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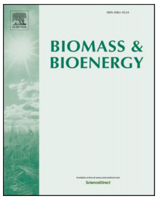

Emerging technologies, policies and challenges toward implementing sustainable aviation fuel (SAF)

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ABSTRACT

As the regulations related to greenhouse gases (GHG) emissions from fuel become stricter, fundamental changes are being effectuated to achieve the Paris Agreement agenda. Since the aviation sector contributes to 2.5 % of the global CO_2 emission, it is imperative to tackle this conundrum imminently by reducing the CO_2 emission from commercial flights, which are the main contributors to CO_2 emission in the aviation sector. Sustainable aviation fuel (SAF) has garnered tremendous attention in achieving carbon neutrality in the aviation sector. SAF is a suitable alternative since little to no modification of the aircraft is required for SAF usage. There are many challenges when it comes to implementing the use of SAF, including the large-scale production of SAF and the cost associated with the production of SAF. Therefore, this paper aims to provide an overview of various factors related to the global implementation of SAF, considering the latest supporting policy frameworks and from the perspective of feedstock. It examines how existing SAF pathways contribute to large-scale production and explores the role of emerging technologies—from potential feedstocks to the latest advancements. The paper delves into several emerging technologies, including hydrothermal liquefaction, aqueous phase reforming, pyrolysis, and photofermentation, discussing their potential in SAF production and the challenges they present. Furthermore, this paper analyses the life cycle assessment (LCA) and the techno-economic analysis (TEA) of different feedstocks and processes for SAF production.

List of Abbreviations	
ATJ	alcohol to jet
ATJ-WG	alcohol-to-Jet with wheat grain
ATJ-WS	alcohol-to-Jet with wheat straw
ASTM	American Society for Testing Materials
APR	aqueous phase reforming
BtL	biomass-to-liquid
BTC	blender's tax credit
CAPEX	capital expenditure
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CH	catalytic hydrothermolysis
CEPCI	chemical engineering plant cost index
CFS	clean fuels standard
COE	cost of equipment
DCO	decarboxylation
DOE	Department of Energy
DME	dimethyl ether
DAC	direct air capture
DGCEM	dry grind corn methanol mills
EISA	Energy Independence and Security Act
EU ETS	European Union Emissions Trading System
FOG	fats, oils and greases
FT	fischer-tropsch
FT-SPK/A	fischer-tropsch synthetic paraffinic kerosene with aromatics
FCI	fixed capital investment
FCC	fluid catalytic crackers
FFA	free fatty acid
GWP	global warming potential
GHG	greenhouse gases
GDP	gross domestic product
HTFT	high temperature Fischer-Tropsch
HDO	hydrodeoxygenation

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List of Abbreviations	
HEFA	hydroprocessed ester and fatty acids
HFS–SIP	hydroprocessing of fermented sugars-synthetic iso-paraffinic kerosene
HTL	hydrothermal liquefaction
ISED	Innovation, Science and Economic Development department
IPCC	Intergovernmental Panel on Clumate Change
IATA	International Air Transport Association
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ISCC	International Sustainability and Carbon Certification
ITC	investment tax credit
JO	jatropha oil
LCA	life cycle analysis
LCFS	low carbon fuel standard
LTFT	low temperature Fischer-Tropsch
MLPs	master limited partnerships
MFSP	minimum fuel selling price
NPV	net present value
NZA	net zero accelerator
OPEX	operating expenditure
PO	palm oil
ppmV	part per million by volume
PM	particulate matter
PtL	power-to-liquids
RED	renewable energy directive
RFS2	renewable fuel standard 2
RDD&D	research, development, demonstration and deployment
RWGS	reverse water gas shift
RSB	Roundtable on Sustainable Biomaterials
SAK	synthesised aromatic kerosene
SFC MIT	Smart Freight Center and Massachusetts Institute of Technology
S-IP	Stable-Isotope Probing
SIF	Strategic Innovation Fund
SAF	sustainable aviation fuel
SIP	synthesised iso-paraffinic
SPK	synthetic paraffinic kerosene
TOFA	tall oil fatty acid
TEA	techno-economic analysis
TAG	triacylglycerol
USDA	United States Department of Agriculture
UCOs	used cooking oils
WAFS	waste animal fats

1. Introduction

As outlined in the Paris Agreement, leaders worldwide have emphasised the importance of restricting the rise in global temperatures to 1.5 °C by the end of the current century. Achieving this goal requires the peak of greenhouse gases (GHG) emissions by no later than 2025 and a subsequent reduction of 43 % by the year 2030 [1]. The aviation industry contributes approximately USD 3.5 trillion to the economy worldwide, equivalent to 4.1 % of the gross domestic product (GDP), this accounts for approximately 2.5 % of the global CO_2 emission [1]. Globally, the demand for air transport is estimated to increase by 4.5 % annually [2]. Other than creating employment opportunities, aviation drives various sectors, such as global trade and tourism. In addition, air transport allows access to educational opportunities, cultural exchange, and rapid disaster response [1]. Despite aviation's substantial economic and social benefits, this industry accounts for 5 % of the global GHG from anthropogenic activities [2]. Decarbonisation of the aviation industry may be challenging due to the dependence of aircraft on high-energy-density liquid hydrocarbons [3]. Additionally, two primary concerns associated with the aviation industry are fuel price fluctuation and air traffic growth [4]. Therefore, there is a dire need for this industry to devise a solution to fulfil its increasing fuel demand whilst minimising its environmental, economic and social impacts [5]. In line with the International Air Transport Association's (IATA) goal of reducing carbon dioxide emissions by 50 % in 2050 from the level in 2005 [6], SAF is thus a possible alternative to power aircraft and reduce reliance on Jet A1 aviation fuel (i.e. conventional fossil-based jet fuel).

SAF can be defined as 'drop-in' replacements for jet fuel from synthetic fuel or biofuel that meet the sustainability criteria [7]. The term 'drop-in' means that the synthetic fuel or biofuel does not require significant modification to the existing aircraft and fuelling infrastructure to function [7]. There are several sustainability criteria for fuel to be considered SAF: (1) it has to contribute to reducing net GHG emissions and carbon footprint emissions throughout the life cycle [7,8], (2) the need for freshwater should be limited during the SAF production process, and (3) it must not require deforestation and should not compete with food production and land for cultivation [8].

Even though the composition of drop-in fuels is similar to conventional fuels, drop-in fuels must be blended with conventional fuels to achieve the desired performance. Previous studies established that the aromatics content in the fuel is an indicator of particulate matter (PM) emissions when burned, whereby a lower aromatics concentration would lead to lower PM emissions [9]. However, aromatics content is a primary factor in engine compatibility; hence, alternative fuels are always blended with commercial fuels [9]. The 'drop-in' fuels should share properties and standards similar to petroleum gasoline, diesel or jet fuel [5]. The feedstock of the production will determine the composition of the 'drop-in' fuels. The 'drop-in' fuels must undergo the evaluation process specified in ASTM D4054 to ascertain their equivalence to conventional jet fuel. Once this process is completed, the newly approved 'drop-in' fuel is added to ASTM D7566, thereby authorising it to be blended into the existing engines and fuels that meet the American Society for Testing Materials (ASTM) standard: ASTM D1655, widely applied as a standard for jet fuel [5]. The ASTM standard has also set the composition, volatility, fluidity, density and other properties of jet fuel (Table 1).

There are several certified routes for SAF production, such as Fischer-Tropsch (FT), hydroprocessed esters and fatty acids (HEFA), synthesised iso-paraffinic (SIP) and Alcohol to Jet (ATJ) that will be discussed under **Section 4**. However, information on the detailed SAF production processes needs to be provided since extensive research has been undertaken on the SAF production routes. Given the variability of feedstocks and other contributing factors, the best universal route for producing SAF approved by ASTM certification cannot be determined. For example, HEFA is the most economical route for SAF production, but it has a slightly higher GHG emission than the other certified routes [10]. All production routes have their respective strengths and weaknesses and will be discussed further in this review.

The literature search on the Scopus database was carried out using the keywords 'sustainable aviation fuel' in the title, abstract, and keywords gave back 1304 documents, whereby 55 % were articles, 23 % were conference papers, and 10 % were review papers. Fig. 1 shows the

Table 1
ASTM D1655 Standard for conventional aviation fuel [10].

	Component	Range of value
Composition	*n*-alkanes	26-13 wt%
	Iso-alkanes	37-19 wt%
	Monocyclic alkanes	19-30 wt%
	Bicyclic alkanes	3-17 wt%
	Sulphur	0.30 wt% (max)
	Aromatics	25 vol% (max)
Properties	Hydrogen to carbon ratio (H/C)	2.01–1.90
	Specific energy (MJ kg^{-1})	43.2–42.9
	Density @ 15 °C (kg m^{-3})	775.0–840.0
	Energy density (MJ L^{-1})	33.7–35.5
	Net heat of combustion	42.8
	Average molecular weight (g mol^{-1})	152–166
	Viscosity (cSt)	3.5–6.5
	Flashpoint (°C)	42-60 (Min. 38)
	Freezing point (°C)	−47

Table 2
Comparisons of different aviation fuels.

Fuel Types	Advantages	Disadvantages	References
SAF	• Produced from sustainable feedstocks and helps reduce the emission of GHG and air pollutants. • Reduces reliance on fossil fuels. • Has similar functions and characteristics as the Jet A1, thus requiring minimum alteration to the existing system and infrastructure of the aircraft. • Has an equivalent energy density, which is an order of magnitude higher than hydrogen. • Minimises direct and indirect land usage and lifecycle emissions.	• Has relatively low-price competitiveness. The price of bio-based aviation fuel ranges from €950 tonne^{-1} to €1015 tonne^{-1}, whereas that of Jet A1 is €600 tonne^{-1}. • Reliance on first-generation feedstock conflicts with food security, limiting availability and necessitating conversion of significant land areas for reforestation and bioenergy crop cultivation. • Ineffective long-term solution due to high dependence on biomass resources.	[4,5,11]
Jet A1	• Has an energy density that is an order of magnitude higher than hydrogen. • Requires low operational cost.	• Produced from non-renewable energy sources, particularly fossil fuels. • Causes high emissions of GHG and contributes significantly to adverse environmental impacts, such as global warming and climate change.	[1,4,5]
Hydrogen fuel	• Can be produced from diverse sources, such as biomass wastes, industrial effluents and water. • Has energy density per unit volume that is an order of magnitude lower than Jet A1 and SAF. • Helps reduce the direct emissions of pollutants.	• Contributes to global warming due to the emission of water vapour. • Requires high production costs and significant adjustments to the architecture of the aircraft to incorporate the fuel cells.	[1,5]

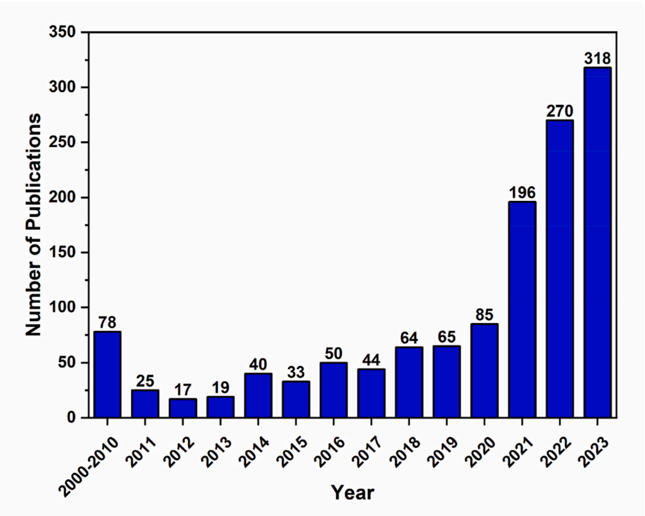

Fig. 1. The total annual numbers of publications on SAF between 2000 and 2023.

bar chart of the number of publications annually between 2000 and 2023. The total number of publications from 2018 to 2023 is approximately 2.67 times that from 2000 to 2017, which indicates the rapid increase in the interest and significance of SAF technologies. There have been 174 documents published so far in 2024, but only 16 of them are review papers. Among these review papers, none address the emerging SAF pathways comprehensively, covering the latest policies, SAF production, fuel blending, TEA and LCA analysis, and ASTM standards. Table 3 summarises the scopes of the existing review papers on SAF, including that of this review paper, to show the differences. Unlike the other papers, this review paper seeks to provide a comprehensive overview of various feedstocks and their suitability in SAF production, ASTM-certified technologies, emerging routes for SAF production, different fuel blends, government policies and participation of private sector and organisations that support SAF implementation. Additionally, this paper analyses the potential scale-up of several technologies along with the Techno-Economic Analysis (TEA) and Life Cycle Analysis (LCA) of several SAF production routes. After an in-depth review, the most suitable feedstock, effective production route and blend are presented.

2. Prospective policies and Synchronised approaches for the wide scale implementation of SAF

To ensure the development and distribution of SAF, several restrictions have to be addressed. If the production cost of SAF is higher than that of fossil kerosene inclusive of the advanced production infrastructure and availability of feedstock then SAF production and

Table 3
Overview of the review papers on SAF.

Year	Main contents	References
–	Reviewed various feedstock from different generation fuels, ASTM-certified processes, fuel blends, as well as emerging and potential technologies for SAF production. Explored the different policies introduced associated with SAF growth. Analysed the results of the Techno-Economic Analysis (TEA) and Life Cycle Analysis (LCA) related to the feedstocks and processes for SAF production.	Current study
2023	Discussed the emerging technologies that could help achieve greener aviation by reviewing the operational concepts, energy storage, materials, structures and manufacturing processes.	[5]
2022	Reviewed the advancement of the production pathways of aviation fuels and discussed the factors, which influence the waste plastics catalytic pyrolysis as well as the technological viability of this process.	[12]
2022	Focused on hydrogen production from microalgae, including the pre-treatment stage, to increase the production rate.	[13]
2022	Discussed the commercialisation of the converted pennycress as a feedstock to produce renewable diesel and SAF.	[14]
2022	Discussed the production processes, potential and challenges related to the logistics and the technology readiness of alternative fuels.	[15]
2021	Reviewed the simulation works and models developed for the synthesis and supply chain problem-solving. Suggested possible alternatives to improve the current methods by considering the approaches adopted by different industries.	[16]
2019	Reviewed the conversion technology, environmental impact, economic evaluation, current status of the SAF, and the opportunities and barriers encountered by the aviation industry. Provided suggestions related to policy to enhance fuel development.	[17]
2018	Explored the potential of Power-to-Liquids (PtL) as a renewable fuel that may be scaled up to replace fossil fuels in civil aviation by discussing the processes and technologies related to PtL. Reviewed the environmental and economic aspects of PtL.	[18]
2018	Reviewed the scientific and technological advancement in SAF production and possible pathways that could enhance the sustainability of the aviation fuel supply chain.	[19]

consumption will not be promoted. Therefore, policy interventions have to be implemented to advance SAF production. Policy options can be put in place to address the economic barriers associated with SAF. There are three fundamental aspects that denote the effectiveness of a policy, these are (i) practicability whereby the outcome of the policy is targeted rather the ideas or theories, (ii) feasibility where the policy can be easily implemented and (iii) effectiveness where the desired results are successfully achieved [20].

Establishing enduring and reliable policies is crucial to establishing a stable market for SAF. The most effective policies for SAF development are likely to differ from one country to another, influenced by their specific combination of geography, politics, natural resources and socio-economic factors. The SAF supply can be encouraged by these policy approaches, such as through research and development, investment, and financial incentives. They can also create demand for SAF through mandates, subsidies and commitments while facilitating the SAF marketplace through standards [21]. The International Civil Aviation Organisation (ICAO) outlined policy categories that aim to enhance the capacity and supply of SAF feedstock and fuel production, as shown in Table 4. This will be achieved through initiatives such as research and development (R&D), investments, production incentives, and favourable tax treatments [21]. The SAF policy outlined by ICAO primarily comprises three key phases. Firstly, it aims to boost SAF production by providing financial support to enhance technology readiness and offering tax exemptions and incentives to mitigate investment risks and encourage stakeholder involvement. Secondly, it focuses on creating demand for SAF by integrating it into the current aviation industry. Governments are pivotal in this phase, establishing mandates to incorporate SAF and reduce reliance on conventional fossil aviation fuel. They demonstrate leadership by setting ambitious carbon reduction goals through SAF utilisation and promoting its use in government and military transportation. The third phase involves the government acting as a facilitator by certifying SAF production, supporting the development or recognition of systems, and providing essential information and feedback to policymakers.

Several policies have been introduced to promote the growth of SAF due to the challenges for SAF deployment on a large scale. Table 5 provides an overview of these policies. Over the years, there has been a notable increase in collaboration between various countries and aviation stakeholders in the promotion and adoption of SAF. This collaboration involves countries or regions focusing on manufacturing SAF, while aviation services are adopting the use of SAF in their planes. The growing interest in SAF has led many countries and industry players to introduce policies aimed at encouraging the use of SAF in the aviation sector. These policies include constructing SAF production plants, imparting incentives, and blending SAF into existing fuel, among others. The primary purposes of these policies are to address climate change, reduce GHG emissions and foster sustainability in the aviation industry. One of the policy examples of the construction of an SAF production plant was the Qatar University Biofuels Project, which aimed to build a plant that could produce 1.5 million litres of SAF in 2010. Besides that, an incentive-based policy was also implemented in the United Kingdom, where benefits will be provided to individuals who produce SAF [22]. Furthermore, the Fossil-free Sweden industry initiative intended to attain a 30 % SAF blend ratio is one of the efforts of blending SAF to current fuel. France uses SAF to meet the demand for jet fuel using a 5 % blend. Global Bioenergies, Indian Airlines, Total Energies, Virgin and Boeing have recently established similar policies to promote SAF from 2022 to 2023. The Council of the European Union adopted a new law in 2021 called the RefuelEU Aviation Initiative, to kick-start the large-scale production of SAF. Starting in 2025, fuel suppliers must ensure that the fuel used by all aircraft operators at EU airports contains a minimum of 2 % SAF. This percentage will increase annually, aiming for 63 % SAF usage by 2050.

Table 4
Available SAF Policy Selection stipulated by the ICAO [21].

Strategy	Initiative	Policy Framework	Description
Promoting the supply of SAF	1 - Providing funds for SAF research, development, demonstration and deployment (RDD&D) to expedite knowledge advancement	1.1 Government-funded R&D	Government-supported research and financial aid targeted at addressing challenges in the production and utilisation of SAF can accelerate the progress of initial-stage innovations in SAF production. Moreover, this assistance plays a role in enhancing the economic feasibility of SAF by expediting the learning process related to enhancing feedstock yields and optimising production methods. Such support may manifest through specialised programs for ongoing private research endeavours, or partnerships with universities and comparable institutions.
		1.2 Demonstrations and Deployments led by the Government	Government-supported research and funding can provide support during entity engagement by demonstrating and mitigating risks linked to novel feedstock and production technologies. This aid empowers them to expand and incorporate the existing production methods. Such assistance boosts the advancement process associated with scaling up technology and supply chains. This support can be implemented through the creation of specialised programs tailored to assist the existing producers in private sectors.
	2 - Specific Incentives and tax benefits for the expansion of SAF Supply Infrastructure	2.1 Financial grants	A fund allocated by the government to an organisation for the development or acquisition of infrastructure

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Table 4 (*continued*)

Strategy	Initiative	Policy Framework	Description
			specifically designed for SAF can provide support in multiple areas, including production facilities, transportation, refuelling or blending infrastructure. Capital grants aim to reduce the financial demands and risks associated with the designated capital.
		2.2 Loan guarantee programs	A government-supported overdraft enhances the financial viability of the project, concurrently diminishing the overall project risk. This, in turn, simplifies the acquisition of additional equity or debt, ultimately leading to a reduction in the cost of capital.
		2.3 Entitlement of SAF projects to tax-advantaged business status	Master limited partnerships (MLPs) represent a specialised form of organisation structure in the United States, primarily utilised in industries like real estate and natural resources, such as oil production. Unlike other types of corporate entities, MLPs are not subject to federal income taxes.
		2.4 Accelerated depreciation/ 'bonus' depreciation	Accelerated depreciation is a way of accounting where the deduction of capital investment is faster, allowing the possibility of deducting an amount greater than the actual capital investment. This results in a decrease in the projected tax payments over the project's duration, ultimately improving the overall economic feasibility of the project.
		2.5 Investment Tax Credit (ITC) for SAF-related Investments	ITC provides the opportunity to deduct the cost of construction and any commissioning expenses associated with a qualifying asset, thereby reducing the income tax liability and passing on benefits to investors. This leads to a decrease in the anticipated tax payments throughout the project's lifespan, enhancing the overall economic feasibility of the project.
		2.6 Tax Credit Based on Performance	The concept introduces a tax credit for projects that meet defined criteria. This credit may be structured as a performance-based sliding scale, with projects showcasing superior performance in GHG emissions receiving a higher credit. Furthermore, a designated policy duration, typically spanning from 10 to 15 years, should be established.
		2.7 Bonds/Green Bonds	Private corporations, supranational organisations, and governmental bodies, including regional and local governments, can issue bonds to secure financing at favourable interest rates and with tax exemptions for the facility construction for fuel production. In contrast, Green Bonds are tailored specifically to finance projects associated with climate or the environment.
	3 - Specific Incentives and Tax Benefits to Support the operation of SAF Facilities	3.1 Incentives for Blending: Tax Credit for Blenders	An incentive aimed at fuel providers or blenders, providing a tax credit to mitigate the cost difference between producing or purchasing SAF and traditional fossil jet fuel.
		3.2 Incentives for Production: Tax Credit for Producers	An incentive aimed at fuel producers, offering a tax credit to alleviate the cost

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Table 4 (*continued*)

Strategy	Initiative	Policy Framework	Description
			disparity in SAF production compared to traditional aviation fuel.
		3.3 Tax Credit on Excise for SAF	In regions where taxes are levied on the consumption of commercial aviation fuel, a tax reduction or tax write-off proportional to the amount of SAF utilised acts as an incentive for fuel consumers. This helps lower the overall cost of SAF, promoting its procurement.
		3.4 Assistance for establishing and producing Feedstock Supply	Focused assistance has the potential to ease the difficulties and expenses faced by farmers and suppliers of raw materials when introducing a new crop and cultivating it amid uncertain circumstances. Additionally, exploring support through crop insurance programs for SAF and providing subsidies to farmers to stimulate production is a viable consideration.
	4 - Acknowledgment and enhancement of environmental benefits of SAF	4.1 Acknowledge the advantages of SAF in carbon taxation	In places where there is a carbon tax or levy based on emissions, aiming to encourage reduced emissions, SAF might get classified with either no tax or a tax proportionate to the emissions benefits it offers. This means SAF users would pay less in taxes. This approach is different from a cap-and-trade system, because there is no specific target determined to reduce emissions.
		4.2 Acknowledge the advantages of SAF in cap-and-trade systems	Cap-and-trade systems set a limit on total GHG emissions. Those who emit less can sell their extra allowances to those emitting more. This creates a market for emission permits, establishing a price for emissions and valuing emission reductions. SAF was included, SAF users would not have to meet certain regulatory requirements in this system.
		4.3 Acknowledge the non-carbon benefits of SAF: enhancements to air quality	There are initiatives that give a monetary value to making the air cleaner locally. SAFs should be eligible to join the related incentive programs because of the air quality improvements that certain SAFs can bring.
		4.4 Acknowledge the non-carbon Benefits of SAF: decrease in contrails	As scientific knowledge advances, the potential environmental benefits of using SAF, such as reduced formation of condensation trails (contrails), may become acknowledged.
Creating Demand for SAF	5 - Creation of SAF mandates	5.1 Establish requirements for the volume of renewable energy in the fuel supply	Requiring fuel sellers to gradually include more SAF in the current fuel supply over several years provides promotion for producing more SAF and green fuels that fulfil the green energy standards in the program. These standards could involve criteria like life-cycle GHG emissions.
		5.2 Require to decrease the carbon intensity of the fuel supply	Requiring fuel sellers to gradually reduce the carbon footprint (which refers to the emissions throughout the life cycle) of transportation fuels over time underscores the significance of SAF production. Established standards further highlight the commitment to reducing the carbon footprint within the state's fuel supply.
	6 - Update existing policies to incorporate SAF	6.1 Integrating SAF into current national policies	Adjustment of national policies is necessary to incorporate SAF. Historically, national policies

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Table 4 (*continued*)

Strategy	Initiative	Policy Framework	Description
			regarding biofuel have neglected SAF and mainly concentrated on fuels for road transport. However, with the recent development of technologies allowing the production of drop-in jet fuel/SAF, there is a chance to update current policies to promote and back the production of SAF.
		6.2 Integrating SAF into current subnational, regional or local policies	Existing incentive policies for alternative fuels at sub-national, regional or local levels could be adjusted to recognise SAF as a valid fuel type. Modifying these existing policies can stimulate SAF production, while simultaneously offering extra support and potentially creating a synergistic blend of incentives at different levels, thereby enhancing the economic feasibility of SAF.
	7 - Showcase leadership by the government	7.1 Establishing direction through policy statements	Setting ambitious goals for specific amounts of production or use indicates the intention to create comprehensive policies for SAF in the future. This alignment with future policies indicates how projects should be planned. Examples could include state-level commitments, like a defined goal for SAF usage or carbon reduction within a specific timeframe, or industry indications, such as a dedication to attaining zero net emissions by the year 2050.
		7.2 Government commitment to SAF use, carbon-neutral air travel	Encouraging a strong demand for SAF includes requiring national, state, and local governments, as well as the military, to use renewable fuels. Governments, especially those with good credit ratings, can commit to long-term contracts, reducing risks for projects. They can either get SAF for their planes or collaborate with commercial airlines to supply SAF for government travel.
Facilitating SAF Markets	8 - Initiatives to facilitate market growth	8.1 Certifying the supply of raw materials and the production of fuel by well-defined and widely accepted sustainability standards, along with methods to measure GHG emissions throughout the life cycle.	Adhering to clear rules and using consistent approaches to calculate GHG emissions throughout the life cycle and obtain sustainability certification will help SAF markets grow and ensure that SAF is environmentally credible.
		8.2 Support development/recognition of systems for environmental attribute ownership and transfer	Established procedures and collaborative administrations for accrediting, and certifying positive impacts on the environment of SAF could make the process of getting SAF through "book and claim" easier. This approach separates where the fuel is physically from its environmental benefits, aiming to make SAF more efficient and widely used, contributing to reduced GHG emissions
		8.3 Backing initiatives led by SAF Stakeholders	Groups for discussion that include stakeholders can be arranged by the government, industry, or non-governmental organisations (NGOs). These groups are vital for bringing together the different parties involved in the SAF supply chain. They are essential for directly coordinating efforts and providing crucial information and feedback to policymakers.

Table 5
Summary of SAF policies introduced in different countries.

Policy	Regulating body	Year	Objective	Target Year	References
Energy Independence and Security Act (EISA)	United States Congress	2007	To create biofuels from cellulosic materials that would produce 16 billion gallons of ethanol (equivalent to 9.8 billion gallons of jet fuel).	2022	[23]
–	IATA	2009	To reduce the total emissions of the aviation industry by 50 % by the year 2050, in comparison to the levels recorded in 2005.	2050	[24]
Farm to Fly	United States Department of Agriculture, Boeing and Airlines	2010	To manufacture one billion gallons of aviation biofuels that can be used as a direct replacement for conventional fuels every year.	2018	[25]
Qatar University Biofuels Project	Qatar Airways, Qatar University, and Qatar Science and Technology Park	2010	To generate one barrel of SAF per day and to construct a pre-commercial pilot plant, which can produce 1.5 million litres of SAF.	–	[26]
Renewable Fuel Standard 2 (RFS2)	United States Environmental Protection Agency	2011	To implement a credit trading mechanism that would make it compulsory for petroleum fuel importers and producers to use renewable fuels as part of their operations.	2020	[27]
European Advanced Biofuels Flightpath	European Union (EU)	2011	To manufacture two million tonnes of SAF annually.	2020	[28]
Emission Trading Scheme (Directive) 2008/101/EC	European Union (EU)	2012	To implement a carbon emission fee for all flights that arrive within the European Union region.	–	[29]
Indonesia's National Action plan	Indonesian Aviation Biofuels and Renewable Energy Task Force	2013	The target is to blend renewable fuels at a rate of 2 % in 2016, 3 % by 2020, and 5 % by 2025.	2016, 2020, and 2025	[26,30]
Archipelagic Carbon Scheme	Indonesia	2013	To establish a carbon credit system to validate any decrease in GHG emissions. Each unit of credit would signify a reduction of 1.1 tons of carbon dioxide. The carbon credits would be transferable among registered users.	–	[31]
Initiatives for Next-generation Aviation Fuels	Japan	2014	To create a system enabling Japan's SAF production and distribution.	2020	[26]
Advanced Drop-in Biofuels Production Project	United States Department of Agriculture, Department of Energy and United States Navy	2014	To manufacture 100 million gallons of eco-friendly marine diesel and SAF for the military at a cost that is less than $4 per gallon. These fuels are expected to have 50 % lower emissions than traditional fuels.	–	[32]
–	Japan Ministry	2015	To use SAF for the flights operated during the Tokyo Olympic and Paralympic Games.	2020	[26]
Low Carbon Fuel Standard policy	California Air Resources Board	2018	To create a financial incentive utilising a credit trading mechanism, which would be earned by producing clean fuels.	–	[33]
Renewable Transport Fuel Obligation	United Kingdom	2018	To reward or benefit those who produce SAF.	–	[33]
Carbon Offsetting and Reduction Scheme for International Aviation	International	2018	To achieve carbon-neutral growth starting from 2020 by reducing GHG emissions in the aviation industry on a global scale. This effort is projected to address around 80 % of the anticipated carbon dioxide (CO_2) increase between 2021 and 2035.	2035	[33]
Brazilian National Biofuel Policy	Brazil	2019	To lower carbon intensity by promoting the process of decarbonisation across all types of fuels and establishing a market for carbon credits.	–	[34]
Roadmap for carbon neutrality 2050	Portugal	2019	To achieve the elimination of carbon emissions in the aviation industry.	2050	[33]
–	Between Malaysian Palm Oil Board and China Chamber of Commerce Foodstuffs and Native Producers	2019	To establish a SAF plant, which would require an investment of $480 million from China.	–	[31]
–	Netherlands	2019	To create the initial SAF plant, named SkyNRG, in the Netherlands.	2022	[35]
–	Malaysia	2020	To produce high-value products derived from palm oil, such as SAF, with an approximate budget of $6.8 million.	–	[31]
Climate change law	Spain	2020	To provide SAF to satisfy 2 % of the total demand for jet fuel.	2025	[35]
Climate change law	France	2020	To provide SAF to satisfy 5 % of the total demand for jet fuel.	2030	[35]
Fossil-free Sweden industry initiative	Sweden	2020	To attain a blend ratio of 30 % for SAF.	2030	[35]
Sustainable Aviation Fuel Act	United States Whitehouse	2021	To introduce a tax credit for SAF, ranging from $1.50 to $1.75 per gallon, based on the reduction in GHG emissions achieved by the SAF.	–	[36]
ReFuelEU Aviation initiative	European Union	2021	To reach a usage rate of 2 % for SAF in 2025 and increase it to as much as 63 % by 2050.	2050	[37]
–	Global Bioenergies	2022	To build a plant that can produce 30,000 tons of SAF.	2027	[38]
–	Indian Airlines	2022	To start blending 1 % of SAF into regular fuel.	–	[38]
–	Total Energies	2023	To produce 150,000 tonnes of SAF per year by 2030 and 10 % of the world SAF market.	2030	[38]
–	Virgin and Boeing	2023	To support the development of the local, SAF industry to achieve net zero by 2050.	–	[38]

3. Feedstocks for SAF production

The selection of feedstock plays a crucial role in determining the distinct category of aviation fuel based on its origin and characteristics, particularly in the context of SAF [39]. There are some fundamental attributes that potential SAF feedstocks are required to have:

The feedstock should have a high SAF yield and should be [40,41].

(i) Feedstock availability
(ii) Does not compete with food production
(iii) Cost-effective
(iv) Low environmental footprint

The first requirement for SAF feedstock is its availability, as about 95 % of global biodiesel production relies on edible oils, which are readily sourced from local large-scale agriculture [40]. However, this practice raises significant concerns, as it utilises substantial food resources towards fuel production, thereby depleting the food supply in the market [40]. Consequently, it is essential for SAF feedstock to not compete with food production. Besides that, feedstock should be cost-effective and have a low carbon footprint, including minimal land use [41]. Using food crops for SAF can result in land use changes, including deforestation and ecosystem destruction [40], and can also drive up food prices due to increased resource competition [41]. Furthermore, indirect land use changes, including irrigation, pesticide, and use of fertiliser, can harm the environment and increase greenhouse gas emissions [41].

Fig. 2 shows a summary of SAF feedstocks. First-generation SAF feedstocks, typically derived from food crops, lack some attributes. Their widespread use is driven by continuous availability. In contrast, second-generation biofuels derived from non-edible plants or waste provide a more sustainable and cost-effective SAF option than first-generation SAF. Third-generation SAF feedstocks, mainly microalgae, require less cultivation space but carry substantial cultivation and conversion expenses.

3.1. First-generation SAF feedstock

First-generation SAF is derived from edible sources such as palm oil and corn grains. While these sources are readily accessible, the use of edible oil as feedstock to produce biofuel is not desirable due to the competition between energy and food. This competition hinders the utilisation of first-generation SAF for the mass production of biofuel [42]. However, due to the above criteria, first-generation fuels have been excluded as SAF fuels since they are produced from food crops and are not considered sustainable.

3.1.1. Palm oil

Palm oil is among the most efficient oil-producing crops in terms of oil content per unit of land at an average of 5000 kg per hectare than other vegetable oils [40]. The high oil content significantly contributes to palm oil's widespread use and its excellent potential as an aviation fuel feedstock. A high degree of saturated fatty acids in palm oil, such as palmitic acid (i.e. 45 wt%) makes it a suitable aviation fuel feedstock. The resulting biofuels tend to have lower NO_x emissions, improved cetane number and more desirable flow properties than feedstock with higher unsaturated fatty acids content [5]. Palm oil can be converted into SAF using the HEFA-SPK method as certified in ASTM 7566. The food versus fuel factor is a significant concern when palm oil is used as

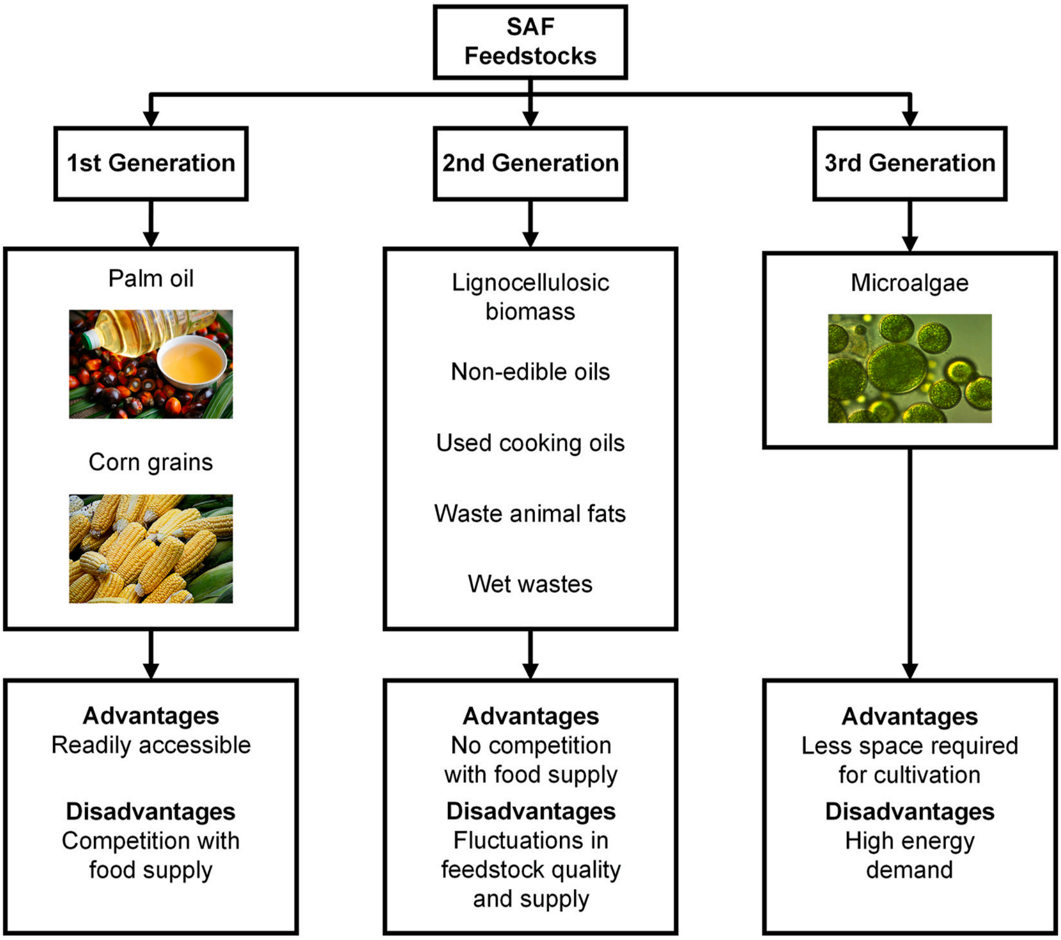

Fig. 2. Overview of SAF feedstocks.

SAF feedstock. In nations like Malaysia and Indonesia, where palm oil production exceeds domestic requirements, its use for fuel production can be driven by economic, environmental and strategic factors [38]. The abundance of palm oil serves as a valuable resource for economic diversification and the development of a sustainable biofuel industry. However, certain countries, such as Europe have implemented regulations restricting first-generation SAF feedstocks [43]. This regulatory approach aims to safeguard food supplies by ensuring that feedstocks derived from food crops do not compromise the availability and affordability of essential food resources. The concerns associated with using palm oil as a feedstock for biofuel primarily revolve around its potential impact on global food market prices [43]. Major producers like Indonesia and Malaysia have implemented restrictions on palm oil resources allocated for biodiesel to ensure food supply stability [43]. The rapid growth of palm tree farms in these countries is driven more by the demand for industrial and food processes in Asia, such as China and India, than by the need for biodiesel production [43]. The concerns highlight the need for comprehensive and sustainable approaches to using palm oil as a biofuel feedstock.

3.1.2. *Corn grains*

Corn grain comprises 70 % starch, which can be used for alcohol production [44]. The alcohol can then be converted to biofuel. Biochemical processes, such as the ATJ process, are carried out to convert corn grains into aviation fuel. Corn grains are generally converted into ethanol in biorefineries such as Dry Grind Corn Ethanol Mills (DGCEM) [45]. This process involves the extraction of carbohydrates and starch from corn grains and the conversion of the extracted components into ethanol *via* fermentation [46]. Then, ethanol undergoes a series of reactions, such as dehydration, oligomerisation, hydrogenation, and fractionation, to produce hydrocarbons that are suitable for use as aviation fuels [44]. Utilising corn grain as a feedstock for SAF offers distinct advantages within the realm of SAF technologies. For instance, integration with processes such as ATJ, HEFA and FT allows for a versatile and efficient production environment. The conversion of existing Dry Grind Corn Ethanol Mills for SAF production provides cost-reduction opportunities and enhances the overall economic feasibility of biofuel production, especially when merged with ATJ processes [45]. Besides that, corn grain's global dominance in ethanol production, commanding a significant share of 53.7 %, surpasses other feedstocks like sugar crops, molasses, and wheat [44]. This underscores the advantages of employing corn grain as a fuel and feedstock for alcohol to jet synthetic paraffinic kerosene (ATJ-SPK) process. With a proven track record and a consistent supply, corn grain emerges as a reliable and efficient choice for SAF production, demonstrating its prowess in contributing to sustainable aviation solutions.

3.2. *Second generation SAF feedstock*

Second-generation SAF feedstocks are from inedible sources that do not compete with food [44]. As these feedstocks are residues and wastes, fluctuations in feedstock quality and inconsistent supply are some of the challenges in using these feedstocks [47].

3.2.1. *Lignocellulosic biomass*

Lignocellulosic biomass is one of the world's most abundant types of biomasses. The Intergovernmental Panel on Climate Change (IPCC) defines biomass as carbon-neutral when the carbon released during the utilisation of biomass for energy purposes is balanced by the carbon sequestered during the growth of the biomass feedstock [48]. Lignocellulosic biomass can be further grouped into forestry residues (e.g. softwood, hardwood and sawdust), agricultural residues (e.g. rice straw, bagasse and corn stoves) and energy crops (e.g. switchgrass and elephant grass) [43,44]. The typical high oxygen content and longer hydrocarbon chains are potential challenges in their use as feedstock in aviation fuel production. Oxygenated compounds are undesirable in aviation fuels as they reduce their heating value and chemical stability. Extra processing steps are required to remove the oxygen atoms and to break the long hydrocarbon chains into C8 to C16 [49]. Pyrolysing cellulose is a possible technique for breaking down the lengthy hydrocarbon chains, yielding furfural and acetone as byproducts. Subsequently, aldol condensation and hydrogenation of the two chemicals produce alkanes with carbon atoms similar to aviation fuel [50]. Lignocellulosic biomass could be converted to SAF *via* biochemical route (ATJ and synthesised isoparaffins (SIP)) and thermochemical approach such as gasification, followed by FT process [44].

3.2.2. *Non-edible oils*

Non-edible oil feedstocks could be generated from castor, jatropha, babassu, camelina and carinata seeds. Choosing non-edible oil as the primary source for SAF production is imperative to avoid competition with food security concerns. The ideal non-edible requires characteristics such as widespread availability, low water and nutrient requirements and minimal energy investment for cultivation and collection [51]. Non-edible crops are particularly advantageous, as they can be cultivated in diverse global regions including wastelands, which do not require any deforestation, thereby mitigating competition for food resources [52]. Additionally, the cultivation of non-edible crops is known for its efficiency and environmental friendliness, making it a sustainable choice for SAF production. Plants like castor beans have been grown in most tropical and sub-tropical regions globally, producing a high growth rate and yield due to their strong climate adaptability to thrive under relatively low input of water and nutrients [51]. It can resist drought and salinity during its growth [53]. Jatropha is characterised by its high oil content, fast growth, resilience to drought, adaptability to various types of land and minimal need for irrigation and agricultural inputs such as fertiliser. Furthermore, this crop exhibits tolerance to insects and pests, and is not grazed upon by animals [54]. Jatropha and carinata are also plants that can survive drought and are highly resistant to pests and diseases [54,55]. Jatropha was originally found in North and Central America, but it has since spread extensively to tropical and subtropical regions globally, including Africa, India, Southeast Asia, and China [56]. Camelina is an annual oilseed crop originating from regions in southeastern Europe and southwestern Asia [57]. What sets camelina apart from traditional oilseed crops like rapeseed/canola, soybeans and sunflowers is its ability to thrive in cool and arid climates [57]. This adaptability makes camelina particularly well-suited for cultivation in the more northerly regions of North America, Europe and Asia [57]. Babassu is primarily found in northern regions of Brazil, and it also flourishes in Mexico and Bolivia [58]. The composition of babassu oil, with a predominant lauric fatty acid content of around 44 mass%, makes it highly suitable for biodiesel production [58]. Given their resilience and versatility, these robust oilseed crops have gained attention as a potential aviation feedstock. Table 6 summarises their oil content and respective carbon chain lengths.

Longer carbon chains, such as the 22 carbon atoms in carinata oil, require additional cracking steps to get shorter chains of 8–16 carbon atoms (i.e. within the jet fuel carbon chain range) [61]. On the other hand, jatropha oil with 14 and 16 carbon chain lengths, within the typical hydrocarbon chain size range of conventional aviation fuel, can be used directly to produce SAF with properties similar to those of conventional jet fuel [59]. Furthermore, castor, jatropha and camelina oils have cetane numbers lower than conventional jet fuel, which is at

Table 6
Oil contents and carbon chain lengths of non-edible oils.

Feedstock	Oil content (weight%)	Carbon chain length	Ref.
Castor	47	16 to 18	[51,52]
Jatropha	35	14 to 16	[51,59]
Camelina	36	16 to 22	[51,60]
Carinata	25 to 47	22	[61]

least 47, while carinata oil has a slightly higher cetane number of 52 [39]. The low cetane numbers are likely due to their high unsaturated fatty acids composition [62].

Castor oil generally undergoes alcohol-to-jet and hydrotreating processes to be converted into SAF [53]. Recently, study of blending SAF produced from transesterification and subsequent fractional distillation is introduced, where jatropha oil and babassu oil are used as the feedstock [59]. At the same time, camelina oil can be converted to jet fuel through hydrolysis, decarboxylation and reforming processes. Lastly, carinata oil can be converted *via* catalytic hydrothermolysis jet conversion, with up to 25.27 % conversion rate [19].

3.2.3. *Used cooking oils and waste animal fats*

Used cooking oils (UCOs) are readily obtainable at a low cost from many sources, such as households and restaurants [63]. UCOs usually contain over 90 wt% of triglycerides, with the balance being free fatty acid (FFA). As the structure of triglyceride (or triacylglycerol (TAG)) consists of three fatty acid molecules attached to a glycerol molecule, UCOs serve as a promising feedstock for SAF. However, the diverse sources of UCOs introduce considerable variability in their quality, leading to challenges in pre-treatment before conversion into aviation fuel [64]. Nevertheless, using UCOs in SAF production is environmentally advantageous in mitigating the impact of UCO discharge into water courses and landfills. UCOs are converted to SAF *via* hydrotreatment processes [65].

Waste animal fats (WAFS), including chicken fat, pork lard, and beef tallow [65], often require pre-treatments to reduce FFA content before the main conversion processes. These fats are secondary resources from slaughterhouses, and eateries are readily available from various outlets [66]. For instance, the global generation of chicken fat has shown an upward trajectory, with 26.16 million tons recorded in 2018. The conversion of chicken fat into SAF through the hydrotreatment process can be up to 47.46 %, as reported by Moreno-Gómez et al. [67]. Generally, WAFS can be converted into SAF using the HEFA process [68].

3.3. *Third-generation SAF feedstock*

Third-generation SAF feedstock are generally non-food sources that are potentially more efficient and sustainable. They can be derived from plants and algae explicitly cultivated for use in the aviation industry, and are also SAF-appropriate [8].

3.3.1. *Microalgae*

Microalgae are becoming a popular contender feedstock for SAF production driven by their attractive characteristics, which include (i) their ability to sequester CO_2 during photosynthesis to generate neutral lipids, predominantly triacylglycerol (TAG), (ii) versatility in cultivation, and (iii) non-competitive with food production.

With an impressive growth rate, microalgae can yield approximately 19,000 to 57,000 L of oil per acre per year [69], as microalgae demonstrate a high TAG yield of 81.5 % with 40.5 % of dry cell weight [70]. TAG is the primary component in microalgae lipids converted to SAF. One of the key advantages of microalgae is their versatility in cultivation, thriving in freshwater, saltwater, or wastewater environments. The cultivation process can be managed in culture vessels, providing flexibility and adaptability [42,71]. Microalgae do not pose a significant risk to the "food versus fuel" competition, as they are not a mainstream food source compared to first-generation SAF feedstocks. However, the high energy demand from microalgae cultivation to bio-oil generation remains a challenge that is imperative to overcome for the overall sustainability of microalgae-based SAF production [72].

The conversion of microalgae lipids into SAF requires a pre-processing step of lipid extraction. Microalgae strains are typically harvested and dried before lipid extraction. The complex cell walls of microalgae are broken down using cell disruption techniques, with popular methods being organic solvent extraction and supercritical fluid method. Non-polar solvents are preferred over polar solvents in organic solvent extraction to avoid the simultaneous removal of lipids and chlorophyll [36]. The productivity and quality of the lipids are closely associated with the microalgae strains selected. Take for instance, *Chlorella vulgaris* strain and *Botryococcus braunii* strain yielded 41.31 % and 56.42 % lipid, respectively, when subjected to the same extraction technique using the microwave radiation cell disruption method [42,73]. Different strains exhibit unique characteristics, including lipid content, composition, and response to extraction methods. This underscores the importance of strain selection in microalgae-based biofuel production. After lipid extraction, the microalgae lipids are converted into SAF*, employing* methods such as transesterification, gasification, pyrolysis and hydroprocessing.

The transesterification method involves the conversion of microalgae lipids into biodiesel (i.e. the conventional biodiesel production involving reversible catalytic chemical reactions where alcohol reacts with TAG to produce biodiesel), followed by decarboxylation and deoxygenation to produce high-purity SAF. Lastly, the isomerisation process decreases the SAF freezing point by breaking long molecule chains into shorter alkane chains, falling within the range of conventional aviation fuel [42]. Converting microalgae lipids through transesterification offers versatility in product output as residual constituents and can be further used to produce biogas, bioethanol and bio-oil [74].

The thermal conversion of microalgae lipids into SAF is another plausible option using gasification and hydrothermal processing coupled with FT process, or fast pyrolysis. Hydrothermal gasification takes place at temperatures exceeding 375 °C, resulting in the production of syngas, which generally contains higher concentrations of either hydrogen or methane along with carbon dioxide [75]. The gasification method involves exposing the microalgae lipid to high temperatures (150–300 °C) and pressure (10–40 bar), leading to the production of syngas [76]. After that, the catalytic reaction between syngas and hydrogen *via* FT synthesis produces liquid long-chain hydrocarbons. In the fast pyrolysis approach, microalgae are subjected to high temperatures (400–600 °C) without oxygen, potentially producing bio-oil yield up to 80 wt% [76]. The bio-oil produced through fast pyrolysis can undergo upgrading processes, such as catalytic hydrodeoxygenation (HDO), to reduce the oxygen, producing saturated hydrocarbons with improved oxidative stability to meet aviation fuel standards [77]. The hydrocarbons from gasification or fast pyrolysis are then subjected to hydroprocessing (hydrocracking and isomerisation) to break long molecule chains into shorter alkane chains suitable for aviation fuel. Lastly, the purification step (fractionation and separation) refines hydrocarbons to harvest specific fractions that meet aviation fuel specifications [72]. Despite numerous approaches proposed for the conversion of microalgae into SAF, opportunities still lie in enhancing the economic viability of these methods to facilitate their commercialisation [78].

4. ASTM-certified SAF production processes

SAF blends must meet rigorous physicochemical characterisation tests before being used as aviation fuel. These tests ensure that the fuel meets stringent safety, performance, and compatibility standards with existing aviation infrastructure as a reliable and effective alternative in the aviation industry.

4.1. *ASTM standards and testing procedures for fuels or additives*

The three key ASTM standards governing aviation fuel are D1655, D7566 and D4054 (in Supporting **Material** listed as Tables 1–3) [7]. ASTM D1655 specifies the minimum requirements for Jet A and Jet A1 aviation fuel. In comparison, ASTM D7566 defines the property and compositional requirements for drop-in fuels before the fuels can be blended with ASTM D1655-approved fuels [7]. Additionally, ASTM D1655 serves as a comprehensive guide for aviation fuel developers, outlining the necessary test and analysis requirements to ensure that the developed drop-in fuel seamlessly integrates into the existing aviation infrastructure [79].

ASTM D4054 details the test and property benchmarks for assessing a potential alternative jet fuel. The ASTM D4054 test program comprises comprehensive tests and evaluations involving the candidate fuel developer in testing fuel samples to gauge the properties, composition, and performance of the alternative jet fuel to those of the conventional petroleum-based jet fuel. The test program comprises four distinct tiers, each consisting of tests focused on critical considerations affecting engine and aircraft design, safety, durability, performance and reliability.

The first tier is designed to test fuel specification properties following the requirements stated in ASTM D1655, DEF STAN 91-091, MIL-DTL-

Table 7
Summary of all ASTM-certified production processes.

SAF Production Process	Year of Approval	Technology Readiness Level (TRL)	Fuel Readiness Level (FRL)	Feedstock Blending Limit	Advantages & Disadvantages	Ref.
FT-SPK	1999 – approved for commercial use 2009 – qualified ASTM D7566 Annex A1, which was developed to approve alternative fuels by process rather than producer	6–8	6–7	50 %	Advantages • High flexibility of feedstock • Sulphur-free and low aromatic contents SAF Disadvantages • Dispersed production • High electricity consumption • Strict requirements for syngas production	[9,81,82]
HEFA-SPK	2011 – qualified ASTM D7566 Annex A2	9	9	50 %	Advantages • Possible to be used without blending with petroleum-derived jet fuel • Higher energy content than JP-8 • Highest energy conversion efficiency among all the SAF production routes Disadvantage • Restricted to oil-derived feedstock	[81–83]
HFS–SIP	2014 – qualified ASTM D7566 Annex A3	7–8	5–7	10 %	Advantages • Farnesane has a higher energy density than ATJ-SPK • Lower emission of pollutants • Similar combustion behavior with Jet A1 fuel Disadvantages • High viscosity and poor combustion performance in aviation turbine engines. • Expensive feedstocks and high energy consumption • Lowest blending ratio limit	[7,81,83]
FT-SPK/A	2015 – qualified ASTM D7566 Annex A4	6–8	6–7	50 %	Advantages • Achieve up to 20 wt% of alkylated aromatics • Possible to be used without blending with petroleum-derived jet fuel Disadvantage • Restricted to coal tar feedstock	[9,81,83]
ATJ-SPK	2018 – qualified ASTM D7566 Annex A5	7–8	7	30 %	Advantage • Provide synthetic methods to produce aromatic hydrocarbons Disadvantages • Restricted to ethanol and isobutanol feedstocks • High-value alcohols are needed as feedstockLower energy density	[81–84]
CHJ	2020 – qualified ASTM D7566 Annex A6	4–6	6	50 %	Advantage • Identical molecular composition and chemical constituents of petroleum crude Disadvantage • Higher energy consumption	[85,86]
HC-HEFA-SPK	2020 – Qualified ASTM D7566 Annex A7	–	6	10 %	Advantage • Utilises algae, which has a higher growth rate compared to other agricultural crops. Disadvantage • Low blending limit	[87,88]
FOG Co-processing) FT Co-processing	2018 – qualified ASTM D1655 Annex A1 2020 – qualified ASTM D1655 Annex A1	7–8	6–7	5 %	Advantages • Produces lower-carbon intensity fuels • Utilises infrastructure from existing petroleum refineries • Able to handle diverse biogenic feedstocks Disadvantages • Requires oxygen removal process. • Operational difficulties due to factors such as type of biogenic feedstocks, blend rates and product characteristics	[81,85]

83133 and MIL-DTL-5624 [80]. Before commencing the physical and chemical property tests, a complete chemical description of the fuel or additive and a description of the manufacturing process for new fuels are required in the test program to facilitate the internal approval processes with aviation regulatory authorities [80]. Additives are substances added to aviation fuel to enhance fuel efficiency or to address fuel handling and maintenance requirements [80]. If the material is an additive, its carrier solvent and recommended concentration must also be provided [80]. This information is crucial in determining test requirements and their order. However, these additives can only be used if they fulfil the specific requirements in ASTM D1655 for conventional and ASTM D4054 fit-for-purpose jet fuel.

The second tier of the ASTM D4054 test program is concerned with Fit-for-Purpose properties. "Fit-for-purpose" in aviation fuel terms means that the alternative fuel and additives meet the acceptable performance standards for use in aircraft and aircraft engines [80]. Fit-for-purpose properties are not included in the fuel specification criteria of ASTM D1655 but are inherent in petroleum-derived jet fuel [80].

After completing Tier 1 and Tier 2 testing, the collected data is presented to the subcommittee task group from the Federal Aviation Administration (FAA) and Original equipment manufacturers (OEMs) for a Phase 1 review [80]. OEMs are the aircraft and aircraft engine manufacturers. Prominent names like Pratt & Whitney, General Electric (GE) Aviation, Williams International, and Honeywell Aerospace are engine OEMs. Boeing, Airbus, Bombardier and Beechcraft, and Dassault Aviation are some of the renowned airframe OEMs [80]. These companies need all the details about new fuels and additives to support their internal approval process with the aviation regulatory authorities. This group of FAA and OEMs will thoroughly evaluate the Phase 1 data report to determine whether the fuel or additive is suitable for further evaluation [80]. If the data meets the criteria, the fuel or additive can move on to Tier 3 and 4 tests. Tier 3 consists of Component, Rig, and Materials Tests, and the final Tier 4 consists of Engine and Aircraft Tests [80]. As these last two tiers require testing with specialised aerospace materials, engine component rigs, and complete aircraft or engines, the subcommittee task group will request input from the FAA and OEMs for Tier 3 and 4 testing recommendations [80]. The properties essential for assessing fuel compatibility with engine and airframe fuel system design include fuel surface tension, seal swell, minimum aromatic level, maximum flash point and minimum lubricity. These properties are typically compared to those of petroleum-derived fuel and must fall within a range of established experience [80]. The FAA and each OEM will also conduct an internal review of the data to determine whether the fuel or additive is acceptable for use on their respective aircraft and engines. The qualified fuels would be listed as a new annexe in ASTM D7566. Alternative fuels can be used as drop-in fuels to conventional fuels [9].

The following sections discuss the different ASTM-certified SAF production processes, and an overview of all the processes is presented in Table 7.

4.2. Fischer-Tropsch Synthetic Paraffinic Kerosene

Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) is the earliest SAF conversion pathway approved by ASTM. The process consists of 3 main stages, which include (i) the production of syngas, (ii) the generation of synthetic crude (syncrude) *via the* FT process, and (iii) the subsequent separation, upgrading and refining of syncrude before generating the final product [89]. Syngas are produced from carbon-based feedstocks such as coal, natural gas and biomass into synthetic paraffinic kerosene (SPK) [90]. One challenge in the FT process is that the feedstock, i.e. syngas, must meet stringent specifications (i.e. the concentration of impurities and the hydrogen-to-carbon monoxide ratio) for the FT synthesis to be efficient.

Syngas purification is an essential stage to prevent fouling of the FT reactor. The solid particles, tars and compounds containing nitrogen or sulphur are typically removed in the purification stage [41]. The concentration of the removal levels of the potential impurities are listed in Table 8. Concentration levels of organic compounds are typically maintained below the dew point of the FT operating pressure (25–60 bar) to prevent fouling and condensation within the system [91].

According to the study of the FT process, the expenses associated with purified syngas production generally constitute around 60–70 % of the total capital and operational costs [92]. Given the high syngas cost, maximising its conversion within the downstream FT reactors becomes crucial.

Two of the most common FT-SPK routes are PtL and biomass-to-liquid (BtL) processes [89]. A slurry-phase reactor (SPR) is commonly used to conduct FT processes with Co/Al_2O_3 as a catalyst at reaction conditions of 240 °C and 14 bar [93]. One of the key advantages of the FT process is the capacity to produce sulphur-free and aromatic-free SAF.

4.2.1. Biomass to liquid

BtL represents the SAF production pathway that uses biomass as feedstock. Given that the bulk of aviation fuels presently stem from lipid sources like vegetable oils, which are projected to maintain market dominance in the foreseeable future, upcoming demand will shift towards SAF derived from biomass sources like woody residues, agricultural wastes, oleaginous microorganisms and municipal solid waste [84]. Fig. 3 shows the block diagram for the BtL route with FT-SPK. FT can be integrated with biomass conversion processes like gasification, pyrolysis and hydrothermal liquefaction to produce syngas [41]. However, the gasification-FT route is the only certified and commercialised route for SAF production [41].

The choice of gasifier depends on feedstock attributes and downstream application [94]. Table 9 presents three types of gasifiers used in the BtL process, their feedstock usage, and their advantages and disadvantages. The thermochemical process in the gasifier produces syngas with an oxidising agent (e.g. O_2, H_2O, CO_2) [95]. The gasification process also generates contaminants like tars, alkali compounds, sulphur compounds and particulates, which must be removed to increase the ratio of CO/H_2. Long-chain hydrocarbons from the FT process are hydrocracked to produce fuels meeting ASTM D7566 specifications [95]. The shorter hydrocarbons are then separated by distillation to obtain the fraction suitable for jet fuel.

The dispersed production of residual biomass from various locations creates logistical challenges for BtL, including collection, transportation, and storage due to its low bulk density and biodegradability. These factors significantly increase the overall cost of BtL [83].

4.2.2. Power to liquid

The PtL technique combines water electrolysis, carbon capture, and the FT process to produce SAF [3]. CO_2 is sourced from the atmosphere or from CO_2-rich effluents, such as fossil fuel plants, refineries, and heavy industrial [96]. A major challenge for PtL is the electricity demand for electrolysis, necessitating cheaper renewable electricity for commercialisation [97].

The PtL process involves two main steps: electrolysis and the FT process. A direct air capture plant captures CO_2 from the air and supplies it to the PtL plant, while hydrogen is produced from water electrolysis.

Table 8
The required levels of removal for the FT feed gas [91].

Impurity	Removal Level
$H_2S + COS + CS_2$	<1 ppmV
$NH_3 + HCN$	<1 ppmV
$HCl + HBr + HF$	<10 ppbV
Alkaline metals	<10 ppbV
Solids (soot, dust, ash)	Essentially completely below the dew point
Organic compounds (tars)	
- *class 2 (hetero atoms)*	<1 ppmV

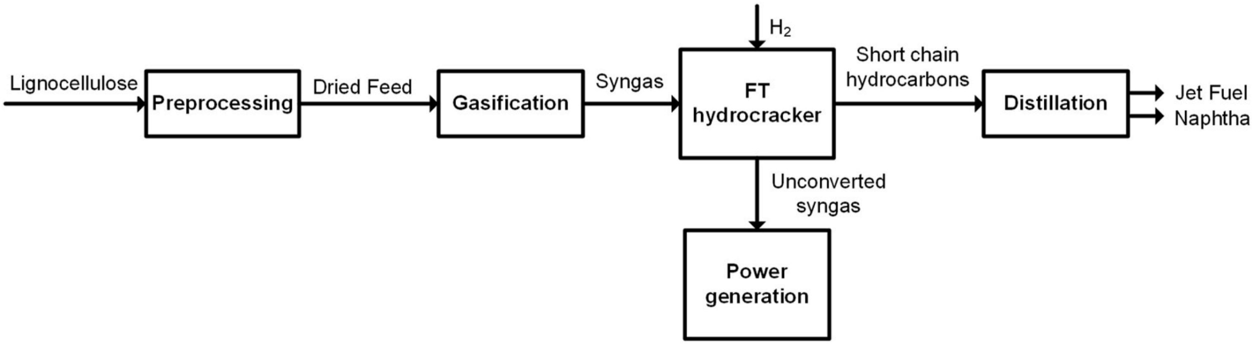

Fig. 3. Block diagram for the BtL route with FT-SPK.

Table 9
Circulating Fluidised bed gasifier, Updraft Fixed-bed gasifier and Downdraft Fixed-bed Gasifier.

Types	Circulating Fluidised bed (CFB) Gasifier	Updraft Fixed-bed (UFB) Gasifier	Downdraft Fixed-bed (DFB) Gasifier
Feedstocks	Fine particles materials (e.g. sawdust, garden waste)	Large particles (e.g. wood chips)	Large particles (e.g. wood chips)
Advantages	• Efficient combustion at a low-temperature range (843–899 °C) • High reduction efficiency of nitrogen oxides in exhaust gas (50–90 %)	• Higher thermal efficiencies and less sensitivity to moisture content of the feed • Perform well at elevated pressure	• Generates product with less tar
Disadvantages	• Elevated pressure will cause fluidising disruption due to ash clinkering • Low operating temperature (<1094 °C) promotes the generation of N_2O	Higher tar contents in the produced syngas	

The reverse water gas shift reactor converts CO_2 and H_2 into syngas for the FT process, which then converts it into kerosene, diesel, and gasoline, followed by refining within the PtL plant (Fig. 4).

4.3. Fischer-Tropsch Synthetic Paraffinic Kerosene with aromatics

Fischer-Tropsch synthetic paraffinic kerosene with aromatics (FT-SPK/A) and FT-SPK are both derived from FT synthesis. FT-SPK/A are classified under ASTM D7566, Annex A4, with a maximum blending of 50 % [16]. Fig. 5 shows the overview of FT-SPK/A conversion pathway. The primary difference is the presence of aromatics in FT-SPK/A.

FT-SPK/A can contain up to 20 wt% alkylated aromatics [98]. Higher FT synthesis temperatures increase aromatic by-products, with high-temperature Fischer-Tropsch (HTFT) producing a small amount, mainly in the naphtha fraction (about 5 vol%) [99]. ASTM D7566 only allows the use of nonpetroleum-derived aromatics forFT-SPK/A production [100]. Therefore, coal tar, a common petrochemical benzene source industry has become the feed material for aromatics in FT-SPK/A [101]. FT-SPK/A is a variation of FT-SPK, particularly refined in HTFT synthesis, producing SAF with improved aromatic content [99]. Currently, FT-SPK/A is restricted to coal tar as the feedstock to qualify for ASTM D7566. However, the combined process of oligomerisation, aromatisation and alkene-aromatic alkylation shows the potential of FT-SPK/A to produce SAF with sufficient levels of aromatics and density to allow it to be qualified for re-designation as Jet A1 as 100 % synthesised kerosene [99].

4.4. Hydroprocessed esters and fatty acids-synthetic paraffinic kerosene

Hydroprocessed esters and fatty acids-synthetic paraffinic kerosene (HEFA-SPK) is classified under ASTM D7566, Annex A2, with a maximum blending of 50 % [9]. With future technology advancements, HEFA-SPK could potentially replace 100 % of petroleum-derived jet fuel. It has a slightly higher energy content than military jet fuel (JP-8),

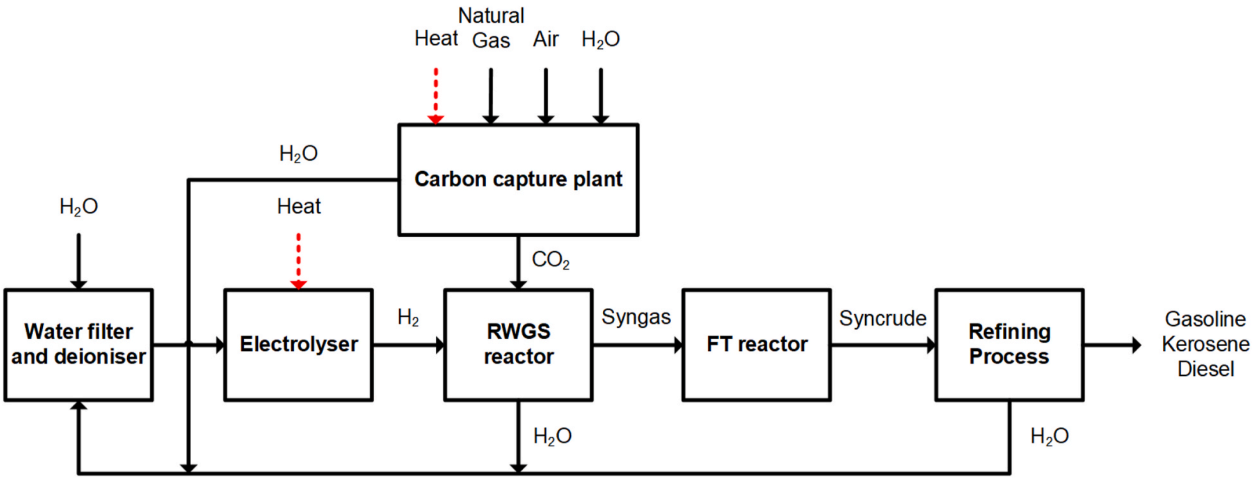

Fig. 4. Block diagram for power-to-liquid route with FT-SPK.

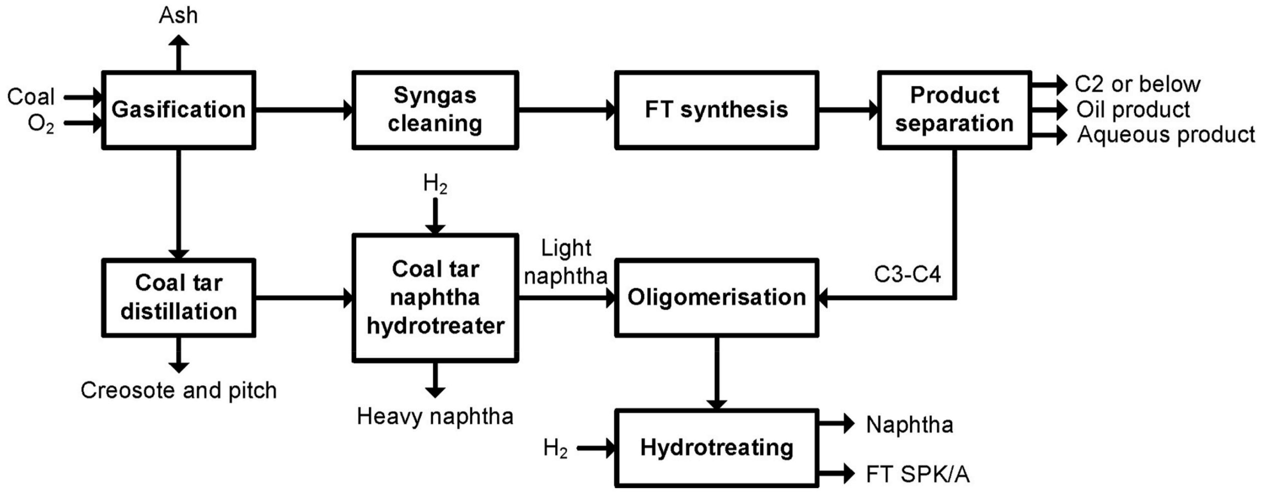

Fig. 5. Block diagram for FT-SPK/A.

allowing for longer flight durations. HEFA-SPK is the most energy-efficient SAF production method, achieving about 76 % energy conversion efficiency [102]. However, its major limitation is low feedstock availability, since first-generation feedstocks are used in the process [102]. Recent literature indicates a broad price range of 23–310 USD per gallon for HEFA-SPK and 34–82 USD per gallon for FT-SPK [103]. This disparity arises because HEFA-SPK costs are more influenced by feedstock expenses, whereas FT-SPK costs are more influenced by capital investment [103].

In 2020, hydrocarbon-hydroprocessed esters and fatty acid-synthesised paraffinic kerosene (HC-HEFA-SPK) was added to ASTM D7566, Annex A7 [100]. The main difference between HC-HEFA-SPK and HEFA-SPK is the use of the algae (Botryococcus braunii) as the feedstock for HC-HEFA-SPK [87]. This choice avoids food security issues and reduces life-cycle GHG emissions. However, HC-HEFA-SPK is the newest approved SAF, thus it has a low TRL and the blending ration is limited to 10 %.

The HEFA-SPK process involves extracting oil from biomass and hydrogenating the unsaturated fatty triglycerides. The hydrogenation occurs at a pressure range of 0.7–4 bar, and temperatures range of 150–220 °C with nickel catalysts, or 80–120 °C with palladium or platinum catalysts [41]. The resulting saturated triglycerides are then broken down into glycerol and FFA *via* thermal hydrolysis reactions. Glycerol can be dehydrated into propane, while FFA undergoes either HDO to produce long linear alkanes ($C_{18}H_{38}$) and water, or decarboxylation (DCO) produces heptadecane ($C_{17}H_{36}$) and CO_2 [41,104]. Compared to CDO, HDO process necessitates a significant amount of hydrogen consumption at high pressure. It is typically carried out at temperatures ranging from 300 to 600 °C using heterogeneous catalysts such as sulphides, nickel/molybdenum and cobalt/molybdenum supported on alumina.

The straight-chain paraffins ($C_{18}H_{38}$ or $C_{17}H_{36}$) are further processed through hydro-isomerisation to create branched-chain paraffins, lowering the fuel's freezing point to meet jet fuel specifications. Hydrocracking reactions are also involved, occurring sequentially or concurrently with hydro-isomerisation. These reactions serve to crack and saturate the hydrocarbons, resulting in the formation of synthetic paraffinic kerosene (SPK) [104]. A block diagram of the process is displayed in Fig. 6.

4.5. *Hydroprocessing of fermented sugars-synthetic iso-paraffinic kerosene*

The production of hydroprocessing of fermented sugars-synthetic iso-paraffinic kerosene (HFS–SIP) involves the processing of farnesene, derived from fermentable sugars through a combination of hydroprocessing and fractionation operations. In HFS, sugars or lignocellulosic biomass is consumed by genetically modified yeasts to produce long-chain alkenes and β-farnesene (Fig. 7) [104]. The β-farnesene is then converted to farnesane through a series of processes, including hydrogenation, isomerisation and hydrocracking [104]. According to ASTM D7566, SIP has been approved for blending with conventional aviation fuel at a maximum of 10 % by volume, provided that the SIP contains at least 97 % by volume of farnesane [105]. Farnesane has a higher energy density than ethanol and iso-butanol, making it a promising alternative fuel [106]. Farnesane significantly decreases GHG emissions and exhibits similar combustion behaviour to Jet A1 at temperatures below 727 °C [105].

Nevertheless, the long carbon chains of farnesane (C15) lead to a high viscosity and poor combustion performance in aviation turbine engines [98]. The implementation of HFS–SIP is currently hindered by two main challenges, namely the high cost of its feedstock and its high energy consumption [104]. The cost of HFS–SIP is £4000 tonne^{-1}, which was reported to be the most costly fuel production route [102].

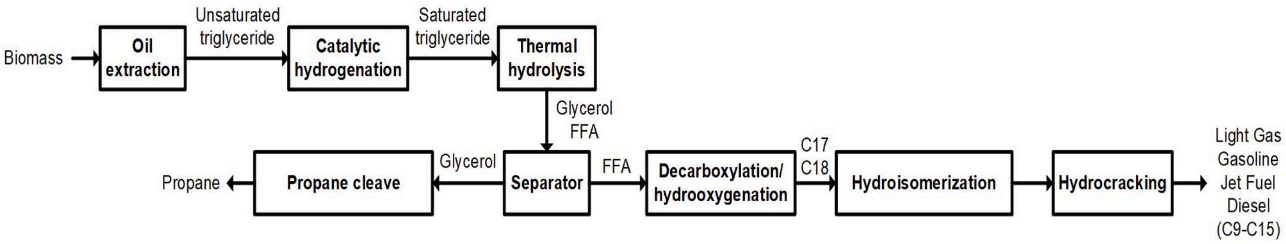

Fig. 6. *Block diagram of HEFA-SPK route.*

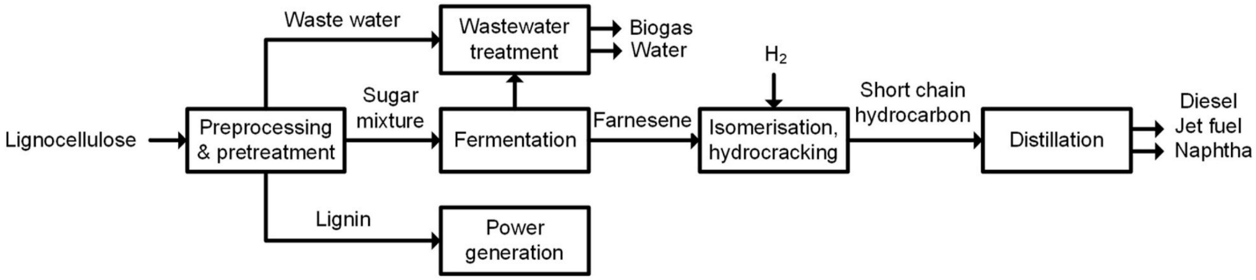

Fig. 7. Block diagram of HFS–SIP route.

4.6. *Alcohol-to-jet synthetic paraffinic kerosene*

The ATJ-SPK process involves generating alcohol from renewable sources and upgrading it to SAF through the ATJ process [107]. Fig. 8 illustrates the general ATJ-SPK process. It converts short-chain alcohols (C1–C4) to longer hydrocarbons (C8–C16) [41]. ATJ-SPK is classified in ASTM D7566, Annex A5, with a maximum blending of 50 % [9]. Three catalytic reactions are involved in the ATJ process, including dehydration, oligomerisation and hydrogenation [107]. Iso-butanol and ethanol are the only two alcohols currently used in ATJ-SPK processes. Dehydration occurs at pressures below 14 bar and temperatures ranging from 288 to 374 °C, with acidic catalysts such as alumina-based catalysts, ZSM-5 zeolites, γ-type zeolites and Amberlyst acidic resins [41]. Oligomerisation takes place at 100 °C using Amberlyst-35 or Nafion catalyst [41]. Hydrogenation saturates olefins with hydrogen supplied over PtO_2 catalyst. The synthetic paraffin products are then refined into gasoline, aviation fuel and diesel in the distillation process [107].

Current ATJ-SPK dehydration is limited to C2 and C4 alcohols. Currently, thorough investigations have been undertaken on the production of alcohols higher than C2 through biochemical routes. A huge challenge encountered by ATJ lies in the high market value of alcohol intermediates, hindering its progression beyond the demonstration stage [84]. Therefore, SAF production *via* this pathway remains economically unfeasible due to the utilisation of high-value alcohol as feedstock [108]. Alternatively, new technology is required to incorporate all C2–C5 alcohols (i.e. inclusive of C3 and C5) in the ATJ-SPK processes [104]. While SAF produced from ATJ-SPK has a lower energy density, this could decrease the aircraft flight range, limiting the implementation of this fuel within short-haul flights only [104]. However, focusing on iso-butanol in ATJ-SPK can produce aromatic paraffins, critical for promoting valve sealing in the engine systems [104].

4.7. *Catalytic hydrothermolysis jet*

Fig. 9 depicts catalytic hydrothermolysis jet (CHJ) process, which utilises triglycerides and water as feedstock. CHJ process operates at supercritical conditions with catalyst [86]. CHJ involves high temperatures and pressures, leading to increased energy consumption compared to HEFA [86]. The process comprises three main steps: preconditioning, CHJ conversion and post-refining [86].

Preconditioning involves conjugation and cyclisation reactions to enhance the SAF quality, resulting in a significant 25 % reduction in hydrogen consumption during post-refining, compared to the direct hydrotreating approach for triglycerides [109]. Conjugation employs a Ni/C catalyst in a stirred tank reactor at 170 °C under atmospheric pressure for 4 h, while cyclisation occurs in a similar reactor at 15 bar pressure for 1 h [86].

CHJ conversion takes place in plug-flow reactors with a zinc acetate catalyst at 240–450 °C and 1.5–25 MPa pressure [86]. Lastly, post-refining involves mild hydrotreating of biocrude oil to reduce oxygen content before the fractionation [86]. The CHJ process could achieve 85 % feedstock conversion to CH crude and 72 % conversion of CHJ crude to hydrocarbon [110]. The resulting product breakdown includes 36.81 % SAF, 27.94 % diesel, and 25.3 % gasoline [86].

4.8. *Co-processing bio-crude up to 5 % by volume of lipidic feedstock in petroleum refinery processes*

Co-processing refers to transforming the hydrocarbons from biomass or lipids to intermediate petroleum distillates [111]. It aims to produce low-carbon intensity fuels at an economical price, by leveraging the existing oil refineries [111]. Therefore, the viability of this method often depends on the specific refinery configuration, but the three common insert points for co-processing are fluid catalytic crackers (FCC), diesel hydrotreaters and hydrocrackers [112].

There are two co-processing routes approved in ASTM D1655, Annex 1, which are FT co-processing and Fats, Oils and Greases (FOG) co-processing [79]. FT co-processing involves the integration of FT into the existing petroleum refining processes [10], thus inheriting its ability to handle diverse bio-feedstocks, while maintaining biodiesel quality

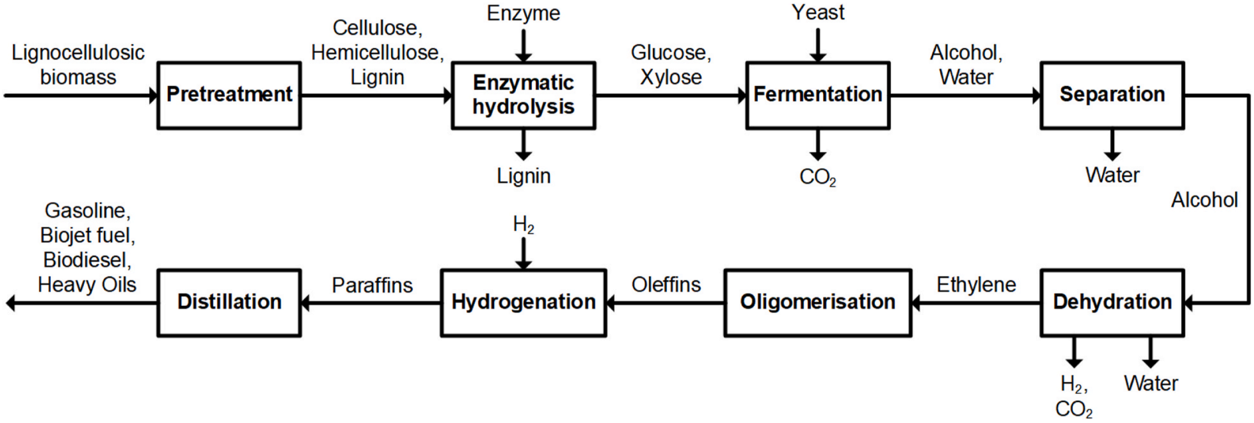

Fig. 8. Block diagram for ATJ-SPK process.

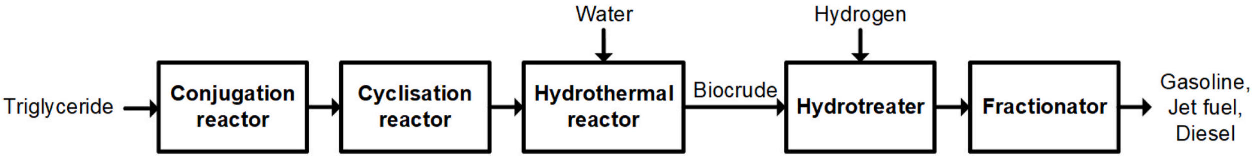

Fig. 9. Block diagram of CHJ process.

[112]. On the other hand, FOG co-processing utilises pyrolysis or thermal liquefaction to produce bio-oils from biomass feedstock, and bio-oils would undergo HEFA process before blending with the petroleum jet fuel [10]. The diversity in feedstocks displays a wide range of oxygen content (5–50 %) [111]. Under this circumstance, biomass pretreatments, such as HDO and DCO are crucial for oxygen removal in co-processing biocrudes [111]. Notably, the characteristics of lipid and biocrude feedstocks differ considerably from those of fossil crudes, hence coke formation is the major problem, resulting in a low blending rate of co-processing biocrude [112]. Despite being the only SAF pathway approved under ASTM 1655, the co-processing biocrude is sometimes not classified as a “drop-in” fuel, but is more widely accepted as a method for incorporating renewable contents into petroleum refineries [10].

5. Emerging technologies for SAF production

This section examines potential technologies for producing SAF from diverse feedstocks that have not yet received ASTM approval. However, researchers have actively explored the following technologies as proof of concept, and extensive simulations have been conducted to validate their feasibility. This section is structured into four categories, focusing on producing SAF from various feedstocks. These feedstocks include wet algae, bio-biased polycyclic alkane, carbon-rich waste gas, and lignin. The potential of hydrogen as a viable SAF option has also been explored. The discussions within this section delve into the potential technologies, processes, and considerations related to each feedstock, shedding light on their feasibility and potential contributions to SAF production. Fig. 10 demonstrates the different materials and technologies evaluated in **Section 4**.

5.1. Lignocellulosic feedstocks and wet algae to Liquid Jet Fuel: hydrothermal liquefaction

Moisture in biomass can lead to time and energy-intensive dewatering or harvesting processes. While utilising solar energy to dry the biomass can be a viable option, it requires significant time and space [76]. Therefore, studies have focused on extracting oil directly from wet algae to reduce the production cost. Bio-oil can be extracted from algae with a solvent such as dimethyl ether (DME) or with a mixture of

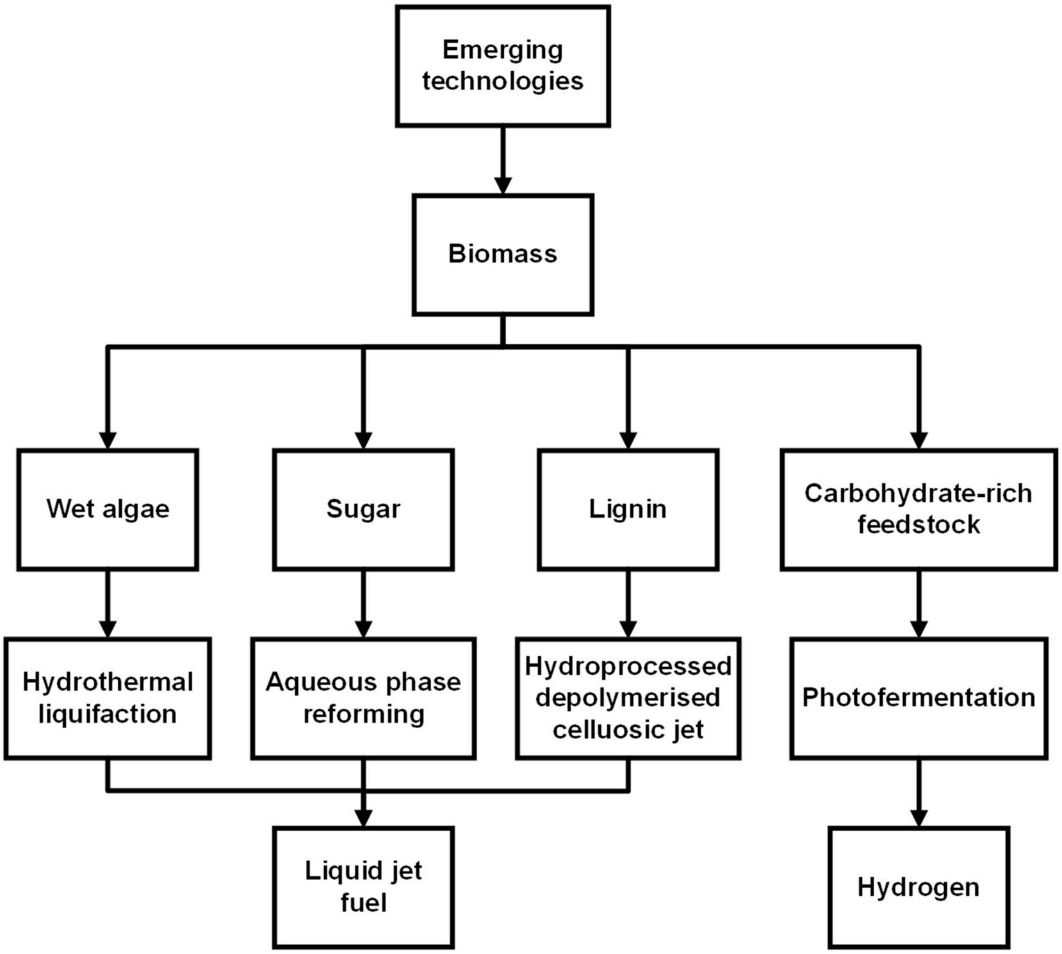

Fig. 10. Emerging technologies for SAF production.

chloroform and methanol [76]. The process is tested to have lower energy consumption than the drying approach, and the solvent can be recovered by evaporation at lower temperatures [76].

Additionally, bio-oil extraction is feasible, using homogenisers or ultrasound to disrupt the cells and extract the oil mechanically [76]. However, this technique is currently utilised only in laboratory settings due to the considerable capital costs involved and high levels of acoustic energy requirement at larger scale [76]. The hydrothermal liquefaction (HTL) process using lignocellulosic feedstock is depicted in Fig. 11.

HTL operates at a temperature between 250 and 375 °C. HTL is suitable for wet biomass such as sewage sludge, manure and macroalgae [102]. This capability allows HTL to efficiently produce biocrude from diverse biomass types, even those with variable moisture levels [113]. The pre-treatment involved is only restricted to specific feedstock, such as woody biomass, requiring size reduction and alkaline treatment to obtain a pumpable and stable slurry [75]. While the HTL process does not involve drying, dewatering is still essential to generate a slurry that contains approximately 20 % solid content [114]. For microalgae feedstock, homogeneous catalysts such as formic acid and acetic acids and heterogeneous catalysts such as Pt/C and Cobalt–Molybdenum (CoMo) were used [75]. An advantage of the HTL route is that the nutrients generated from the HTL process could be recycled and used to cultivate microalgae [114]. The HTL process converts treated biomass into biocrude, solid residue, gaseous phase (mainly CO_2) and aqueous phase products [75]. Lignocellulosic feedstocks typically use base catalysts like $NaCO_3$, KOH or K_2CO_3 [75]. Biocrude is separated from the by-products and upgraded through hydrotreating with hydrogen gas at 400 °C to eliminate impurities from the SAF.

Currently, HTL faces challenges with low yield, prompting research for higher-performance catalysts to enhance efficiency and product quality [115]. Furthermore, HTL also encounters technical problems in the feedstock pretreatment, involving agitation and transportation of large slurry volumes at high pressure [115]. The process's high temperature and pressure conditions may induce equipment corrosion, necessitating costly alloy materials to mitigate corrosion effects [102]. Additionally, algae-based feedstocks contain significant nitrogen levels (about 5–7%), posing challenges during the combustion and hydrotreating process [75]. Moreover, the biofuel produced from microalgae still has a limitation in that its freezing point (−30 °C) is higher than that of conventional jet fuel (<−77 °C) [116]. However, the emergence of HTL opens up another route for SAF production, which could disrupt the dominance of first-generation SAF produced by HEFA process [103].

5.2. Sugar to Liquid Jet Fuel: aqueous phase reforming (APR)

APR process involves the breakdown of cellulose and hemicellulose components present in lignocellulosic biomass through acid hydrolysis. Sulphuric acid is commonly added to sugar-based biomass with a molar ratio of 9:1 to produce furfural at 175 °C and 0.9 MPa. The reaction takes place in a stripping column to extract 95 % of furfural with saturated steam immediately to avoid self-polymerisation of furfural and the co-polymerisation reaction with xylose. The condensed furfural is heated to remove the water content. On the other hand, the steam stripping residual is subjected to H_2SO_4 with 9 times its mass to produce levulinic acid at 180 °C [117]. The hydrolysis residue and levulinic acid are filtered out; lime is added to remove impurities (e.g. colloid and lignin) and neutralise the pH. The concentrated furfural and levulinic acid are then condensed in a reactor at 50 °C, and oxygenated long-chain hydrocarbons (C10–C15) are formed in a base catalyst (e.g. NaOH) under atmospheric pressure. A sulphuric acid solution is added to the products to remove the oxygen from the hydrocarbon chain. For the hydrotreating process, methanol is added to saturate the product at 150 °C and 4 MPa in the presence of Ru/C as catalyst [117]. Subsequently, the saturated hydrocarbon is heated to 280 °C to remove the oxygen atom in the form of carbon dioxide, carbon monoxide and water (Fig. 12). The resulting product undergoes additional deoxidation at 300 °C to achieve an approximate yield of 51 wt% SAF [117].

5.3. Lignocellulose to Liquid Jet Fuel: pyrolysis

The conversion of lignocellulose to jet fuel involves three main steps: bio-oil extraction, HDO, and upgrading of cycloaklane into suitable hydrocarbons to produce jet fuel as shown in Fig. 13. This bio-oil extraction is commonly achieved *via* conventional pyrolysis in the absence of oxygen, which involves the thermal decomposition of lignin, cellulose and hemicellulose into oxygen-containing bio-oil mixture, with a complex mixture of phenolics, furans, acids, alcohols, carbonyls, esters and ethers [118]. The presence of oxygen content, high viscosity, high acidity, corrosiveness, reduced heating value, and compromised oxidation stability, are restricting bio-oil to be used as a jet fuel [17].

Various pyrolysis methods have been investigated for aviation fuel production, including microwave-assisted, solar-assisted, and plasma pyrolysis each providing different yields and product properties [119]. Microwave-assisted pyrolysis is reported to achieve a high bio-oil yield of 98.78 wt% [120]. The bio-oil production from microwave-assisted pyrolysis primarily consists of linear-chain alkanes, but lacks cyclohexane which has a compact molecular structure and better combustion characteristics [119]. Plasma pyrolysis offers no significant advantages over other pyrolysis methods, as it yields the lowest amount of bio-oil, and the properties of the bio-oils produced are similar to those obtained through conventional pyrolysis [119]. While solar-assisted pyrolysis appears promising since it does not require additional energy, using solar radiation to heat lignocellulose, the main products obtained from the pyrolysis are diesel and gasoline, where the yield of aviation fuel only ranging from 15.1 to 21.7 % [119].

Consequently, bio-oil must undergo HDO to eliminate oxygen and

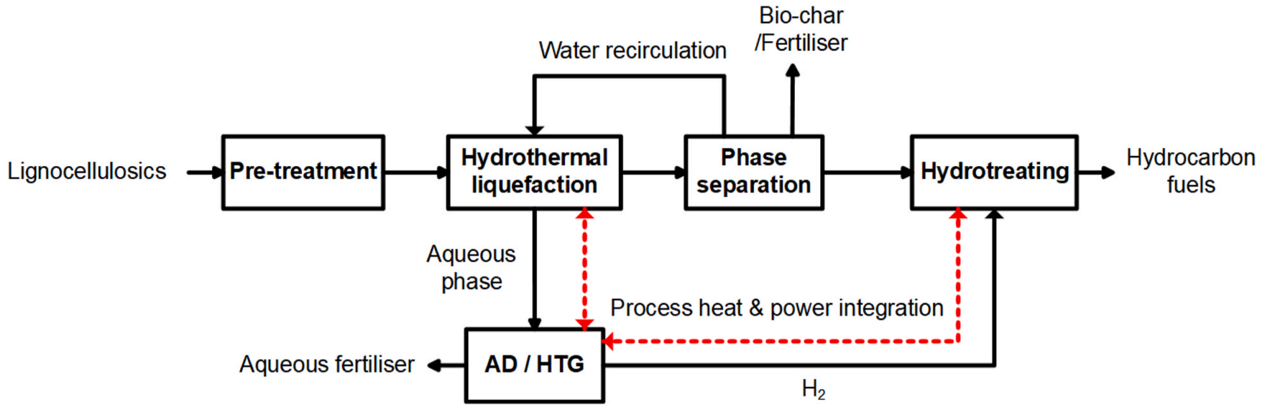

Fig. 11. Block diagram of HTL process using lignocellulosic feedstock.

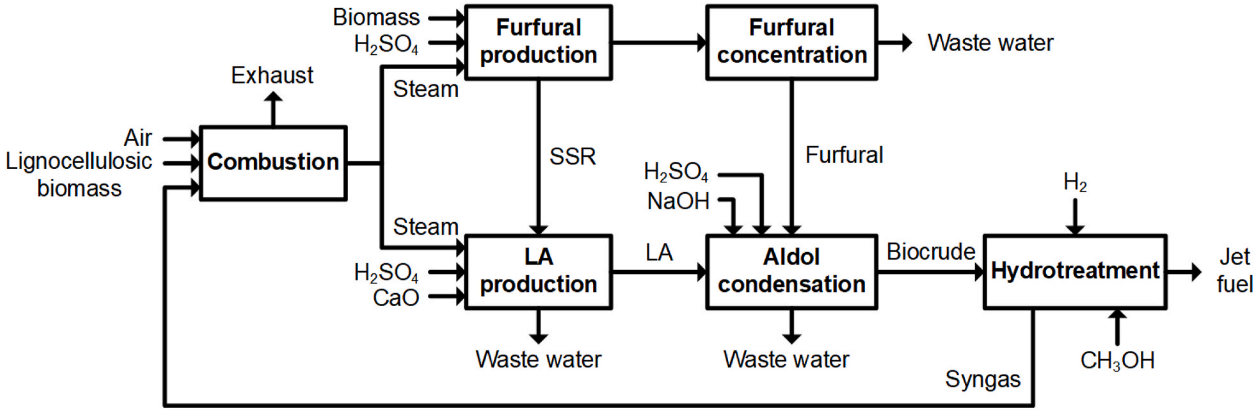

Fig. 12. Block diagram of APR process.

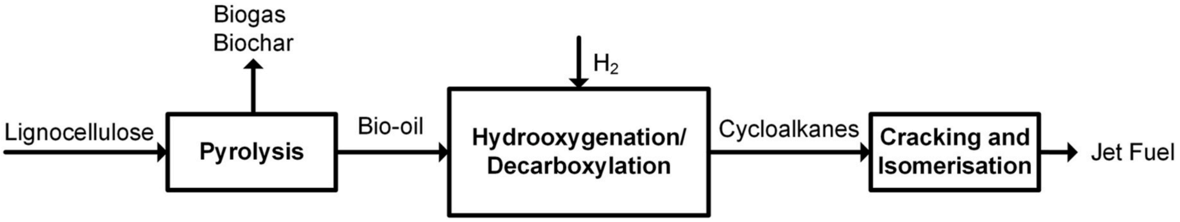

Fig. 13. Block diagram of Lignocellulose to Liquid Jet Fuel *via* pyrolysis process.

saturate the cyclic hydrocarbons [17,119]. The HDO process deoxygenates and hydrogenates the bio-oils under high pressure (typically above 15 bar) and at temperatures predominantly ranging from 100 to 300 °C [118]. Transition metals, metal sulphides, metal phosphides, metal nitrides, carbides and metal oxides are commonly used as catalysts for HDO with supports such as mesoporous nanoparticles, activated carbons and metal oxides [17]. The HDO process produces mainly alkylated cycloalkanes and aromatic hydrocarbons [17].

Cycloalkanes exhibit comparable combustion characteristics to iso-alkanes [121]. They have higher density when compared to acyclic hydrocarbons and greater gravimetric heats of combustion than aromatic compounds. Recent studies have indicated that when the concentration of cycloalkanes exceeds 30 % in SPK, it exhibits similar swelling properties as conventional jet fuel [121]. These findings have proven the feasibility of using cycloalkane to replace aromatic contents in the SAF. Hydrocracking and isomerisation are carried out after HDO process to enhance the quality of the produced fuel. Hydrocracking breaks down longer hydrocarbon chains into shorter chain structures that are compatible with jet fuel [119]. Meanwhile, isomerisation transforms n-paraffins into iso-paraffins structures, which lowers the fuel freezing point to fulfil ASTM specifications [122]. The findings have paved the way for advancing bio-based fuels without aromatics that exhibit elevated gravimetric heats of combustion and superior emission characteristics, extending the range of commercial and military aircraft and significantly mitigating the environmental impact of jet fuel combustion [121].

5.4. Carbohydrate to hydrogen: photofermentation

Hydrogen produced from fermentation of organic feedstock by microorganisms is commonly known as "biohydrogen" [1]. Photofermentation involves two primary types of enzymes: nitrogenase and hydrogenase. Nitrogenase plays a crucial role in nitrogen fixation, transforming nitrogen from wastewater or other carbohydrate-rich sources into ammonia and hydrogen [123], as shown in the equation below:

$$N_2 + 8H^+ + 8e^- + 16ATP \rightarrow 2NH_3 + H_2 + 16ADP + 16Pi \quad (1)$$

A limitation of photofermentation is its low efficiency in converting hydrogen, as it yields only 1 mol of hydrogen for every mole of nitrogen consumed [13]. When carbohydrate sources are substituted with volatile fatty acids such as lactate, acetate, butyrate and propanate, the biohydrogen yield can be augmented due to the impact of substrate conversion efficiency on production rates [123]. Hence, a sequential approach involving photofermentation after dark fermentation has emerged as highly promising for biohydrogen production. During dark fermentation, fermentative bacteria break down organic carbohydrate-rich substrates into volatile fatty acids which would be further transformed into hydrogen in the next stage [124]. The integration of these two stages, dark and photofermentation, holds the potential to theoretically enhance biohydrogen production by three to fivefold compared to standalone processes [124].

In the cases where nitrogen sources are limited, the hydrogenase enzyme facilitates the reversible oxidation of hydrogen to generate protons and electrons [13]. Under such conditions, the rate of light penetration becomes a crucial determinant in driving the reduction of protons to produce hydrogen [13], as depicted in the equation below:

$$2H^+ + 2e^- + 4ATP \rightarrow H_2 + 4ADP + 4Pi \quad (2)$$

As a by-product of dark fermentation, ethanol consumes protons in photofermentation process, thereby hindering the production of hydrogen [123]. Ag nanoparticles could act as catalysts in the dark fermentation process to stimulate the acetic acid metabolic pathways and reduce the ethanol generation [125]. Nanoparticles enhance the rate and yield of biohydrogen production for several reasons. Nanoparticles can immobilise both enzymes and fermentative bacteria, ensuring thermal and pH stability within the system, thus maintaining the optimal conditions with maximum biohydrogen production [126]. Besides that, nanoparticles have a relatively larger surface area that could enhance the metabolism of nitrogenase and hydrogenase enzyme, thus favouring hydrogen generation [123]. Photoactive nanoparticles, such as TiO_2, improve the efficiency of photo-active bacteria by facilitating the electron transfer to the active site of nitrogenase enzyme, and acquiring the light energy required for hydrogen evolution [126]. Furthermore, nanoparticles aid in breaking down the complex organic matter into smaller molecular compounds that could be easily broken down by the photo fermentative bacteria [125]. Although most nanoparticles such as Ag, Fe, Ni, TiO_2, etc, have demonstrated their ability to enhance biohydrogen production, their concentration is often capped due to the risk of impaired cell metabolism caused by high levels of metal ions [125].

In recent developments, a new work item, ASTM WK85474, has been proposed to establish a standard for aviation hydrogen fuels. This forthcoming standard aims to define the minimum property requirements for aviation hydrogen, making it suitable for use in fuel cells and turbines [127]. The proposed standard will serve as a comprehensive guideline for ensuring the quality of aviation hydrogen fuel from production to its use in aircraft [127]. However, the implementation of hydrogen as a fuel for aircraft presents significant challenges. It necessitates the development of a new fuel delivery system and the redesign of aircraft engines or the aircraft itself. Given these substantial modifications, drop-in fuels are currently preferred as replacements for conventional jet fuel due to their compatibility with existing infrastructure and technology. Although ASTM WK85474 is still in progress and has not yet been released, ASTM's intention to explore hydrogen as an aviation fuel is evident. This initiative underscores the potential of hydrogen fuel and warrants further investigation into its feasibility, including a comparison of its advantages and disadvantages relative to other existing fuels and SAF.

As shown in Fig. 14, the gravimetric density of ethanol, ecalene, methane, Jet A1, SAF, gasoline, diesel, biodiesel and hydrogen are 25, 28.4, 55, 43.28, 44, 44. 48.1, 38 and 120 MJ kg^{-1}, respectively. Ecalene is a blend of alcohols, and is generated through the process of biomass gasification, syngas purification, and alcohol synthesis [128]. It can be either used as a standalone fuel or as a fuel additive. The composition consists of approximately 30 % methanol, 45 % ethanol, 15 % propanol, 7 % butanol and 2 % hexanol [128]. In contrast, the volumetric density of ethanol, ecalene, methane, Jet A1, SAF, gasoline, diesel, biodiesel and hydrogen are 19, 22.7, 23, 35.06, 34.1, 32, 40.3, 33.3 and 8 MJ L^{-1}, respectively. The SAF has volumetric and gravimetric densities nearly similar to Jet A1, the most widely used fuel for aviation. The similarity is due to the modifications of SAF to have properties similar to Jet A1 to ensure compatibility and performance of the infrastructure system and existing aircraft. Most fuels have different properties from the Jet A1, which will require the modification of the infrastructure system and existing aircraft. This will augment research/modification costs and increase uncertainty in the existing system.

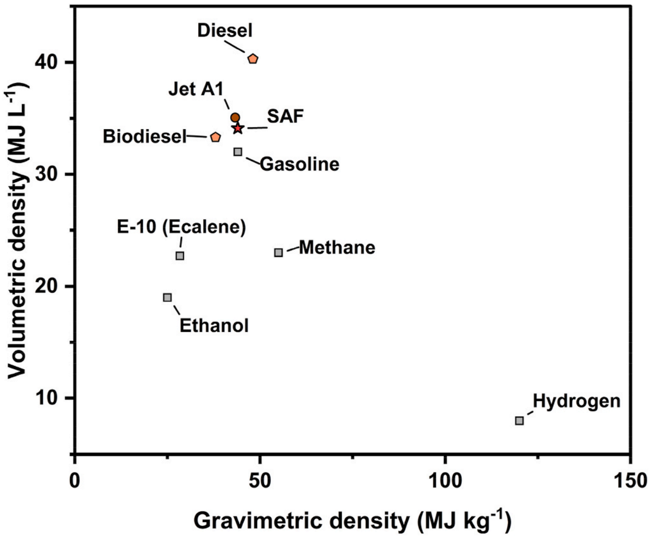

Fig. 14. Graph of volumetric density against gravimetric density of different fuels.

Hydrogen is a widely recognised clean and sustainable fuel option that does not emit harmful pollutants when consumed [129]. The ongoing development of hydrogen-powered aircraft is characterised by the need for substantial engine and aircraft design modifications when transitioning from kerosene to hydrogen as a fuel source. Disparities in combustion gases and properties drive this transformation. Consequently, despite the lower operational costs associated with hydrogen-operated aircraft compared to kerosene-operated ones, the conversion process incurs a significant 25 % increase in production and maintenance expenses [130]. The low volumetric density of hydrogen fuel indicates that it occupies more space than kerosene for an equivalent mass or energy content, thus requiring larger fuel tanks. This requirement for larger hydrogen storage tanks poses challenges for aviation engines as they need to be strategically positioned within the main body of the aircraft instead of the wings, resulting in a decrease in available space for passengers or cargo compartments, which is an economic drawback [130]. Consequently, effective hydrogen storage presents a significant hurdle for aviation engines, demanding careful development of tanks with specific criteria.

Table 10 summarises the potential of emerging technologies in addressing the challenges that have been faced by existing approved SAF pathways, and current challenges of emerging technologies.

6. Aviation fuel blends

The purpose of blending SAF with conventional aviation fuels is to ensure the same qualities and characteristics between SAF and conventional aviation fuels [9]. This is crucial to prevent the need to change the existing engine and aircraft design and a new fuel delivery system [9]. Unnecessary costs such as altering or updating the engine, transportation and storage system can be avoided by keeping the qualities and characteristics of the fuel constant [107]. The uncertain risk associated with fuel incompatibility and the existing engine and aircraft system can be reduced by blending. Several types of aviation fuel blends are summarised in Table 11. The three most prominent aviation fuel blends are discussed in the section below.

Aviation fuel blends that are prospective SAF are jatropha oil + Jet A1, babassu oil + Jet A1 and camelina oil + Jet A1. Jatropha oil, babassu oil and camelina oil present a promising blend with petroleum-derived jet fuel. Their sustainability is evident as these oils are non-edible, eliminating the competition between food and fuel resources. In 2017, the predominant feedstocks for global biodiesel production were still edible oils like palm oil (31 %) and soybean oil (27 %) [131]. Consequently, a shift towards second-generation, non-edible feedstocks is crucial. Exploring the feasibility of this blend requires a comprehensive study of its characteristics. Jatropha aviation fuel blend has a higher flash point, which makes it less flammable and reduces fire risk [8]. The transportation, handling and storage of jatropha aviation fuel blend is safe, and no alteration to the current transportation, handling and storage is required. The calorific value of the jatropha aviation fuel blend is 44.068 MJ kg^{-1}, which is higher than Jet A1 (42.8 MJ kg^{-1}) [8]. Jatropha aviation fuel blends can provide the same energy as conventional jet fuel but with less consumption. The kinematic viscosity of jatropha aviation fuel blends is 4.01 mm^2 s^{-1}, which is still within the acceptable range value of 3.5–8 mm^2 s^{-1} by the ASTM [8]. Lower kinematic viscosity is desired for aviation fuel to reduce the risk of accumulation of undesired compounds in the engine. Jatropha aviation fuel blend as SAF can reduce GHG emissions.

The next potential aviation fuel blend is babassu + Jet A1. It has a higher flash point than conventional jet fuel and jatropha + Jet A1, making it an even safer aviation fuel blend. Moreover, the calorific value of babassu + Jet A1 is 44.187 MJ kg^{-1}, which is much higher than that of Jet A1 at 42.8 MJ kg^{-1} [8]. The kinematic viscosity of babassu + jet

Table 10

Outlook on emerging technologies and current challenges.

Emerging Technologies	Potential of Emerging Technologies to address challenges in existing approved SAF Pathways	Summary of Current Challenges
Hydrothermal Liquefaction	The utilisation of microalgae as feedstock can have a minimal impact on land use change and overall lifecycle GHG emissions. This approach offers a solution to the issue of SAF dependence on first-generation feedstocks while leveraging mature technologies from the HEFA process. While HC-HEFA-SPK also utilises microalgae as feedstock, hydrothermal liquefaction allows bio-oil extraction from wet biomass, thus eliminating the energy-intensive and time-consuming drying process.	At the same time, using microalgae as a feedstock for SAF production presents several challenges. The nitrogen content in microalgae can create issues during the combustion and hydrotreating processes. Additionally, it is reported that SAF derived from microalgae typically has a higher freezing point than conventional jet fuels, which poses a challenge to fuel blending. The distinct properties of bio-oil derived from microalgae compared to vegetable oil, pose challenges in hydrothermal liquefaction. This issue also affects HC-HEFA-SPK, limiting its blending ratio to 10 %. Therefore, further research is encouraged to explore hydrotreating steps that could enhance the properties of SAF produced from microalgae.
Aqueous Phase Reforming	The APR process involves biomass conversion under moderate conditions, avoiding the high temperature and pressure modifications required by processes like FT. This offers an alternative technical route for converting biomass into SAF. It is essential to evaluate the technical and economic aspects of this SAF pathway to understand its energy consumption and feasibility compared to other SAF routes.	The process is raising environmental concerns as it generates wastewater throughout the process. Therefore, a wastewater recovery system is necessary, which potentially increases the production cost of SAF. Virent is leading the evaluation under ASTM D4054 for synthesised aromatic kerosene (SAK) produced through APR of sugars and catalytic processing.
Pyrolysis	Pyrolysis of lignocellulosic biomass produces cycloalkanes, which have combustion characteristics comparable to isoalkanes and higher gravimetric heats of combustion compared to aromatic compounds. This process might address the issue of low aromatic content in SAF, resulting in an aromatic-free SAF with comparable engine compatibility and lower particulate matter emissions.	Currently, Alder and Green Lizard are the two leading developers, who are undergoing the evaluation process of biomass pyrolysis under ASTM D4054. Additionally, Vertimass is being evaluated for using cycloalkane derived from ethanol as SAF.
Photofermentation	The advantages of hydrogen include its potential to completely replace conventional jet fuel, leading to a significant reduction in greenhouse gas emissions from the aviation sector due to its clean combustion process. Additionally, its high gravimetric density indicates its lightweight nature, which is especially beneficial for aircraft where weight is a crucial factor. A proposed new ASTM standard for hydrogen aviation fuel, ASTM WK85474, indicates the progress in hydrogen fuel technology. The implementation and normalisation of hydrogen SAF may be realised in the near future.	The primary challenge associated with using hydrogen as an aviation fuel, is the need for extensive aircraft design modifications, marking a revolutionary transition phase that demands significant investment and determination. Additionally, the low volumetric density of hydrogen implies the necessity of larger storage tanks in aircraft, which further reduces available space of the aircraft.

A1 is 3.87 $mm^2\ s^{-1}$, which is close to the best possible quality of aviation fuel of 3.5 $mm^2\ s^{-1}$.

In contrast, the camelina fuel blend has rapid ignition onset (RIO), ensuring efficient engine startup [132]. The RIO can prevent incomplete combustion of fuel, which can increase the safety of passengers and aircraft as no carbon monoxide is produced. Furthermore, camelina fuel has a higher calorific value than conventional by a slight margin [132]. The aircraft's flight range can be increased as more energy can be carried by the existing fuel tank due to higher calorific value. It also reduces GHG, particle number, and mass by around 50 % and 60 %, respectively [132].

7. Techno-economic analysis and Life Cycle Analysis for SAF production

Techno-Economic Analysis (TEA) is used to analyse industrial processes' technical performance and economic viability [116,137]. It helps predict the processes' expenditures and profits [138]. In TEA, the processes are usually modelled using simulation software to estimate the mass and energy balances. Alternatively, Life Cycle Analysis (LCA) is a technique for assessing the potential environmental impacts associated with the life cycle of a process or product [138]. The cradle-to-grave LCA, defined by the International Organization for Standardization (ISO 14040 and ISO 14044), consists of four stages: defining goal and scope, inventory analysis, impact assessment and interpretation of results [137]. By considering the results of LCA in critical decision-making of the aviation industry, the emissions of GHG could be decreased by 3 % annually [9]. In the past, the LCA of aviation fuels mainly focused on the carbon emissions during the combustion of fossil fuels [9]. Today, the new processes developed to produce jet fuels may emit more carbon than the combustion stage. Hence, the LCA has to consider the total carbon footprint of various stages. The environmental impact of GHGs is a significant concern as the aviation industry produces approximately 915 million tons of GHGs, including carbon dioxide, nitrous oxide and methane. Generally, the global warming potential (GWP) is used to quantify the energy that can be absorbed by one ton of GHG [137]. It is expressed as carbon dioxide equivalent emissions (CO_2eq) per functional unit. This allows better comparisons between the impacts of different gases and consistency with the Intergovernmental Panel on Climate Change (IPCC) guidelines [137,139].

7.1. SAF production processes

7.1.1. Gasification

Umenweke et al. [137] conducted TEA and LCA to evaluate the economic and environmental impacts of two SAF production processes from tall oil fatty acid (TOFA) using catalytic deoxygenation. Scenario 1 used the commercial grey hydrogen gas generated from steam reforming, whereas Scenario 2 adopted hydrothermal gasification to produce

Table 11
Different types of potential aviation fuel blends.

Blend type	Blend percentage	Performance	Advantages	Limitations	Ref.
Jatropha + Jet A1	10 %	• Higher flash point (48 °C) • Higher calorific value (44.068 MJ kg^{-1})	• Reduce waste as it utilises the jatropha oil, which is toxic to human and animal • Reduce GHG emission	–	[8]
Babassu + Jet A1	10 %	• Higher flash point (49 °C) • Higher calorific value (44.187 MJ kg^{-1})	• Reduce GHG emission	–	[8]
Palm kernel + Jet A1	10 %	• Higher flash point (48 °C) • Higher calorific value (43.990 MJ kg^{-1})	• Reduce GHG emission	–	[8]
Lignin-based jet fuel + Jet A1	10 %	Similar surface tension, density, viscosity at 20 °C derived cetane number and flash point of Jet A1	• Higher fuel performance, higher fuel efficiency • Higher average carbon number • Lower aromatics content than conventional jet fuel (14–20 wt%)	• Higher viscosity at low temperature • Higher freezing point	[133]
Canola + ethanol + Jet A1	20 % Canola 10 % Ethanol	–	• Has a 35 % reduction in nitrogen oxides and 42 % in carbon monoxide if compared to Jet A fuel	• The static thrust of Jet A fuel is 30 % more than C20E at the speed of the engine of 30,000 rpm	[134]
Pyrolysis oil (PO) + ethanol + Jet A1	20 % PO 10 % Ethanol	–	• Has a 42 % reduction in nitrogen oxides and 47 % in carbon monoxide if compared to Jet A fuel	• The static thrust of Jet A fuel is 16 % more than P20E at the speed of the engine of 30000 rpm	[134]
Butyl butyrate + Jet A1	20 %	• Kinematic viscosity of 4.191 mm^2/s • Same flash point with Jet A1	• Reduce GHG emission	• Lower energy density	[135]
Camelina oil + Jet A1	50 %	• Rapid onset of ignition • Higher energy density (43.2 MJ kg^{-1})	• Reduce GHG emission • Reduce particle number and mass emissions behind the aircraft by 50 %–70 % if compared to petroleum fuel	• Yield of camelina oil is relatively low, 273.4 kg/ha over a 4-year growing season	[132, 136]

hydrogen gas. In this study, the processes were modelled using Aspen Plus. The plant was proposed to be in Kentucky, United States. The currency and the tax rate were the United States Dollar (USD) and 30 %, respectively. In this model, three years were required to construct the plant that operated for 8000 h $year^{-1}$ and had a lifetime of 20 years. A straight-line depreciation method was used, and the time estimated was 15 years. The land cost was 2 % of the fixed capital investment (FCI). The base year used to develop the model was 2021. The cost of inputs, such as feedstock, electricity, and catalyst, were considered when estimating the minimum fuel selling price (MFSP). Capital expenditure (CAPEX) included direct and indirect costs, whereas operating expenditure (OPEX) included fixed and variable operating costs. The net present value (NPV) was also used to determine the plant's profitability over the operating period.

Using **Equation (3)**, it was estimated that 18 and 25 operators were needed for Scenario 1 and 2, respectively. N_{OL} is the number of operators, N is the number of non-particulate processing steps, and P is the number of steps that handle solid.

$$N_{OL} = \sqrt{31.7P^2 + 0.23N + 6.29} \tag{3}$$

As represented in **Equation (4)**, the scaling exponent method was employed to estimate the equipment cost. C and S are the calculated equipment costs and the capacity obtained from the simulation, whereas Co and So are the base equipment costs and capacity. The scaling exponent is denoted by f. The factor ranges between 0.8 and 0.9 if the process involves gas compression and mechanical work.

$$C = C_o\left(\frac{S}{S_o}\right)^f \tag{4}$$

Based on the TEA results, the cost of equipment (COE) of Scenario 2 ($80.6 million) was higher than that of Scenario 1 ($71.6 million). The reactor and the membrane housing were added for hydrothermal gasification to produce hydrogen in Scenario 2. The hydrothermal gasification unit increased the plant's capacity. This resulted in higher maintenance costs, labour and materials in Scenario 2. In the study, OPEX was mainly contributed by the costs of raw materials. Hence, the OPEX of Scenario 2 ($70.51 million) was relatively low as hydrogen was produced *via* hydrothermal gasification.

On the contrary, Scenario 1 required commercial hydrogen (US$ 0.7955 kg^{-1}) as its raw material, making its OPEX higher ($122.14 million). The positive undiscounted NPV of both scenarios showed that the processes were profitable during the plants' operating periods. Considering the profitability indicators, i.e. payback period (PBP), MFSP, and NPV, Scenario 2 with the hydrothermal gasification process was more profitable. The shorter PBP indicated that Scenario 2 needed a shorter time to recover the investment cost. Additionally, the sensitivity analysis found that equipment and raw materials costs impacted the MFSP significantly. The MFSP of SAF increased from US$ 0.39 to US$ 0.45 and US$ 0.43 when the total raw materials and equipment purchase costs increased by 30 %, respectively. Other parameters investigated, including tax rate and capital, had a minor impact on the MFSP.

The CCalC2 software (v.1.1) and Ecoinvent were used for the LCA to obtain the inventory data. Aspen Plus simulation provided the mass and energy balances required to identify and quantify SAF production input and output parameters. Generally, the inventories involved were transesterification, hydrothermal gasification, SAF production and product separation and purification processes. Fig. 15 illustrates the LCA system boundary defined for the process. The inventories were hydrothermal gasification and transesterification. In the study, hydrothermal gasification was only included in Scenario 2. The production process involved TOFA production, catalyst synthesis, and decarboxylation/decarbonylation reactions (deCOx). This was followed by product separation and SAF upgrading through purification. LCA revealed that the environmental footprint of Scenario 2 was lower than Scenario 1. By adopting the SAF production process with hydrogen generation through hydrothermal gasification, the GHG emission of Scenario 2 (5.1 g CO_2eq MJ^{-1}) was 94 % lower than the commercial jet fuel production process (85 g CO_2eq MJ^{-1}). Also, the GHG emission of Scenario 1 was 20.8 g CO_2eq MJ^{-1}, which was 75 % higher than Scenario 2 as the commercial hydrogen produced from the steam reforming was used. This indicated that integrating the hydrothermal gasification process, as in Scenario 2, helped to reduce the global warming potential significantly. Based on the GWP of different stages in the LCA, hydrogen production and distillation emissions were the greatest. These processes required high energy, and the combustion of fuel was involved. The emissions associated with the $deCO_x$ and product separation were relatively low,

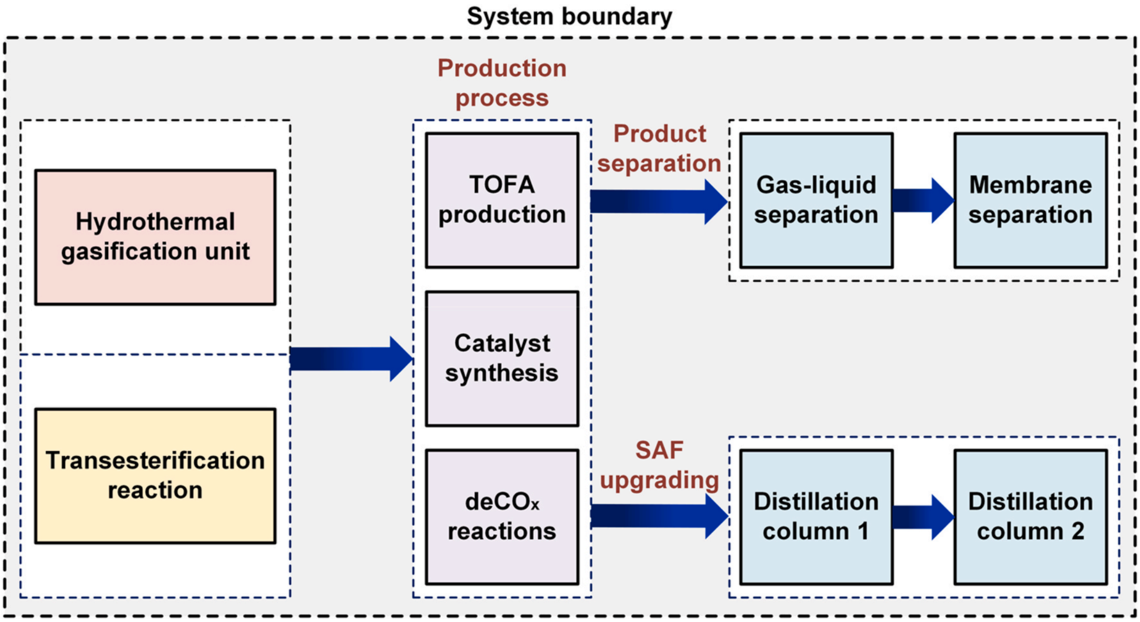

Fig. 15. The LCA system boundary for the process integrates hydrothermal gasification and decarboxylation [137].

ranging between 0.00015 and 0.0092 kg CO_2eq functional unit^{-1}.

7.1.2. ATJ process

Neuling and Kaltschmitt [139] performed TEA and LCA on the biokerosene production from wheat grain *via* the ATJ process. In that study, the parameters considered were the total process efficiency, provision of biokerosene and GHG emissions throughout the complete life cycle. Process modelling and simulation using Aspen Plus were performed for the TEA to obtain the mass and energy balances. The Aspen Energy Analyser was used for heat integration through the pinch analysis. The TEA applied the nth plant theory. The Chemical Engineering Plant Cost Index (CEPCI) was applied to normalise the costs to the base year 2014. The ATJ process was assumed to have an economic lifetime of 20 years and operate 7500 h year^{-1}. The required interest rate was 4 %. Subsequently, the total costs incurred were calculated by summing up the costs associated with capital, consumption, and operation. Finally, the total costs to produce the biokerosene were computed by dividing the total costs by the kerosene amount in a year.

In this case, the capital costs included the investment costs determined using **Equation (5)** and equipment installation costs. The costs related to consumption were calculated based on the flows of mass and energy obtained from the simulation workflow. Table 12 presents the assumed prices of the feedstock and by-products from the kerosene production. The costs of processing water, electricity, chemical and biocatalysts were also considered. The ATJ production process modelling results are presented in Table 13, where the negative and positive values were the input and output parameters, respectively. Based on the simulation results, ATJ produced 65 t h^{-1} kerosene with an overall process efficiency of 68 % and kerosene-specific efficiency of 42 %. Table 14 lists the costs for the ATJ production process. The economic analysis found that the costs related to consumption were higher than the production costs. However, the cost competitiveness of the biokerosene produced *via* the ATJ process was lower than that of fossil kerosene. The price gap between fossil fuel and biokerosene may be reduced due to increasing prices and carbon penalties. The uncertain parameters in the TEA, including the technical availability, economic lifetime and costs of the wheat grain and investments of the ATJ process, were deemed to vary by ±60 % potentially. The wheat grain (feedstock) expenditure was a critical factor influencing production costs. It was

Table 12
Price of the feedstock and biobased by-products.

Feedstock/Biobased by-products	Price
Wheat grain	160 €/t
Butane	1185 €/t
Naptha	870 €/t
Diesel	908 €/t
Electricity	0.07 €/kWh

Table 13
Results of the ATJ production process modelling.

Parameter	Value
Mass flow (kg h^{-1})	
Feedstock	−385050
Methane	−5109
Butane/Naptha	9249
Kerosene	65777
Diesel	31756
Energy flow (MW)	
Feedstock	−1823
Methane	−67
Electricity	−11
Butane/Naptha	112
Kerosene	798
Diesel	386
Energy efficiency	
Overall process	68
Kerosene fraction	42

Table 14
Calculated costs for the ATJ production process.

Cost	Value
Total investment costs (M€)	654.5
Operation-related costs (M€ a^{-1})	12.0
Consumption-related costs (M€ a^{-1})	624.7
Other costs (M€ a^{-1})	21.3
Revenues	
Butane/Naphtha (M€ a^{-1})	82.2
Diesel (M€ a^{-1})	216.2
Electricity (M€ a^{-1})	0
Biokerosene production costs (€ t^{-1})	827

estimated that a price drop of 100 € t^{-1} in wheat grain could result in a 4-fold (400 € t^{-1}) reduction in the production costs of kerosene.

$$(\text{cost of equipment})_x = (\text{cost of equipment})_{\text{base}} \bullet \left(\frac{\text{capacity}_x}{\text{capacity}_{\text{base}}}\right)^{\text{scaling factor}} \tag{5}$$

The system boundary covered the pre-chains and conversion process to perform the LCA assessment. Fig. 16 depicts the LCA system boundary for the SAF production from the ATJ process. The plant was in Germany, and the functional unit was defined to be 1 MJ of kerosene. By using energy as the basis, the total emissions of the kerosene and other by-products were determined. An inventory analysis was carried out to identify and quantify the input and output parameters. In the environmental impact assessment, the period used for global warming potential was 100 years. The GHG emission of the Jet A1 reference in this study was 87.5 g CO2eq MJ^{-1} kerosene. The results of the LCA showed that the GHG emission of the ATJ production route of 71.5 g CO_2eq MJ^{-1} kerosene was lower than that of Jet A1. Suppose the fossil methane was substituted with the biomethane to produce hydrogen through the steam methane reforming. In that case, the GHG emission of the ATJ production pathway might be further reduced by 1.2 g CO_2eq MJ^{-1} kerosene. Based on the sensitivity analysis, the biomass cultivation stage was the major contributor to GHG emissions. Hence, the emissions may be reduced by optimising the cultivation, improving the specific yields and minimising the effects of land use. Additionally, the use of nitrogen fertilisers also leads to the emissions of nitrous oxide. As the energy density of the biomass feedstock is low, the logistics have a more significant impact on the emissions. Thus, optimising feedstock transportation may also help to reduce emissions further.

7.2. *Feedstock*

7.2.1. *Bio-hydrocarbon*

Vela-García et al. [140] conducted TEA and LCA on sequentially producing tri isobutane from cellulosic isobutanol *via* dehydration, oligomerisation and hydrogenation. The system boundary is presented in Fig. 17. The dehydration and hydrogenation stages involved separation and distillation processes, whereas the oligomerisation stage comprised separation and reaction. Generally, the investment costs per dehydration, oligomerisation and hydrogenation were 3,591,414 €, 918,300 € and 1,816,608 €, respectively. Assuming that 390 tonnes day^{-1} of isobutanol was used, 31.78 million gallons $year^{-1}$ of tri isobutane could be obtained. The MSP of the tri isobutane (1.34 € kg^{-1}) almost doubled the MSP of Jet A1 (0.76 € kg^{-1}). One of the factors that caused process overpricing was that the feedstock price was high and contributed to about 68 % of the variable operating costs. Also, more complex technologies may be required to ensure that the fuel produced fulfils the ASTM Standard, resulting in higher costs. In addition, the input costs were expected to be relatively high as the production of tri isobutane is less common compared to Jet A1. Although the price of triisobutane was 0.58 € kg^{-1}, more elevated than the conventional fuel, the low mixture rate (about 30 vol%) required for the triisobutane-ATJ could help reduce the cost. By assuming that distribution of an additional 0.42 € L^{-1} to 1.20 € L^{-1} was required for the intra-EU-27 and domestic flights, the fare for a 1000 km flight would increase from €1.20 to €4.30 per passenger. This improved the affordability of the flight fare.

In the sensitivity analysis, the parameters considered were lignin's MSP and isobutanol's cost. Lignin is a valuable by-product that is saleable after reconditioning. It may be used to generate energy. Considering the market value, the MSP of low-purity and high-purity lignin was between 165 € t^{-1} for low and 680 € t^{-1} for high-purity lignin. In addition, the cost of isobutanol was between 1.53 € kg^{-1} and 0.64 € kg^{-1} for the 45 % and 95 % conversion yields of glucose and xylose, respectively. Although the reduced MSP of triisobutane was higher than the MSP of Jet A1, selling the high-purity lignin could significantly lower the MSP of triisobutane. If the European price of CO_2eq emissions was considered, additional charges of 0.10 € kg^{-1} Jet A1 and 0.06 € kg^{-1} triisobutane may be required. Overall, by adequately varying the costs of CO_2eq emissions and lignin's sales, the MSP of triisobutane (0.85 € kg^{-1}) may be lower than the Jet A1 (0.87 € kg^{-1}).

The emission caused by the production of triisobutane from isobutanol was 6.60 g CO_2eq MJ^{-1} triisobutane, with 91.3 % contributed by the natural gas combustion for isobutanol dehydration. Another 8.4 % of the emission was caused by hydrogen production. Also, the calculation of the total emission of the process incorporated the GHG footprint of 57.96 g CO_2eq MJ^{-1} triisobutane formed during the conversion of isobutanol. This resulted in the process emissions of 64.54 g CO_2eq MJ^{-1} tri isobutane. Fig. 18 compares the emissions of the studied process with those caused by the ASTM-certified production routes for Jet A1, ATJ and HEFA. HEFA with palm oil (PO) and jatropha oil (JO) were chosen for comparison as it is a commercial route approved by ASTM which has been successfully implemented on an industrial scale. Other routes compared are the Alcohol-to-Jet with wheat straw (ATJ-WS) and Alcohol-to-Jet with wheat grain (ATJ-WG) pathways. It was found that 28 % relative reduced GHG emissions to the Jet A1.

The isobutanol production process needs to be more efficient to lower GHG emissions. It consumed 17.14 MJ kg^{-1} isobutanol of fossil fuel, which is 70 % higher than necessary to upgrade the isobutanol to

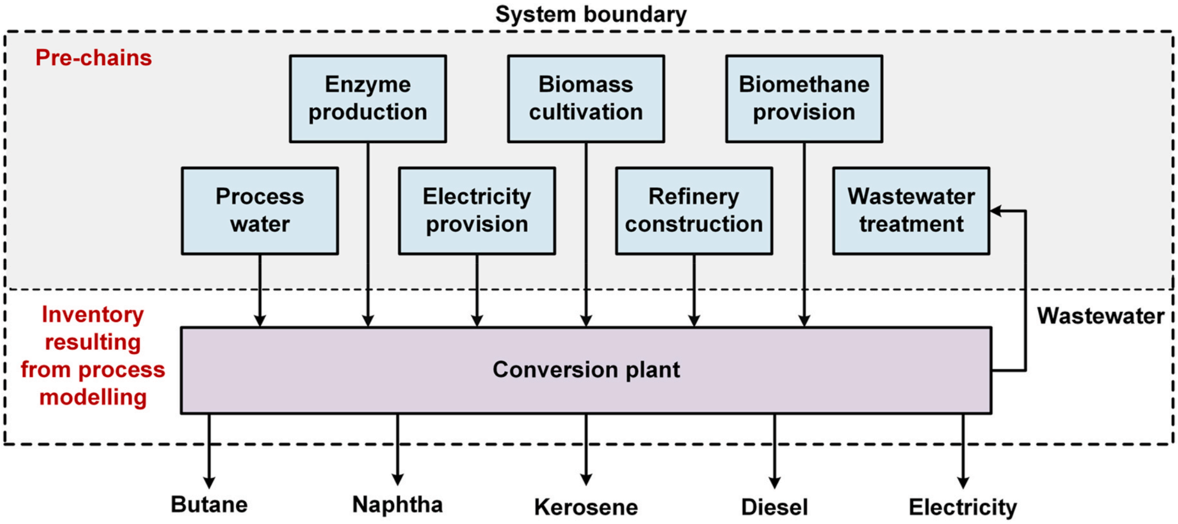

Fig. 16. LCA system boundary for the SAF production from the ATJ process [139].

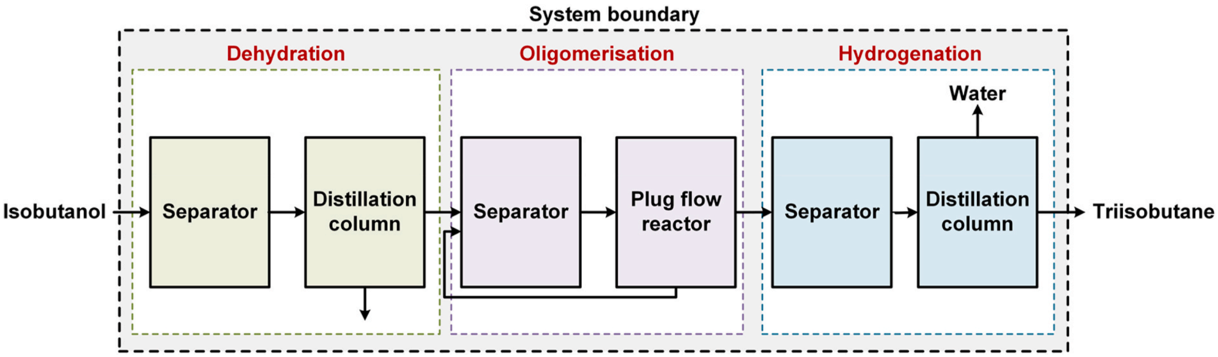

Fig. 17. System boundary for the production of tri-isobutane from cellulosic isobutanol.

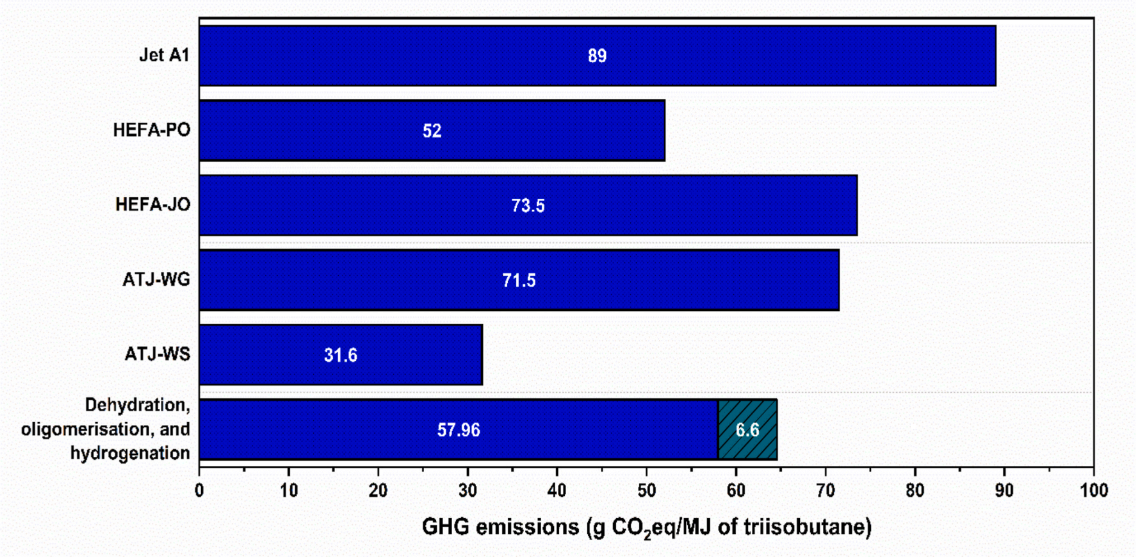

Fig. 18. Emissions of the studied process in the work by Vela-García et al. [140] with those caused by the ASTM-certified production routes for Jet A1, ATJ and HEFA.

tri-isobutane. This caused 90.24 % of direct CO_2eq emissions. The emissions were primarily associated with the processes involved in producing, harvesting and pre-treating the raw materials and converting the cellulose into simple sugars. Hence, developing novel catalysts to enhance the process efficiency seems significant. Additionally, the water directly consumed to produce isobutanol was 11.40 L kg^{-1} isobutanol. However, water was not required to upgrade the isobutanol. To dehydrate the isobutanol, 0.44 L water kg^{-1} tri-isobutane was collected as the wastewater due to impurities. Notably, the physicochemically treated wastewater may be recycled to pre-treat the biomass in the isobutanol conversion stage.

Challenges and outlook

Large-scale SAF production faces several challenges that must be addressed for widespread adoption. The primary challenge is securing a sufficient, sustainable feedstock supply for SAF production. Common feedstocks include waste oils, agricultural residues and non-food energy crops. However, scaling up production to meet the demand for SAF requires finding sustainable and abundant feedstock sources without competing with food production or causing deforestation [8]. Currently, the cost of producing SAF is significantly higher than conventional jet fuel. This cost disparity challenges large-scale adoption, as airlines are often price-sensitive. Reducing production costs through technological advancements, process optimisation and economies of scale is crucial to make SAF economically viable. Moreover, developing and commercialising efficient and scalable conversion technologies for converting feedstocks into SAF is a significant hurdle. The existing conversion processes, such as hydroprocessing and FT synthesis, need further improvement to enhance efficiency, reduce costs and increase production volumes [41,141]. Research on nanomaterials with advanced surface-functionalisation properties is essential to improve the efficiency of biomass conversion [113]. Implementing these nanocatalysts in SAF production could significantly optimise the process, boosting overall efficiency and reducing costs [113]. Furthermore, the aviation industry requires a well-established SAF production, blending, and distribution infrastructure. Expanding the infrastructure to support large-scale SAF production would require significant investments, including retrofitting existing refineries, establishing new production facilities and developing a distribution network that can reach airports worldwide [107].

Governments and international organisations must implement policies encouraging investment in SAF technologies, providing financial incentives and setting mandates for SAF usage to drive demand and create a stable market. It is also imperative to establish robust certification and standardisation processes for SAF to ensure quality, sustainability, and compatibility with existing aircraft and infrastructure. Developing reliable and internationally recognised standards will enhance confidence in SAF and facilitate its widespread use. Lastly, scaling up SAF production requires collaboration among stakeholders, including feedstock suppliers, fuel producers, airlines, and policymakers. Collaboration is needed to share knowledge, invest in research and development and establish partnerships to overcome large-scale production's technical, financial and logistical challenges. As outlined in the preceding sections, a pivotal strategy involves delving into a diverse array of feedstock options to tackle the challenges associated with large-scale SAF production. Researchers are investigating alternative sources such as algae, municipal solid waste, and carbon dioxide (CO_2) capture and utilisation. Diversifying feedstocks can help reduce competition with food production, minimise environmental impact, and ensure a sustainable supply. Furthermore, advancements in conversion technologies are being researched and developed to improve efficiency and reduce costs; this includes catalyst development, process optimisation, and innovative techniques like pyrolysis, gasification, and bioconversion [41,142]. These advancements aim to enhance the conversion efficiency of feedstocks into SAF and reduce overall production costs. Another option to reduce production costs is incorporating renewable energy sources into the production process, which can help reduce the carbon footprint of SAF production. Utilising solar, wind, or geothermal energy to power production facilities can significantly enhance the sustainability of the entire value chain.

Governments and international organisations are implementing policies as listed in Section 1 and providing incentives to support SAFproduction; this includes setting blending mandates, offering tax credits or subsidies, and establishing favourable regulatory frameworks that encourage investment in SAF technologies [33,36]. These measures aim to create a stable market and attract private sector participation. Nonetheless, collaboration between the public and private sectors is essential for scaling up SAF production. Public-private partnerships can leverage both sectors' expertise, resources, and funding to accelerate research and development, facilitate investments, and establish production and distribution infrastructure. Increasing investments in research and development (R&D) is crucial for advancing SAF technologies. Governments, industry players, and research institutions are allocating funding and resources towards R&D initiatives focused on feedstock development, conversion processes, and efficiency improvement. These investments aim to drive innovation and accelerate the deployment of cost-effective and sustainable SAF production. International collaboration and establishing common standards are fundamental for the global adoption of SAF. Organisations like the ICAO and the Roundtable on Sustainable Biomaterials (RSB) are working towards setting globally recognised sustainability criteria, certification standards, and best practices for SAF production [37]. These efforts promote consistency, transparency, and trust in the SAF market. Airlines and other stakeholders can provide certainty to SAF producers by entering into long-term contracts and offtake agreements. Such agreements guarantee a market for SAF, reduce financial risks and provide a stable foundation for upscaling production [143]. By combining these proposed solutions and approaches, the challenges associated with large-scale SAF production can be overcome and accelerate the transition towards a more sustainable aviation industry.

CRediT authorship contribution statement

Jason Ik Cheng Lau: Writing – original draft, Conceptualization. **Yu Si Wang:** Writing – original draft, Conceptualization. **Tiffany Ang:** Writing – original draft, Conceptualization. **James Chai Fah Seo:** Writing – original draft, Conceptualization. **Sabeeha N.B.A. Khadaroo:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Jiuan Jing Chew:** Writing – review & editing, Funding acquisition. **Andrew Ng Kay Lup:** Writing – review & editing. **Jaka Sunarso:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they possess no identifiable conflicting financial interests or personal connections that might have seemed to impact the findings presented in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2024.107277.

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