to-fuel technology such as hydrotreatment, gasification, or pyrolysis affects SAF production potential, with the efficiency and scalability of these technologies, as well as ongoing advancements and optimizations, playing crucial roles in enhancing SAF yields. Furthermore, government policies, incentives, and the aviation industry's commitment to reducing carbon emissions significantly impact SAF production, with a supportive regulatory

Table 2 Key aspects of the new proposed paradigm in solid waste management

Aspect	Description
Smart Technologies	Integration of sensor-equipped waste bins, Internet of Things (IoT) devices, and data analytics for real-time monitoring and optimization of waste management practices. Automated sorting systems and predictive analytics enhance recycling rates and operational efficiency.
Sustainable Aviation Fuel Production	Conversion of waste materials into SAF through processes like gasification and pyrolysis, supporting the circular economy and reducing reliance on fossil fuels in the aviation sector.
Circular Economy and Resource Recovery	Optimization of waste prevention, reuse, recycling, composting, and incineration processes, maximizing resource recovery and minimizing waste generation. Utilization of waste as a valuable resource aligns with circular economy principles.
Decarbonization of the Aviation Sector	Contribution to the global objective of decarbonizing the aviation industry by reducing carbon emissions using sustainable aviation fuel produced from waste materials.
Energy Recovery and Renewable Energy Generation	Generation of renewable energy from waste through processes like gasification and pyrolysis, supporting a sustainable and resource-efficient energy system.

environment and increasing market demand from airlines driving production growth.

The global aviation sector, essential for economic activities such as tourism and trade, is experiencing substantial growth. The IATA forecasts that global passenger numbers will more than double from 3.8 billion in 2016 to 8.2 billion by 2037, with an annual growth rate of 3.5% [35]. The Asia-Pacific region is expected to see the highest growth in international passengers, followed by the Middle East, Africa, Latin America, Europe, and North America [35].

In 2017, global aviation fuel consumption was approximately 300 Mt [36]. With the aviation industry's rapid expansion, fuel demand is projected to more than double by 2050 [37]. This rising demand, particularly in rapidly growing aviation markets in developing countries, highlights the urgent need for sustainable alternatives to fossil fuels. In 2017 alone, global flights emitted 859 Mt of CO_2, with the aviation sector responsible for 2% of global anthropogenic CO_2 emissions [38]. This underscores the critical need for SAF to address the environmental impacts of aviation.

The demand for SAF is being driven by airline commitments to emission reduction, regulatory mandates, and corporate sustainability initiatives. The global SAF market, valued at approximately USD 576.2 million in 2022, is expected to grow at a compound annual growth rate of 57.5% from 2023 to 2030, reaching an estimated USD 15,716 million [39]. This growth not only supports the aviation industry's sustainability goals but also presents significant economic opportunities.

The economic viability of waste-to-fuel technologies depends on airlines' and consumers' willingness to pay premiums for sustainable alternatives, along with a stable and predictable market. As SAF demand rises, waste-to-fuel technologies will play a crucial role in meeting this demand, advancing sustainable aviation practices, and mitigating the aviation industry's environmental impact.

Integrating SAF production into the SWM hierarchy represents a significant opportunity to address both waste management challenges and the sustainability of the aviation industry. SAF is produced from renewable sources and offers an eco-friendlier alternative to conventional fossil-based jet fuel. By incorporating SAF production into waste management practices, waste can be converted into a valuable resource, contributing to a circular economy and reducing the environmental impact of air travel.

The SWM hierarchy prioritizes waste prevention and reduction at its top (Fig. 3). When waste cannot be prevented or reduced, the focus shifts to recovery and recycling. In the context of SAF production integration, certain waste streams can be strategically processed to produce biofuels suitable for aviation. While composting represents the preferred pathway for clean biodegradable waste, certain non-compostable or contaminated organic residues such as mixed food waste or lignocellulosic biomass can be converted through advanced thermochemical or biochemical processes into feedstocks for SAF production [40]. These feedstocks are then further processed through methods like hydro-processing and hydrotreating to produce refined SAF [41]. The resulting SAF can be blended with conventional jet fuel, thereby lowering the carbon footprint of flights.

Moreover, integrating SAF production into the waste management hierarchy offers several benefits (Table 3). Firstly, it provides a sustainable option for managing waste streams that are challenging to recycle or dispose of through traditional methods. Converting waste into SAF recovers valuable resources, reduces dependence on fossil fuels, and minimizes carbon emissions. Secondly, SAF integration supports circular economy principles by transforming waste into a valuable product, enhancing resource efficiency, and contributing to a more sustainable waste management system.

Moreover, incorporating SAF into waste management helps address the environmental impact of aviation, a major contributor to GHG emissions. SAF provides a renewable and low-carbon alternative to traditional jet fuel, thus reducing the carbon intensity of flights [42]. By utilizing waste-derived feedstocks, SAF supports the

Table 3 Environmental impacts of integrating SAF production into SWM hierarchy

Environmental Impact	Description
Reduction of Greenhouse Gas Emissions	SAF production from waste or biomass reduces net greenhouse gas emissions compared to fossil fuels.
Resource Conservation	Integrating SAF production reduces dependence on finite fossil fuel resources and promotes a circular economy.
Waste Management and Valorization	Utilizing waste materials as feedstocks for SAF production supports sustainable waste management and valorization.
Air Quality Improvement	SAF has lower levels of harmful emissions, contributing to improved air quality and human health.
Biodiversity and Land Use Impact	Utilizing waste-derived or sustainably sourced biomass as feedstocks reduces pressure on land and ecosystems.
Sustainable Development Goals (SDGs)	Integrating SAF production aligns with several SDGs, including clean energy, responsible consumption, climate action, and biodiversity conservation.

Table 4 Decision support matrix for smart technologies – SAF integration feasibility

Context	Technological Readiness	Infrastructure Maturity	Policy Alignment	Economic Feasibility	Social Acceptance	Overall Feasibility
Urban Developed (e.g., EU, Japan)	5	5	4	4	5	High
Urban Developing (e.g., Middle East, North Africa, South Asia)	3	3	2	3	4	Moderate
Rural/Decentralized (e.g., sub-Saharan Africa, small islands)	2	2	2	2	3	Low–Moderate

aviation industry's shift towards more sustainable practices and helps mitigate the environmental impact of air travel.

To evaluate the feasibility of integrating smart technologies and SAF production across different socioeconomic and infrastructural contexts, a scenario-based assessment was conducted. The outcomes of this evaluation are presented in Table 4. As illustrated in the table, integration is most viable in technologically advanced and policy-coherent urban settings, whereas developing and rural areas require targeted incentives, capacity-building initiatives, and infrastructure investment to achieve comparable levels of feasibility.

3.3 Evaluating environmental priorities in solid waste management: a comparative study of composting, SAF production, and incineration

The reconfiguration of SWM systems necessitates a hierarchy that reflects not only operational feasibility but also environmental sustainability. Within this hierarchy, composting and SAF production represent critical alternatives to traditional incineration practices. A comparative analysis of these strategies demonstrates their respective environmental merits and their synergistic potential within a circular economic framework.

Composting constitutes the most environmentally preferable treatment option for biodegradable MSW. It facilitates the return of essential nutrients to the soil, improves soil structure and water retention, and reduces reliance on synthetic fertilizers [40]. By diverting organic matter from landfills, composting also significantly mitigates methane emissions, a potent GHG with a global warming potential approximately 25 times that of carbon dioxide [41]. In addition, composting supports ecosystem health by enhancing soil biodiversity and promoting carbon sequestration. Given its relatively low technological and financial requirements, it is suitable for broad implementation in both developed and developing contexts. Composting thus aligns with circular economic principles by reintegrating organic waste into ecological nutrient cycles.

However, composting is not applicable to all waste streams, particularly non-compostable or contaminated materials such as certain synthetic organics and mixed municipal waste. In such cases, SAF production emerges as a viable and environmentally superior alternative to incineration. SAF can be produced through advanced thermochemical and biochemical conversion processes such as gasification, pyrolysis, hydro processing, and fermentation. These technologies enable the transformation of residual waste into low-carbon liquid fuels that can be blended with conventional jet fuel and utilized in existing aviation infrastructure.

Compared to incineration, SAF production yields substantial environmental advantages. It avoids the release of dioxins, heavy metals, and particulate matter typically associated with combustion-based disposal methods [42]. In addition, SAF production from waste has been shown to reduce net GHG emissions by 27 to 87%, depending on the feedstock type and conversion pathway [43]. This contrasts sharply with the environmental burden of incineration, which not only emits large quantities of CO_2 but also destroys materials that could otherwise be valorized, undermining resource efficiency objectives.

Quantitative assessments further highlight these disparities. Converting 1000 kg of MSW into SAF can avoid approximately 380 kg of CO_2-equivalent emissions [44], whereas landfilling 1000 kg of waste produces an estimated 780 kg of CO_2-equivalent emissions due to anaerobic decomposition and methane release [45]. SAF's role in climate change mitigation is further underscored by its compatibility with international agreements such as the Paris Agreement and its capacity to reduce emissions in the aviation sector without requiring significant changes to existing fuel distribution systems [46].

In view of these findings, an environmentally rational waste hierarchy should place composting at the top tier for all suitable organic waste, followed by SAF production for non-compostable and non-recyclable waste fractions. Incineration, due to its relatively high emissions and inefficiencies, should be reserved as a last resort. This proposed sequence, composting, then SAF, then incineration, supports optimized environmental outcomes while advancing climate mitigation, resource recovery, and public health goals.

While regional variations in infrastructure, policy, and feedstock availability may influence practical implementation, the environmental rationale for this prioritization remains robust. Adoption of this revised hierarchy enables a transition from linear, disposal-centric systems to integrated, circular waste management frameworks that align with long-term sustainability plans.

3.4 Smart technologies and data analytics in waste management

3.4.1 Application of smart technologies for waste monitoring, sorting, and optimization

Smart technologies have the potential to revolutionize the six elements (waste generation, on-site handling/storage, collection, transfer and transport, processing and recovery, and final disposal) of SWM by optimizing processes, enhancing efficiency, and improving decision-making. In waste prevention, smart technologies can be employed to monitor and analyze consumption patterns, allowing for targeted interventions and education campaigns. For waste collection and transportation, waste monitoring systems and IoT devices can track bin fill levels, optimize routes, and improve scheduling, leading to more efficient waste management.

Smart technologies are increasingly transforming waste management across collection, treatment, and recycling stages. In the domain of waste collection and transportation, Rahman et al. present an integrated IoT and deep learning framework using Smart Bin technology, enabling real-time tracking of bin fill levels and facilitating route optimization [47]. While the study demonstrates promising efficiency gains, it primarily focuses on controlled environments, leaving questions about scalability and interoperability in diverse urban contexts. In the treatment and disposal phase, Vafeiadis et al. proposes a data analytics platform to optimize waste management procedures [48]. Their platform highlights the potential of data-driven decision-making in improving treatment selection and energy recovery; however, the lack of long-term implementation data limits its practical evaluation. Finally, Bazrbachi et al. review smart waste management technologies in Malaysia, with a particular focus on automated sorting systems [49]. Their work effectively maps current applications and potential avenues, but it relies heavily on secondary data and lacks empirical validation.

The emergence of smart technologies has enabled new possibilities for revolutionizing waste management processes. Table 5 explores the application of smart technologies in waste monitoring, sorting, and optimization, highlighting their potential to improve efficiency, reduce environmental impacts, and promote sustainable waste practices.

3.4.2 Benefits of data analytics in optimizing waste management processes

Data analytics offer numerous benefits in optimizing waste management processes (Table 6). Firstly, they enhance operational efficiency by analyzing historical and real-time data to identify patterns and anomalies in waste generation, collection, and disposal [50]. This leads to more efficient and cost-effective waste management operations. Secondly, data analytics improve resource allocation by analyzing data on waste generation rates,

Table 5 Integration of smart technologies in solid waste management

Aspect	Description
Waste Monitoring	Uses sensor-equipped bins and IoT devices to measure waste fill levels, temperature, humidity, and gas emissions for optimized collection.
Waste Sorting and Recycling	Automated systems with AI and robotics sort waste, improve recycling rates, and offer real-time feedback and incentives.
Optimization of Waste Management	Predictive analytics and route optimization enhance waste collection efficiency, minimize fuel consumption, and reduce emissions.
Waste-to-Energy Conversion	Smart systems for converting waste into energy through methods like anaerobic digestion and gasification, reducing landfill use and generating renewable energy.
Citizen Engagement and Education	Mobile apps and social media platforms provide information, guides, and incentives for sustainable behavior, with gamification elements to encourage participation.

Table 6 Benefits of data analytics in optimizing waste management processes

Benefits	Explanation
Enhanced operational efficiency	Data analytics help improve operational efficiency in waste management by analyzing historical and real-time data, optimizing operational processes.
Improved resource allocation	Data analytics enable better resource allocation by analyzing data on waste generation rates, composition, and geographical distribution.
Optimal collection route planning	Data analytics help determine the most efficient collection routes, considering factors like traffic conditions, geographic locations, and fill levels.
Predictive analytics for planning	Data analytics enable predictive modeling to forecast waste generation patterns, aiding in planning and resource allocation.
Waste composition analysis	Data analytics analyze waste composition data, providing insights for tailored recycling and disposal strategies.
Identification of operational issues	Data analytics identify operational issues and inefficiencies, allowing authorities to implement preventive measures and enhance system reliability.
Performance monitoring and reporting	Data analytics enables monitoring and reporting of key performance indicators to assess the effectiveness of waste management strategies.

Table 7 Examples of successful implementations of smart technologies in waste management with explanations

Example	Explanation
Smart Waste Bins	Smart waste bins equipped with sensors and IoT technology monitor their fill levels and notify waste management authorities for efficient emptying [55].
Route Optimization Software	Route optimization software utilizes data analytics and GIS to optimize waste collection routes considering factors such as traffic conditions and waste generation patterns [56].
Waste Sorting Robots	Intelligent robots equipped with computer vision and machine learning algorithms automate waste sorting, improving the efficiency and accuracy of recycling operations [57].
Smart Fleet Management	GPS tracking systems and telematics in waste management fleets monitor vehicle locations, fuel consumption, and driver behavior for optimized routes and efficient waste collection [58].
Smart Recycling Stations	Smart recycling stations equipped with sensors and interactive displays provide real-time information, guidance on waste disposal, and incentivize recycling through gamification [59].

composition, and geographical distribution [51]. This enables waste management authorities to allocate collection trucks, personnel, and equipment more effectively, reducing unnecessary trips and optimizing resource utilization. Additionally, data analytics facilitate optimal collection route planning by considering factors such as traffic conditions, geographic locations, and fill-level information from waste bins [52]. This minimizes fuel consumption, reduces emissions, and improves overall operational efficiency. Moreover, data analytics enable predictive modeling to forecast waste generation patterns, allowing authorities to plan and allocate resources in advance [53]. Data analytics also provide insights into waste composition, aiding in tailored recycling and disposal strategies. By analyzing waste composition data, authorities can identify opportunities for material recovery, recycling, and waste reduction initiatives. Furthermore, data analytics help identify operational issues and inefficiencies, enabling authorities to implement preventive maintenance measures and enhance system reliability [54]. They also enable monitoring and reporting of key performance indicators to assess the effectiveness of waste management strategies. Lastly, data analytics drive continuous improvement and innovation in waste management by informing decision-making, fostering adaptation to changing waste generation patterns, and promoting sustainable practices.

3.4.3 Successful implementation of smart technologies in waste management

Table 7 illustrates how advanced technologies are reshaping waste management practices. Smart waste bins use sensors and IoT to alert authorities when full. Route optimization software enhances collection routes based on traffic and waste patterns. Waste sorting robots automate recycling with precision. Smart fleet management tracks vehicles for optimized routes. Smart recycling stations provide guidance and incentives for recycling. These innovations signify a shift towards efficient and sustainable waste management practices.

The integration of smart technologies into SAF production represents a pivotal advancement in realizing a data-driven, circular SWM system. While smart technologies and SAF have been extensively discussed as separate domains, their synergy lies in how digital innovations can enhance the efficiency, reliability, and traceability of the waste-to-fuel conversion chain.

First, smart technologies particularly the IoT, sensor networks, and AI enable real-time waste monitoring and predictive analytics. Smart bins equipped with IoT sensors can record fill levels, waste type, and location data, allowing optimized collection routes and scheduling. This ensures a consistent and high-quality feedstock supply to SAF production facilities, reducing logistical inefficiencies and GHG emissions from transport. Second, automated sorting and AI-driven material recognition systems improve feedstock purity and conversion efficiency. By minimizing contamination and identifying suitable organic or non-recyclable fractions for fuel conversion, smart sorting systems enhance the yield and carbon performance of SAF production processes such as pyrolysis, gasification, or Fischer–Tropsch synthesis. Third, blockchain and digital traceability platforms can be employed to verify the origin, composition, and sustainability of waste feedstocks. Such systems create transparent audit trails for carbon accounting and certification, ensuring compliance with international frameworks such as Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and the EU Renewable Energy Directive (RED II). This digital transparency supports stakeholder trust and enables the monetization of verified carbon savings through credit mechanisms. Finally, data integration and advanced analytics tools facilitate system optimization and decision support. By linking waste generation data with energy demand, municipalities and plant operators can forecast SAF production potential, plan capacity expansions, and evaluate environmental impacts using near real-time datasets. These insights support evidence-based policy and investment decisions, aligning waste management, renewable energy, and aviation decarbonization agendas.

3.4.4 Limitations of smart waste technologies and adaptations for SAF distribution systems

While smart technologies provide substantial opportunities for enhancing the efficiency and traceability of waste-to-fuel systems, several technical, financial, and operational limitations must be acknowledged to ensure realistic expectations and balanced policy planning.

First, the deployment of smart technologies in waste management is often constrained by high initial investment costs associated with IoT infrastructure, sensor calibration, data management systems, and maintenance requirements. Municipalities in developing regions may find it difficult to justify these expenses without clear cost-recovery models or external funding support. Additionally, the interoperability of digital platforms remains a challenge, many sensor systems and software solutions operate on proprietary protocols, complicating data integration across municipal, industrial, and aviation sectors.

Second, cybersecurity and data privacy concerns can arise from continuous waste tracking and user-level data collection, particularly when linked to public networks. Ensuring secure data storage and ethical data governance frameworks is therefore essential to prevent misuse or breaches. Technical reliability also poses risks, as sensor malfunctions or network interruptions can disrupt automated sorting or collection processes, reducing system efficiency.

Third, the digital divide between urban and rural areas limits the scalability of smart waste management systems. In low-resource contexts, the absence of stable internet connectivity or trained personnel may hinder real-time monitoring and data-driven optimization, reinforcing regional inequalities in technological adoption.

In parallel, the integration of SAF into existing fuel distribution systems - though technically feasible - requires certain operational and regulatory adjustments to ensure full compatibility and safety. From an infrastructural perspective, SAF can generally be blended with conventional Jet A or Jet A-1 fuel using existing pipelines, storage tanks, and refueling systems, as it meets ASTM D7566 specifications. However, to accommodate higher SAF blending ratios, additional quality assurance protocols, dedicated blending tanks, and fuel certification systems may be required to maintain compliance and traceability throughout the supply chain.

On the policy side, national aviation authorities should update fuel logistics standards and sustainability reporting frameworks to recognize waste-derived SAF within domestic supply chains. Such updates would enable seamless integration of circular fuel systems into existing airport infrastructure while supporting international decarbonization targets.

3.5 Smart waste management and SAF: synergies, strategies, and market opportunities

The successful implementation of smart waste technologies and SAF production within modern SWM systems is highly dependent on enabling policy environments and economic viability. While the technological and environmental benefits of such integration are substantial, their realization requires a combination of robust governance frameworks, market incentives, and long-term investment strategies.

At the policy level, international, regional, and national frameworks play a pivotal role in fostering the transition toward integrated and sustainable waste systems. Countries that have implemented comprehensive waste management regulations, particularly those that mandate recycling, extended producer responsibility, and resource recovery, have demonstrated significant progress. For instance, South Korea's volume-based waste fee system, combined with recycling targets and producer responsibility, has led to considerable reductions in waste generation and the development of advanced recycling infrastructure [60]. Similarly, Sweden has achieved near-zero landfill dependency by investing in source separation, producer responsibility, and waste-to-energy incineration, coupled with strong public engagement and incentives [61].

Global frameworks such as the United Nations Sustainable Development Goals (SDGs), the European Union's

Table 8 Economic opportunities from integration of smart technologies and SAF production

Opportunity	Description
Operational Cost Savings	Smart routing and predictive maintenance reduce waste management expenditures.
Revenue from SAF	Sale of SAF provides new income streams from previously low-value waste.
Circular Economy Development	Resource recovery fosters new recycling and remanufacturing industries.
Market Demand	Growing demand for sustainable practices supports innovation and technology adoption.
Carbon Pricing and Incentives	Emissions trading schemes and carbon credits create financial advantages for low-emission operations.
Entrepreneurial Innovation	Demand for smart solutions spurs growth in IoT, software, and data analytics sectors.
Partnerships and Collaboration	Public-private partnerships encourage infrastructure investment and knowledge exchange.

Table 9 Comparative Levelized Cost of Fuel (LCOF) for major SAF pathways

SAF Pathway	Feedstock Type	Estimated LCOF (USD L^{-1})	Key Cost Drivers	Cost Reduction Potential
Fischer–Tropsch (FT)	MSW, lignocellulosic biomass	2.0–2.7	Gasification energy input, catalyst cost	Moderate (via scale-up and CCU integration)
Alcohol-to-Jet (ATJ)	Waste ethanol, food waste	1.4–4.6	Feedstock cost, conversion yield	High (via improved fermentation efficiency)
Power-to-Liquid (PtL)	CO_2 + green H_2	2.8–5.8	Electrolysis energy demand	High (via renewable electricity cost decline)

Circular Economy Action Plan, and the International Civil Aviation Organization's SAF roadmap provide strategic direction and regulatory alignment for the deployment of both smart technologies and SAF production. These frameworks emphasize clean energy transitions, climate action, and responsible consumption, all of which are supported by the dual application of digital waste systems and renewable fuels.

Economically, the integration of smart technologies in SWM offers cost savings through improved route planning, reduced fuel consumption, predictive maintenance, and automation. These operational efficiencies lower overhead and improve reliability while opening new avenues for entrepreneurship, particularly in data analytics, software development, and sensor manufacturing [62]. In parallel, SAF production creates economic value through the conversion of low- or negative-value waste streams into high-value fuels. The global SAF market is expected to experience significant growth to reach a multibillion-dollar level within the next decade [63, 64]. This growth reflects increasing demand from airlines, regulatory mandates for low-carbon fuels, and voluntary commitments to decarbonization.

The economic benefits and innovation potential of this integrated paradigm are summarized in Table 8, highlighting the dual value propositions of smart infrastructure and SAF deployment.

Despite its long-term potential, SAF production faces a few economic and structural barriers that challenge its short-term scalability. Chief among these is the high cost of production relative to fossil-based jet fuel. Depending on feedstock and conversion pathway, SAF costs between two to eight times more than conventional fuel due to high capital expenditures, complex processing, and energy requirements [65, 66]. Advanced pathways such as Fischer-Tropsch, Alcohol-to-Jet, and Power-to-Liquid require sophisticated infrastructure and reliable feedstock supply chains, both of which are underdeveloped in many regions. To strengthen the economic dimension, a comparative analysis of the Levelized Cost of Fuel (LCOF) across major SAF production pathways was undertaken (Table 9) [67]. Cost data were consolidated from Watson et al. [43], IEA (2023) [68], and International Council on Clean Transportation (ICCT, 2019) reports [69]. The LCOF includes capital, operating, and feedstock costs normalized over fuel energy content. These findings confirm that SAF remains costlier than fossil jet fuel but is expected to reach parity within 10–15 years through policy incentives, carbon pricing, and technological learning curves.

Feedstock availability presents another critical constraint. While MSW, agricultural residues, and used cooking oil are promising feedstocks, their supply is often regionally limited or already allocated to other sectors [70]. Purpose-grown energy crops, although technically viable, raise ethical concerns related to land use, food security, and biodiversity [71].

The SAF industry also suffers from a lack of economies of scale. With SAF currently accounting for less than 1% of total aviation fuel consumption, producers are unable to benefit from cost reductions associated with high-volume production [72]. Technological immaturity and limited commercial deployment further drive-up costs, while investment remains constrained by market uncertainty and insufficient regulatory incentives [73].

Market dynamics reflect a "chicken-and-egg" dilemma: airlines are hesitant to commit to long-term SAF procurement without stable policy support and competitive pricing, while producers are reluctant to invest without guaranteed offtake agreements [65]. Government

Table 10 Economic challenges to the production and commercialization of SAF

Constraint	Description
High Production Cost	SAF is 2–8 times more expensive than fossil jet fuel due to complex processing and energy intensity.
Feedstock Competition	Limited supply and competing demand for waste and bio-based feedstocks increase cost and volatility.
Technological Immaturity	Many SAF production technologies lack commercial-scale deployment and efficiency optimization.
Lack of Economies of Scale	SAF represents < 1% of global jet fuel use, limiting cost reductions through mass production.
Market Uncertainty	Airlines and fuel producers are deterred by unclear policy, pricing, and demand signals.
Capital Investment Risk	High upfront infrastructure costs with uncertain return on investment.
Regulatory Gaps	Insufficient mandates, incentives, and carbon pricing slow SAF adoption and market entry.

interventions - such as carbon pricing, blending mandates, tax incentives, and capital subsidies are essential to bridging the cost gap and de-risking investment [74]. The European Commission's ReFuelEU Aviation initiative proposes blending mandates and subsidies up to €0.5 per liter for bio-based SAF and €6 per liter for synthetic e-fuels, yet further fiscal instruments may be required to achieve economic parity with fossil fuels [67]. The key economic constraints facing SAF deployment are summarized in Table 10.

In summary, while the integration of smart technologies and SAF production presents an environmentally and economically promising model for modern SWM, its success is contingent on favorable regulatory frameworks, targeted financial incentives, and strategic investment in infrastructure. Policy coherence, market coordination, and technological innovation are essential to overcoming the economic and structural barriers currently limiting large-scale SAF deployment. In combination, these factors define the enabling environment necessary for realizing a circular, low-carbon, and digitally optimized waste management future.

3.6 Policy coherence and governance challenges

Despite increasing global alignment under the ICAO, EU, and UN frameworks, policy fragmentation remains a major barrier to effective integration between waste management and aviation energy sectors. Municipal waste regulations in many countries continue to prioritize recycling and incineration, with limited recognition of fuel valorization pathways. Conversely, policies governing SAF, particularly under ICAO mechanisms, focus primarily on reducing aviation-sector emissions without adequately addressing feedstock traceability or the integration of urban waste streams into SAF supply chains.

This lack of coherence manifests in several key misalignments. First, regulatory responsibilities for waste and aviation are typically distributed across separate ministries or agencies, resulting in siloed governance structures that impede cross-sectoral coordination. Second, inconsistencies between international certification frameworks such as RED II and CORSIA create barriers to the global deployment and recognition of SAF produced from waste. Third, most national policy frameworks lack sufficient economic incentives, such as tax exemptions, feed-in tariffs, or subsidies, to encourage large-scale investment in waste-derived SAF production and use.

To overcome these gaps, a set of governance reforms is recommended. Establishing integrated circular-economy legislation that explicitly links municipal waste valorization with national aviation fuel mandates would enhance policy coherence and resource efficiency. Developing a unified SAF certification protocol harmonizing RED II and CORSIA standards would also facilitate international trade and recognition of waste-based fuels. Additionally, introducing green procurement policies and carbon-credit incentives for airports and airlines that utilize waste-derived SAF could stimulate market demand and accelerate private-sector investment.

Collectively, these measures can promote the cross-sectoral adoption of smart, circular waste-to-fuel systems while ensuring alignment with the United Nations SDGs specifically SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

4 Conclusions

This study demonstrated the transformative potential of integrating smart technologies and SAF production into modern SWM frameworks. The transition from linear, disposal-oriented systems to circular and technologically advanced approaches presents a viable pathway for addressing the twin challenges of escalating MSW and rising GHG emissions particularly from the aviation sector.

Key findings highlighted that traditional practices such as landfilling and incineration are increasingly inadequate, both environmentally and economically. In contrast, smart technologies, such as IoT-based monitoring, AI-assisted sorting, and predictive analytics, optimize waste collection and processing, reduce costs, and enhance environmental outcomes. Simultaneously, SAF production from non-compostable and non-recyclable waste streams offers a circular, low-carbon solution for hard-to-abate sectors like aviation.

However, the successful deployment of these innovations is contingent on several enabling factors. Supportive regulatory frameworks, consistent policy signals, investment in technological infrastructure, and stakeholder collaboration are critical in overcoming the economic and logistical barriers associated with SAF production and digital transformation. Moreover, a tiered waste hierarchy that prioritizes prevention, reuse, composting, and SAF, while relegating incineration and landfilling to last-resort options, must guide future policy and infrastructure development.

Overall, this integrated model supports multiple sustainability objectives, including resource efficiency, climate mitigation, renewable energy generation, and urban resilience. By reimagining waste as a strategic asset, cities and nations can accelerate their transition toward circular economies and contribute meaningfully to global environmental goals.

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