Received: 31 May 2023 | Revised: 19 January 2024 | Accepted: 5 March 2024
DOI: 10.1002/ep.14395

ORIGINAL RESEARCH
Climate Change

ENVIRONMENTAL PROGRESS & SUSTAINABLE ENERGY

The pathway for achieving sustainable aviation fuel production in the Middle East and North Africa region

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Abstract

The Middle East and North Africa (MENA) region faces significant challenges in the production of sustainable aviation fuel (SAF) due to high costs, limited feedstock availability, and underdeveloped infrastructure. However, the region has diverse feedstock options and can leverage existing refining capabilities and advanced conversion technologies for SAF production. Addressing these challenges requires research and development (R&D) collaboration, supportive policies, and international knowledge exchange. To promote the production of SAF in the MENA region, a comprehensive strategy is required that includes collaboration, policy alignment, research and development, infrastructure development, and training. Market incentives such as regulations and financial support can help drive demand for SAF. Collaborating with international organizations can improve knowledge sharing and promote sustainable practices. Research and development collaboration is crucial for innovation and establishing a strong SAF industry. Policy harmonization can create a supportive framework for investment and innovation. Monitoring and reporting mechanisms can ensure transparency and verify sustainability. By addressing these aspects, the region can become a leading hub for SAF production and contribute to a sustainable aviation industry.

KEYWORDS
challenges, conversion technologies, feasibility, feedstock, sustainable aviation fuel

1 | INTRODUCTION

The aviation industry, a key driver of global connectivity and economic growth, is now facing increasing concerns about climate change and the environmental impact of air travel.[1,2] In 2017, the annual global consumption of aviation fuel reached approximately 300 million metric tons.[3] With the industry's rapid growth, it is projected that by 2050, the global demand for aviation fuel will more than double, led by developing countries.[4] However, the industry's heavy reliance on fossil fuels and resulting greenhouse gas emissions have caused significant environmental consequences. In 2017 alone, flights contributed around 859 million metric tons of CO2 emissions, accounting for 2% of global anthropogenic CO_2 emissions.[5] To address these challenges, there is an urgent global need to promote the adoption of sustainable aviation fuel (SAF), a cleaner and greener alternative to conventional jet fuels.[6,7] The aviation industry began showing interest in biofuels in the early 2000s due to their potential to reduce emissions and decrease reliance on fossil fuels.[8,9] The International Civil Aviation Organization (ICAO) initiated efforts to promote SAF, with successful commercial flights demonstrating feasibility and performance without requiring modifications to existing aircraft or infrastructure.[10,11] Governments worldwide have implemented supportive policies and regulatory frameworks, including ASTM International's specifications for aviation biofuels in 2011, which provide a clear pathway for SAF certification, ensuring quality and compatibility with existing aircraft engines.[12]

In recent years, a significant rise in SAF production and use has been witnessed, propelled by advancements in production technologies, increased investment, and collaborations across the aviation and biofuel industries.[13,14] Governments, airlines, and private investors are committing resources to recognize the potential of SAF as a sustainable solution, aligning with ambitious sustainability goals and the global aviation industry's commitment to using a significant share of SAF by 2050.[15–19] To fully realize the potential of SAF, collaboration and investment from governments, industry stakeholders, and international organizations are crucial. Supportive policies, financial incentives, and regulatory frameworks are needed to encourage the adoption and production of SAF on a larger scale, making SAF production processes vital in enabling the aviation industry's transition toward a more environmentally sustainable future.[13] These processes involve converting renewable feedstocks into a cleaner alternative to conventional jet fuel through pathways like hydroprocessing, Fischer-Tropsch synthesis, and alcohol-to-jet processes.[20,21] These production processes offer distinct advantages over conventional fossil fuels, significantly reducing carbon dioxide (CO_2) emissions and other pollutants such as sulfur dioxide (SO_2) and particulate matter (PMx).[22–24]

In this context, SAF has gained significant attention as a vital solution for reducing greenhouse gas emissions in the aviation sector, aligning with the global focus on environmental sustainability.[25–27] The Middle East and North Africa (MENA) region, a key player in the global energy sector, is increasingly prioritizing SAF production to address the environmental impact of aviation.[28,29] With abundant feedstock availability, technological advancements, supportive policies, and growing market demand, the region has significant potential for SAF production.[30,31] The MENA region, renowned for its abundant energy resources, has the potential to play a significant role in SAF production by leveraging diverse feedstock resources, such as agricultural residues, energy crops, and dedicated bioenergy crops, as well as various technological advancements like pyrolysis, gasification, hydrothermal liquefaction, and biochemical processes. However, the specific opportunities, challenges, and strategies associated with SAF production in the MENA region remain relatively unexplored. This research problem holds considerable importance for both research and practical applications, as exploring the feasibility and opportunities of SAF production in the MENA region can contribute to environmental sustainability, energy security, economic growth, and job creation.

This paper aims to bridge the identified research gap by presenting a comprehensive strategy that considers feedstock availability, technological advancements, policy support, infrastructure development, and stakeholder collaboration. By doing so, it highlights the MENA region's significant potential for SAF production and its broader contributions to environmental sustainability, energy security, economic growth, and job creation. The findings and proposed strategy carry practical implications for policymakers, industry stakeholders, and researchers interested in advancing SAF production in the MENA region, with the goal of fostering a more environmentally sustainable future for air travel.

The manuscript is structured to provide a thorough exploration of these aspects. It begins with a foundational Section 2 and then delves into challenges such as high production costs, limited feedstock availability, limited infrastructure, and technological readiness and scale-up. A detailed roadmap is provided for initiating SAF production. The feasibility and potential of SAF production are discussed, focusing on the availability and sustainability of feedstocks and the technical and economic performance of conversion technologies. Policy and regulatory aspects are emphasized, along with an analysis of market demand for SAF. A comprehensive strategy for the development and implementation of SAF in the MENA region is proposed, including the importance of regional collaboration, research and development, and production infrastructure. International cooperation and partnerships are highlighted, as are monitoring and reporting mechanisms. The manuscript concludes by summarizing key points and suggesting directions for future research and action.

2 | MATERIALS AND METHODS

The research paper focuses on SAF production in the MENA region, and it employs a comprehensive analysis of data and facts gathered from relevant literature sources. The study adopts a systematic approach to collect and analyze information regarding SAF production processes, feedstock availability, technological advancements, and environmental impacts in the MENA region. Primary sources such as scientific journals, research papers, industry reports, and governmental publications are extensively reviewed to ensure the accuracy and reliability of the data. Additionally, secondary data sources, including databases and statistical records, are utilized to supplement the analysis. The materials and methods employed in this research paper aim to provide an in-depth understanding of the current state of SAF production in the MENA region and serve as a valuable resource for policymakers, industry stakeholders, and researchers interested in the sustainable development of aviation fuels.

3 | RESULTS AND DISCUSSION

3.1 | Challenges for sustainable aviation fuel (SAF) production in the MENA region

The MENA region holds substantial potential for SAF production; however, several challenges must be addressed to harness this potential. The key barriers include high production costs, limited feedstock availability, limited infrastructure, and technological readiness and scale-up (Figure 1).

High production costs pose a significant challenge in the MENA region. SAF production currently incurs higher costs compared to conventional jet fuels.[32] Factors contributing to these high costs include limited availability and high costs of feedstocks, complex conversion technologies, the need for additional investments in dedicated production facilities, limited economies of scale, and challenges related to

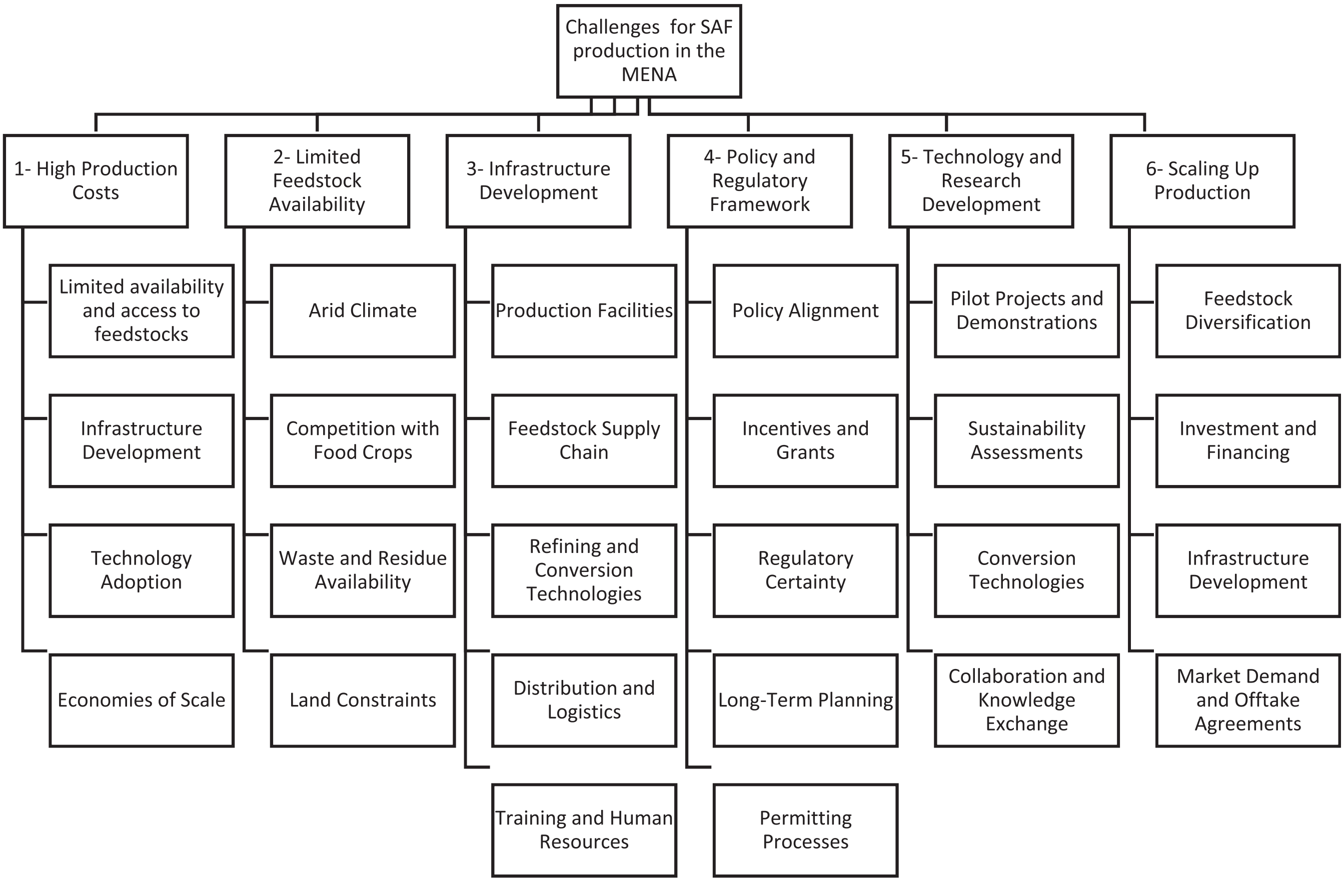

FIGURE 1 Challenges for sustainable aviation fuel (SAF) production in the MENA region.

the availability and affordability of renewable energy sources. To tackle this challenge, the region can focus on research and development, collaboration with international partners, and knowledge sharing to optimize technologies, develop innovative processes, and explore alternative feedstock options. Government support through incentives and subsidies can also help reduce production costs and encourage market growth for SAF.

Limited feedstock availability is another significant challenge. The arid landscapes and limited agricultural land in the region hinder the cultivation of traditional biofuel feedstocks. The competition for land resources between food crops and biofuel feedstocks further exacerbates this issue. Additionally, the inconsistent supply of waste oils and residues poses challenges for their utilization in SAF production. To address this, research and development efforts are exploring alternative feedstock options such as saltwater-tolerant crops like Salicornia.[33] Collaborations with international organizations and knowledge exchange contribute to the exploration of feedstock options. The International Renewable Energy Agency (IRENA) provides valuable insights and guidance on feedstock availability and suitability in the region.[34,35]

Limited infrastructure for SAF production is a significant challenge in the MENA region. Existing refining capabilities are primarily designed for conventional fuels, requiring substantial modifications to produce SAF. Dedicated production facilities are needed to scale up production and ensure a consistent supply. The transportation and distribution infrastructure for SAF are also underdeveloped, hindering its widespread availability. Additionally, the absence of specific regulations and standards for SAF can impede infrastructure development. Collaborative efforts involving governments, industry stakeholders, and investors are crucial in addressing these limitations.[36] Governments can provide incentives and policy support, while public-private partnerships and international collaborations can facilitate infrastructure development and knowledge exchange.

Technological readiness and scale-up present a significant hurdle for SAF production in the MENA region. Adapting existing SAF production technologies to the region's specific conditions, feedstock availability, and climate requires comprehensive research and development efforts. Increasing investments in R&D is necessary to enhance technological readiness, optimize conversion processes, improve energy efficiency, and reduce costs through innovation. Establishing pilot-scale demonstration projects is crucial for validating SAF production technologies in the MENA region, assessing their performance, scalability, and feasibility under local conditions, and attracting potential investors and stakeholders. Access to funding, both public and private, is essential to overcome financial barriers and accelerate the deployment of SAF production technologies in the region.

Addressing these barriers to SAF production in the MENA region requires concerted efforts from governments, industry stakeholders, research institutions, and international collaborations. By investing in R&D, exploring alternative feedstocks, developing infrastructure, and focusing on technological readiness and scale-up, the region can overcome these challenges and unlock the potential for SAF production.

3.2 | Roadmap for starting sustainable aviation fuel production in the MENA region

The aviation industry's growing recognition of the importance of reducing carbon footprint has led to a focus on more sustainable practices.[37] SAF emerges as a promising solution, offering a cleaner alternative to conventional jet fuel. In the MENA region, with its strategic location and abundant resources, there is considerable potential to play a significant role in SAF production, necessitating careful planning, and coordination (Figure 2).

The roadmap for SAF production in the MENA region begins with a comprehensive feasibility study, assessing market demand, feedstock availability, regulatory landscape, infrastructure requirements, and financial viability. Identifying sustainable and locally available feedstock sources, including biomass, waste oils, and agricultural residues, is crucial for ensuring abundance, sustainability, and compliance with environmental criteria.

Technology selection is paramount, with a need to evaluate options such as hydrotreating, Fischer-Tropsch, and alcohol-to-jet processes based on technical feasibility, scalability, cost-effectiveness, and environmental impact. Navigating the regulatory landscape, understanding sustainability certifications, blending requirements, and carbon reduction targets is essential for market access and long-term viability.

The development of infrastructure and facilities, including production plants, storage tanks, blending facilities, and transportation logistics, requires collaboration with engineering firms, contractors, and suppliers to ensure efficient and reliable operations. Establishing strategic partnerships with feedstock suppliers, airlines, industry stakeholders, and technology providers is instrumental, providing access to funding opportunities, knowledge exchange, and policy support.

Determining financial requirements and exploring various financing options, including private equity firms, venture capitalists, impact

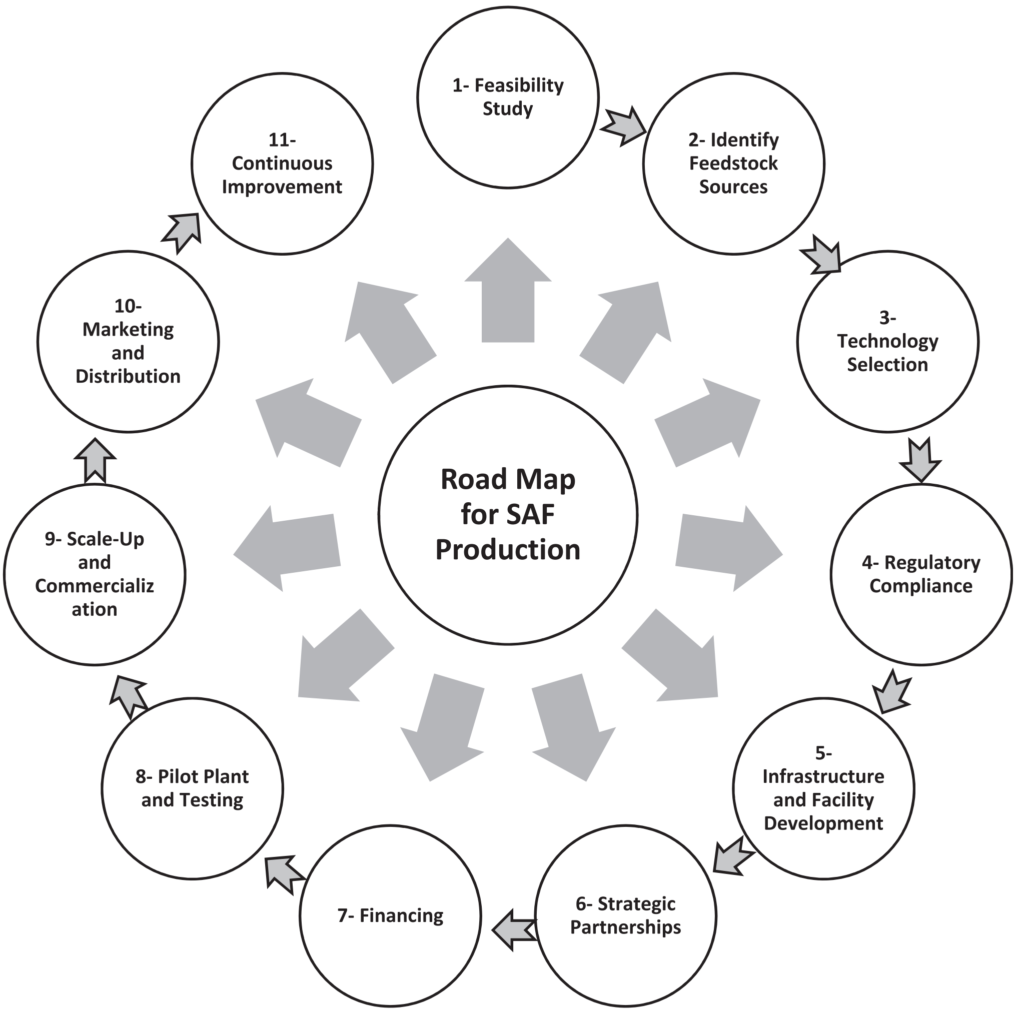

FIGURE 2 Roadmap for starting sustainable aviation fuel production in the MENA region.

funds, and government entities focused on sustainable energy projects, is crucial. Building a pilot plant for comprehensive testing of the SAF production process, optimization of operations, and assessment of fuel quality informs subsequent scaling efforts.

Based on the success of the pilot plant, scaling up production capacity, optimizing processes, and establishing a reliable supply chain for feedstock are key steps. Collaboration with airlines to secure long-term off-take agreements ensures a sustainable market for the SAF produced. Developing a robust marketing and distribution strategy, educating stakeholders, and integrating SAF into existing supply chains ensure availability and accessibility. Committing to continuous improvement in SAF production processes, feedstock sourcing, and technology advancements is essential to stay abreast of industry trends and enhance sustainability and efficiency in SAF production in the MENA region.

3.3 | Feasibility and potential of SAF production

The MENA region, known for its prominence in the global energy sector, is increasingly turning its attention to SAF production. As the aviation industry seeks to reduce its environmental impact and mitigate carbon emissions, the MENA region holds immense potential for SAF production. This section explores the feasibility and potential of SAF production in the MENA region, considering factors such as feedstock availability, technological advancements, policy support, and market demand (Figure 3).

3.3.1 | Availability and sustainability of feedstocks

The MENA region's unique climate and natural resources offer a diverse range of feedstock options for SAF production. While traditional biofuel feedstocks may face limitations due to limited agricultural land, the region can explore alternative options. Saltwater-tolerant crops have shown promise in arid conditions,[38] while non-food biomass and waste oils and residues from agricultural and industrial processes can also be utilized.[39] Ensuring the sustainability of feedstock production through responsible land use practices and adherence to environmental standards will be crucial for long-term viability.

3.3.2 | The technical and economic performance of conversion technologies

Technological advancements in conversion processes play a vital role in making SAF production economically viable. The MENA region can leverage its existing refining capabilities and expertise in

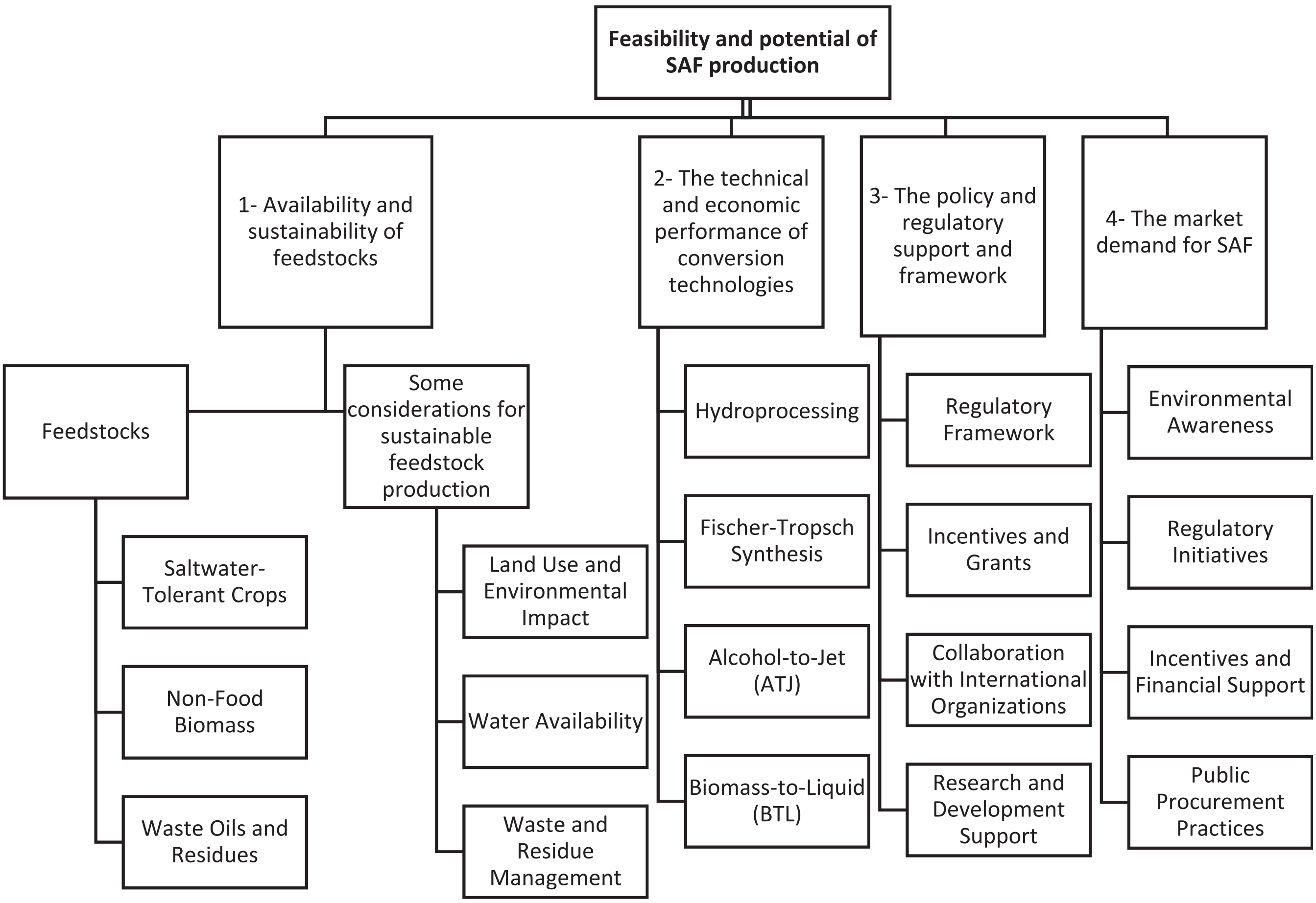

FIGURE 3 Feasibility and potential of SAF production in the MENA region.

hydroprocessing or Fischer-Tropsch synthesis to convert feedstocks into SAF. Continued research and development efforts can further enhance the efficiency and cost-effectiveness of these conversion technologies, making SAF production more competitive in the market.

3.3.3 | Policy and regulatory support and framework

A supportive policy and regulatory environment is essential for the growth of SAF production in the MENA region. Governments can provide incentives, grants, and tax credits to attract investments and promote the establishment of dedicated SAF production facilities. Clear and robust regulations defining sustainability criteria, quality standards, and certification requirements for SAF production and use are necessary to ensure transparency, compliance, and consumer confidence. Policy frameworks can also encourage research collaborations, knowledge exchange, and partnerships with international organizations to leverage global expertise.

3.3.4 | Market demand for SAF

The market demand for SAF in the MENA region has been growing steadily in recent years due to increasing environmental awareness, sustainability commitments by airlines, and regulatory efforts to reduce carbon emissions in the aviation sector. The market demand for SAF in the MENA region is driven by several key factors. First, governments in the region have implemented regulations to promote SAF use, setting targets and mandates for blending SAF into aviation fuel. Major airlines in the region, such as Emirates, Etihad Airways, and Qatar Airways, have made sustainability commitments and are investing in SAF to reduce their carbon footprint. Corporate social responsibility is also a driving force, as airlines and companies prioritize sustainability to demonstrate their environmental responsibility.[40,41] Collaboration with stakeholders across the aviation value chain, including fuel suppliers and airports, is crucial for establishing a sustainable SAF supply chain. Offering SAF as a cleaner alternative to conventional jet fuel enhances brand value and meets customer preferences. The MENA region has abundant feedstock resources, providing a localized and sustainable supply chain. International cooperation and collaboration, as well as adherence to carbon offsetting and emissions reduction targets, further contribute to the demand for SAF. These factors present significant opportunities for SAF producers and stakeholders in the MENA region to contribute to a more sustainable aviation industry globally.

3.4 | Comprehensive strategy for the development and implementation of sustainable aviation fuel in the MENA region

Developing and implementing SAF in the MENA region requires a comprehensive strategy that addresses various aspects of production, infrastructure, and policy (Figure 4). Outlined below is a comprehensive strategy for the development and implementation of SAF in the MENA region:

3.4.1 | Establish regional collaboration

Creating a collaborative platform is an essential step in expediting the development and adoption of SAF production in the MENA region. This platform would serve as a central hub, bringing together stakeholders from the aviation industry, feedstock suppliers, technology providers, research institutions, government bodies, and financial institutions. By fostering collaboration and knowledge-sharing, the platform would facilitate informed decision-making and mutual learning. It would also promote regulatory harmonization, resource pooling, and collaboration, leading to economies of scale and accelerated growth in SAF production. Additionally, the platform would provide funding and investment opportunities, support market development, and advocate for supportive policies. Through this collaborative effort, the platform can drive the transition to sustainable aviation practices and contribute to a greener aviation industry in the MENA region.

Achieving policy alignment is crucial for the successful production of SAF in the MENA region. To create a supportive environment, clear policy objectives should be established, with a focus on the development and production of SAF. Harmonizing regulatory frameworks across countries is essential, ensuring consistency and facilitating regional trade. Supportive incentives, such as financial mechanisms and streamlined administrative processes, should be put in place to encourage SAF production. Defining and enforcing sustainability criteria, along with robust certification schemes, ensures compliance and transparency in the market.

3.4.2 | Research and development

In the MENA region, research and development (R&D) efforts play a crucial role in advancing SAF production. These initiatives focus on developing advanced technologies, optimizing feedstock utilization, and enhancing production processes to ensure the availability of environmentally friendly aviation fuel. Notable collaborations include Abu Dhabi National Oil Company (ADNOC) and Honeywell, as well as King Abdulaziz City for Science and Technology (KACST) and Aramco Services Company, which are exploring SAF production opportunities and sustainable biofuels derived from non-food biomass sources, respectively.[42,43] Research institutions like the Masdar Institute are actively engaged in studying and advancing SAF production technologies, particularly in waste biomass conversion. Government support is also evident through initiatives like the Abu Dhabi Sustainable Bioenergy Research Consortium (SBRC), which focuses on developing innovative technologies for SAF production.[44] These R&D efforts align with global initiatives and partnerships, such as the Sustainable Bioenergy Research Consortium between the UAE and the Netherlands, to accelerate the development of advanced biofuels,

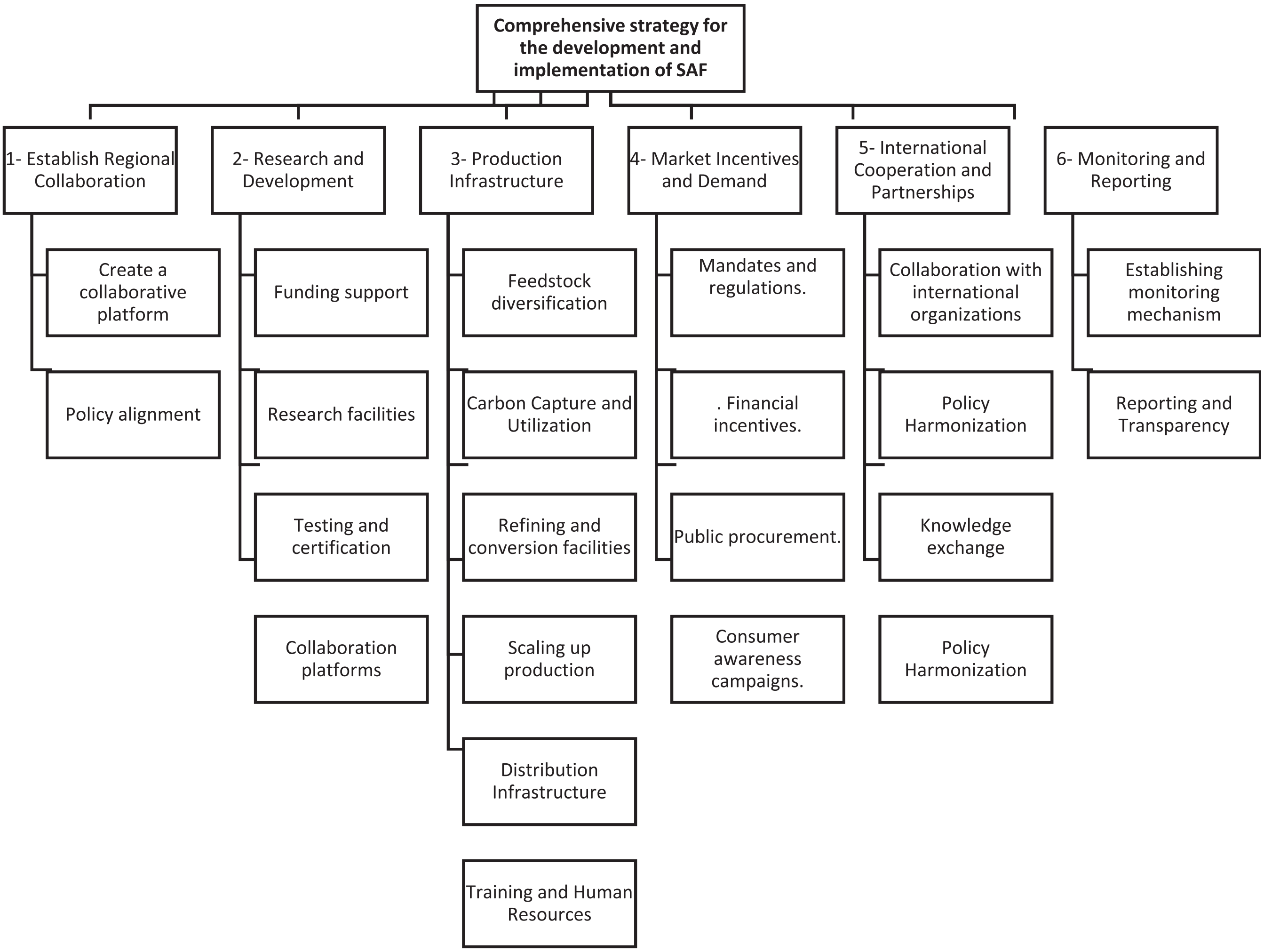

FIGURE 4 Comprehensive strategy for the development and implementation of sustainable aviation fuel in the MENA region.

including SAF.[45,46] The MENA region's commitment to research and innovation underscores its dedication to supporting global environmental objectives and promoting sustainable aviation practices. Collaboration platforms, such as research consortia, public-private partnerships, and industry forums, provide avenues for stakeholders to come together, share resources, exchange ideas, and collaborate on R&D initiatives. By providing funding support, establishing research facilities and partnerships, implementing robust testing and certification processes, and fostering collaboration platforms, the MENA region can drive significant progress in SAF production, fostering technological advancements, and sustainable solutions for the aviation sector in the region.

3.4.3 | Production infrastructure

Feedstock diversification

In the MENA region, feedstock diversification is a key aspect of SAF production. Assessing regional resources is crucial to identify and evaluate the availability and suitability of different feedstock options for SAF production (Table 1). The MENA region possesses significant potential for producing SAF from various feedstocks, including solid waste, date palm residues, animal wastes, and used cooking oil (Table 2).

The data on municipal solid waste (MSW) in the MENA region indicates varying quantities and compositions, providing insights into the potential for SAF production from this feedstock. Several countries exhibit notable amounts of organic content in their MSW, which can be harnessed for biofuel production. Countries such as Algeria, Bahrain, Egypt, Iraq, Jordan, KSA, Kuwait, Lebanon, Morocco, Oman, Qatar, and the UAE generate considerable volumes of MSW, with varying percentages of organics. The high organic content in the solid waste of these countries, ranging from 36.3% to 77%, suggests a substantial potential feedstock for biofuel production. Technologies like gasification, pyrolysis, or biochemical conversion can be employed to convert the organic fraction of MSW into SAFs.

In terms of date palm residues, Egypt stands out with an estimated 660,000 tons per year. Date palm residues, including branches, leaves, and fruit waste, can be processed through thermal or biochemical conversion methods to produce bio-oil or biogas, which can then be further refined into SAF.

TABLE 1 Feedstock diversification in the MENA region.

Feedstock	Examples	Potential conversion technologies	Economic and environmental benefits
Saltwater-tolerant crops (halophytes)	Salicornia, Jatropha, Suaeda, and Salsola	a. Hydrothermal liquefaction b. Gasification c. Pyrolysis d. Fermentation e. Biochemical processes	a. Diversification of feedstock b. Utilization of marginal lands c. Reduced pressure on freshwater resources d. Carbon emission reductions e. Economic development and job creation
Non-food biomass	Agricultural residues (e.g., crop residues, straw, and bagasse, husks, stalks) Forestry residues (branches, sawdust, and wood chips)	a. Gasification b. Pyrolysis c. Fermentation d. Anaerobic digestion	a. Diversification of energy sources b. Reduce dependence on fossil fuels, c. Promote sustainable forestry practices. d. Create job opportunities e. Mitigate greenhouse gas emissions
	Algae and aquatic biomass	a. Algal oil extraction b. Hydrothermal liquefaction c. Pyrolysis, d. Biochemical conversion e. Catalytic conversion	a. High productivity and rapid growth b. Reduced land and water footprint c. Carbon dioxide absorption and mitigation d. Utilization of waste and wastewater
Waste oils and residues	Cooking oil, lubricating oil, hydraulic oil, palm oil residues, olive oil residues, and date palm residues	a. Transesterification b. Hydroprocessing c. Pyrolysis	a. Contribute to energy security by reducing reliance on imported petroleum products. b. Promote sustainability by repurposing waste materials c. Reducing greenhouse gas emissions, d. Supporting the circular economy concept.
Municipal solid waste	Food waste and green waste	a. Anaerobic digestion b. Gasification, c. Pyrolysis, d. Hydrothermal liquefaction	a. Waste management cost reduction b. Resource recovery and circular economy c. Energy independence and security d. Greenhouse gas emission reduction e. Waste reduction and environmental preservation f. Air quality improvement
Industrial and agro-industrial residues	Fruit pomace, sawdust, and paper waste	a. Gasification, b. Pyrolysis, c. Hydrothermal liquefaction d. Transesterification e. Fischer-tropsch synthesis	a. Waste valorization and cost reduction b. Greenhouse gas emission reduction c. Reduced land use pressure d. Air quality improvement

Used cooking oil (UCO) is another valuable feedstock for SAF production. Egypt, with 500,000 tons of UCO per year, and the UAE, with 182,000 L annually, can leverage these resources to produce biofuels suitable for aviation. Conversion technologies such as transesterification or hydrotreatment can be applied to UCO to obtain high-quality SAF.

While some countries in the given data do not have specific figures for date palm residues or used cooking oil, it is important to note that these resources are often present in significant quantities throughout the MENA region. Therefore, countries such as Bahrain, Jordan, Kuwait, Lebanon, Libya, Oman, Qatar, and Saudi Arabia can explore the potential of date palm residues and used cooking oil as additional feedstocks for SAF production.

The data on animal wastes in the MENA region suggests a significant potential for the production of SAF from this feedstock. Several countries in the region, including Bahrain, Egypt, Jordan, KSA, Kuwait, Lebanon, Morocco, Oman, Qatar, and the UAE, generate substantial quantities of animal wastes. This organic material can be effectively utilized for biofuel production through processes such as anaerobic digestion or other biochemical pathways. The varying volumes of animal wastes across these countries indicate diverse opportunities for biofuel production. For instance, Egypt's considerable amount of 11.00 Mtpa presents a notable feedstock base. Technologies like anaerobic digestion, gasification, pyrolysis, or microbial fermentation can be employed to convert the animal wastes into SAFs.

To fully leverage the potential of these feedstocks, it is crucial for MENA countries to invest in advanced biofuel production technologies, establish proper waste management systems, and develop supportive policies and incentives. Collaborative efforts between governments, private sectors, and research institutions can drive the development of a SAF industry in the region, reducing carbon emissions from aviation and contributing to a more sustainable future.

Refining and conversion facilities

In the MENA region, the development of efficient and advanced refining and conversion facilities is crucial to produce SAF. The MENA region hosts a diverse and technologically advanced network of refining and conversion facilities that play a pivotal role in meeting regional and global energy demands. With significant oil and gas reserves, countries in the region have established modern and sophisticated refineries equipped with advanced technologies for crude oil refining, ensuring the production of various fuels, including aviation fuel.

TABLE 2 Amounts of some Feedstock candidates for SAF production in the MENA region.

Country	Solid waste Mtpa (% organics)[47,48]	Date palm residues (ton/year)[49–51]	Animal wastes (Mtpa)[52–55]	Used cooking oil (ton/year)[56–58]
Algeria	13.5 (54)	900,000	NA	NA
Bahrain	2.6 (71.9)	NA	0.27	NA
Egypt	26 (56)	660,000	11.00	500,000
Iraq	12.8 (58.9)	630,000	NA	NA
Jordan	3.4 (70)	NA	3.65	15,000
KSA	17.4 (77)	345,000	14.35	NA
Kuwait	3.2 (67)	NA	1.71	NA
Lebanon	2.04 (50)	NA	3.20	NA
Libya	3.2 (36.3)	NA	NA	1650
Morocco	7.4 (70)	NA	35.74	100,000
Oman	4.0 (49)	NA	3.57	11,000
Qatar	11.4 (68)	NA	1.39	NA
UAE	12.3 (64)	500,000	4.24	182,000 L annually

Some nations in the region have embraced technologies for converting biomass or waste into biofuels, contributing to SAF initiatives.[59] The strategic placement of these facilities near key transportation hubs ensures a reliable and efficient supply chain for aviation fuel, supporting the growing air travel industry. Moreover, there is significant potential for these existing facilities to accelerate the production of SAF by integrating SAF production units, implementing advanced conversion technologies, and fostering collaborations with research institutions. Government support, alignment with market demands, and initiatives to raise public awareness further create an environment conducive to the growth of the SAF industry, emphasizing the region's commitment to global environmental objectives and sustainable aviation practices. Continuous investments in technology upgrades and personnel training underscore the region's dedication to maintaining a resilient and environmentally conscious energy infrastructure.

Distribution infrastructure

The establishment of a robust distribution infrastructure is essential for the successful production and supply of SAF in the MENA region. The MENA region boast a well-established and comprehensive distribution infrastructure for aviation fuel. Major international airports, strategically located storage facilities, and dedicated fueling stations contribute to the efficient supply of aviation fuel. These airports are equipped with state-of-the-art facilities, including fuel storage tanks and hydrant systems, ensuring a seamless provision of jet fuel for both domestic and international flights. Some countries in the region have also developed extensive pipeline networks to transport aviation fuel from refineries or storage terminals to major airports, offering a cost-effective and efficient means of distribution. Additionally, road and rail transportation play a role in delivering fuel to airports without direct pipeline connections. Stringent regulatory standards, adherence to international aviation fuel quality requirements, and robust emergency response and contingency plans further enhance the reliability and safety of the aviation fuel distribution network in the MENA region. Continuous investment in infrastructure and compliance with global best practices contribute to the region's ability to meet the growing demands of the aviation industry while maintaining high standards of safety and efficiency. By investing in storage facilities, transportation networks, logistics partnerships, quality control measures, and industry collaboration, the MENA region can establish a robust distribution infrastructure that supports the widespread adoption of SAF in the aviation sector.

Market incentives and demand

The CAAF/3, which was held in Dubai, United Arab Emirates, from November 20 to 24, 2023, resulted in the adoption of a global goal for the implementation of SAF by 2030.[60] Additionally, a comprehensive framework was established to facilitate this objective. The conference outcomes presented the Global Vision for 2030, which aims to reduce CO_2 emissions in international aviation by 5% through the use of SAF, liquefied compressed alternative fuels (LCAF), and other more environmentally-friendly aviation fuels.

Various countries in the MENA region are actively pursuing initiatives in the aviation sector to promote sustainability (Table 3). In the United Arab Emirates (UAE), the Dubai Supreme Council of Energy has set a goal of incorporating 5% SAF in Dubai airports by 2030, and the Abu Dhabi National Oil Company (ADNOC) is collaborating with Etihad Airways to create a roadmap for SAF production. Similarly, in the Kingdom of Saudi Arabia, Saudia is committed to emissions reduction and exploring SAF options, while the General Authority of Civil Aviation (GACA) collaborates with stakeholders to explore SAF production opportunities. In Qatar, Qatar Airways is investing in SAF research and development, and the Qatar General Civil Aviation Authority (GCAA) is actively supporting initiatives for the use of SAF in the aviation industry. Royal Jordanian Airlines in Jordan is engaged in SAF research and exploring partnerships for sustainable aviation, and in Morocco, the National Office of Airports (ONDA) collaborates with airlines to explore SAF usage and reduce carbon emissions.

TABLE 3 Initiatives for SAF production in the MENA region.

Country	Initiative
United Arab Emirates (UAE)	• Dubai Supreme Council of Energy set a target of using 5% SAF in Dubai airports by 2030. • Abu Dhabi National Oil Company (ADNOC): Collaborating with Etihad Airways to develop a roadmap to produce SAF in the UAE.
Kingdom of Saudi Arabia	• Saudi Arabian Airlines (Saudia): Committed to reducing emissions and exploring SAF options to achieve sustainability goals. • General Authority of Civil Aviation (GACA): Collaborating with stakeholders to explore opportunities for SAF production and usage.
Qatar	• Qatar Airways: Committed to reducing carbon emissions and investing in SAF research and development. • Qatar General Civil Aviation Authority (GCAA): Supporting initiatives to promote the use of SAF in the aviation industry.
Jordan	Royal Jordanian Airlines: Engaging in SAF research and exploring partnerships for sustainable aviation initiatives
Morocco	National Office of Airports (ONDA): Collaborating with airlines to explore SAF usage and reduce carbon emissions.

These initiatives collectively underscore a regional commitment to adopting sustainable aviation practices, aligning with global efforts to mitigate the environmental impact of the aviation sector.

3.4.4 | International cooperation and partnerships

The MENA region recognizes the importance of SAFs in mitigating the environmental impact of the aviation industry. Collaborations with international organizations (International Civil Aviation Organization [ICAO], Global Sustainable Aviation Fuels Alliance [SAFUG], and International Renewable Energy Agency [IRENA]) are crucial for advancing SAF adoption and production. These partnerships facilitate the development of sustainable practices, knowledge sharing, and the establishment of robust frameworks for SAF implementation. Aligning with ICAO ensures consistency in sustainability criteria and regulations. Engagement with SAFUG allows for best practice exchange and market insights, contributing to scaling up SAF production. Collaboration with IRENA strengthens the region's position in renewable energy-based SAF production. Continued collaboration with international organizations is vital for driving research, creating markets, fostering innovation, and supporting capacity building. Knowledge exchange with research institutions and industry associations enhances expertise in SAF production. Research and development collaboration drives innovation and accelerates the development of sustainable SAF production methods tailored to the MENA region. The MENA region aims to establish itself as a hub for SAF production expertise by investing in R&D and fostering partnerships.

3.4.5 | Monitoring and reporting

Monitoring and reporting play a vital role in promoting SAF production in the MENA region. By implementing robust mechanisms, the region can ensure transparency, track progress, and verify the sustainability of SAF. Monitoring involves assessing the entire value chain, from feedstock cultivation to fuel distribution, to evaluate environmental and social factors. Data collection systems, standardized reporting templates, and verification processes are necessary for effective monitoring. Collaboration among stakeholders is crucial to establish frameworks and guidelines, minimize duplication, and enhance credibility. Regular updates and communication of results foster transparency and stakeholder engagement. Public awareness campaigns contribute to informing the public about the benefits of sustainable aviation and the progress made in the MENA region.

4 | CONCLUSION

In the MENA region, the potential for SAF production is substantial, yet several challenges must be addressed to fully exploit this opportunity. High production costs, limited feedstock availability, infrastructure constraints, and technological readiness pose significant hurdles. To overcome these challenges, the region can focus on research and development, international collaborations, and knowledge-sharing initiatives. Government support, including incentives and subsidies, can alleviate production costs and promote SAF market growth. The region's commitment to addressing these challenges aligns with global efforts to reduce the aviation industry's carbon footprint.

In terms of feedstock diversification, the MENA region possesses ample resources, including municipal solid waste, date palm residues, used cooking oil, and animal wastes. Leveraging these resources through advanced biofuel production technologies, waste management systems, and supportive policies can enhance SAF production. The existing refining and conversion facilities, distribution infrastructure, and training programs in the region play a crucial role in accelerating SAF production. Continuous investments in technology upgrades, personnel training, and market incentives further highlight the region's dedication to sustainable aviation practices.

International cooperation and partnerships, particularly with organizations like ICAO, IATA, SAFUG, and IRENA, contribute to the development of robust frameworks, knowledge exchange, and research collaboration. Monitoring and reporting mechanisms ensure transparency and progress tracking, fostering public awareness and stakeholder engagement. The MENA region's comprehensive strategy addresses various aspects of SAF production, infrastructure development, and policy support, emphasizing its commitment to a greener aviation industry and global environmental objectives.

AUTHOR CONTRIBUTIONS

Ismail Abbas: Conceptualization; writing – review and editing; validation; data curation; resources; investigation; writing – original draft. **Ali Shaar:** Investigation; writing – review and editing; validation; conceptualization; data curation. **Rola El Osta:** Conceptualization; validation; writing – review and editing; data curation; investigation.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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How to cite this article: Abbas I, Shaar A, El Osta R. The pathway for achieving sustainable aviation fuel production in the Middle East and North Africa region. *Environ Prog Sustainable Energy*. 2024;e14395. doi:10.1002/ep.14395