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Catalytic Processes for Sustainable Aviation Fuel Production in Biorefineries

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Abstract: This study focuses on the production of Sustainable Aviation Fuel (SBAF) within the framework of biorefineries, emphasizing the critical role of catalysis in enabling efficient and sustainable conversion of biomass feedstocks. The research explores various production pathways, including Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch (FT) synthesis, and Alcohol-to-Jet (ATJ), and discusses their associated challenges, such as feedstock availability, high production costs, and technological limitations. A comprehensive overview of different catalyst types, including zeolites, metal oxides, and novel catalysts like MOFs and bifunctional catalysts, is presented, along with their catalytic mechanisms, deactivation pathways, and regeneration strategies. The paper also delves into the importance of catalyst characterization techniques in understanding catalyst performance and optimizing reaction conditions. Finally, the environmental and economic aspects of biorefinery-based SBAF production are discussed, highlighting the need for sustainable feedstock sourcing, efficient process design, and supportive policies to ensure the commercial viability and environmental sustainability of this emerging technology. This review aims to provide a comprehensive understanding of the catalytic challenges and opportunities in the production of SBAF within integrated biorefinery systems, paving the way for future research and development efforts.

Keywords: Bio-Aviation Fuel (SBAF), Biorefinery, Catalysis, Biomass Conversion, Sustainable Aviation, Catalyst Deactivation.

1. INTRODUCTION

The global increase in energy demand, combined with the urgent need to address climate change, has driven a shift towards sustainable and renewable energy sources. Among these, biofuels have been identified as a viable alternative to fossil fuels, presenting a pathway to reduce emissions and lessen the environmental impact of transport (Chiaramonti & Maniatis, 2020; Abderrahim et al., 2024; Alalwan et al., 2024).

Aviation, which heavily depends on fossil fuels, is facing pressure to decarbonize. Sustainable aviation fuels (SBAF), derived from biomass, are seen as a solution to decrease the carbon footprint of the aviation sector (International Civil Aviation Organization [ICAO], 2024). These fuels can be produced from a diverse array of feedstocks, including non-edible oils and agricultural waste, providing an economically and environmentally sustainable alternative to traditional jet fuels (Alalwan et al., 2024; Chowdhury et al., 2024). Non-edible oils and agricultural residues are particularly noteworthy due to their potential to produce high-quality biofuels without competing with food resources for land use (Kumar et al., 2023). These feedstocks can be processed into SBAF using various thermochemical methods, leveraging their high triglyceride content (Yusuff et al., 2022). However, the path to commercializing SBAF is fraught with challenges including feedstock availability, high production costs, and infrastructural limitations.

Biorefineries have been proposed as a solution to these challenges by converting biomass into multiple products, potentially enhancing the economic and environmental sustainability of SBAF production (Bauen et al., 2024; Undavalli et al., 2023; Osman et al., 2024; Sachdev, 2024; Wang et al., 2024; Rios-Hurtado et al., 2024). Despite this, biorefinery-based SBAF production encounters numerous obstacles such as high costs, feedstock availability issues, and technological hurdles in conversion and catalyst development.

The cost of producing biorefinery-based SBAF often exceeds that of conventional jet fuel due to factors like feedstock expenses, the complexity of processing, and lack of economies of scale (de Jong et al., 2021; Rios-Hurtado et al., 2024). Feedstock availability and cost can fluctuate based on location, agricultural practices, and market conditions (Kumar et al., 2023; Chowdhury et al., 2024). The diverse composition of biomass necessitates advanced catalytic processes for efficient conversion into suitable aviation fuels, alongside the development of cost-effective, environmentally friendly catalysts (Yusuff et al., 2022; Sharma et al., 2023).

The conversion technologies essential for SBAF production involve complex processes needing both efficiency and economic viability. Catalytic approaches, in particular, are pivotal for transforming biomass feedstocks into biofuels, with the need for multifunctional catalysts that can handle various chemical reactions to produce high-quality fuel

(Sharma et al., 2023; Chowdhury et al., 2024). However, challenges like high energy consumption, low product yield, and catalyst deactivation persist (Yusuff et al., 2022; Karatzos et al., 2022).

Ensuring that SBAF meets stringent aviation standards for properties like cetane number, freezing point, and thermal stability is crucial for compatibility with existing infrastructure (ICAO, 2024). Economically, SBAF production needs to overcome its higher cost profile through strategic analyses to reduce expenses and enhance viability (de Jong et al., 2021; Rios-Hurtado et al., 2024). Additionally, significant infrastructural investment is required to integrate SBAF into the current aviation fuel system (International Air Transport Association [IATA], 2024).

Policy and regulatory support are vital for promoting SBAF, with mechanisms like carbon pricing, mandates for sustainable fuel use, and funding for research playing key roles (ICAO, 2024; European Union Aviation Safety Agency [EASA], 2024). Without such support, the commercialization of SBAF remains challenging.

This paper aims to provide a comprehensive overview of the challenges, opportunities, and future perspectives of biorefinery-based Sustainable Aviation Fuel (SBAF) production from non-edible seed-oils and waste cooking oil. It focuses on critically analyzing the role of catalysis in enabling efficient and sustainable biomass conversion within integrated biorefinery systems. The review will explore various production pathways, evaluate the performance of different catalyst types, including zeolites, metal oxides, and novel catalysts, and investigate the challenges associated with catalyst deactivation and regeneration. Furthermore, the review will assess the environmental and economic impacts of biorefinery-based SBAF production, considering factors such as feedstock availability, production costs, and government policies. By examining the existing literature and identifying key research gaps, this review seeks to contribute to the advancement of SBAF production technology, its successful commercialization, and its integration into the aviation industry.

2. BIO-AVIATION FUEL

Aviation fuel, a complex hydrocarbon blend, must meet specific properties like energy density, volatility, freezing point, thermal stability, and lubricity to ensure aircraft performance and safety. These characteristics are critical for maintaining the efficiency of aircraft engines, reducing emissions, and ensuring operational safety in various climatic conditions (ICAO, 2022; ASTM International, 2021). Organizations such as the International Civil Aviation Organization (ICAO), ASTM International, and the International Air Transport Association (IATA) set stringent standards to guarantee fuel quality. These standards address the fuel's chemical composition, physical properties, and performance requirements, including specifications for Jet A and Jet A-1 fuels (American Society for Testing and Materials [ASTM], 2021; IATA, 2020).

The aviation sector's notable contribution to greenhouse gas emissions has driven the demand for sustainable alternatives like bio-aviation fuel (SBAF). SBAF, sourced from renewable materials such as agricultural residues, waste oils, and algae, offers a pathway to lower carbon emissions, enhance air quality, and decrease reliance on fossil fuels (ICAO, 2022; EASA, 2021; IATA, 2020). By blending SBAF with conventional jet fuel, the aviation industry can move towards more sustainable practices.

The adoption of SBAF yields several environmental and economic benefits, including significant reductions in greenhouse gas emissions, better air quality due to lower emissions of pollutants, and a reduction in the dependence on non-renewable fossil fuels, which also promotes energy security (ICAO, 2022; EASA, 2021). Economically, SBAF can lead to job creation and stimulate growth in the renewable energy sector, fostering a circular economy by utilizing waste-based feedstocks (European Commission, 2020).

However, the transition to SBAF is not without challenges. Higher production costs, limited feedstock availability, and the need for new infrastructure to handle the production, storage, and distribution of SBAF pose significant barriers (European Commission, 2020; IATA, 2020).

To overcome these challenges, governments and international bodies are implementing supportive policies. These include carbon pricing, sustainable aviation fuel mandates, research and development funding, infrastructure development, and mandated blending requirements (ICAO, 2022; EASA, 2021; European Commission, 2020). Such policies aim to create economic incentives for airlines and fuel producers to shift towards SBAF, thereby aiding in achieving broader climate goals.

The ongoing research and development in this field are crucial for enhancing the efficiency and cost-effectiveness of SBAF production, exploring new feedstocks, and advancing conversion technologies that could make sustainable aviation fuels a more viable option in the global market. Through these combined efforts, the aviation industry is working towards reducing its environmental footprint while continuing to meet the demands of global air travel.

2.1 Production Pathways for Sustainable Aviation Fuel: A Comparative Review

The production of Sustainable (Bio-) Aviation Fuel (SBAF) involves several pathways (Table 1), each with distinct advantages and challenges. The most established pathway is Hydroprocessed Esters and Fatty Acids (HEFA), where triglycerides from vegetable oils or animal fats are converted into SAF through hydroprocessing steps like hydrolysis and esterification (Schneiders et al., 2017). HEFA is noted for high fuel quality and is commercially well-established, with yields often reaching 80-90% depending on the feedstock and catalytic system (Lemoine et al., 2020; European

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Commission, 2020). The costs for HEFA-based fuels range from $1.00 to $1.50 per liter, influenced by feedstock availability and market demand. Fischer-Tropsch (FT) synthesis is another pathway, which converts biomass-derived syngas into liquid hydrocarbons. It's versatile in terms of feedstock, capable of using lignocellulosic biomass among others, and can achieve bio-aviation fuel yields of 70-85%. However, the process is costlier, with operating costs between $2.50 to $4.00 per liter due to high capital costs and technological complexity (Dry, 2002; Bridgwater, 2012; Demirbas, 2009). FT synthesis holds potential for significant greenhouse gas (GHG) reductions but requires technological advancements for broader adoption. The Alcohol-to-Jet (ATJ) pathway involves converting alcohols like ethanol or methanol into jet fuel through dehydration and subsequent hydroprocessing. This method can leverage renewable ethanol from biomass fermentation, offering yields of 60-70% with carbon ranges suited for aviation (C8-C14). The production cost is estimated at $1.50 to $2.00 per liter, with potential for optimization to enhance both yield and cost efficiency (Hameed et al., 2017; Wang et al., 2017; Lemoine et al., 2020).

Hydrotreated Renewable Jet (HRJ) fuel production uses triglyceride-rich feedstocks like used cooking oil or palm oil through hydroprocessing, similar to HEFA, with yields of 75-85% and costs between $1.30 and $1.60 per liter. HRJ fuels have carbon compositions (C8-C16) that make them suitable for blending with conventional jet fuels, positioning HRJ as a promising technology for waste oil utilization (ASTM International, 2021; Doliente et al., 2020).

Synthetic Paraffinic Kerosene (SPK) involves biomass gasification followed by FT synthesis, producing fuels with properties akin to conventional jet fuel (C10-C18). Despite high potential for GHG emission reduction (up to 80%), SPK's production remains costly at $3.00 to $4.50 per liter due to process complexity and high capital investment (European Commission, 2020).

Emerging technologies such as catalytic cracking, pyrolysis, and Hydrothermal Liquefaction (HTL) are under development but offer the potential for using a wider range of feedstocks, including lignocellulosic biomass and algae. These pathways are not yet economically viable at scale, with costs significantly higher than established methods, but they could enhance the sustainability of SBAF production as they mature (Corma et al., 2007; Demirbaş, 2009).

The choice of production pathway is determined by factors like feedstock availability, technological maturity, and economic considerations, with HEFA leading due to its established status, while FT and ATJ show promise for future scalability and environmental benefits.

Table 1 Comparative Table of Recent Studies on Sustainable Aviation Fuel Pathways

Pathway	Fuel Yield (%)	Properties (Carbon Range)	Operating Conditions	Cost Estimation ($/L)	Key References
HEFA (Used Cooking Oil)	80-90	C8-C15	300-350°C, 5-10 MPa	1.00-1.50	European Commission (2020), Lemoine et al. (2020)
FT Synthesis (Lignocellulosic)	75-85	C10-C18	350-500°C, 1-5 MPa	2.50-4.00	Doliente et al. (2020), Demirbas (2009)
ATJ (Ethanol)	60-70	C8-C14	300-350°C, 5-10 MPa	1.50-2.00	Wang et al. (2017)
HRJ (Palm Oil)	75-85	C8-C16	300-350°C, 5-10 MPa	1.30-1.60	ASTM International (2021), Doliente et al. (2020)
SPK (Gasification, FT)	70-80	C10-C18	400-500°C, 1-5 MPa	3.00-4.50	European Commission (2020)
HEFA (Jatropha Oil)	80-85	C12-C15	300-350°C, 5-10 MPa	1.10-1.40	Atabani et al. (2013)
FT Synthesis (Waste Biomass)	70-75	C10-C18	350-500°C, 1-5 MPa	3.50-4.00	Bridgwater (2012)
ATJ (Butanol)	65-70	C8-C14	300-350°C, 5-10 MPa	1.50-2.30	Hameed et al. (2017)
HEFA (Pongamia Oil)	75-80	C10-C15	300-350°C, 5-10 MPa	1.20-1.50	Rajvanshi et al. (2021)
SPK (FT, Microalgae)	70-75	C10-C18	350-500°C, 1-5 MPa	3.50-4.00	Doliente et al. (2020)
ATJ (Methanol)	60-65	C8-C14	300-350°C, 5-10	1.60-2.30	Hameed et al. (2017)

Pathway	Fuel Yield (%)	Properties (Carbon Range)	Operating Conditions	Cost Estimation ($/L)	Key References
			MPa		
FT (Syngas)	70-80	C10-C18	400-500°C, 1-5 MPa	3.00-4.20	Bridgwater (2012)
HEFA (Castor Oil)	65-75	C12-C16	300-350°C, 5-10 MPa	1.50-1.80	Vazquez et al. (2021)
ATJ (Isobutanol)	65-70	C8-C14	300-350°C, 5-10 MPa	1.50-2.30	Lemoine et al. (2020)
HTL (Algae Biomass)	55-65	C10-C18	300-400°C, 10-20 MPa	4.00-5.00	Corma et al. (2007)

2.2. SAF Production: Challenges and Future Perspectives

The transition to sustainable bio-aviation fuels (SBAF) is essential for reducing emissions in the aviation sector, but several challenges impede the commercial viability of current production pathways. These challenges include technological inefficiencies, economic constraints, and issues related to supply chains. Among the pathways, Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch (FT) synthesis, and Alcohol-to-Jet (ATJ) are notable, each presenting unique obstacles.

Technological challenges are significant. FT synthesis, despite its feedstock flexibility, involves complex gasification and catalytic processes, leading to high operational and capital costs. The complexity of syngas production and the need for high-quality biomass further complicate this method's commercial viability (Mawhood et al., 2016). The ATJ pathway, involving multiple conversion steps like dehydration and hydroprocessing, is also energy-intensive and costly due to lower conversion efficiencies. Similarly, Hydrotreated Renewable Jet (HRJ) fuel faces challenges due to its high hydrogen demand during processing, escalating costs (Hameed et al., 2017). Emerging technologies like hydrothermal liquefaction (HTL) and catalytic cracking, while promising, need further catalyst design and process optimization to meet aviation fuel specifications (Huang & Qiu, 2019). Scaling up HTL and ensuring consistent fuel quality remain significant hurdles.

Economic viability poses another major challenge. The volatility of feedstock prices impacts all pathways, with HEFA benefiting from lower-cost waste oils, costing between $1.00-$1.50 per liter (Doliente et al., 2020). However, the availability of waste oils limits their potential to meet global demand, leading to research into alternative sources like algal or synthetic lipids, which are still in developmental stages. For FT synthesis and ATJ, the high capital costs for infrastructure like gasification units or dehydration systems result in production costs ranging from $2.50-$4.00 per liter. The reliance on renewable hydrogen adds another layer of economic uncertainty, as its current high price significantly affects biofuel costs (Baral et al., 2019).

Feedstock supply and sustainability issues are crucial. The availability of biomass can fluctuate seasonally and is subject to competing uses and environmental constraints. FT synthesis, for instance, depends on lignocellulosic biomass, which can be challenging to supply consistently (Demirbas, 2009). Sustainability concerns also arise, as while bio-aviation fuels generally reduce GHG emissions compared to fossil fuels, the lifecycle sustainability depends on avoiding negative environmental impacts like land-use change or water scarcity from large-scale energy crop cultivation (Rajvanshi et al., 2021). The future of SBAF production hinges on diversifying feedstocks and developing advanced biorefineries to process a broader range of materials, including waste biomass and algae, ensuring both supply stability and environmental sustainability.

3. CATALYST SYSTEMS DEVELOPMENT FOR SUSTAINABLE BIOAVIATION FUEL PRODUCTION

Catalysts play a pivotal role in the conversion of biomass-derived feedstocks into bio-aviation fuel (SBAF). They enhance reaction rates, selectivity, and product yield, making the process economically viable and environmentally friendly. The choice of catalyst significantly influences the reaction pathways, product distribution, and overall process efficiency. Hence, the selection of appropriate catalysts is crucial for achieving high product yields, selectivity, and stability (Sabadie et al., 2012).

Conventional Catalysts Traditional catalysts, widely employed in the petrochemical industry, have been adapted for biofuel production. These catalysts primarily include Zeolites, metal oxides and heterogeneous (supported) metal catalysts. Zeolites are microporous aluminosilicates with well-defined pore structures and acidic properties, zeolites exhibit excellent catalytic properties for various reactions, including cracking, isomerization, and aromatization (Corma et al., 2007). However, their hydrothermal stability and susceptibility to deactivation can limit their application in

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biomass conversion (Corma et al., 2007). Metal oxides, such as alumina, zirconia, and titania, are employed as supports for active metal components or as catalysts themselves. They exhibit acidity or basicity, influencing their catalytic performance (Saba et al., 2016). Supported metal catalysts consist of active metal nanoparticles dispersed on a support material. Common metals include platinum, palladium, nickel, and cobalt, supported on materials like alumina, silica, and carbon (Corma et al., 2007). Heterogeneous metal catalysts like Noble metals (platinum, palladium, rhodium) and transition metals (nickel, cobalt, iron) supported on various supports (e.g., alumina, silica) are employed for hydrogenation, deoxygenation, and hydrocracking reactions (Sabadie et al., 2012). Noble metals like Platinum, palladium, and rhodium are known for their high catalytic activity but are often expensive and susceptible to deactivation (Chen et al., 2011).
The performance of conventional catalysts (Table 2) is often limited by factors such as deactivation, low selectivity, compatibility with complex biomass feedstocks and the requirement for harsh reaction conditions. While conventional catalysts have shown some success in biofuel production, their limitations in terms of selectivity, stability, and tolerance to feedstock impurities necessitate the development of novel catalyst systems.

Table 2 Conventional Catalysts for SBAF Production

Catalyst Type	Active Sites	Applications	Challenges
Zeolites	Brønsted and Lewis acid sites	Cracking, isomerization, aromatization	Deactivation, hydrothermal instability
Metal oxides	Acidic or basic sites	Support for metal catalysts, deoxygenation	Lower activity compared to metal catalysts
Heterogeneous metal catalysts	Metal active sites	Hydrogenation, deoxygenation, hydrocracking	Deactivation by coke formation, metal sintering

Novel Catalyst Systems In recent years, there has been a growing interest in developing novel catalyst systems to overcome the limitations of conventional catalysts. These advanced catalysts aim to enhance catalytic activity, selectivity, and stability for biofuel production. These novel catalysts (Tables 3-4) often exhibit enhanced performance and selectivity compared to conventional catalysts. Common novel catalyst systems include bifunctional catalysts, metal-organic frameworks (MOFs), heterogeneous catalysts with hierarchical structures, supported ionic liquids (SILS) and Heterogeneous homogeneous catalysis (Liu et al., 2015; Wang et al., 2014).
Bifunctional catalysts combine acidic and metallic functions within a single catalyst to improve catalytic performance by promoting multiple reaction steps. For example, combining zeolites with metal nanoparticles can enhance deoxygenation, isomerization, and aromatization reactions (Corma et al., 2007). Metal-organic frameworks (MOFs) are highly porous catalyst materials with tunable pore structures and functional groups for selective adsorption and catalysis (Furukawa et al., 2014). Their potential as catalysts for biofuel production is being explored due to their large surface area and ability to accommodate various active sites (Li et al., 2012). Heterogeneous catalysts with hierarchical structures are catalysts with hierarchical pore structures, combining micropores, mesopores, and macropores, can enhance mass transfer and improve catalytic performance (Chen et al., 2013). Supported ionic liquids catalysts combining the advantages of ionic liquids with solid supports can create novel catalysts with enhanced stability and recyclability (Liu et al., 2015). Heterogeneous homogeneous catalysis combining homogeneous and heterogeneous catalysts can offer synergistic effects and enhanced catalytic performance (Sabadie et al., 2012).
By exploring and optimizing these novel catalyst systems, researchers aim to develop more efficient and sustainable processes for SBAF production. The development of novel catalyst systems is an ongoing area of research, with the aim of achieving higher SBAF yields, improved product quality, and reduced process costs. The novel catalyst systems development is a dynamic area of research, with continuous advancements in catalyst design and synthesis. Identifying and optimizing catalysts for specific biomass feedstocks and desired biofuel products is crucial for achieving sustainable and economically viable biofuel production.

Table 3 Novel Catalyst Systems for SBAF Production

Catalyst Type	Active Sites	Advantages	Challenges
Bifunctional catalysts	Acidic and metallic sites	Improved selectivity and efficiency	Complex synthesis, potential deactivation
Supported metal nanoparticles	High surface area, metal active sites	Enhanced activity and selectivity	Stability issues, metal leaching
Metal-organic frameworks (MOFs)	Tunable pore structure, functional groups	High surface area, selectivity	Synthesis complexity, stability concerns

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Heterogeneous homogeneous catalysis	Combination of homogeneous and heterogeneous components	Improved performance, flexibility	Catalyst recovery, mass transfer limitations

Table 4 Comparison of Conventional and Novel Catalysts for Sustainable Bioaviation fuel Production

Catalyst Type	Advantages	Disadvantages
Conventional (zeolites, metal oxides, supported metals)	Well-established, commercially available	Lower selectivity, deactivation, harsh reaction conditions, high cost (noble metals)
Novel (bifunctional catalysts, MOFs, hierarchical catalysts, SILS)	Enhanced activity and selectivity, improved stability	Higher cost, limited commercial availability

3.1 Catalyst Types for Sustainable Bioaviation fuel Synthesis

A variety of catalyst types have been explored for bioaviation fuel production, each with its own strengths and weaknesses. These catalysts can be classified based on their active components, support materials, and catalytic functions. The catalysts are classified into homogeneous catalysts, heterogeneous catalyst and biocatalysts.
Homogeneous catalysts are soluble in the reaction medium, and offer high activity and selectivity but can be difficult to separate from the product and often require harsh reaction conditions (Corma et al., 2007). Heterogeneous catalysts are insoluble in the reaction medium, easily recoverable and can be reused, making them more environmentally friendly and economically attractive (Sabadie et al., 2012). They are preferred for industrial applications due to their stability and reusability (Sabadie et al., 2012). Bio-catalysts such as enzymes or microorganisms can catalyze specific reactions under mild conditions, but their stability and activity can be limited (Chen et al., 2011).

Zeolites as Catalysts for Bioaviation fuel (SBAF) Production. Zeolites (Table 5), crystalline aluminosilicates with well-defined pore structures, have emerged as promising catalysts for biofuel production. Their unique properties, including high surface area, acidity, and shape selectivity, make them suitable for various catalytic reactions involved in biofuel synthesis (Corma et al., 2007). They promote different reactions such as catalytic cracking, isomerization, and dehydration. Zeolites can convert heavy hydrocarbon fractions into lighter products, such as gasoline and diesel, through cracking reactions (Corma et al., 2007). Zeolites can catalyze the isomerization of linear hydrocarbons into branched isomers, improving fuel properties (Sabadie et al., 2012). Zeolites can facilitate the dehydration of alcohols to produce olefins, which are intermediates in biofuel synthesis (Chen et al., 2011). They can catalyze aromatization, the dehydrocyclization of aliphatic hydrocarbons to produce aromatic compounds, enhancing fuel octane number (Corma et al., 2007). Zeolites can be modified through ion exchange, dealumination, and other methods to tailor their properties for specific reactions. However, challenges such as coke formation and hydrothermal stability may limit their long-term performance.

Table 5 Zeolite Catalysts and applications in Sustainable Bioaviation fuel Production

Zeolite Type	Applications	Advantages	Disadvantages
H-ZSM-5	Cracking, isomerization, aromatization	High acidity, shape selectivity	Deactivation by coke formation
Beta zeolite	Cracking, hydrocracking, isomerization	Large pore size, high acidity	Lower hydrothermal stability
Y zeolite	Cracking, hydrocracking	High surface area, large pore size	Lower selectivity

Molybdenum Carbide as a Catalyst for Bioaviation fuel (SBAF) Production. Molybdenum carbide (Mo_2C) (Table 6) has gained attention as a promising catalyst for bioaviation fuel production due to its unique properties, including high selectivity, high metallicity, hydrophobicity, resistance to sulfur poisoning, and low cost compared to noble metals (Sabadie et al., 2012). Molybdenum carbide catalysts catalyzes hydrodeoxygenation (HDO) and effectively remove oxygen from bio-oil components, producing hydrocarbon-rich products (Sabadie et al., 2012). Mo_2C can catalyze the hydrogenation of unsaturated compounds, improving fuel stability and reducing emissions (Chen et al., 2011). Its unique electronic properties and resistance to sulfur poisoning make it a suitable alternative to noble metal catalysts (Sabadie et al., 2012). Mo_2C catalysts can catalyze decarbonylation and decarbonylation, the removal of carbonyl and carboxyl groups from biomass-derived molecules, leading to the formation of hydrocarbons (Chen et al., 2011).

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Table 6 Comparison of Zeolite, Noble metals and Molybdenum Carbide Catalysts

Catalyst Type	Advantages	Disadvantages
Zeolite	High acidity, shape selectivity	Deactivation by coke formation, limited metal function
Molybdenum carbide	High activity for HDO, resistance to sulfur poisoning, low cost	Lower acidity, potential for deactivation by coke formation
Noble metals (Pt, Pd, Ru)	High activity, selectivity	High cost, susceptibility to poisoning

While zeolites and molybdenum carbide exhibit different strengths and weaknesses, combining these catalysts in bifunctional systems or using them sequentially can offer synergistic effects, enhancing catalytic performance, product selectivity, and enhance the overall performance of the biofuel production process. Supported Mo_2C catalysts have shown promising results in converting oxygenated compounds into hydrocarbon fuels. However, further research is needed to optimize catalyst preparation, reaction conditions, and long-term stability.

3.2. Catalyst Support Materials

The choice of support material significantly influences the performance of a catalyst. An ideal support should possess high surface area, thermal stability, mechanical strength, and compatibility with the active phase. Common support materials (Table 7) include alumina, silica, carbon-based material, and zeolites (Liu et al., 2012). Alumina is widely used as a support due to its high surface area, thermal stability, and mechanical strength. It is suitable for various metal and oxide catalysts (Sabadie et al., 2012). Silica offers high surface area and thermal stability, but it may lack mechanical strength compared to alumina. It is often used as a support for acidic catalysts (Corma et al., 2007). Carbon-based materials such as activated carbon, carbon nanotubes, and graphene possess high surface area and porosity, making them attractive supports for metal and metal oxide catalysts. However, they may suffer from oxidation at high temperatures (Liu et al., 2012). Besides being active catalysts, zeolites can also serve as supports for other active components, combining catalytic and structural functions, and providing additional advantages such as shape selectivity, additional active sites, improved stability and acidity (Corma et al., 2007). The selection of an appropriate support material depends on the specific catalyst, reaction conditions, and desired product properties.

Table 7 Comparison of Catalyst Support Materials

Support Material	Advantages	Disadvantages
Alumina	High surface area, thermal stability, mechanical strength	Potential for interaction with active phase
Silica	High surface area, thermal stability	Lower mechanical strength compared to alumina
Carbon-based materials	High surface area, porosity	Susceptibility to oxidation, mechanical instability
Zeolites	Combined catalytic and structural functions	Potential for pore blockage, hydrothermal instability

3.3. **Catalyst Deactivation and Regeneration Mechanism**

Catalyst deactivation which is the loss of catalyst activity, is a critical issue in biofuel production, leading to reduced activity, selectivity, and process efficiency. A comprehensive understanding of deactivation mechanisms is essential for developing strategies to mitigate its impact and prolong catalyst lifetime. (Zhao et al., 2021).

Catalyst deactivation can occur through various mechanisms. Several factors contribute to catalyst deactivation, including coking, sintering, poisoning, phase transformation, and mechanical failure (Zhang et al., 2016). Coking is the deposition of carbonaceous materials or residues on the catalyst surface, blocking active sites and hindering mass transfer (Zhang et al., 2020). Sintering is the growth and agglomeration of metal particles, leading to a decrease in surface area (Chen et al., 2018). Poisoning is the adsorption of impurities (e.g., sulfur, nitrogen compounds) on the catalyst surface, inhibiting catalytic activity (Sabadie et al., 2012; Liu et al., 2019). Phase transformations changes the crystal structure or composition of the catalyst, leading to a decrease in catalytic activity (Wang et al., 2017). Mechanical failure or degradation is the physical damage to the catalyst, such as attrition or crushing, abrasion, or thermal stresses resulting in loss of active material (Zhao et al., 2021).

To extend catalyst lifetime and maintain process performance, regeneration techniques are essential as shown in Table 8. Common regeneration methods include calcination, regeneration with hydrogen, and solvent washing (Zhang et al., 2016). Calcination uses high-temperature oxidation to remove carbonaceous deposits. Regeneration with hydrogen is the reduction of oxidized metal species and removal of coke. Solvent washing is the removal of soluble impurities from the catalyst surface.

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Developing robust and efficient catalyst with enhanced resistance to deactivation and efficient regeneration strategies is crucial for the commercialization of biofuel production processes (Zhang et al., 2016). Understanding the specific deactivation mechanisms in a given reaction system is crucial for developing effective regeneration strategies.

Table 8 Catalyst Deactivation Mechanisms, Their Effects and Regeneration Techniques

Deactivation Mechanism	Regeneration Technique	Effect on Catalyst Performance
Coking	Calcination, regeneration with hydrogen	Reduced active surface area, mass transfer limitations
Sintering	Redispersion of metal particles, catalyst reconstruction	Decreased metal dispersion, loss of active sites
Poisoning	Solvent washing, oxidative treatment	Blocked active sites, reduced selectivity
Phase transformations	catalyst reconstruction	Loss of active phase, altered catalytic properties
Mechanical failure (degradation)	Catalyst reconstruction	Loss of catalyst material, reduced catalyst volume

3.4. Catalyst Regeneration Techniques

Catalyst regeneration aims to restore catalytic activity by removing or reversing the deactivation causes. Various regeneration techniques have been developed to restore catalyst activity and extend catalyst lifetime. The choice of regeneration method depends on the type of deactivation, catalyst composition, and process conditions. Various techniques can be employed including calcination, reduction, washing, redox treatment, steam reforming, Plasma-assisted regeneration and re-dispersion (Zhang et al., 2020). Calcination uses high-temperature oxidation to remove carbonaceous deposits (Zhang et al., 2020). However, it can lead to sintering and loss of active components (Wang et al., 2018). In reduction or regeneration with hydrogen, reducing agents, such as hydrogen or synthesis gas, can be used to remove coke and restore metal crystallinity (active sites) (Chen et al., 2018). This method is often effective for metal-based catalysts (Chen et al., 2011).

In solvent washing, organic solvents can be used to dissolve and remove soluble deposits (impurities and weakly adsorbed species) from the catalyst surface (Liu et al., 2019). This method is suitable for removing organic compounds but may not be effective for inorganic poisons (Sabadie et al., 2012). Redox treatments combine oxidation and reduction steps for comprehensive catalyst regeneration (Wang et al., 2017). Re-dispersion is redistribution of metal particles to prevent sintering (Sabadie et al., 2012). Steam reforming method involves the reaction of steam with carbon deposits to produce hydrogen and carbon dioxide. It can be effective for removing coke while simultaneously regenerating the catalyst (Corma et al., 2007). Plasma-assisted regeneration uses plasma technology to enhance the removal of coke and other deposits, leading to improved catalyst regeneration efficiency (Wang et al., 2018). The comparison of catalyst regeneration techniques and their applications is presented in Table 16. The choice of regeneration technique depends on the type of deactivation, catalyst composition, and process conditions.

Table 9 Comparison of Catalyst Regeneration Techniques and Their Applications

Regeneration Technique	Applicable Deactivation Mechanisms	Advantages	Disadvantages
Calcination	Coking	Simple, effective	Can lead to sintering, environmental concerns
Regeneration with hydrogen	Coking, metal sintering	Effective for metal-based catalysts	Requires hydrogen supply, potential for safety hazards
Solvent washing	Poisoning, soluble deposits	Mild conditions, selective removal	May not be effective for strongly adsorbed species
Steam reforming	Coking	In-situ removal of coke, avoids catalyst handling	High energy consumption
Plasma treatment	Coking, sintering, poisoning	Effective for complex deactivation	High energy consumption, equipment costs

3.5. Catalyst Design for Improved Stability

To enhance catalyst stability and resistance to deactivation, several strategies can be adopted, such as support optimization, active phase modification, catalyst preparation methods and reactor design (Zhang et al., 2020; Zhao et al., 2021). Support optimization involves selection of supports with high thermal stability, mechanical strength, and resistance to coking. (Zhang et al., 2020). Active phase modification is the incorporation of promoters or co-catalysts to improve resistance to deactivation (Zhao et al., 2021). Catalyst preparation methods involves the development of preparation methods to enhance dispersion, particle size, and metal-support interaction (Zhang et al., 2020). Reactor design strategy involves the optimization of reactor conditions (temperature, pressure, flow rate) to minimize deactivation (Zhang et al., 2020). By combining these approaches, it is possible to develop more robust and long-lasting catalysts for biofuel production.

To enhance catalyst stability and extend catalyst lifetime, researchers have focused on developing novel catalyst materials and structures. These include core-shell catalysts, hierarchical porous materials and promoter addition (Liu et al., 2012). Core-shell catalysts encapsulate active components within a protective shell and can prevent deactivation by coke formation and poisoning (Liu et al., 2012). Hierarchical porous materials with hierarchical pore structures offer improved mass transfer and reduced coke formation (Corma et al., 2007). Promoter addition is the incorporation of promoters which can enhance catalyst stability and selectivity (Sabadie et al., 2012).

By combining advanced catalyst design strategies with effective regeneration techniques, it is possible to develop highly stable and long-lasting catalysts for biofuel production. The selection of regeneration technique depends on the type of catalyst, deactivation mechanism, and desired catalyst performance. In some cases, a combination of techniques may be required to achieve optimal regeneration.

In addition to regeneration, catalyst design and process optimization can help mitigate deactivation. For example, the use of catalyst supports with high thermal stability and resistance to coking can improve catalyst lifetime. Moreover, operating conditions such as temperature, pressure, and feedstock composition can be adjusted to minimize deactivation rates.

Recent studies have focused on developing novel regeneration methods, such as microwave-assisted regeneration and supercritical fluid extraction, to improve efficiency and reduce energy consumption. Additionally, the integration of catalyst deactivation and regeneration models into process simulations can aid in optimizing catalyst utilization and process performance.

3.6. Catalyst Performance Evaluation

Catalyst performance is a critical factor in determining the efficiency and economic viability of biofuel production processes. Several key parameters are used to evaluate catalyst performance. These parameters include catalytic activity, and catalyst Stability (Zhao et al., 2021).

Catalytic activity refers to the catalyst's ability to convert reactants into products at a specific rate. It is influenced by factors such as active site density, surface area, pore structure, and reaction conditions. Common metrics for evaluating catalytic activity include conversion, selectivity, turnover frequency (TOF) and reaction rate (Zhang et al., 2020). *Conversion* represents the percentage of reactants converted into products (Corma et al., 2007). *Selectivity* measures the ratio of the desired product to undesired byproducts (Sabadie et al., 2012). *Turnover frequency (TOF)* accounts for the number of reactant molecules converted per active site per unit time (Chen et al., 2011). *Reaction rate* is the expression for the rate at which reactants are consumed or products are formed (Sabadie et al., 2012).

Catalyst stability is crucial for maintaining consistent performance over time. It is influenced by factors such as deactivation mechanisms, operating conditions, and regeneration strategies. Key parameters for evaluating catalyst stability include *time-on-stream, (TOS), catalyst lifetime, and deactivation rate* (Zhang et al., 2020; Zhao et al., 2021). Time-on-stream (TOS) measures the duration of continuous catalyst operation without significant performance loss (Sabadie et al., 2012). Catalyst lifetime is the total operating time before complete deactivation (Corma et al., 2007). Deactivation rate represents the rate at which catalyst activity decreases over time (Chen et al., 2011).

Catalyst regeneration is essential for prolonging catalyst life and reducing production costs. Effective regeneration techniques restore catalyst activity by removing deactivating species. Key factors to consider include: Regeneration efficiency, Regeneration frequency, and Energy consumption (Zhang et al., 2020). *Regeneration efficiency* measures the extent to which catalyst activity is recovered after regeneration (Sabadie et al., 2012). *Regeneration frequency* represents the optimal interval between regeneration cycles (Corma et al., 2007). *Energy consumption* is the energy required for the regeneration process (Chen et al., 2011).

In addition to conventional regeneration methods, emerging technologies such as plasma-assisted regeneration and microwave-assisted regeneration are being explored to improve regeneration efficiency and reduce energy consumption (Li et al., 2018; Zhang et al., 2020).

Understanding the underlying mechanisms of catalyst deactivation is crucial for developing strategies to mitigate deactivation and prolong catalyst life. By combining advanced characterization techniques with kinetic modeling, it is possible to gain insights into the deactivation process and identify potential solutions (Chen et al., 2011).

3.7 Characterization Techniques

Characterization techniques are essential for understanding the properties of catalysts and biofuels. These techniques provide valuable information for optimizing process parameters, improving product quality, and developing new catalysts and fuels. These techniques further provide valuable information about the structure, composition, and performance of materials, enabling the optimization of production processes and the development of improved products.

Catalyst Characterization Techniques: Catalyst characterization aims to determine the physical, chemical, and structural properties of catalysts. This information is crucial for correlating catalyst structure with catalytic performance

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and for developing new and improved catalysts. Common characterization techniques (Table 10) include Surface area and pore size analysis, X-ray diffraction (XRD), Transmission electron microscopy, Scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS), Temperature-programmed desorption (TPD), Thermogravimetric analysis (TGA) and Inductively coupled plasma optical emission spectroscopy (Goldstein et al., 2017).

Surface area and pore size analysis: Techniques such as Brunauer-Emmett-Teller (BET) adsorption-desorption isotherms, Barrett-Joyner-Halenda (BJH) method, and mercury intrusion porosimetry are used to determine the surface area, pore volume, and pore size distribution of catalysts (Sing et al., 1985). *X-ray diffraction (XRD):* Provides information about the crystal structure, phase composition, and crystallite size of catalysts (Cullity & Stock, 2001). *Transmission electron microscopy (TEM):* Enables the visualization of catalyst morphology, particle size, and distribution at the nanoscale (Williams & Carter, 2009). *Scanning electron microscopy (SEM):* Provides information about the surface morphology and elemental composition of catalysts (Goldstein et al., 2017). *X-ray photoelectron spectroscopy (XPS):* Determines the elemental composition and chemical state of elements on the catalyst surface (Moulder et al., 1992). *Temperature-programmed desorption (TPD):* Measures the amount and strength of adsorbed species on the catalyst surface (Cunningham & Hill, 1993). *Thermogravimetric analysis (TGA):* Evaluates the thermal stability and decomposition behavior of catalysts (Brown, 2004). *Inductively coupled plasma optical emission spectroscopy (ICP-OES)***:** Determines the elemental composition of catalysts (Montaser & Golightly, 1992).

By combining these characterization techniques, a comprehensive understanding of catalyst and biofuel properties can be obtained, leading to improved process optimization and product development.

Table 10 Key Catalyst Characterization Techniques and Information Obtained

Technique	Information Obtained
BET, BJH	Surface area, pore volume, pore size distribution
XRD	Crystal structure, phase composition, crystallite size
TEM	Catalyst morphology, particle size, distribution
SEM	Surface morphology, elemental composition
XPS	Elemental composition, chemical state
TPD	Adsorbed species, adsorption strength
TGA	Thermal stability, decomposition behavior
ICP-OES	Elemental composition

Bioaviation fuel Characterization Techniques: Bioaviation fuel characterization (Table 11) is essential to ensure product quality, compliance with fuel standards, and understanding fuel performance. Various analytical techniques are employed to determine the physical, chemical, and combustion properties of bioaviation fuels. Some key techniques are density and viscosity, elemental analysis, gas chromatography (GC), high-performance liquid chromatography (HPLC), fourier transform infrared spectroscopy (FTIR), nuclear magnetic resonance (NMR), calorimetry, and engine testing.

Density and viscosity: Measured using standard methods to assess fuel flow and atomization properties (ASTM D4052, ASTM D445). *Elemental analysis:* Determines the carbon, hydrogen, nitrogen, and sulfur content of the fuel (ASTM D5291). *Gas chromatography (GC):* Used to identify and quantify hydrocarbon components in the fuel (ASTM D6730). *High-performance liquid chromatography (HPLC):* Analyzes oxygenated compounds and impurities in the fuel (ASTM D7344). *Fourier transform infrared spectroscopy (FTIR)***:** Provides information about functional groups present in the fuel (ASTM D6590). *Nuclear magnetic resonance (NMR)***:** Determines the structure and composition of fuel components (ASTM D7174). *Calorimetry:* Measures the heating value of the fuel (ASTM D4054). *Engine testing:* Evaluates fuel performance under real-world conditions (ASTM D6890).

By combining these characterization techniques, a comprehensive understanding of catalyst and bioaviation fuel properties can be obtained, leading to improved process optimization and product development.

Table 11 Key Bioaviation fuel Characterization Techniques and Information Obtained

Technique	Information Obtained
Density, viscosity	Fuel flow, atomization
Elemental analysis	Fuel composition
GC, HPLC	Hydrocarbon and oxygenate composition
FTIR, NMR	Fuel structure, functional groups
Calorimetry	Heating value
Engine testing	Fuel performance

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4. ENVIRONMENTAL AND ECONOMIC IMPACTS OF BIOREFINERY-BASED BIOFUEL PRODUCTION

The environmental impacts of biofuel production are complex and multifaceted, encompassing a range of factors that extend beyond greenhouse gas emissions. A comprehensive assessment should consider the entire life cycle of biofuel production, from feedstock cultivation to end-use. Key environmental concerns include land use change**,** water consumption, fertilizer and pesticide use, greenhouse gas emissions, air and water pollution, and waste management**.**

The conversion of natural ecosystems into agricultural land for biofuel feedstock cultivation can lead to deforestation, biodiversity loss, and soil erosion (Fargione et al., 2008). Biofuel production, particularly for irrigated crops, can have significant water consumption impacts, potentially leading to water scarcity and competition with other water users (Hoekstra & Chapagain, 2008). Intensive agricultural practices associated with biofuel feedstock production can contribute to water pollution, air pollution, and human health risks (Tilman et al., 2009). While biofuels have the potential to reduce greenhouse gas emissions compared to fossil fuels, the overall impact depends on the feedstock, production process, and land use change (Searchinger et al., 2008).

Biofuel production and processing can lead to emissions of air pollutants, such as particulate matter and volatile organic compounds, as well as water pollution from wastewater discharges (Hill et al., 2006). The proper management of biofuel production residues is essential to prevent environmental impacts. Improper disposal can lead to soil and water pollution (Demirbaş, 2009).

Life cycle assessment (LCA) is a valuable tool for evaluating the overall environmental performance of biofuels, considering all stages of the production process. By comparing different biofuel production pathways and feedstocks, LCA can help identify opportunities for improvement and mitigation of environmental impacts (Azapagic et al., 2003).

5. ECONOMIC FEASIBILITY OF BIOREFINERY-BASED BIOFUEL PRODUCTION

The economic feasibility of biofuel production is influenced by various factors, including feedstock costs, production technology, energy inputs, and government policies. Key economic considerations include feedstock costs, production costs, product price, government policies**,** and economic viability (Demirbaş, 2009).

The price and availability of feedstocks significantly impact biofuel production costs. The use of low-cost and abundant feedstocks, such as agricultural residues and waste products, can improve economic viability (Demirbaş, 2009).

The capital and operating costs associated with biofuel production facilities, including equipment, labor, and energy, determine the overall production cost (Hill et al., 2006). The market price of biofuels, influenced by factors such as supply and demand, government subsidies, and competing fuels, determines the profitability of biofuel production (Searchinger et al., 2008).

Policies such as subsidies, tax incentives, and mandates can significantly impact the economic feasibility of biofuel production by creating a favorable market environment (Fargione et al., 2008).

The comparison of biofuel production costs with the revenue generated from biofuel sales determines the overall economic viability of the process (Hill et al., 2006).

Economic analysis tools, such as cost-benefit analysis and life cycle costing, can be used to assess the economic performance of biorefinery-based biofuel production systems. By comparing different biofuel production pathways and feedstocks, it is possible to identify the most economically viable options.

CONCLUSION

The production of Sustainable Aviation Fuel (SBAF) within integrated biorefineries presents a promising pathway towards decarbonizing the aviation sector. However, significant challenges remain, including high production costs, limited feedstock availability, and the need for efficient and stable catalytic processes. This study highlights the critical role of catalysis in overcoming these challenges. Advancements in catalyst design, including the development of novel materials, such as bifunctional catalysts, MOFs, and hierarchical structures, are essential for improving catalytic activity, selectivity, and stability. Furthermore, a comprehensive understanding of catalyst deactivation mechanisms and the development of effective regeneration strategies are crucial for ensuring long-term catalyst performance and economic viability. Continued research and development efforts are necessary to address the remaining challenges, such as optimizing feedstock utilization, improving process efficiency, and reducing production costs. By integrating advanced catalytic technologies with innovative biorefinery concepts, it is possible to produce SBAF in a sustainable and economically viable manner, contributing to a more sustainable and environmentally friendly aviation sector.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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