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A critical review of holistic 4E approaches for assessing sustainable aviation fuel pathways: Implications for feedstock, technology, policy and scale-up

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ABSTRACT

The aviation sector urgently requires decarbonization, positioning Sustainable Aviation Fuels (SAF) as the most viable near-term option for reducing fossil jet fuel dependence. However, SAF scale-up remains constrained by coupled technological, thermodynamic, economic, environmental, and policy related trade offs. Although many studies assess individual dimensions of SAF production, the literature still lacks a critical synthesis explicitly connecting Energy, Exergy, Economic, and Environmental (4E) evidence across certified pathways. This review examines 4E related approaches applied to SAF by linking energy and exergy analyses with techno economic assessment, life cycle assessment (LCA), and their exergoeconomic and exergoenvironmental extensions where available. The systematic review reveals a fragmented evidence base, with only a limited subset of studies quantitatively addressing all four dimensions. Hydroprocessed Esters and Fatty Acids remains the most mature and economically competitive route, but its scalability is limited by sustainable lipid feedstock availability, hydrogen sourcing, and land use constraints. Gas-to-Jet, Alcohol-to-Jet, and Sugar-to-Jet offer greater feedstock flexibility or biochemical innovation, but face higher capital intensity, upgrading complexity, hydrogen demand, or blend limit restrictions. Across pathways, thermodynamic irreversibilities in heat exchange, separation, syngas conditioning, fermentation, and upgrading stages propagate into cost formation and environmental burdens. LCA evidence shows that Greenhouse gases reductions depend strongly on feedstock origin, hydrogen source, allocation choices, and system boundaries. By organizing these interdependencies through a pathway level 4E indicator linking matrix, this review provides an evidence based foundation for more transparent comparative assessments, process optimization, investment analysis, and policy design for SAF deployment.

Index summary

Abbreviation	Description
1G	First-generation feedstock
2G	Second-generation feedstock
3G	Third-generation feedstocks
4G	Fourth-generation feedstocks
4E	Energy, Exergy, Economic, and Environmental
LCA	Life Cycle Assessment
AUEC	Average Unitary Exergy Cost
AP	Acidification Potential
AtJ	Alcohol-to-Jet pathway
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CED	Cumulative Energy Demand
CH	Catalytic Hydrothermolysis
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
EBITDA	Earnings Before Interest, Taxes, Depreciation, and Amortization
EU ETS	European Union Emissions Trading System
FD	Fossil Depletion
FFB	Fresh Fruit Bunch (palm feedstock)
FRL	Fuel Readiness Level
FT	Fischer–Tropsch synthesis (Gas-to-Jet pathway)
FU	Functional Unit
GHG	Greenhouse Gas
GtJ	Gas-to-Jet pathway
GWP	Global Warming Potential

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Abbreviation	Description
HEFA	Hydroprocessed Esters and Fatty Acids (Oil-to-Jet)
HRJ	Hydroprocessed Renewable Jet fuel
HT	Human Toxicity
HTL	Hydrothermal Liquefaction
H_2	Hydrogen
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
ISO	International Organization for Standardization
LMC	Land Management Change
LUC	Land Use Change
LCI	Life Cycle Inventory
MJSP	Minimum Jet Selling Price
MSW	Municipal Solid Waste
NPV	Net Present Value
OPEX	Operational Expenditure
OtJ	Oil-to-Jet pathway
PO	Photochemical Oxidation Potential
ProBioQAV	National Sustainable Aviation Fuel Program
ROI	Return on Investment
RTFO	Renewable Transport Fuel Obligation
SAF	Sustainable Aviation Fuel
SB	System Boundary
SDGs	Sustainable Development Goals
SIP	Synthetic Iso-Paraffins
SPK	Synthetic Paraffinic Kerosene
StJ	Sugar-to-Jet pathway
TRL	Technology Readiness Level
UC	Unit Cost (economic indicator)
UCO	Used Cooking Oil

1. Introduction

The aviation industry has grown rapidly in recent years, supporting tourism, trade, and global economic activity [1–3]. According to the International Air Transport Association (IATA), the trade association for the world's airlines, passenger numbers are expected to more than double over the next 20 years, with an annual growth rate of 3.5% [1]. In 2018, aviation accounted for 2.4% of global anthropogenic greenhouse gas (GHG) emissions, and CO_2 emissions reached 0.8 Gt in 2022, with projections of 2.0 Gt by 2050 [4]. This sharp increase underscores the urgency of emission mitigation.

The International Civil Aviation Organization (ICAO), a United Nations agency that sets global aviation standards, established the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), a global mechanism designed to stabilize net carbon dioxide emissions from international aviation by offsetting growth above baseline levels. At the same time, IATA introduced the "Fly Net Zero" strategy. Both initiatives converge on the sector's commitment to achieve net-zero carbon emissions by 2050 [5]. This transition depends heavily on SAF, recognized as the most viable short-term strategy to decarbonize air transport [6,7].

SAF can be produced from renewable feedstocks including dedicated biomass crops (e.g., oilseeds and sugar/starch crops), bio-oils, animal fat, recycled oils, municipal solid waste, and lignocellulosic (forest and agricultural) residues. Conversion pathways include gas-to-jet (GtJ), oil-to-jet (OtJ), alcohol-to-jet (AtJ), and sugar-to-jet (StJ) [8–11]. Certified under ASTM D7566 and D1655, these fuels are chemically similar to Jet-A1, the kerosene-based aviation fuel used in turbine engines and serving as the international standard for commercial aircraft, and function as drop-in replacements compatible with existing infrastructure, with blending ratios typically between 5% and 50% [8,12].

At the global level, policy mechanisms are accelerating the deployment of SAF. Initiatives such as CORSIA [13], ReFuelEU Aviation [14], and Brazil's RenovaBio [15,16] and ProBioQAV program [17] highlight the key role of regulation in reducing market uncertainty and encouraging private investment.

SAF production has expanded significantly in recent years, reaching 0.6 million m^3 in 2023, compared to 0.1 million m^3 in 2021, yet still represents only 0.2% of global jet fuel consumption [18]. The promotion of SAF directly contributes to the Sustainable Development Goals (SDGs) 7, 9, and 13, by fostering clean energy, eco-efficient industries, and climate action [19]. Table S1 in the supplementary material summarizes recent reviews on SAF feedstocks, pathways, and policies, and shows a fragmented treatment of sustainability dimensions.

Although several studies have assessed SAF pathways from techno-economic and environmental perspectives, no comprehensive review to date has systematically synthesized the four pillars of sustainability into a unified analytical framework: energy, exergy, economic, and environmental (4E). This fragmented treatment limits the ability of such assessments to capture systemic trade-offs, potentially leading to technology rankings or policy recommendations that are optimal within isolated dimensions but suboptimal when evaluated from an integrated sustainability perspective. In practice, this limitation hampers the comparability of SAF pathways and constrains the formulation of coherent long-term decarbonization strategies. The present study, structured around the 4E analyses, addresses this gap by combining individual assessments and their interactions, enabling a systemic evaluation of SAF production. Fig. 1 illustrates the proposed process of knowledge building through integrated system understanding, providing robust inputs for more assertive policies and standards.

The existing literature extensively covers individual aspects of SAF, such as conversion processes, feedstock potential, techno-economic assessments (TEA), and environmental life cycle assessments (LCA). However, reviews integrating these dimensions are rare. As noted by Afonso et al. [20], TEA and LCA studies are often conducted independently, using disconnected methods and boundaries. This fragmentation makes it difficult to see system interdependencies, for example, how thermodynamic losses (exergy) simultaneously increase costs and environmental impacts. As a result, such siloed assessments may generate conclusions that are internally consistent within individual dimensions, yet misleading when used to inform technology selection, investment decisions, or policy design at system level. The 4E analytical framework overcomes this limitation by treating these dimensions as interconnected pillars of a single system, revealing critical synergies and trade-offs for holistic assessment.

Without such an integrated perspective, sustainability evaluations of SAF pathways remain structurally incomplete, as apparent improvements in environmental performance or economic feasibility may be achieved through increased thermodynamic irreversibilities, hidden cost transfers, or upstream environmental burdens. This limitation is particularly relevant for SAF scale-up, where small inefficiencies propagate across the supply chain and amplify systemic risk.

A systematic review of the peer-reviewed literature reporting one or more 4E-related dimensions for SAF confirms the scarcity of truly integrated 4E studies and highlights the need for harmonized, multidimensional evaluations. Therefore, this study has four primary objectives: (i) to conduct a systematic literature review that maps and synthesizes the application of 4E-related analyses across SAF conversion pathways and identifies the dominant sources of fragmentation in the existing evidence base; (ii) to synthesize and compare findings on energy/exergy efficiency, economic viability, and environmental performance across the major certified pathways; (iii) to identify, through an integrative lens, the key sources of thermodynamic irreversibility, cost formation, and environmental burden within these systems; and (iv) to develop a critical synthesis that supports a coherent 4E evaluation structure by linking energy, exergy, economic, and environmental dimensions at the pathway level.

This synthesis is intended to support future development of more consistent comparative 4E assessments by clarifying how thermodynamic inefficiencies, cost formation, environmental burdens, hydrogen demand, and feedstock constraints interact across SAF pathways. Rather

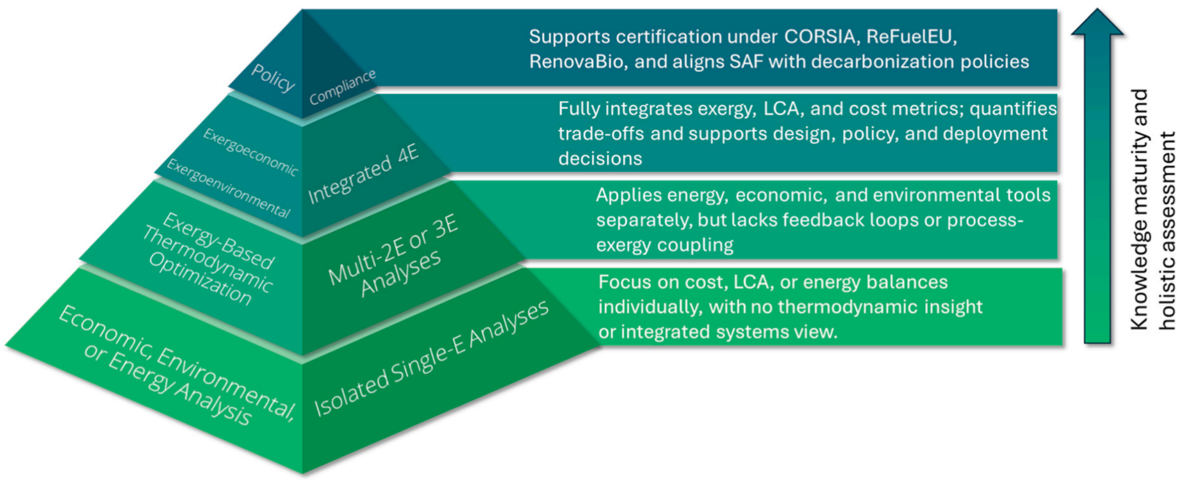

Fig. 1. Knowledge building and maturity through an integrated understanding of the SAF framework assessment.

than proposing a fully operational decision-making model, the review provides a critical evidence-based structure to inform future methodological development, process optimization, investment analysis, and policy design.

It is important to acknowledge that the system boundary adopted in this review treats biomass as a feedstock allocated to aviation decarbonization through SAF, i.e., as a CO_2 avoidance strategy. Alternative allocations of the same biomass base, most notably Biomass Carbon Removal and Storage (BiCRS) [21], represent CO_2 removal strategies that, in some configurations, may exhibit lower abatement costs ($/t$CO_2$) and higher carbon removal efficiencies (tCO_2 abated per tonne of biomass) than fuel substitution [22]. The relative attractiveness of SAF is also coupled to fossil energy markets: if decarbonization in other sectors reduces oil demand and depresses oil prices, the relative abatement cost of SAF tends to increase [22]. The choice to focus on SAF in this review is therefore not a claim that SAF is the most cost-effective use of biomass in absolute terms, but rather a recognition that aviation is a hard-to-abate sector with limited near-term drop-in alternatives, and that ASTM-certified SAF pathways are the focal mitigation lever framed by current sectoral policies (CORSIA, ReFuelEU Aviation, RenovaBio/ProBioQAV). A systematic comparison of CO_2 avoidance (SAF) and CO_2 removal (BiCRS) under shared biomass-supply constraints lies beyond the scope of this review and is identified in Section 7 as a priority for future integrated assessments [23].

Accordingly, the article is structured as follows: Section 2 presents the literature assessment on 4E-related studies; Section 3 describes SAF conversion processes; Section 4 discusses feedstocks; Section 5 examines E-analyses; Section 6 reviews policies promoting SAF; and Section 7 provides final remarks and future perspectives.

Table 1
Comparative overview of selected SAF studies by pathway, feedstock, country, and reported Energy, Exergy, Economic, and Environmental assessment dimensions.

Pathway[a]	Feedstock	E-Analysis	Country	Coverage level[b]	Ref.
OtJ, GtJ, and AtJ	Palm, Macaúba, and Soybean oils, Lignocellulosic Material (Sugarcane, Eucalyptus), Ethanol and Isobutanol	Energy Economic Environmental	Brazil	Partial multi-dimensional	[10]
AtJ	Ethanol (1G & 2G)	Energy Economic	Brazil	Partial multi-dimensional	[24]
GtJ	Pinewood	Energy Environmental	United Kingdom	Partial multi-dimensional	[25]
OtJ	Used cooking oil (UCO)	Energy/Exergy Economic Exergoeconomic Environmental	Taiwan	Full 4E	[26]
OtJ	Palm oil	Economic Environmental	Mexico	Partial multi-dimensional	[27]
OtJ and AtJ	Kernel oil, fatty acid distillates, and lignocellulosic biomass	Energy/Exergy Economic Exergoeconomic Environmental	European Union	Full 4E	[28]
OtJ and AtJ	Palm Fresh Fruit Bunch (FFB) + 2G ethanol	Energy/Exergy Economic Exergoeconomic Environmental	Brazil	Full 4E	[29]
OtJ and AtJ	Palm Fresh Fruit Bunch (FFB) and derivatives, and second-generation ethanol	Energy/Exergy Economic Exergoeconomic Environmental	Brazil	Full 4E	[30]
OtJ	Canola	Environmental	Canada	Single-dimension	[31]
OtJ	Pennycress (*Thlaspi arvense*)	Economic	USA	Single-dimension	[32]

[a] OtJ: Oil-to-Jet; GtJ: Gas-to-Jet; AtJ: Alcohol-to-Jet.
[b] Exergoeconomic and exergoenvironmental analyses are reported as integration mechanisms; the "Coverage level" considers only the four fundamental dimensions (Energy, Exergy, Economic, Environmental).

2. Literature assessment

To support the comparative analysis presented in the following sections, a systematic search of the peer-reviewed literature was conducted in Scopus and Web of Science using three groups of terms: (i) terms relating to sustainable aviation fuel and biojet fuel; (ii) terms relating to the four ASTM-certified pathways (HEFA, GtJ, AtJ, StJ); and (iii) terms relating to the four 4E dimensions, including exergy, techno-economic assessment, life cycle assessment, exergoeconomic, and exergoenvironmental analyses. Studies were retained if peer-reviewed and if they reported quantitative results in at least one of the 4E dimensions for at least one ASTM-certified pathway. Priority was given to studies coupling exergy analysis with techno-economic and/or life cycle results, in alignment with the integrated framework adopted in this review. Table 1 summarizes the selected studies according to pathway, feedstock, country, and the 4E dimensions explicitly reported in the 'E-Analysis' column. Full 4E coverage refers to studies addressing all four dimensions, whereas studies covering two or three dimensions are interpreted as partial multi-dimensional assessments, and studies focused on only one dimension are interpreted as single-dimension assessments.

Table 1 reveals that studies reporting 4E-related dimensions for SAF production remain concentrated in a limited set of conversion pathways and feedstocks, with only a subset addressing the full Energy, Exergy, Economic, and Environmental framework. Most studies focus on Oil-to-Jet (OtJ) and hybrid OtJ–AtJ routes, predominantly using vegetable oils, lipid residues, and ethanol as feedstocks, while Gas-to-Jet (GtJ) pathways are comparatively underrepresented. From a methodological perspective, only a subset of studies combines energy and exergy analyses with economic and environmental assessments, with exergoeconomic approaches appearing primarily in OtJ-based systems. Geographically, the literature is dominated by case studies from Brazil and the European Union, reflecting the availability of biomass resources and policy-driven research agendas, whereas other regions remain sparsely explored. These patterns highlight both technological and regional gaps in the current application of integrated 4E frameworks to SAF production. These findings provide the foundation for the comparative analysis of SAF conversion pathways discussed in the following section.

3. Pathway and conversion process

The operational conditions in the aviation sector require strict fuel quality assurance in line with internationally accepted standards. Thus, in 2009, the American Society for Testing and Materials (ASTM) introduced the ASTM D7566 standard, which evaluates and approves SAF conversion processes for "drop-in" alternative aviation fuels [8,12]. This standard defines the conversion processes and sets the maximum proportion of SAF that can be blended with conventional aviation kerosene (Table 2) [8,33]. The certification focuses exclusively on technical performance parameters, without considering aspects such as emissions or costs [20]. Each new certified pathway is added as an annex to the standard [8].

Table 2
Pathway, conversion process with the respective abbreviation, blend limit (% SAF in conventional jet fuel, and year of certification of four ASTM-certified technologies. Adapted from Refs. [8,11,12,33,34].

Pathway[a]	Conversion process (Abbreviation)	Blending ratio by Volume	ASTM reference (year of certification)
GtJ	Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene (FT-SPK)	50%	ASTM D7566 Annex A1 (2009)
OtJ	Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids (HEFA-SPK)	50%	ASTM D7566 Annex A2 (2011)
StJ	Synthetic iso-paraffins from hydroprocessed fermented sugars (HFS-SIP)	10%	ASTM D7566 Annex A3 (2014)
AtJ	Alcohol to jet synthetic paraffinic kerosene (AtJ-SPK)	50%	ASTM D7566 Annex A5 (2016)

[a] OtJ: Oil-to-Jet; GtJ: Gas-to-Jet; StJ: Sugar-to-Jet; AtJ: Alcohol-to-Jet.

Building on the ASTM-certified pathways summarized in Table 2 and illustrated in Fig. 2(a), this section introduces the main SAF conversion routes and highlights the route-specific constraints identified in the reviewed literature. For each pathway, the following subsections examine the main SAF conversion routes based on their technological maturity, feedstock characteristics, and relevance in the literature, providing a basis for a critical comparison before the integrated 4E assessment in Section 5.

3.1. Oil-to-jet (OtJ)

As the most extensively investigated and commercially mature SAF route, the OtJ pathway, present in most studies in Table 2, encompasses three main conversion processes: Hydroprocessed Esters and Fatty Acids (HEFA), so-called hydro-processed renewable jet (HRJ); Catalytic Hydrothermolysis (CH), which is also known as Hydrothermal Liquefaction (HTL); and Hydrotreated Depolymerized Cellulosic Jet (HDCJ) [9,35,36].

The HEFA process (Fig. 2(b)) is currently the most established and widely recognized SAF production pathway, owing to its strong operational similarities with conventional petroleum refining technologies [8]. This maturity is reflected in its Technology Readiness Level (TRL) and Fuel Readiness Level (FRL) of 9, indicating full readiness for commercial deployment [11]. It essentially involves the hydrogenation of feedstocks, in which free and esterified fatty acids (mainly as triglycerides) are converted into their saturated counterparts, using hydrogen and catalysts such as platinum, nickel, or palladium, aiming to improve the properties and stability of the final fuel [9,35,37]. The main steps include hydrodeoxygenation, which removes oxygen from organic compounds, and hydroisomerization/hydrocracking, which adjusts the molecular structure to meet ASTM specifications [9,35,38,39]. Finally, the product is separated into fractions, including HEFA-SPK (biojet), diesel, gasoline, propane, and naphtha [8,9,35,40].

Despite its technological maturity (TRL/FRL 9), the HEFA pathway illustrates that high readiness levels do not automatically translate into systemic sustainability across economic, environmental, and resource-related dimensions when assessed beyond isolated performance indicators. From an energy and exergy perspective, the route is comparatively mature, with thermodynamic irreversibilities concentrated in heat-exchange networks, hydroprocessing, and product-separation stages required to meet ASTM fuel specifications. However, the economic performance of HEFA remains strongly dependent on lipid feedstock prices and hydrogen sourcing, while its environmental performance is constrained by feedstock origin, indirect land-use change risk when first-generation oils are used, and the carbon intensity of hydrogen supply [11,41].

Although HEFA is the most mature SAF pathway, its broader performance depends on feedstock availability, hydrogen sourcing, and land-use-related constraints, which are examined through the 4E synthesis developed in Section 5.

3.2. Gas-to-jet (GtJ)

Among the different conversion technologies for SAF production, biomass gasification stands out for its ability to harness the bioenergy potential of waste. The GtJ pathway (Fig. 2(c)) relies on the production of synthesis gas (syngas), a mixture of carbon monoxide (CO) and hydrogen (H_2), which is subsequently converted into liquid hydrocarbons via the Fischer–Tropsch (FT) process [9]. The FT process, already deployed at commercial scale by several companies [9], converts syngas

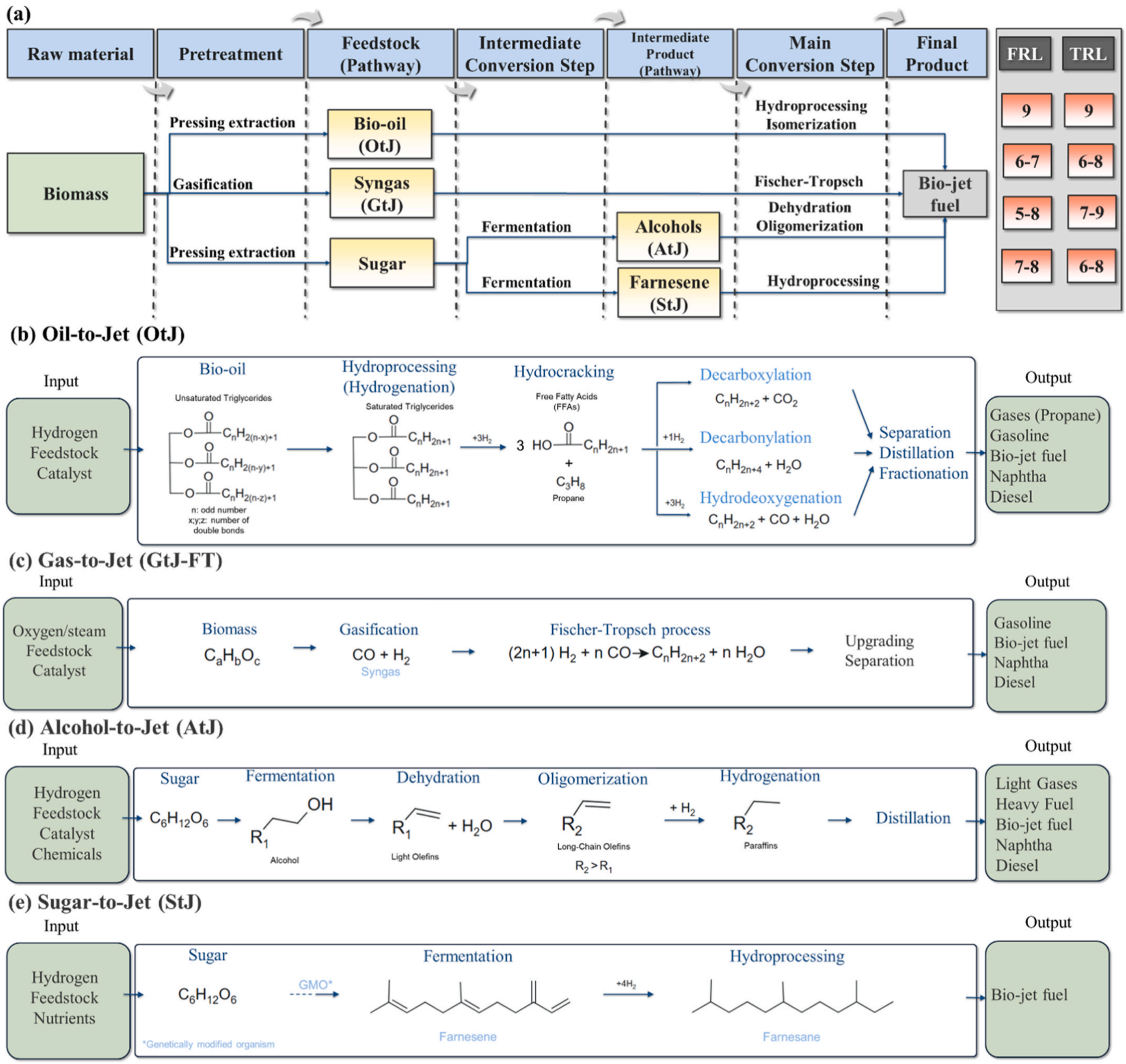

Fig. 2. (a) Pathways of main conversion routes for lignocellulosic biomass conversion to biojet fuel production. Simplified schematic flow sheet diagram for (b) Hydroprocessed Esters and Fatty Acids process, (c) Gasification and Fischer-Tropsch process, (d) Alcohol-to-Jet (thermochemical and fermentative) process, and (e) Synthetic iso-paraffins from hydroprocessed fermented sugar. (adapted from Refs. [9,24,26,35]). TRL - Technology Readiness Level and FRL - Fuel Readiness Level.

into paraffins and olefins, which are then upgraded via hydroprocessing to produce synthetic paraffinic kerosene (SPK) [9,33]. This integrated approach is considered a scalable, promising route to SAF production [33].

Various feedstocks, such as coal or biomass, can be gasified to produce syngas, which is then transformed into liquid SPK via the FT process [9]. This method demonstrates advantages over alternative methods and underscores the need for additional research to evaluate its technical, economic, and environmental viability [42–44]. Depending on the feedstock, GtJ is also referred to as "anything to liquid" (xtL), where "x" varies according to the feedstock used: "B" for biomass, "C" for coal, or "G" for gas [9]. With a TRL of 6–8 and an FRL of 6–7, this process underscores the importance of investments and research to advance its development and readiness for commercial implementation [11,41].

Another GtJ conversion process is carried out via gas fermentation [9,36,45]. In this process, the syngas obtained from gasification is fermented to produce a mixture of alcohols, such as ethanol and 2,3-butanediol [9,36,45]. This alcohol mixture is then converted into jet fuel through dehydration, oligomerization, distillation, and hydrogenation processes (AtJ pathway) [9,45], further detailed in the following section.

The GtJ-FT pathway derives its strategic appeal from feedstock flexibility, since lignocellulosic biomass, residues, municipal solid waste, coal, or gas can be used depending on the system configuration, and from the potential for deep emission reductions when combined with CCS. From an exergetic standpoint, however, substantial irreversibilities are concentrated in gasification, syngas cleaning and conditioning, compression, FT synthesis, and product upgrading. These losses propagate into higher energy demand, equipment complexity, and capital intensity, making CAPEX and scale sensitivity dominant drivers of MJSP. Environmental performance is conditioned by feedstock logistics, electricity demand, syngas-conditioning requirements, and CCS integration where applicable.

For GtJ, the main system-level challenge lies in balancing broad feedstock flexibility with process complexity, syngas conditioning requirements, and scale-dependent capital intensity, issues further interpreted through the integrated 4E synthesis in Section 5.

3.3. Alcohol-to-jet (AtJ)

This specific pathway enables the conversion of various alcohols containing carbon chains with two to five atoms, such as ethanol, isobutanol [9], propanol, and pentanol [33,46], into aviation fuel. These alcohols, derived from biogenic feedstocks like sugars and starches via thermochemical and fermentative (biochemical) processes [9], undergo a series of chemical transformations. A representative AtJ process is illustrated in Fig. 2(d).

In the first production step, alcohols are dehydrated and converted into olefins. These olefins are then oligomerized [9,46] in the presence of catalysts to form intermediate distillates composed of hydrocarbons [9] with a desirable carbon chain length [33]. These intermediate distillates are hydrogenated to produce aviation-grade hydrocarbons [45]. Finally, the process is completed with the fractional distillation of the final synthetic paraffin product [9,45].

With a TRL of 6–8 and an FRL of 7–8 [41], this process shows strong potential for commercial development, especially when using bioethanol as a feedstock, due to its advantages in production, price, and market share. However, the commercialization of this biojet fuel may create competition for the feedstock between the air and land transport sectors, as bioethanol is widely used in the petrochemical industry [11]. From a system-level perspective, this pathway highlights how apparent feedstock availability and infrastructure compatibility can mask deeper thermodynamic and economic penalties associated with multi-step upgrading and intensive hydrogen demand.

AtJ benefits from established alcohol infrastructure and the use of waste-based feedstocks; however, it is constrained by an efficiency–cost trade-off, as high hydrogen demand, still largely supplied from fossil sources, combined with multi-step conversion pathways, leads to significant exergy destruction and elevated production costs. For AtJ, the relevance of existing alcohol infrastructure must therefore be interpreted alongside multi-step upgrading, hydrogen demand, and feedstock competition, which are later connected to economic and environmental implications in the 4E synthesis.

3.4. Sugar-to-jet (StJ)

Farnesane, a non-natural fully saturated hydrocarbon, is classified as both an aviation biofuel and a fossil diesel substitute [47]. Its biological conversion follows three routes: (i) yeasts engineered to ferment sugars into farnesene, a monounsaturated hydrocarbon with one carbon–carbon double bond, later hydroprocessed into farnesane; (ii) heterotrophic algae or yeasts converting sugars into lipids; and (iii) bacteria engineered to transform sugars into alkenes [20]. The ASTM-approved process is Synthetic iso-paraffins from hydroprocessed fermented sugar (HFS-SIP), also termed Direct Fermentation of Sugar to Jet (DFStJ) [35] or Direct Sugar to Hydrocarbons (DSHC) [3,9,35], illustrated in Fig. 2(e). It involves sugar fermentation to farnesene, followed by hydrogenation and distillation [33,35,48]. Genetic engineering enables microorganisms to metabolize sugars via the mevalonate or methylerythritol phosphate pathways [49,50]. Organisms engineered for farnesene biosynthesis include *Escherichia coli*, cyanobacteria, and yeasts such as *Saccharomyces cerevisiae*, *Yarrowia lipolytica*, and *Komagataella phaffii* [9,48,50,51]. However, SIP fuel is limited to a 10% blend due to performance constraints [42].

Despite high capital costs and limited performance, SIP remains a viable SAF option (TRL 7–9, FRL 5–8) [38,41]; however, from a critical systems perspective, its high carbon efficiency at the biochemical conversion stage does not necessarily translate into scalable SAF deployment, as downstream performance limits and fermentation-driven capital intensity constrain economic competitiveness and large-scale implementation [38,41,42]. The StJ pathway demonstrates innovative bio-conversion but is limited by a performance-scale trade-off: low-blend limits and high fermentation costs constrain its exergetic and economic potential despite favorable carbon efficiency. For StJ, the promise of biochemical conversion must be interpreted alongside fermentation intensity, low-blend limits, and sugar-feedstock constraints, which are consolidated in the pathway-level 4E matrix, discussed in Section 5.

3.5. Other process

Early-stage assessments have examined techno-economic and environmental aspects of SAF pathways, including sugar-to-hydrocarbon conversion [52,53], hybrid biorefineries using diverse feedstocks [54], and paper sludge upgrading [55]. By 2018, six SAF processes were certified under ASTM D7566/D1655, rising to 11 by 2023, with 11 more under review [12]. Conversion choice depends on biomass type, making feedstock assessment a critical first step, with options from agriculture, forestry, and waste streams [56].

4. Feedstock

The sustainability and scalability of SAF production depend directly on feedstock choice [57]. SAF is typically produced from renewable resources or waste. Typical sources include oilseeds, lignocellulosic materials, wastes, sugars, and starches [58,59]. Suitable feedstocks must combine high yield, availability, cost-effectiveness, no food competition, and low environmental impact [56]. However, these attributes remain challenging, as large-scale supply may compete with food production, drive monocultures, and cause biodiversity loss [60]. Emerging options include municipal solid waste (MSW) and industrial carbonaceous emissions [58].

4.1. Feedstock classification

Feedstocks are commonly grouped into three [34,56] or four "generations" [51,60]. The four-generation model consolidates their main attributes.

- 1G: edible crops such as palm, soybean, canola, corn, sugarcane, beet, and wheat [51,60]. These are mature and well-supplied, but face severe criticism for competing with food and causing deforestation and water stress [56,60]. Their use in aviation is progressively restricted.
- 2G: non-edible oils (e.g., UCO, tallow, jatropha), lignocellulosic biomass, and agricultural, forestry, and food wastes [56,60]. They avoid food competition and support circular strategies, but face challenges related to supply, quality, and pretreatment. They currently offer the best balance between reduced food competition, circularity potential, environmental performance, and technical feasibility.
- 3G: algae and certain residues or co-products [34,51,60]. Microalgae are highly productive and can avoid arable land use, but they remain energy- and capital-intensive. Their scalability depends on innovation in cultivation and oil extraction.
- 4G: advanced options such as CO_2-derived fuels, e-fuels, and genetically modified organisms [51,60]. These are long-term, transformative solutions, but remain in early development, constrained by economic and regulatory barriers.

4.2. Feedstocks for SAF production

HEFA is the most mature SAF conversion process (TRL/FRL 9), but it is constrained by feedstock availability [61]. The main feedstocks belong to the First Generation (1G), such as palm, soybean, and canola, which dominate global oilseed production and benefit from consolidated supply chains [62,63], conferring a cost advantage to these crops over other feedstocks [34]. Despite their maturity, these feedstocks raise major sustainability concerns, including food competition, land use, and deforestation [34,63,64].

Second-generation (2G) options for SAF production via the HEFA process include oil processing residues (plant kernels [28], palm oil mill effluent [65]) and non-edible oils such as used cooking oil, tallow, jatropha [34,51] and pennycress [32]. These potential by-products mitigate environmental liabilities, and prevent direct food competition [26,54,58]. However, their supply is limited and unevenly distributed, and the commercial production of crops like jatropha is still insufficient to reduce costs [58,61]. New crops (camelina, carinata, macauba [51]) and even microbial lipids from sugar fermentation are under investigation for HEFA plants [61,66].

The AtJ pathway expands feedstock flexibility for SAF production by converting various alcohols (ethanol, methanol, isobutanol) into jet fuels [61]. These can be produced from conventional crops (corn, sugarcane, wheat) [10,42], lignocellulosic residues, and food wastes such as coffee grounds or fruit residues [67]. The main challenge is the pretreatment required for lignocellulosic and food waste feedstocks [67].

The valorization of waste and residues establishes itself as a strategy for the sector and represents the most promising low-carbon route. Biomass and Municipal Solid Waste (MSW) [68] can be gasified to produce syngas for Fischer-Tropsch synthesis [34], while advanced processes such as HTL allow the conversion of mixed organic wastes [25]. These feedstocks maximize environmental benefits by valorizing waste streams but demand high technological readiness and investment. Industrial examples include Aemetis (orchard residues in California) and LanzaTech (ethanol from steel mill gases in the UK) [11,69]. However, the latter is only economically viable under strong carbon pricing regimes [57].

4.3. Strategic assessment of feedstock generations

Fig. 3 synthesizes the characteristics of first-to fourth-generation feedstocks into a strategic SWOT framework. Rather than merely contrasting isolated attributes, this assessment highlights how the strengths and limitations of each generation evolve across different temporal horizons and interact with SAF conversion pathways when evaluated from a systemic perspective.

The analysis indicates that first-generation feedstocks remain dominant in terms of technological maturity and immediate deployability, supporting current SAF production mainly through HEFA and

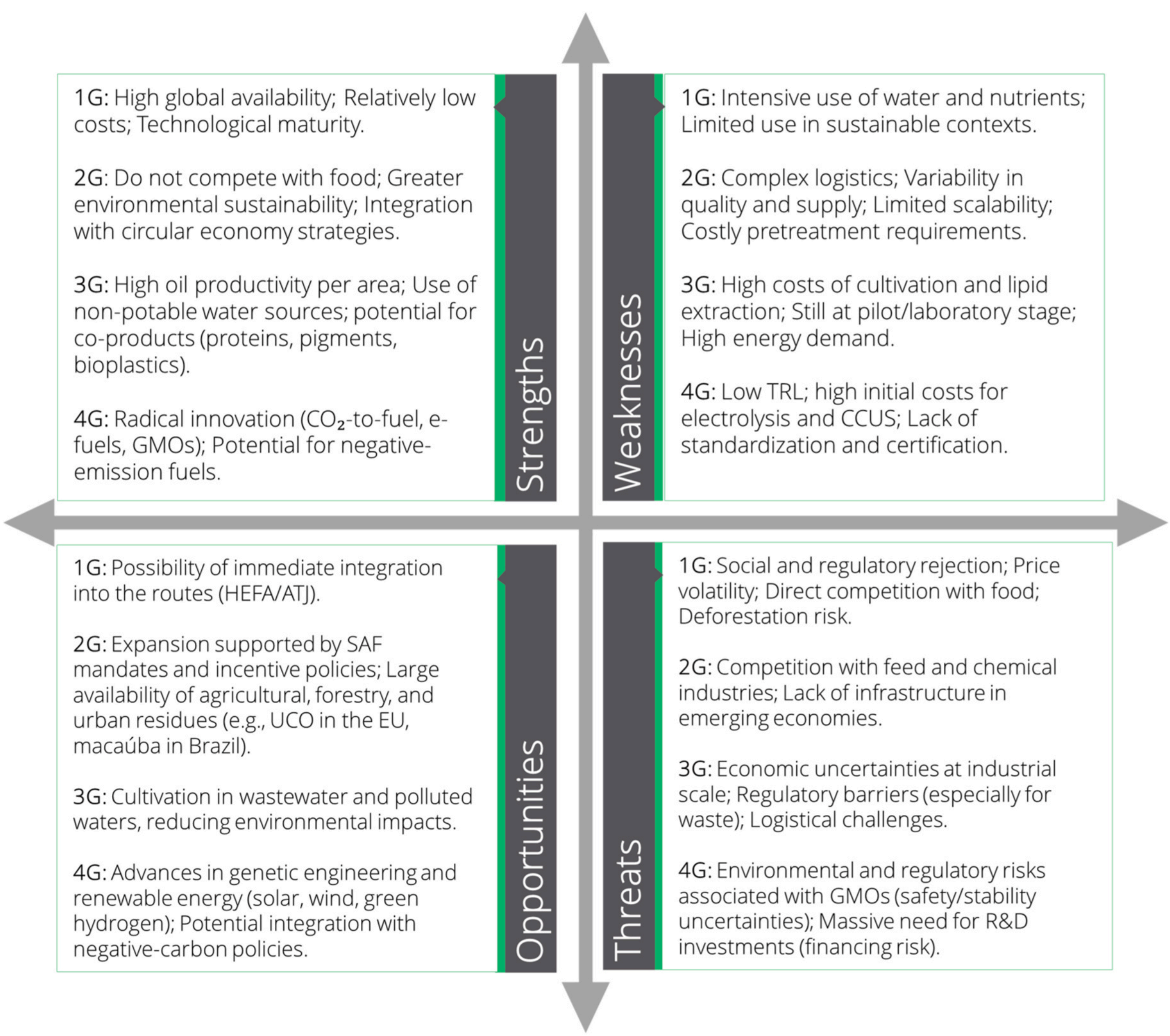

Fig. 3. SWOT analysis of the four feedstock generations for SAF production. GMOs - Genetically Modified Organisms; CCUS – Carbon Capture, Utilization, and Storage.

AtJ routes. However, their long-term contribution is constrained by socio-environmental pressures, including land-use competition, water demand, and regulatory acceptance. Second-generation feedstocks emerge as a critical transition option, offering a more balanced compromise between environmental performance, circularity, feedstock availability, and technical feasibility. Their alignment with circular economy principles and residue valorization positions them as key enablers for short-to medium-term SAF scale-up, particularly in regions with abundant agricultural, forestry, and urban waste streams.

Third-generation feedstocks exhibit strong potential in terms of productivity and resource efficiency, especially through waste and non-arable water utilization. Nonetheless, their contribution remains limited by technological immaturity, high energy demand, and unresolved scale-up challenges. Fourth-generation feedstocks represent the technological frontier of SAF production, encompassing CO_2-based fuels, advanced bioengineering, and e-fuels. While these pathways offer transformative and potentially negative-emission prospects, they are currently constrained by low readiness levels, high capital intensity, and the absence of robust regulatory and certification frameworks.

From a strategic standpoint, Fig. 3 shows that no single feedstock generation can sustain long-term SAF deployment on its own. Instead, scalable decarbonization of aviation requires a diversified and temporally coordinated feedstock portfolio, in which mature generations ensure near-term supply while advanced generations progressively expand the solution space. In this context, the 4E framework plays a central role by quantitatively translating SWOT-level insights into measurable trade-offs across energy efficiency, exergy destruction, economic viability, and environmental performance.

Linking feedstock selection to regional availability further strengthens this strategy, as localized supply chains can reduce greenhouse gas emissions, foster employment, and enhance alignment with the Sustainable Development Goals [58]. Tools such as the SAFMaps portal [70] facilitate this regionalization by identifying promising biomass and waste resources, including those in Brazil, to guide spatially optimized SAF deployment strategies [71,72]. Overall, integrating feedstock generation analysis into a 4E framework enables a more robust, policy-relevant understanding of how biomass cultivation, conversion pathways, and systemic sustainability interact across the SAF life cycle.

5. 4E-analysis

5.1. Economic

Most recent studies on SAF production have concentrated on evaluating the economic feasibility of different conversion pathways, emphasizing cost competitiveness, capital intensity, and market integration [73]. Table 3 consolidates these findings, outlining the main cost drivers, techno-economic indicators, and sensitivity analyses applied to each process.

Commercial-scale SAF production remains limited by high production costs and low conversion efficiencies. The Minimum Jet Fuel Selling Price (MJSP) of biojet fuel typically exceeds that of petroleum-based kerosene, restricting large-scale market adoption [11]. SAF prices are highly sensitive to fluctuations in fossil fuel prices; a 50% increase in fossil jet fuel prices can make most SAF routes economically viable, while a reduction may reverse their competitiveness [4]. Hsu et al. [26] demonstrated that combining efficient UCO collection systems with a carbon tax on emissions can align SAF MJSP with fossil fuel prices.

Economic feasibility is primarily influenced by feedstock costs, process yield, energy requirements, and scale-up challenges [74]. In this context, government incentives such as tax exemptions, subsidies, and carbon credits are crucial to internalize environmental benefits and offset production costs [26,30,38].

Julio et al. [29,30] evaluated HEFA and AtJ pathways under Brazilian conditions and found both financially unviable at current scales,

Table 3
Economic and feasibility assessments of SAF feedstocks and pathways.

Feedstock	Conversion process	Assessed parameters	Main findings/ contributions	Ref.
Palm, macaúba, soybean oils; lignocellulosic biomass (sugarcane, eucalyptus); ethanol, isobutanol	HEFA, GtJ, AtJ	IRR[a], MJSP[b], CAPEX[c], OPEX[d], by-product prices	Compared the economic performance of SAF routes. Modeled agricultural biomass costs via the software CanaSoft. High sensitivity to raw material cost (vegetable oils). Integration with sugarcane mills and local H_2 production reduces costs. Co-product revenues (green diesel, naphtha) improve feasibility	[10]
Ethanol (1G and 2G)	AtJ	CAPEX[c], OPEX[d], NPV[e], break-even price, payback	Ethanol cost dominates production. Viability in Brazil requires 44–55% price reduction (pre-COVID levels). Break-even SAF prices are competitive globally, but not with fossil jet fuel. Highlights tax incentives and subsidies as key enablers	[24]
Used cooking oil (UCO)	HEFA	MJSP[b], CAPEX[c], OPEX[d], cost flow rate	Demonstrates feasibility through process optimization and the use of tax incentives. Carbon tax significantly affects MJSP[b]	[26]
Palm oil	HEFA	ROI[f], utility cost	Heat integration improves ROI[f] and reduces costs. Modular approach optimizes safety, economy, and environmental performance	[27]
Kernel oil, fatty acid distillates, lignocellulosic biomass	HEFA, AtJ	MJSP[b], CAPEX[c], OPEX[d], TCI[g], by-product prices	AtJ costs nearly double that of conventional jet fuel due to high CAPEX. HEFA shows lower MJSP[b] with simpler processing and less catalyst use. By-product sales help offset costs. EU ETS used to monetize refinery emissions	[28]
Palm Fresh Fruit Bunch and derivatives; 2G ethanol	HEFA, AtJ	CAPEX[c], OPEX[d], NPV[e], unit cost, payback, sensitivity	High investment makes projects unattractive. Biodiesel, glycerol, and surplus electricity remain viable. HEFA is more mature and cost-effective than	[29]

(continued on next page)

Table 3 (*continued*)

Feedstock	Conversion process	Assessed parameters	Main findings/ contributions	Ref.
			AtJ; higher HEFA capacity improves economies of scale	
Palm Fresh Fruit Bunch and derivatives; 2G ethanol	HEFA, AtJ	CAPEX[c], OPEX[d], NPV[e], unit cost, payback, sensitivity	Feedstock diversification supported. Excluding cogeneration investment yields a positive NPV[e]. Biodiesel price and feedstock cost are the most sensitive parameters	[30]
Pennycress (*Thlaspi arvense*)	HEFA	CAPEX[c], IRR[a], MJSP[b], OPEX[d], NPV[e], ROI[f]	Grain cost (~45% of OPEX[d]) is the most sensitive factor affecting MJSP[b]. Identifies economic bottlenecks (grain price, plant size, oil content). By-products (electricity, green diesel) are key to the feasibility	[32]

[a] Internal Rate of Return.
[b] Minimum Jet Selling Price.
[c] Capital Expenditure.
[d] Operational Expenditure.
[e] Net Present Value.
[f] Return on investment.
[g] Total capital investment.

since production costs exceeded market prices and payback periods were long. HEFA offers lower costs and higher yields but requires substantial capital investment, while AtJ is constrained by low conversion efficiency and high hydrogen consumption. Increasing HEFA capacity could reduce unit costs, improve competitiveness, and support Brazil's RenovaBio targets and Paris Agreement commitments.

Teixeira et al. [24] showed that the AtJ pathway in Brazil becomes viable only if ethanol prices return to pre-pandemic levels. The authors emphasized that public subsidies and carbon-based incentives are key to closing the cost gap. At the same time, expanding corn ethanol production can further lower feedstock costs and enhance long-term feasibility.

Mousavi-Avval and Shah [32] identified feedstock, facility, and labor costs as the dominant factors in SAF production expenses, with biorefinery scale directly affecting MJSP. They suggest strategic siting of biorefineries, genetic improvement of pennycress, and by-product valorization (e.g., meal and electricity) as viable strategies to increase profitability.

Most studies summarized in Table 3 focus on the economic viability of SAF production, utilizing classic indicators such as CAPEX, OPEX, and payback period to evaluate productivity and competitiveness. Recent meta-analytical evidence confirms that the MJSP remains the dominant economic indicator in SAF techno-economic assessments, while also highlighting that methodological heterogeneity, boundary choices, and variable interdependencies strongly affect cost comparability across pathways. Farooq et al. [75] demonstrated that feedstock cost, capital estimation methods, by-product credit allocation, and financial assumptions are major drivers of MJSP variability, reinforcing the need for integrated and harmonized economic assessments rather than isolated cost indicators alone.

While current SAF assessments rely predominantly on CAPEX-, OPEX-, and MJSP-based indicators, future studies could benefit from incorporating additional profitability-oriented metrics commonly used in industrial project appraisal, provided that they are consistently integrated with system-level thermodynamic and environmental analyses.

Overall, the economic success of SAF depends on scaling up production, implementing stable fiscal mechanisms, and developing transparent market frameworks. Consistent public policies and targeted financial instruments are essential to attract investors, mitigate uncertainties, and position SAF as a competitive, resilient energy alternative. In this regard, integrated assessments, such as exergoeconomic analyses, are fundamental for identifying hidden inefficiencies, quantifying cost–energy trade-offs, and supporting evidence-based decision-making toward economically viable and sustainable SAF pathways.

5.2. Environmental assessment

5.2.1. LCA and methodological scope

Table 4 provides a detailed overview of the environmental assessments conducted in the reviewed studies, emphasizing the parameters evaluated and their main contributions. One of the key advantages of SAF lies in its potential to reduce CO_2 emissions significantly throughout its life cycle [76], an aspect that has driven the widespread application of LCA as the dominant environmental evaluation tool.

However, a critical limitation arises from the predominant focus on climate-related indicators, particularly Global Warming Potential (GWP), which can result in a partial representation of environmental performance. LCAs restricted to GWP may overlook relevant trade-offs associated with land use, resource depletion, toxicity, and water consumption, especially in biomass-based systems characterized by strong regional and agricultural dependencies. This methodological narrowing limits the capacity of environmental assessments to inform technology comparisons and policy design fully.

The LCA assumptions reported in Table 4 reveal clear trends in system definition and modeling choices. SimaPro is the most frequently applied software, followed by OpenLCA and the GREET and GHGenius models. Ecoinvent databases, ranging from versions 2.2 to 3.8, dominate inventory modeling, while ReCiPe Midpoint, IMPACT 2002+, ILCD 2011 Midpoint, and CML-IA baseline are the most commonly adopted impact assessment methods. Functional units are typically defined as 1 MJ or 1 GJ of SAF, although some studies adopt feedstock-based units, such as 1 ton of biomass, to represent agricultural inventories better.

System boundaries range from cradle-to-gate to cradle-to-grave and well-to-wake configurations, reflecting different analytical objectives. Allocation procedures are predominantly economic or energetic, whereas exergy-based allocation is used in only a limited number of multi-product systems, particularly those involving biodiesel, electricity, and glycerol co-products. Across studies, the most common impact categories are GWP, human toxicity (HT), acidification potential (AP), land use (LU), fossil depletion (FD), and cumulative energy demand (CED).

Collectively, these methodological choices demonstrate a preference for midpoint indicators and system boundaries that extend beyond gate-to-gate analyses, enabling comparability across conversion routes such as HEFA, GtJ, and AtJ. Nevertheless, heterogeneity in allocation methods, databases, and system boundaries remains a significant source of uncertainty and limits direct cross-study comparison.

A broader application of LCA enables a more comprehensive assessment of impacts by including the environmental burdens associated with the agricultural phase of biomass production. From biomass cultivation to fuel use in aircraft turbines, the assessment takes a cradle-to-grave perspective, encompassing impacts on fertilizers, water consumption, and land use.

Finally, the lack of standardized LCA methodologies remains a fundamental barrier to robust environmental benchmarking across SAF pathways. Variations in functional units, system boundaries, allocation rules, and impact categories hinder meaningful comparison between mature and emerging technologies [11].

Table 4
Life Cycle Assessment (LCA) of SAF feedstocks and pathways.

Feedstock/Conversion process	LCA Approach	LCA Parameters and Impact Categories (IC)	Main findings/contributions	Ref.
Palm, macaúba, soybean oils; lignocellulosic biomass (sugarcane, eucalyptus); ethanol, isobutanol/HEFA, FT, AtJ	**Software:** SimaPro; **Database:** Ecoinvent v2.2; **Methodology:** ReCiPe Midpoint	**FU:** 1 MJ; **SB:** Cradle-to-grave; **Allocation:** Economic; **IC:** GWP[a], HT[b], AP[c], LU[d], CC[e], FD[f]	All pathways significantly reduce climate impacts vs. fossil jet fuel. The agricultural stage (fertilizers, and diesel) dominates GHG emissions. Biomass electricity improves self-sufficiency. Renewable H_2 lowers carbon footprint	[10]
Pinewood (lignocellulosic biomass)/FT	**Software:** SimaPro; **Database:** ILCD 2011 (European Commission – Joint Research Centre); **Methodology:** ILCD 2011 Midpoint+ (v1.11)	**FU:** 1 MJ; **SB:** Well-to-wake; **Allocation:** Energetic; **IC:** GWP (100-years)	The FT route, integrated with CCS[l], achieves significant GHG reductions. 100% FT-SPK + CCS yields net-negative emissions; 50% blend cuts fossil emissions by 37%. CCS captures 72% of CO_2. Catalyst supply chain = 22% of conversion emissions	[25]
Used cooking oil (UCO)/HEFA	**Software:** SimaPro 9; **Database:** Ecoinvent 3.5; **Methodology:** IPCC (2006) Guidelines	**FU:** 1 TJ; **SB:** Well-to-wake; **Allocation:** -; **IC:** GWP (100-years), Ecological efficiency	UCO-to-SAF shows substantial GHG reduction. Green H_2 and biogas from food waste could further decrease emissions	[26]
Palm oil/HEFA	**Software:** OpenLCA; **Database:** Ecoinvent 3.8; **Methodology:** CML-IA baseline (2016)	**FU:** 1 GJ; **SB:** Gate-to-gate and cradle-to-gate; **Allocation:** Energy-based; **IC:** GWP, HT, PO[g], Acidification, Eutrophication, Photochemical oxidation, Aquatic ecotoxicity	Dual boundaries enhance comparability. Electricity and thermal demand are the primary sources of impact. The modular approach integrates safety, economy, and environmental aspects	[27]
Kernel oil, fatty acid distillates, lignocellulosic biomass/HEFA and AtJ	**Software:** SimaPro 9; **Database:** Ecoinvent 3.3; **Methodology:** IPCC + CED[h]	**FU:** 1 MJ; **SB:** Cradle-to-grave; **Allocation:** Mass-based, Energy (LHV)-based, and Market value (€)-based; **IC:** GWP (100-years)	Both pathways emit less GHG than fossil fuels. Lignocellulose-to-ethanol conversion is the main source in AtJ. Using lignin for electricity generation cuts emissions. H_2 use in HEFA is a major emission factor	[28]
Palm FFB and derivatives; 2G ethanol/HEFA and AtJ	**Software:** SimaPro v8; **Database:** Ecoinvent 3; **Methodology:** IMPACT 2002+	**FU:** 1 ton FFB[i]; **SB:** Cradle-to-gate; **Allocation:** Exergy-based; **IC:** GWP	Provides LCI[m] for palm bunches. HEFA SAF has a lower footprint than fossil jet fuel and better performance than AtJ, primarily due to lower ethanol-related emissions in AtJ	[29]
Palm FFB and derivatives; 2G ethanol/HEFA and AtJ	**Software:** SimaPro; **Database:** Ecoinvent 3; **Methodology:** IMPACT 2002+	**FU:** 1 ton FFB[i]; **SB:** Cradle-to-gate; **Allocation:** Exergy-based; **IC:** GWP	All biofuels show benefits over fossil fuels. Palm cultivation has the greatest impact due to the use of agrochemicals and diesel consumption. Exergy-based allocation is suitable for multi-product systems	[30]
Canola/HEFA	**Software:** -; **Database:** -; **Methodology:** GREET 2016, GHGenius 4.03a (IPCC AR5)	**FU:** 1 MJ; **SB:** Cradle-to-grave; **Allocation:** Energetic; **IC:** GWP, LUC[j], LMC[k]	Compares GREET vs. GHGenius results for regional canola SAF. Highlights methodological differences and the sensitivity of emission factors	[31]

FU: functional unit; SB: system boundaries.
[a] GWP – Global Warming Potential.
[b] HT – Human toxicity.
[c] TAP – Terrestrial acidification.
[d] LU – Land use (Agricultural and occupation impact).
[e] CC – Climate change.
[f] FD – Fossil depletion.
[g] PO – Photochemical Oxidation.
[h] CED – Cumulative Energy Demand.
[i] FFB – Fresh fruit bunches.
[j] LUC – Land Use Change.
[k] LMC – Land Management Changes.
[l] CCS – Carbon Capture and Storage.
[m] LCI – Life Cycle Inventory.

To address this fragmentation, future research must prioritize methodological harmonization in environmental assessments. Standardized functional units, transparent boundary definitions, and consistent treatment of co-products are essential for aligning environmental results with exergy and economic analyses, enabling genuinely integrated 4E evaluations.

5.2.2. Land use, land use change and sustainability constraints

Beyond methodological variability, land use and land-use change (LUC) associated with SAF production pathways emerge as structural constraints that cannot be captured by climate indicators alone. Klein et al. [10] compared SAF conversion routes (HEFA, GtJ, and AtJ) using different feedstocks within an integrated Brazilian biorefinery context and evaluated the land area required to supply 375 million liters of SAF per year, corresponding to 5% of Brazil's 2014 aviation kerosene demand.

Under these assumptions, AtJ production integrated into sugarcane biorefineries would require approximately 158,000 ha of sugarcane, whereas HEFA routes would demand about 250,000 ha of macaúba or 350,000 ha of palm oil. These results indicate that GWP and land-use indicators do not follow the same trend across SAF feedstocks. While AtJ and HEFA routes exhibit similarly favorable climate change performance, their land occupation requirements differ substantially, demonstrating that climate-driven metrics alone are insufficient to capture structural sustainability constraints.

Importantly, the lower land requirement associated with sugarcane-based AtJ does not stem from superior intrinsic crop productivity, but rather from the high degree of industrial integration, energy self-sufficiency, and logistical maturity of the Brazilian sugarcane sector. This distinction highlights that land-use indicators must be interpreted within their broader regional, technological, and systemic contexts, rather than as isolated measures of feedstock performance.

Despite short-term emission reductions, LUC remains a major source of uncertainty and long-term environmental risk in SAF supply chains. Converting areas that previously acted as carbon sinks can result in life cycle emissions exceeding those of fossil fuels [77].

In this context, Obnamia et al. [31] evaluated canola-based SAF via the HEFA process using the GREET 2016 and GHGenius 4.03a models, including both LUC and Land Management Change (LMC). Their results indicate that variations in soil organic carbon associated with LUC and LMC exert a stronger influence on life-cycle GHG emissions than regional differences in fertilizer inputs or crop yields.

While canola-derived SAF may deliver short-term climate-change mitigation benefits, its broader environmental sustainability depends on reducing trade-offs across non-climate LCA categories, particularly eutrophication, toxicity, freshwater consumption, land use, and land-use-related effects, which are strongly influenced by nitrogen fertilizer management, upstream agricultural inputs, and hydrogen sourcing [78]. These findings reinforce the tight coupling between environmental performance and upstream agricultural practices and land dynamics, underscoring the limitations of climate-focused metrics that neglect land-use effects.

5.2.3. Process optimization and emission mitigation

Several environmental analyses of SAF production explore process-level mitigation strategies. Castillo-Landero et al. [27] applied modularity and heat integration in palm oil biorefineries, demonstrating reductions in energy consumption and GWP. Julio et al. [29,30] and Hsu et al. [26], found that SAFs produced via HEFA and AtJ routes have lower carbon footprints than fossil jet fuel. The use of waste oils, such as used cooking oil (UCO), can reduce emissions by up to 80%, while direct conversion of vegetable oils achieves reductions of around 40%. These findings highlight the environmental benefits of feedstock selection and process integration, but also reveal that such gains are highly pathway- and context-dependent, reinforcing the need for integrated assessments that capture trade-offs across environmental, energetic, and economic dimensions.

5.2.4. Emerging technologies and future directions

Technological integration represents a complementary pathway for mitigating environmental impacts beyond feedstock and process optimization. Almena et al. [25] explored Carbon Capture and Storage (CCS) in SAF production, showing that incorporating CCS can achieve significant emission reductions. These systems can also enable the production of e-fuels, synthetic fuels formed from captured CO_2 and green hydrogen, offering an intermediate route toward a hydrogen-based economy [79]. In addition to being easier to transport and store compared to pure hydrogen, e-fuels can be blended with conventional fuels, facilitating their adoption by industries and consumers [79]. This is particularly valuable in sectors where direct electrification still faces significant challenges [79,80].

Although alternative fuels such as hydrogen and ammonia have been considered for aviation decarbonization, the direct use of hydrogen requires new aircraft designs and robust infrastructure, which currently increases its costs [1,81]. Hydrogen derived from wet biomass gasification can be stored as ammonia through the Haber–Bosch process [82]. Despite its high hydrogen content and carbon-free composition, ammonia poses operational and toxicity challenges and still requires further validation for aviation use [1,81].

SAF production pathways such as HEFA, AtJ, and StJ still depend largely on hydrogen from fossil sources, with only a small fraction originating from renewable processes [11]. Global interest in renewable hydrogen has expanded rapidly, driven by its potential to decarbonize multiple sectors [68,83–85]. However, approximately 95% of industrial hydrogen production still relies on natural gas reforming [83]. Thus, increasing H_2 production by using a mixture of biomass residues could be a viable alternative for H_2 production [68].

5.3. Energy and exergy performance

The thermodynamic analyses summarized in Table 5 reveal strong methodological convergence across the reviewed studies, with a clear predominance of HEFA and AtJ pathways, followed by a smaller number of investigations addressing GtJ systems. This distribution reflects not only the technological maturity of these routes, but also their greater data availability, which facilitates detailed steady-state modeling using process simulators such as Aspen Plus. GateCycle appears in a smaller subset of studies, primarily when cogeneration systems and power cycle integration are explicitly analyzed, particularly in lignocellulosic-based biorefinery configurations.

Consistent with the feedstock (Section 4) and Economic (Section 5.1) discussion, energy and exergy analyses are largely focused on lipid-based feedstocks and sugar- or ethanol-derived intermediates, mirroring the dominance of HEFA and AtJ pathways in process-level thermodynamic modeling. Lignocellulosic feedstocks are mainly explored in GtJ configurations and, to a lesser extent, in integrated AtJ systems. In contrast, third- and fourth-generation feedstocks remain virtually absent from rigorous energy–exergy assessments. This imbalance indicates that thermodynamic analyses have largely prioritized pathway maturity and modeling feasibility over systematic exploration of the broader feedstock diversity identified in the SAF literature.

Most investigations prioritize first-law indicators, such as energy efficiency and conversion yields, whereas second-law metrics are typically restricted to global exergetic efficiency and aggregated exergy destruction. This methodological pattern indicates that, although thermodynamic modeling is well established in SAF research, exergy analysis is still predominantly applied as a diagnostic tool rather than a decision-oriented framework. Consequently, the full potential of exergy-based metrics to support integrated 4E assessments remains underexplored, reinforcing the need for more systematic and harmonized energy–exergy evaluation approaches.

5.3.1. Energetic performance and conversion efficiency

Energy-based indicators are generally used to quantify feedstock-to-fuel conversion efficiency, without enabling a direct hierarchy among pathways. Instead, reported efficiencies are strongly dependent on process configuration, feedstock characteristics, and boundary definitions, which limits direct comparison across studies [10,25]. For example, energy consumption associated with alcohol dehydration and purification stages plays a central role in AtJ configurations [28], while hydrogen demand and upgrading steps dominate the energetic balance of HEFA systems [26].

Pretreatment strategies, such as torrefaction in lignocellulosic GtJ-FT pathways, may reduce downstream energy penalties and improve fuel handling characteristics [25], but their net contribution depends on how additional energy inputs and capital requirements are accounted for at the system level.

In summary, the energetic analyses (Table 5) provide a consistent basis for identifying major energy sinks and conversion losses within each pathway, but remain largely descriptive. These results highlight the need to complement first-law metrics with exergy-based analyses to better capture the quality of energy flows and support integrated performance evaluation.

5.3.2. Exergy analysis and process irreversibilities

Exergy analysis provides deeper insight into the sources of inefficiency within SAF production systems by accounting for the quality degradation of energy flows and the irreversibilities associated with real

Table 5
Summary of thermodynamic and exergetic analyses of SAF production pathways.

Feedstocks/Conversion process	Simulation Software	Pathway and assessed parameters	Main findings/contributions	Ref.
Palm, macaúba, soybean oils; lignocellulosic biomass (sugarcane, eucalyptus); ethanol, isobutanol/ HEFA, FT, AtJ	Aspen Plus v8.6	Mass and energy balances; conversion efficiency based on renewable carbon and total energy recovery.	HEFA biorefineries are most efficient in biomass conversion. FT shows high carbon recovery; AtJ has lowest conversion efficiency due to ethanol and electricity use.	[10]
Ethanol (1G and 2G)/AtJ	Aspen Plus v12.1	Operating conditions for AtJ: dehydration (400–405 °C, 5.23–5.83 atm, >97%), oligomerization (85 °C, 21.41 atm, 100%), hydrogenation (200 °C, 34.54 atm, 100%).	Defines optimal operating conditions for each AtJ step.	[24]
Pinewood (lignocellulosic biomass)/ GtJ	Aspen Plus	Operating conditions for GtJ-FT: pretreatment (275 °C, 0.1 MPa), gasification (1300 °C, 6.9 MPa), FT synthesis (220 °C, 6.0 MPa).	Energy-intensive process. Thermal integration covers heat demand, but electricity is still required. Enables quantification of SAF and co-products (gasoline, diesel).	[25]
Used cooking oil (UCO)/HEFA	Aspen Plus v10	Energy and exergy efficiency, exergy destruction, mass and heat flows. HEFA: hydroprocessing (643 K, 5.5 MPa, H_2/oil = 800), hydrocracking (728 K, 5.5 MPa, H_2/alkane = 1000), distillation (25 and 20 stages).	Exergy destruction highest in heat exchangers and distillation units. Identifies inefficiencies and proposes heat recovery strategies via cogeneration and thermal integration.	[26]
Kernel oil, fatty acid distillates, lignocellulosic biomass/HEFA and AtJ	Aspen Plus	Exergy and energy balance; exergy destruction ratio; exergetic efficiency. HEFA: hydrolysis (250 °C, 5 MPa), decarboxylation (280 °C, 2 MPa), hydroprocessing (280 °C, 6 MPa). AtJ: pretreatment (190 °C), SSCF[a] (40 °C), dehydration (350 °C), oligomerization (55–235 °C), hydrogenation (185 °C), cracking/ isomerization (280 °C).	AtJ has higher energy demand; ethanol purification requires thermodynamic improvement. HEFA consumes less energy but relies on natural gas, while AtJ generates surplus electricity from lignin.	[28]
Palm FFB and derivatives; 2G ethanol/HEFA and AtJ	GateCycle	Exergy and energy balance; exergy efficiency; exergy destruction.	Provides operational parameters and a Sankey diagram for exergy distribution. Exergy destruction linked to plant size; process integration improves efficiency.	[29]
Palm FFB and derivatives; 2G ethanol/HEFA and AtJ	GateCycle	Exergy and energy balance; exergy and energy efficiency; exergy destruction.	Cogeneration is identified as the main irreversibility source. Combining technologies without synergy can be unfavorable.	[30]

[a] SSCF – Simultaneous Saccharification and Co-Fermentation.

processes. Across the studies summarized in Table 5, exergy destruction consistently emerges as a critical factor limiting overall system performance, particularly in energy-intensive upgrading and separation stages.

For HEFA-based configurations, Hsu et al. [26], showed that the highest exergy losses are concentrated in heat exchangers and distillation columns, reflecting the strong impact of thermal gradients and phase-change operations on irreversibility generation. These findings indicate that process integration strategies, such as heat recovery and cogeneration, are essential to reduce exergy destruction and improve system efficiency.

In integrated HEFA and AtJ biorefineries, cogeneration systems consistently emerge as the dominant source of exergy destruction, underscoring the strong dependence of overall performance on energy integration design [29]. In AtJ configurations, a substantial fraction of total irreversibilities originates from upstream stages, particularly those related to fermentation and second-generation ethanol production, while the alcohol-to-jet upgrading unit itself contributes only marginally to total exergy losses [29]. This pattern is corroborated by studies combining HEFA and AtJ pathways based on kernel oil, lignocellulosic biomass, and ethanol intermediates, which identify fermentation, ethanol purification, and dehydration as the main exergy-intensive steps due to their reliance on thermal separation and high energy inputs [28]. By contrast, HEFA pathways exhibit lower overall energy demand but remain strongly constrained by hydrogen supply, introducing additional exergetic penalties when fossil-derived hydrogen is employed [28].

For GtJ-FT systems, Almena et al. [25] demonstrated that exergy losses are strongly linked to syngas conditioning, compression, and thermal integration constraints. These thermodynamic inefficiencies are closely coupled with the high capital intensity observed in techno-economic assessments, revealing an intrinsic exergoeconomic limitation that constrains large-scale deployment.

Overall, the exergy-based findings summarized in Table 5 reveal that thermodynamic inefficiencies in SAF pathways are highly pathway-specific and often dominated by upstream conversion and energy integration stages. While exergy analysis is effective in diagnosing these losses, its application remains largely descriptive, with limited integration into economic and environmental decision metrics.

5.4. *Integration of the 4E-analyses*

Table 6 consolidates the pathway-level 4E synthesis for the main ASTM-certified SAF routes. The table organizes the evidence reviewed in the previous sections by connecting exergy-related hotspots, techno-economic cost drivers, environmental hotspots, hydrogen demand, and feedstock flexibility. This structure highlights how thermodynamic inefficiencies in specific process stages can influence cost formation and life cycle environmental burdens, following the logic of exergoeconomic and exergoenvironmental assessment. Given the heterogeneity of functional units, system boundaries, allocation procedures, cost years, capital-cost assumptions, hydrogen-sourcing scenarios, and technological maturity across the reviewed studies, this synthesis should be interpreted as a directional comparison of coupling mechanisms rather than as a normalized numerical benchmark. Reading the table row-wise reveals the cascade of consequences from exergy destruction hotspots, such as heat exchange and separation in HEFA, syngas conditioning in GtJ, fermentation and dehydration in AtJ, and sugar conversion and intermediate upgrading in StJ, to where costs and environmental burdens accumulate.

Having established the key technical, environmental, and economic constraints of SAF pathways, the discussion now shifts toward their integrated interpretation. The 4E framework is used here to synthesize these findings and derive critical insights aimed at addressing the systemic barriers here identified. As shown in Fig. 4, these dimensions converge to form a multidimensional evaluation framework in which sustainability, efficiency, operational performance, and cost interact through exergoeconomic and exergoenvironmental approaches.

Exergoeconomic analysis provides a quantitative link between

Table 6
Comparative 4E indicator-linking matrix for ASTM-certified SAF pathways: exergy, cost driver, environmental, and hydrogen-related coupling mechanisms from the reviewed literature.

Pathway	TRL/FRL	Exergy-related hotspot	TEA indicator or cost driver	LCA indicator or environmental hotspot	H_2 demand	Feedstock flexibility	4E indicator linkage
HEFA, Hydroprocessed Esters and Fatty Acids	9/9	Heat exchangers, hydroprocessing, and product separation stages, particularly distillation and fuel-fraction upgrading	MJSP is strongly affected by lipid feedstock cost and H_2 supply, while CAPEX is comparatively lower due to higher process maturity	Life cycle GHG intensity and land-use-related risks depend on feedstock type, cultivation system, ILUC risk, and H_2 source	High	Low to moderate, restricted to lipid-based feedstocks such as vegetable oils, fats, recycled greases, and UCO	Process maturity reduces technical risk, but H_2 demand and lipid feedstock constraints link exergy performance to MJSP formation and life cycle GHG burdens
GtJ, Gasification and Fischer-Tropsch	6-8/6-7	Gasification, syngas cleaning and conditioning, compression, Fischer-Tropsch synthesis, and product upgrading	MJSP is strongly affected by CAPEX, scale sensitivity, and the complexity of the gasification, cleanup, and Fischer-Tropsch train	GHG intensity depends on biomass or waste supply chains, electricity demand, syngas conditioning, and CCS integration where applicable	Moderate	High, as the route can process lignocellulosic biomass, residues, MSW, gas, or coal depending on system configuration	Syngas conditioning and upgrading losses increase energy demand and equipment complexity, linking exergy destruction to CAPEX-driven MJSP and environmental burdens
AtJ, Alcohol-to-Jet	6-8/7-8	Alcohol production, dehydration, distillation, oligomerization, and hydrogenation stages	MJSP is affected by ethanol or isobutanol cost, multi-step upgrading, and H_2 supply	GHG intensity depends on alcohol origin, 1G or 2G feedstock, land and water demand, electricity use, and H_2 source	High	Moderate, restricted to alcohol intermediates, mainly ethanol and isobutanol	Upstream alcohol production and upgrading losses propagate into higher energy demand, H_2 use, cost formation, and GHG intensity
StJ, Sugar-to-Jet, HFS-SIP	7-9/5-8	Microbial sugar conversion to farnesene, followed by hydroprocessing and distillation	Cost is affected by fermentation capital intensity, sugar feedstock price, and restricted market uptake due to the low blend limit	Environmental burdens depend on sugar feedstock production, land-use pressure, and H_2 source for hydroprocessing	Moderate to high	Moderate, limited to fermentable sugars such as sugarcane, corn, beet, or other sugar-rich feedstocks	Biological conversion potential is constrained by fermentation costs, low blend limits, and feedstock-related environmental burdens, limiting deployment despite favorable carbon-efficiency potential

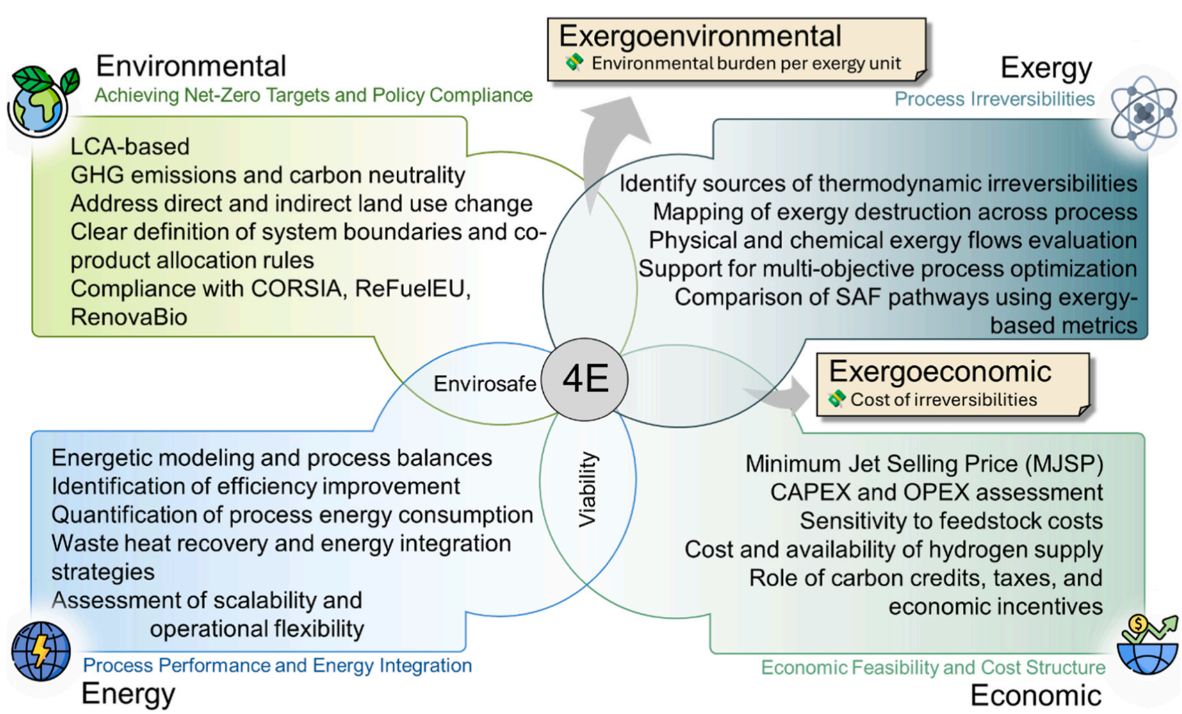

Fig. 4. Integrated 4E nexus for Sustainable Aviation Fuel systems, illustrating the interconnection among sustainability, efficiency, cost, and operational performance through exergoeconomic and exergoenvironmental analyses.

thermodynamic inefficiencies and economic performance by assigning monetary values to exergy streams and irreversibilities. This approach enables the identification of process units where cost formation is dominated by exergy destruction rather than capital investment, thereby supporting targeted optimization strategies in SAF systems [86].

Exergoenvironmental analysis extends this concept by coupling environmental impacts with exergy flows, allowing environmental burdens to be expressed per unit of useful exergy and thereby improving the consistency of trade-off analysis between efficiency and sustainability [86].

When applied jointly, these approaches move beyond descriptive assessments toward decision-oriented evaluations, revealing hidden penalties that may remain obscured under isolated metrics.

The studies summarized in Table 7 consistently demonstrate that exergoeconomic analysis provides a powerful lens for identifying where inefficiencies translate directly into economic penalties. Across HEFA and AtJ configurations, irreversibilities associated with heat exchange, distillation, cogeneration, and upstream biofuel production stages emerge as dominant contributors to total production cost. This reinforces a central insight that is not accessible through energy, exergy, or techno-economic analyses in isolation: cost competitiveness in SAF systems is structurally constrained by the thermodynamic quality of energy transformations throughout the conversion chain.

Comparative results further indicate that the higher costs observed in AtJ pathways are not primarily generated within the alcohol-to-jet upgrading unit itself, but are largely inherited from upstream stages, particularly second-generation ethanol production [29,30]. This reveals a critical limitation of pathway-level assessments that treat conversion routes as independent blocks, underscoring the importance of system-wide integration when evaluating SAF performance [28–30].

Despite these advances, the degree of integration achieved in the reviewed studies remains limited. All identified applications rely on exergoeconomic coupling, while none implements a full exergoenvironmental framework capable of directly linking exergy destruction to quantified environmental burdens [21,28–30]. As a result, environmental performance continues to be assessed separately through conventional LCA indicators, without a direct thermodynamic interpretation of environmental impacts. This methodological separation restricts the ability of current studies to fully capture trade-offs among efficiency, cost, and sustainability.

Overall, the literature represented in Table 7 reflects a partial convergence toward integrated analysis, corresponding to a practical combination of energy, exergy, and economic dimensions, but falling short of a complete 4E framework. While exergoeconomic analyses clearly enhance process-level understanding and optimization, the absence of exergoenvironmental applications constitutes a critical gap. Addressing this gap is essential for advancing SAF assessments from diagnostic studies toward genuinely integrated decision-support tools capable of informing technology development, process design, and policy formulation.

Beyond process-level integration, the deployment of SAF technologies ultimately depends on coordinated decisions across technological, economic, and policy domains. In this context, future research may benefit from combining 4E-based indicators with policy-oriented modeling tools, such as game-theoretic or dynamic incentive frameworks [87], to support robust resource allocation, risk mitigation, and long-term investment strategies for SAF deployment.

6. Policy frameworks for SAF deployment

The large-scale deployment of Sustainable Aviation Fuels remains constrained by high production costs, limited feedstock availability, infrastructure gaps, and competition with other bio-based sectors [88]. In this context, policy frameworks play a decisive role in reducing investment risk, stimulating market demand, and enabling the transition from pilot-scale production to commercial deployment [56,88]. To connect the policy overview with the technical analysis developed in this review, Table 8 maps each instrument according to a standardized set of 4E related policy signals. These signals include life cycle GHG performance, land use and sustainability eligibility, carbon pricing or credit mechanisms, public funding or industrial support, SAF supply mandates, certification or fuel eligibility, production scale-up and supply chain readiness, and research, production, and use. This classification does not imply that current policies apply a complete 4E framework. Rather, it identifies the main environmental, economic, and implementation channels through which each instrument influences SAF deployment.

The legislation, policies, and initiatives summarized in Table 8 reveal a convergent global strategy based on three main pillars: mandatory blending or supply obligations, carbon pricing or offset mechanisms, and financial incentives to de-risk SAF supply chains. The added policy signal column shows that these instruments primarily act through environmental, economic, and implementation channels, while energy and exergy dimensions remain largely indirect in current policy design. Internationally, the establishment of CORSIA by the International Civil Aviation Organization represents a cornerstone policy, linking SAF adoption to carbon offsetting requirements for international aviation and aligning the sector with net-zero emission targets by 2050 [13].

6.1. European Union (EU) framework

Table 8 shows that, at regional and national scales, policy instruments increasingly combine regulatory mandates, market-based mechanisms, and industrial strategies to accelerate SAF deployment. In the European Union, mandatory blending obligations under ReFuelEU Aviation are explicitly aligned with the 2030 and 2050 climate targets of the European Climate Law [14], while aviation inclusion in the EU ETS internalizes carbon costs and creates demand-side incentives for low-carbon fuels. These measures are reinforced by the Innovation Fund, which supports low-carbon fuel projects through competitive

Table 7
Integration of the 4E analyses of SAF.

Feedstocks/Conversion process	Integration of the 4E-analyses	Assessed parameters	Main findings/contributions	Ref.
Used cooking oil (UCO)/HEFA	Exergoeconomic	Exergy destruction cost; Ecological efficiency	Identification of trade-offs between equipment cost and exergy efficiency. Heaters, coolers, and distillation units present the highest cost of exergy destruction. Ecological efficiency is assessed through the relation between thermal efficiency and a CO_2-based pollution indicator	[26]
Kernel oil, fatty acid distillates, and lignocellulosic biomass/HEFA and AtJ	Exergoeconomic	Exergoeconomic cost; Exergy destruction cost; Exergoeconomic factor; Absolute and relative overcost	Evaluation of the influence of economic costs relative to irreversibility-related costs. Equipment with low exergetic efficiency and high exergy destruction, which does not contribute to cost reduction, should be reassessed or replaced	[28]
Palm Fresh Fruit Bunch (FFB) and derivatives; 2G ethanol/HEFA and AtJ	Exergoeconomic	Exergetic costs	Detailed cost formation analysis for each product. The AtJ process exhibits higher costs due to greater irreversibilities, particularly in ethanol production, which directly increases SAF production costs.	[29]
Palm Fresh Fruit Bunch (FFB) and derivatives; 2G ethanol/HEFA and AtJ	Exergoeconomic	Exergetic costs	AtJ requires significantly more resources to produce 1 MW of SAF than HEFA, leading to proportionally higher monetary costs	[30]

Table 8
Summary of SAF policy instruments and their 4E dimension or policy implementation signals.

Implemented by/Year	Legislation/Policy/Project	Objectives related to the aviation industry	4E dimension or policy implementation signal	Ref.
International Civil Aviation Organization (ICAO)/2016	Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)	A program aimed at reducing and offsetting CO_2 emissions from international flights to achieve carbon-neutral growth while allowing continued sector expansion	**Environmental:** life cycle GHG performance, land-use and sustainability eligibility; **Implementation:** sustainability certification or fuel eligibility	[13]
European Union (EU)/ 2023	ReFuelEU Aviation Regulation	Ensures EU aviation meets 2030 and 2050 climate targets and aligns with European climate law while maintaining internal market competitiveness	**Environmental:** life cycle GHG performance, land-use and sustainability eligibility; **Implementation:** SAF supply mandate	[14]
European Union (EU)/ 2003 (initial), updated 2023	EU Emissions Trading System (EU ETS and revisions)	Includes aviation in EU ETS since 2012; supports emission reductions and introduces SAF incentives. Funds innovation projects and reduces climate impact through the Innovation Fund	**Environmental:** life cycle GHG performance; **Economic:** carbon pricing or credit mechanism, public funding or industrial support	[88, 89]
European Union (EU)/ 2024	Europe's net-zero technology manufacturing ecosystem	Ensures regulatory and support frameworks for SAF technology producers, boosting production capacities along the entire fuel value chain	**Economic:** public funding or industrial support; **Implementation:** production scale-up and supply-chain readiness	[90]
United Kingdom (UK)/ 2023	UK SAF Clearing House	Funded by the Department of Transport to support SAF development, testing, qualification, and production across the UK aviation sector	**Implementation:** certification or fuel qualification	[91]
United Kingdom (UK)/ 2008 (initial), updated 2024	Renewable Transport Fuel Obligation (RTFO) scheme	Reduces GHG emissions by promoting the use of low-carbon fuels. SAFs have been included since 2018, receiving incentives similar to road transport biofuels	**Environmental:** life cycle GHG performance, land-use and sustainability eligibility; **Economic:** carbon pricing or credit mechanism	[38, 92, 93]
United Kingdom (UK)/ 2024	SAF Mandate	The main national policy to decarbonize aviation is to encourage SAF supply and integration into the national fuel mix	**Environmental:** life cycle GHG performance, land-use and sustainability eligibility; **Economic:** carbon pricing or credit mechanism; **Implementation:** SAF supply mandate	[94]
USA/2022	SAF Grand Challenge Roadmap	Aims to reduce emissions, de-risk technologies and supply chains, and remove barriers to SAF distribution and use through investment and policy analysis	**Environmental:** life cycle GHG performance, land-use and sustainability eligibility; **Economic:** public funding or industrial support; **Implementation:** production scale-up and supply-chain readiness	[95]
USA/2018	Low-carbon fuel standard (LCFS)	Reduces GHG intensity of transportation fuels (gasoline, diesel, jet fuel) in California, promoting renewable alternatives and improving air quality	**Environmental:** life cycle GHG performance; **Economic:** carbon pricing or credit mechanism	[96]
Brazil/2017	RenovaBio	Expands biofuel use and carbon credit markets to reduce the carbon intensity of transportation. Establishes decarbonization targets and certifies producers based on energy-environmental efficiency and life cycle GHG emission reduction	**Environmental:** life cycle GHG performance; **Economic:** carbon pricing or credit mechanism; **Implementation:** certification or fuel qualification	[15, 16]
Brazil/2021	National Biokerosene Program	Promotes SAF research, production, and use in Brazil's energy matrix to reduce aviation emissions and foster sustainable transitions	**Environmental:** life cycle GHG performance; **Implementation:** research, production, and use	[97]
Brazil/2024	National Sustainable Aviation Fuel Program (ProBioQAV)	Establishes ProBioQAV to promote SAF research, production, and integration in Brazil's aviation fuel system	**Environmental:** life cycle GHG performance; **Implementation:** SAF production and supply integration; production scale-up and supply chain readiness	[17]
Brazil/2024	New Industry Brazil	Mission 5, SAF is prioritized as a strategic supply chain for new energy sources, fostering the development of production technologies through facilitated credit	**Economic:** public funding or industrial support; **Implementation:** production scale-up and supply-chain readiness	[98]

financing mechanisms, and by the Net-Zero Technology Manufacturing Ecosystem, which extends policy support beyond fuel use to encompass feedstock supply, refining capacity, and blending infrastructure, strengthening the entire SAF value chain.

6.2. United Kingdom (UK) framework

Adopting a similarly integrated but nationally tailored framework, the UK represents one of the most structured national-level SAF policy frameworks, characterized by the coordinated use of mandates, fiscal incentives, and qualification mechanisms [99,100]. Economic incentives under the RTFO are coupled with robust lifecycle accounting through the Biofuels Carbon Calculator, which enables verified quantification of greenhouse gas savings and supports compliance and credit allocation. This structure is complemented by the UK SAF Mandate, which introduces progressively binding blending requirements with quantified mitigation outcomes, and by the UK SAF Clearing House, which plays a critical role in technology testing, qualification, and certification, reducing technical and regulatory barriers for emerging SAF pathways. Together, these instruments combine regulatory certainty with technical readiness, reducing risks associated with early-stage deployment.

6.3. United States (USA) framework

The USA stands out for the scale and depth of its SAF policy architecture. Federal tax credits and grants established under the IRA are designed to incentivize SAF production based on lifecycle emission performance [88,101], while the SAF Grand Challenge, coordinated across the DOE, DOT, and USDA, defines clear quantitative targets for production scale-up and long-term market penetration (Table 8). These federal measures are further reinforced by state-level low-carbon fuel standards, such as the LCFS, which reward SAF producers through emission reduction credits. In parallel, the GREET-based methodologies, including the 40BSAF-GREET framework, provide standardized lifecycle accounting to determine eligibility for fiscal incentives, strengthening consistency between policy design and environmental performance assessment [102,103].

6.4. Brazilian scenario and public policy

In Brazil, SAF deployment is embedded within a broader bioenergy policy framework that combines carbon intensity regulation, financial incentives, and industrial development strategies. National jet fuel demand reached an average of 6.2 million m^3 $year^{-1}$ before the COVID-19 pandemic, recovering to 5.4 million m^3 in 2023 alongside the resumption of international air traffic [104,105]. Given that fuel represents approximately 36% of airline operating costs, SAF price competitiveness remains a central barrier in the Brazilian context [104].

Policy instruments such as RenovaBio, the National Biokerosene Program, ProBioQAV, and Mission 5 of New Industry Brazil jointly establish sustainability criteria, certification mechanisms, and financing pathways to stimulate SAF research, production, and market integration (Table 8). In contrast to offset-oriented schemes such as CORSIA, which focus on international aviation emissions, RenovaBio prioritizes reductions in carbon intensity within the national fuel matrix through tradable decarbonization credits (CBIOs) directly linked to verified life-cycle performance. While both frameworks share restrictions on land-use change and GHG thresholds, their scope, credit logic, and implementation timelines differ, reflecting complementary but distinct decarbonization strategies (Table S2).

6.5. Additional initiatives

Beyond major producing regions, additional initiatives highlight the growing global coordination around SAF. In Canada, the C-SAF platform brings together airlines, producers, and government agencies to accelerate domestic SAF production and support the aviation sector's net-zero targets by 2050 [106]. In the Middle East, airline-led commitments, such as Qatar Airways' target of 10% SAF use by 2030, illustrate how voluntary adoption strategies, aligned with ICAO sustainability criteria, can complement regulatory frameworks and stimulate early market formation [107].

6.6. 4E framework within policy instruments

Overall, the policy instruments reviewed in this section demonstrate a clear evolution toward market creation and risk mitigation for SAF deployment. However, as summarized in Table 8, they remain anchored mainly in environmental, economic, and implementation signals, particularly life cycle GHG performance, carbon intensity, carbon pricing, certification, financing, and SAF supply obligations. These signals are essential to trigger early adoption, but they do not yet capture the full set of systemic inefficiencies, cost escalation mechanisms, and hidden environmental trade offs identified throughout this review. Energy and exergy indicators are generally not directly embedded in current SAF policy instruments, which reinforces the relevance of a 4E perspective for future policy design.

By linking exergy destruction to cost formation and environmental burden, future 4E informed indicators could support more nuanced policy instruments, such as differentiated incentives based on process efficiency, feedstock quality, hydrogen sourcing, and upstream integration, rather than uniform pathway level mandates. This shift would allow policymakers to move beyond technology neutral blending obligations toward performance oriented frameworks that reward systemic efficiency, discourage irreversibility intensive configurations, and align industrial innovation with long term decarbonization objectives. Consequently, embedding 4E informed metrics into certification schemes, carbon markets, and SAF mandates represents a key opportunity to enhance policy effectiveness, reduce unintended lock ins, and support the scalable deployment of truly sustainable aviation fuel systems.

7. Conclusions and prospects

The production and adoption of SAF are central to aviation decarbonization, particularly because the sector has limited near-term alternatives compatible with existing aircraft and fuel infrastructure. However, this review shows that SAF deployment cannot be adequately assessed through isolated technical, economic, or environmental indicators. Across the literature, pathway performance is shaped by coupled interactions among thermodynamic inefficiencies, cost formation, environmental burdens, hydrogen demand, feedstock availability, and policy conditions. The main contribution of this review was therefore to organize these interdependencies through a critical 4E based synthesis of the available evidence.

The reviewed studies reveal that HEFA remains the most technologically mature and economically competitive SAF pathway, supported by its compatibility with established refining infrastructure and its comparatively lower process complexity. Nevertheless, its long-term scalability is constrained by sustainable lipid feedstock availability, hydrogen sourcing, land use pressure, and potential indirect land use effects. GtJ, AtJ, and StJ expand the technological and feedstock solution space, particularly through lignocellulosic residues, waste streams, alcohol intermediates, and biochemical conversion routes. However, these pathways remain constrained by capital intensity, multi step upgrading, syngas conditioning, fermentation costs, hydrogen requirements, and, in the case of StJ, restricted blending limits.

A central insight emerging from the 4E synthesis is that thermodynamic irreversibilities are not only process efficiency losses. They also influence economic and environmental performance. Exergy destruction in heat exchange, separation, hydroprocessing, syngas conditioning, fermentation, dehydration, and product upgrading can propagate into higher energy demand, increased MJSP, greater capital or operating costs, and additional life cycle burdens. This reinforces the importance of process integration, heat recovery, renewable hydrogen, improved feedstock logistics, and hybrid biorefinery configurations as strategies capable of simultaneously improving exergetic performance, economic viability, and environmental outcomes.

The environmental evidence reviewed confirms that SAF pathways can reduce greenhouse gas emissions relative to fossil jet fuel, but these benefits are strongly conditional. Feedstock origin, hydrogen source, allocation method, system boundary, land use assumptions, electricity mix, and treatment of co products can significantly alter results and limit direct comparability across studies. This methodological heterogeneity explains why the pathway level matrix developed in this review should be interpreted as a structured critical synthesis, not as a numerical ranking. Its purpose is to clarify where and how 4E indicators interact, and to identify the methodological consistency required for future comparative assessments.

Policy frameworks such as CORSIA, ReFuelEU Aviation, RenovaBio, ProBioQAV, and national SAF mandates are increasingly important for reducing market uncertainty, stimulating demand, and attracting private investment. However, current policy instruments remain primarily anchored in greenhouse gas intensity, carbon credits, supply mandates, and certification criteria. The evidence synthesized here indicates that future policy design could be strengthened by incorporating broader performance signals related to process efficiency, hydrogen sourcing, feedstock sustainability, and economic robustness. Such integration would help avoid incentives that reward only carbon intensity reductions while overlooking hidden thermodynamic, economic, or upstream environmental penalties.

Future research should advance in three main directions. First, primary comparative studies are needed under transparent and consistently reported assumptions, including functional units, system boundaries, allocation rules, cost year, scale, hydrogen sourcing, and feedstock origin. Second, dynamic and spatially explicit assessments should be developed to capture regional biomass availability, infrastructure constraints, electricity mix, logistics, and temporal changes in SAF supply chains. Third, future 4E assessments should be connected with digital tools, optimization methods, and policy oriented models to support more robust investment and deployment strategies. The comparison between biomass use for SAF production as a CO_2 avoidance strategy and Biomass Carbon Removal and Storage as a CO_2 removal strategy also remains an important research frontier.

Overall, this review demonstrated that the value of a 4E perspective lies in revealing interdependencies that remain hidden when SAF pathways are assessed through isolated indicators. By connecting thermodynamic, economic, environmental, feedstock, hydrogen, and policy dimensions, the study provides a structured evidence base for more transparent future assessments and for the development of SAF strategies that are not only low-carbon, but also resource efficient, economically viable, and technically scalable.

Author contributions (CRediT)

Thiago da Silva Gonzales: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft.

Giulia Cruz Lamas: Formal analysis, Visualization, Writing – original draft.

Simone Monteiro e Silva: Writing – review & editing.

Ana F. Ferreira: Writing – review & editing.

Edgar A. Silveira: Conceptualization, Methodology, Supervision, Project administration, Validation, Writing – original draft.

Declaration of generative AI and AI-assisted technologies

During the preparation of this work, the authors used generative artificial intelligence tools to assist with language editing and clarity. The authors carefully reviewed and edited the content and take full responsibility for the integrity, accuracy, and originality of the work.

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2026.117194.

Data availability

Data will be made available on request.

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