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Review Article

Uncovering the economic potential of sustainable aviation fuel production pathways: A meta-analysis of techno-economic studies

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ABSTRACT

Sustainable aviation fuel (SAF) is a key component for the defossilization of the aviation sector. The economic feasibility of SAF production is typically evaluated through techno-economic assessments (TEA), with the Minimum Jet Fuel Selling Price (MJSP) serving as the key economic performance indicator. Comparing MJSP values across different SAF pathways is challenging and potentially misleading due to differences in modelling assumptions, estimation methods for key variables, and their underlying relationships. This study aims to contribute to a more comprehensive understanding of the economic feasibility of four prominent SAF pathways: Hydroprocessed Esters and Fatty Acids (HEFA), Pyrolysis-to-Jet (PTJ), Alcohol-to-Jet (ATJ), and Fischer-Tropsch (FT). We employed qualitative and quantitative methods, including meta-analysis and variable harmonization, to analyze a wide range of TEA studies from the literature and investigate the factors contributing to MJSP variation for these pathways. Our findings reveal that feedstock cost is a primary driver of MJSP variability across all pathways. Moreover, regression and harmonization analyses uncovered complex interdependencies among economic variables often underexplored in individual TEAs. Key sources of MJSP variability include methodological differences in by-product credit valuation, process design choices, capital cost estimation approaches, and financial assumptions. Recognizing and addressing these factors offers strategic opportunities to improve the techno-economic performance and comparability of SAF pathways. Notably, the PTJ pathway emerged as a promising alternative for non-food feedstocks, and all pathways demonstrated improved economic outcomes when integrated with existing industrial infrastructure. The analytical findings of this study provide a robust empirical foundation that can be leveraged by future studies aimed at policy analysis, as well as for project budgeting and investment decisions in sustainable aviation fuels.

1. Introduction

Air travel is a major contributor to greenhouse gas (GHG) emissions. Furthermore, the reliance on fossil fuels in airline operations creates vulnerabilities, as evidenced by the jet fuel shortages in Europe during the Russia-Ukraine conflict [1]. This underpins the critical need for energy diversification within aviation. Sustainable aviation fuel (SAF) represents a promising solution for defossilizing the aviation sector and reducing reliance on crude oil imports. However, the high cost of SAF remains a significant barrier to widespread adoption [2].

The economic viability of SAF is commonly assessed through techno-economic assessments (TEA), with the Minimum Jet Fuel Selling Price (MJSP) as the main techno-economic performance indicator. The wide range of reported MJSPs is often driven by variability in financial assumptions, methodological approaches, and process designs. This variability complicates the interpretation of TEA results and makes it challenging to draw clear conclusions about the near-term economic feasibility of SAF, a challenge that has been largely overlooked in the existing review literature. Our study complements previous review studies by addressing this challenge explicitly and in detail, for several promising SAF pathways. This focus is crucial for future research, as it highlights the importance of adopting consistent assumptions when evaluating SAF pathways to ensure robust conclusions about their economic viability.

A recent bibliometric analysis of sustainable aviation studies identified 61 review articles published between 2001 and 2023, many of which focused on SAF production and use [3]. Review articles

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Nomenclature

ATJ	Alcohol to Jet
AR	Agricultural Residue
BPR	By-Product Revenue
CAPEX	Capital Expenditures
DSHC	Direct Sugar to Hydrocarbon
FT	Fischer-Tropsch
FR	Forest Residue
FRL	Fuel Readiness Level
FSC_F	Feedstock Cost (USD/GJ Feedstock) based on the energy content of the Feedstock
FSC_J	Feedstock Cost (USD/GJ of Jet Fuel) based on energy content of jet fuel
GHG	Greenhouse Gases
HEFA	Hydroprocessed Esters and Fatty Acids
HTL	Hydrothermal Liquefaction
HC-HEFA	Hydrocarbon-Hydroprocessed Esters and Fatty Acids
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
MJSP	Minimum Jet Fuel Selling Price
$MJSP_H$	Minimum Jet Fuel Selling Price (After variable harmonization)
$MJSP_R$	Minimum Jet Fuel Selling Price (Reported)
$MJSP_P$	Minimum Jet Fuel Selling Price (Reproduced in this study).
MSW	Municipal Solid Waste
OPEX	Operational Expenditures
OPLS	Orthogonal Partial Least Squares
PTJ	Pyrolysis to Jet
PLS	Partial Least Squares
PG	Purpose Grown Feedstock
PW	Process Waste
RMSEE	Root Mean Square Error of Estimation
RMSECV	Root Mean Square Error of Cross-Validation
SCENT	Standardized Cost Estimation for New Technologies
TCI	Total Capital Investment
TEA	Techno-Economic Analysis
TPEC	Total Purchased Equipment Cost
TRL	Technology Readiness Level
VIP	Variable Importance Plots
WACC	Weighted Average Cost of Capital

comparing the economic aspects of SAF [4–8] provide a broad overview of the techno-economic landscape. For example, Okolie et al. [8] applied a whole-system approach to map out strategic focus areas for cost reduction in near-term SAF production pathways, including Alcohol to Jet (ATJ), Fischer-Tropsch (FT), and Direct Sugar to Hydrocarbon (DSHC). Dahal et al. [6] compared MJSP across 13 SAF pathways (both near-term and long-term) for different feedstock generations, including greenfield and integrated SAF production. de Jong et al. [9] evaluated greenfield and integrated SAF production (the latter using existing refinery infrastructure) and recommended further exploration of integration strategies to reduce capital and operating costs. Shahriar and Khanal [7] examined the relationship between MJSP and jet fuel production capacity across different feedstocks and pathways. Another recent study conducted a fundamental statistical analysis on 55 peer-reviewed studies (near- and long-term) covering Hydroprocessed Esters and Fatty Acids (HEFA), ATJ, FT, and power-to-liquid pathways, without categorizing results by specific feedstocks [10]. However, the existing review literature does not quantify the influence of key variables on MJSP variability.

To address these gaps, this study conducts a detailed and thematic literature review of SAF pathways and feedstocks, specifically focusing on non-food feedstocks. In contrast to broader overviews by organizations like ICAO and IEA [11,12], which provide a "fish's-eye view" of SAF production routes and related policies, markets and deployment challenges, our analysis zooms in on the economic details of the production process to contribute to understanding underlying drivers and patterns across studies. We statistically assess how key variables (refer to section 2.3) affect MJSP, offering detailed numerical insights and empirical validation. Table A-1 (Appendix A) summarizes review articles from the past decade and their focus areas. Our approach differs in linking the assumptions used in TEA studies to variations in MJSP estimates and performing a meta-analysis to quantify the influence of key economic variables- capital expenditures, operational expenditures, feedstock costs and by-product revenues, on MJSP variability using statistical measures. Building on this, harmonization analysis of these variables is also conducted to enable fair comparisons across pathways and uncover interrelationships among them. The qualitative narrative for each pathway is also presented to discuss the influence of different factors on the MJSP ranges reported in the literature. The system boundaries encompass feedstock processing through jet fuel production.

The study has the following objectives:

1) present MJSP ranges for different SAF pathways based on feedstock categories, and compare greenfield cases with integrated cases,
2) develop a techno-economic database for greenfield cases and review the various assumptions in the literature that lead to MJSP variation, and.
3) identify and quantify pathway-specific key factors that influence the MJSP and conduct a detailed investigation of critical variables to deepen the analysis.

These objectives aim to provide a more accurate and comparable assessment of the techno-economic viability of various SAF pathways, contributing to the broader discourse on sustainable aviation. The detailed analytical assessment MJSP in this study provides a strong empirical foundation that can be leveraged by future policy-oriented research. The study is structured as follows: Section 2 presents the methodology for the literature scanning, the filtering criteria, the process for data extraction, and the data analysis. Section 3 presents and discusses the findings from the literature review, regression analysis, and harmonization analysis. Section 4 presents the conclusions.

2. Methods

The employed working procedure consists of six components, as summarized in the flowchart in Fig. 1 and described in detail in the following sections:

1. **Literature screening**: Peer-reviewed TEA publications conducted between 2010 and 2023 were included (Section 2.1).
2. **Filtering**: Three screening criteria were used to screen studies, ultimately contributing to achieving our research objectives (Section 2.2).
3. **Data extraction and processing**: Key techno-economic variables for different pathways were extracted and standardized to the common unit USD/GJ for the cost year 2022 (Section 2.3).
4. **Reproduction of MJSP:** The MJSP was reproduced ($MJSP_P$) from extracted data and compared to the reported MJSP ($MJSP_R$) (Section 2.4).
5. **Regression analysis:** The impact of TEA variables on MJSP was quantified through multivariate linear regression analysis using SIMCA (Section 2.5.1).

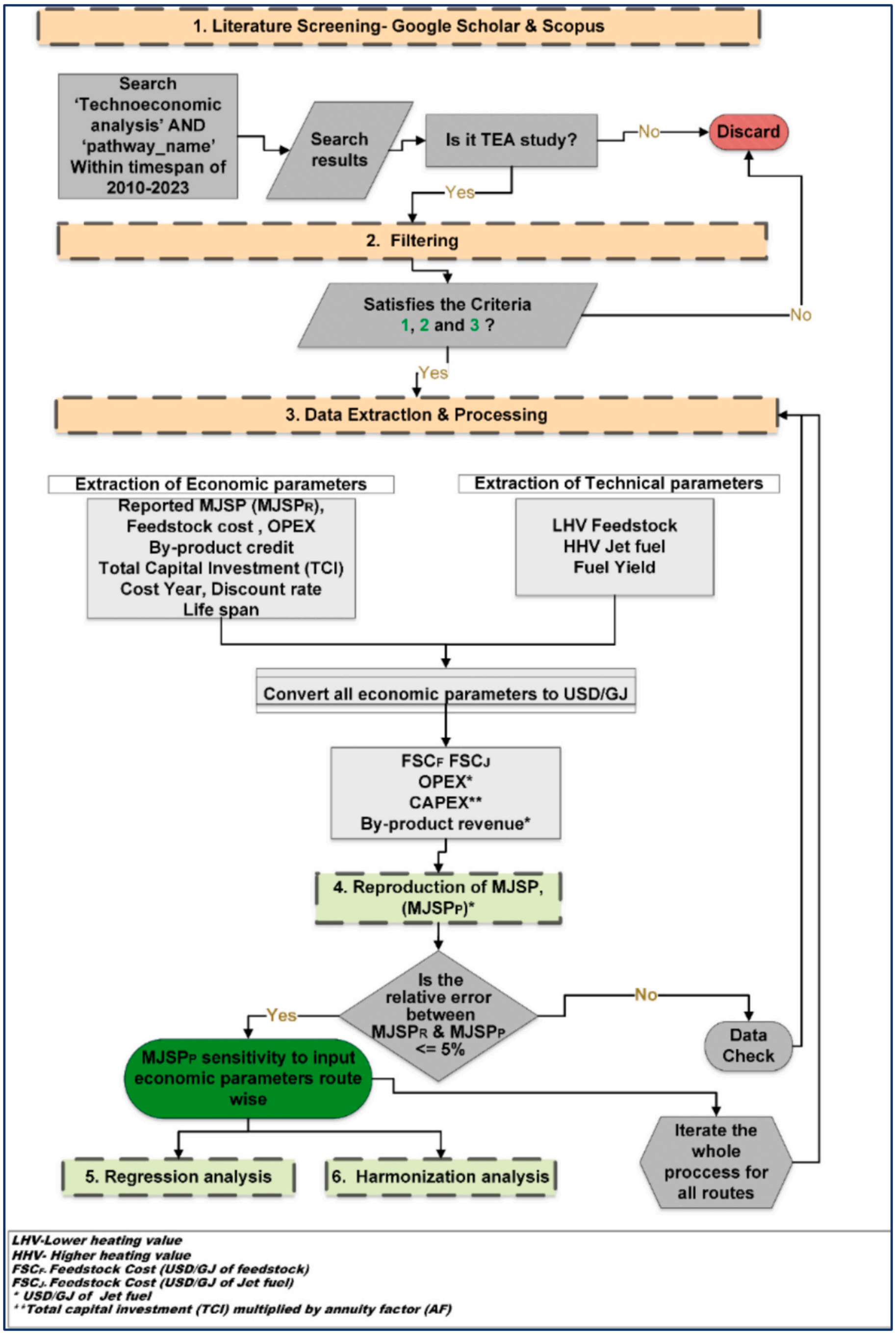

Fig. 1. Methodology flowchart summarizing the working procedure followed. For details about the filtering and screening criteria, see 2.1 to 2.5.

6. **Harmonization analysis**: Key variables were harmonized to understand the variances in reported MJSP range (Section 2.5.2).

2.1. *Literature screening*

The literature search was performed using Google Scholar and Scopus, utilizing Boolean search strings 'Techno-economic analysis' AND 'pathway_name' to find relevant publications from 2010 to 2023. Only techno-economic articles and articles fulfilling the screening criteria outlined in Section 2.2 were considered for further analysis.

2.2. *Screening criteria*

Criteria 1. The analysis focuses on pathways with high (>6) technology and fuel readiness levels (TRL and FRL, respectively) [13]. As of now, ASTM International has approved 11 pathways. Of those, HEFA is the only commercialized pathway, with a TRL of 9, while FT and ATJ pathways have TRLs of 7–8 [14]. In contrast, the Pyrolysis oil to Jet (PTJ) pathway – still not ASTM-approved – has a TRL of 6 for upgrading of pyrolysis oil and a TRL of 8 for the fast pyrolysis process [13]. Refer to Fig. A-1 (Appendix A). This criterion excludes novel pathways with low TRL and FRLs. The low TRL pathways, e.g. Hydrothermal Liquefaction (HTL), may show significant economic potential, but suffer from limited data availability, which hampers reliable comparisons and increases uncertainty related to near-term commercial performance [9,15].

Similarly, emerging pathways such as power to liquid include several low-TRL components, and their economic viability depends heavily on assumptions about carbon capture, electrolysis efficiency, and electricity prices. This contributes to significant uncertainty in both scalability and near-term economic performance [6,15].

Criteria 2. Given concerns about land availability, land-use change, and regulatory constraints, non-food feedstocks are expected to drive most of the medium- to long-term growth in SAF production, from both a GHG emission reduction [16] and a food security perspective [17]. Numerous studies advocate for prioritizing waste-based feedstocks over food crops, e.g. [8,10,18–21]. For example, SAF derived from microalgae processed via the Hydroprocessed Hydrocarbons, Esters and Fatty Acids (HC-HEFA) pathway, shows significant long-term potential [22] and is already ASTM-certified. However, the technologies required for large-scale cultivation, harvesting, and processing of algae into fuels are still underdeveloped and currently not commercially viable [23]. Consequently, such pathways are outside the scope of this study. Accordingly, we considered only non-food feedstocks viable in the near-to-medium-term. Feedstocks were grouped into five categories (Table 1). While several considered TEA studies, such as Diedrich et al. [24], compared both first-generation (e.g., vegetable oil) and second-generation (e.g., lignocellulosic biomass) feedstocks, only data related to non-food feedstocks were extracted and used here.

Criteria 3. The availability of high-quality data was essential for the subsequent analyses. Only studies that adhered to the system boundaries defined in this work (from feedstock conversion to jet fuel production) and that provided sufficient data to reproduce MJSP values were considered. For example, studies focusing solely on partial process steps (e.g., Geleynse et al. [28], which examined only the ethanol-to-jet stage of the ATJ pathway) were omitted. After applying these criteria, 32 out of 54 publications were deemed suitable. Of these, 27 contributed data to greenfield cases (totaling totaling52 cases), and 10 to integrated cases (totaling 39 cases), with five publications contributing to both categories. Table 2 summarizes the number of cases retrieved for each pathway-feedstock combination.

2.3. Data extraction and processing

Key techno-economic variables extracted from the selected studies included: feedstock cost (FSC), total capital investment (TCI), operating expenditure (OPEX), by-product revenue (BPR), discount rate, jet fuel yield, cost year, MJSP, and plant lifetime. The extracted values are presented in the supplementary material in their original reported units

Table 1
Feedstock categories for greenfield and integrated cases.

Feedstock category	Feedstocks included in the studied cases Greenfield cases	Integrated cases
Agricultural residues (AR)	Oleaginous crop waste, Corn stover, Wheat straw, Rice husk, Sugarcane bagasse	Bagasse, Sugarcane stalk and straw, Wheat straw
Forestry residues (FR)	Softwood forest residue, Wood chips, Forestry residues, Lignocellulose, Woody biomass	Forestry residues
UCO (O)	Waste vegetable oil (WVO), Yellow grease/used cooking oil (UCO) [a]	No cases
Waste-based (PW)	Plastic waste, Horse manure, Municipal solid waste (MSW)	No cases
Purpose-grown feedstocks (PG)	Switchgrass, Hybrid poplar biomass, Eucalyptus, Willow	Switchgrass, Eucalyptus
Special category (SC)		Black liquor

[a] UCO/yellow grease is derived from commercially generated used edible oil and may include some animal fat [25,26]. Waste vegetable oil (WVO) or waste cooking oil, primarily used in household or commercial frying, does not contain animal fat [27]. This study categorized WVO and UCO under oil-based (O) feedstocks and collectively referred to them as UCO hereafter.

(Appendix BX).

In the processing, MJSP and cost variables were indexed to 2022 using the Producer Price Index (PPI) [57]. PPI was preferred over the Consumer Price Index (CPI), as it reflects production costs and market conditions relevant to the energy sector. TCI was adjusted using the Chemical Engineering Plant Cost Index (CEPCI) 2022.

All economic values were standardized to USD_{2022}/GJ of jet fuel, with the fuel output based on the Higher Heating Value (HHV) for each production pathway. Two metrics were used for the feedstock cost: cost per GJ of fuel output (FSC_J) and cost per GJ of feedstock (FSC_F), with the feedstock input based on Lower Heating Value (LHV). This comparison juxtaposes the raw economic value of feedstocks against their practical economic efficiency in jet fuel production. If LHV was not provided, proximate or ultimate analysis was used to estimate it, if provided. Otherwise, LHV values were referenced from secondary studies.

2.4. Reproduction of MJSP

For data analysis, we recreated the MJSP ($MJSP_P$) for each greenfield case according to Equation (1):

$$MJSP_P = (TCI^*AF) + (OPEX + FSC_J - BPR) \quad (1)$$

where *TCI* denotes the total capital investment, *AF* the annuity factor, *OPEX* the operational expenditure, FSC_J the feedstock cost, and *BPR* the by-product revenue, all expressed in USD/GJ of jet fuel. The term TCI*AF constitutes the annualized capital expenditure, *CAPEX*. The annuity factor *AF* was calculated according to Equation (2):

$$AF = \frac{\{(1+i)^n * i\}}{\{(1+i)^n - 1\}} \quad (2)$$

where n is the economic lifetime of the plant in years and i is the discount rate. The discount rate is often approximated by the weighted cost of capital (WACC), which accounts for both debt (at its interest rate) and equity (at its expected rate of return).

We achieved an error margin of 2 % on average, compared to reported MJSP ($MJSP_R$) (Fig. 2). Appendix B and D present a pathway-wise comparison of $MJSP_R$ vs. $MJSP_P$ to demonstrate the accuracy of MJSP reproduction in this study.

2.5. Data analysis process

Multivariate regression analysis was conducted to quantify the impact of key economic variables on the variance in reported MJSP. Additionally, key variables were harmonized to further explore the sources of variance in reported MJSP. Similar methodologies were employed in previous studies, such as Aui et al. [58], where multivariate linear regression was used to assess the influence of key parameters on the commercial viability of ethanol, and Cruce et al. [59] who performed techno-economic harmonization for algae-based biofuels to enable a fair comparison of published results. Bann et al. [60] used harmonization methodology to compare six SAF pathways. They focused on cost comparison across different jet fuel production pathways using consistent fundamental financial and technical assumptions, with the goal of evaluating profitability under policy scenarios in the USA. This study instead harmonized key economic variables to understand how the dynamics of these variables impact the MJSP of SAF pathways.

2.5.1. Regression analysis

Multivariate regression analysis was performed using the Orthogonal Partial Least Squares (OPLS) model in SIMCA (Version 17) [61] to investigate how the X variables – CAPEX, OPEX, FSC_J, and BPR – influenced the variation observed in the response variable Y, $MJSP_P$, across different production pathways. CAPEX represents the annualized capital expenditure and thus comprises the combined effect of TCI and the annuity factor in the reduced regression model. OPLS, an extension

Table 2
Number of cases per pathway-feedstock combination retrieved from TEA publications.

Pathways	Pathway-Feedstock	Greenfield cases	Source TEA publications for greenfield cases	Integrated cases	Source TEA publications for integrated cases
HEFA – Hydroprocessed Esters and Fatty Acids	HEFA-O	6	[9,25,26,29–31]	0	NA
PTJ – Pyrolysis to Jet	PTJ-AR PTJ-FR PTJ-PG PTJ-PW	16	[9,32–40]	6	[9,32,41]
FT – Fischer-Tropsch	FT-AR FT-FR FT-PG FT-PW	13	[9,24,32,41–47]	11	[9,32,41,48,49]
ATJ – Alcohol to Jet	ATJ-AR ATJ-FR ATJ-PG	17	[9,24,32,33,44,46,50–53]	22	[9,32,41,48,50,54–56]

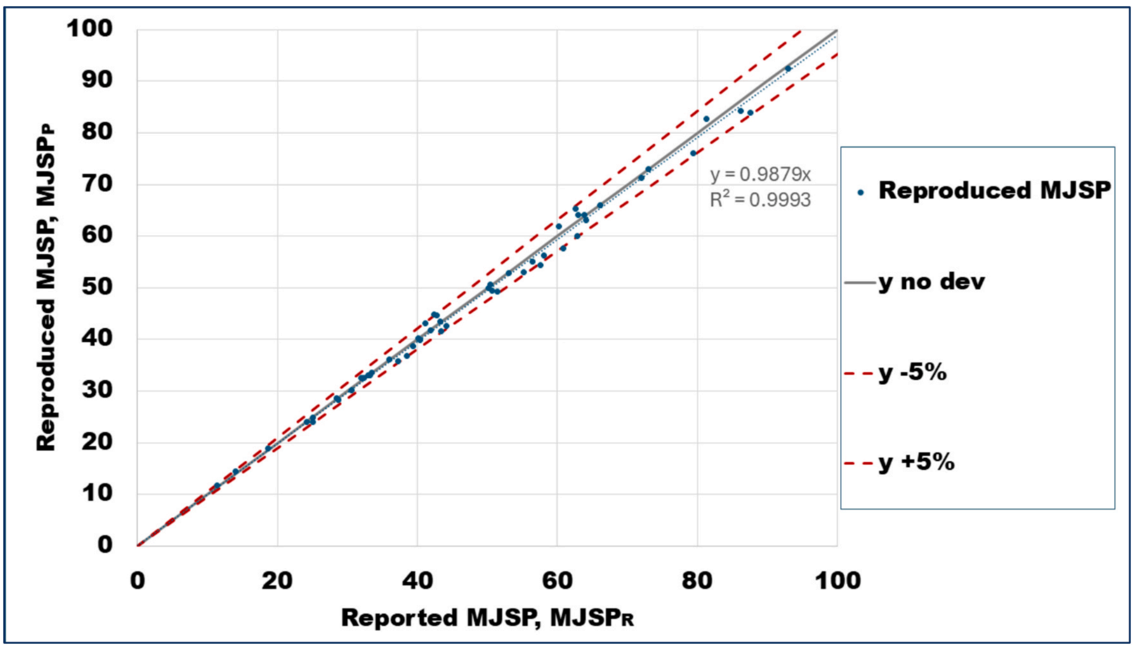

Fig. 2. Reproduced MJSP ($MJSP_P$) vs. reported MJSP ($MJSP_R$).

of Partial Least Squares (PLS), offers greater predictive power and interpretability compared to PLS [60] as it enhances the model's focus on the relevant predictive signal by filtering out noise or irrelevant variation. It is particularly well-suited for multivariate analysis where significant multicollinearity exists among the input (X) variables [62]. As OPLS is based on covariance structures, it captures the patterns of association between variables rather than their absolute levels. It separates dataset variability into systematic and residual components, further breaking down the systematic variation into predictive components (correlated with MJSP) and orthogonal components (uncorrelated with MJSP) [61]. This makes it easier to identify which variables contribute meaningfully to the model. However, the current study solely analysed and predicted the MJSP within the assumptions outlined in Sections 2.1, 2.2 and 2.3. Future research should extend this analysis by including a broader range of datasets representing diverse SAF production pathways.

Pathways were treated as categorical variables, each representing a distinct class or subset (refer to Appendix C for the regression plot of all pathways). OPLS models were developed for each production pathway (ATJ, FT, PTJ, HEFA) in addition to a global model including all pathways. The model fit predictive accuracy was evaluated using the Root Mean Square Error of Estimation (RMSEE) and the Root Mean Square Error of Cross-Validation (RMSECV). A 90 % confidence interval was used to gauge the reliability of the model. All techno-economic variables were expressed in consistent functional units (USD/GJ of fuel) to account for the regional variation in the data. Additionally, the OPLS modelling framework on SIMCA standardizes all input variables by centering and scaling them to unit variance by default. This ensures that the analysis captures the covariance patterns and relative influences of each variable on MJSP, independent of their absolute levels. Regression coefficients for each variable within these classes were visualized in a coefficient plot (Appendix D), with jack-knife uncertainty error bars indicating uncertainty limits. The coefficient size reflects the change in MJSP when CAPEX, FSC_J, OPEX, and BPR vary by one standard deviation (in unit variance-scaled data), while the other variables remain constant at their averages.

The relationships between the X and Y variables, as well as within the Xs and Ys, were visualized in an OPLS loadings scatter plot (Appendix E). The vertical axis represents orthogonal components (X-loadings $p(o)$ and Y-loadings $s(o)$), while the horizontal axis represents predictive components (X-loadings p and Y-loadings q). The distance of a point (representing X variables) from the origin indicates its influence on the model. Variables located further from the origin significantly contribute to variation (predictive or orthogonal) in the data. Variables further along the *X*-axis (*pq(1)*) are more strongly correlated with the variation in *X* variables predicting MJSP, while those further from the origin on the *Y*-axis (*poso(1)*) are more associated with variation in X variables orthogonal (uncorrelated) to MJSP. Together, these plots provide complementary insights into the influence of key economic variables on the techno-economic performance of SAF. Score and Variable Importance Plots (VIP) for individual cases were also examined for deeper insights.

2.5.2. Harmonization analysis

X variables were held constant at their average values (presented in Appendix BX), while other variables remained as reported for each specific pathway-feedstock combination. This approach isolated the impact of variability of *X* variables on MJSP. The MJSP calculated using harmonized variables is denoted as $MJSP_H$ and was compared with reproduced $MJSP_P$ to observe the relative change in the MJSP range. Due to limited number of cases for PTJ-PW, FT-PW, and FT-PG, which prevented any meaningful insights into MJSP variance, these were excluded

Although the review includes MJSP results from both greenfield and integrated systems, the analytical focus was on greenfield scenarios to maintain a manageable scope. Additionally, extracting and processing OPEX for integrated scenarios was not feasible due to insufficient detail in the TEA studies regarding cost-sharing mechanisms between SAF production and host industry operations. The statistical test would thus require more integrated cases as data input. Nevertheless, a brief discussion on the topic is included in 3.3.

3. Results and discussion

Compared to existing reviews that primarily have focused on comparing SAF pathways, this study explored the factors that affect the variation in TEA results, and economic variables in detail. Sections 3.1.1 to 3.1.3 discuss these assumptions, setting the stage for future studies that may build on this framework. In Sections 3.2.1 to 3.2.4, we examined how process design-induced variations influence TEA results. Regression analysis (Section 3.4) and harmonization analysis (Section 3.5) further provided insights into how the underlying patterns and the economic variables' relationship affect MJSP variation.

3.1. General sources of variances in MJSP range

This section addresses the sources of variance in MJSP, which are inherent to TEA and primarily related to TCI estimation techniques, by-product appraisal methods, and financial assumptions.

3.1.1. Variances due to techno-economic assumptions

de Jong et al. [9] noted that uncertainties in capital cost often arise from the use of factorial estimation methods, which can lead to varying TCIs even when starting with identical total purchased equipment costs (TPEC). Most authors applied Lang factorial methods for TCI estimation, such as those proposed by Peter and Timmerhaus [63] and Towler and Sinnott [64]. These methods differ regarding Lang factors, which represent percentages of equipment costs used to estimate other cost items. Towler and Sinnott's factors are higher than the ones from Peter and Timmerhaus [65]. Alternatively, some studies have used Guthrie's method, where factors are applied to individual equipment items rather than to the overall equipment cost [65,66].

Some studies directly used recent vendor quotes for estimating equipment costs, e.g., [37,50], while others, such as [24,26,28,36,40,51,54], have drawn on NREL reports [67–70]-themselves compiled from extensive vendor quotes over many years. Another approach is to employ software tools for the TCI estimates. Examples are the Standardized Cost Estimation for New Technologies (SCENT) tool developed by Ereev and Patel [68], and applied by e.g., de Jong et al. [9]; or the economic analyzer from Aspen Plus. However, depending on the method, these approaches may lead to under- or overestimations of TCI [9]. For example, Hollman [71] found that 10 % of the 1000 process industry projects examined exceeded their budgets by 70 %, a concern also highlighted by Tsagkari et al. [72], as over- or underestimation can affect both biorefineries' profitability and public trust in the economy.

Process design also significantly impacts TCI, BPR, OPEX, yield, and product distribution [51]. More complex processes require more capital for purchasing and installing equipment, which raises costs [9,47,73]. The choice of process depends upon the research motivation, such as seeking value chain benefits. For example, Hsu et al. [25] compared a three-step conversion pathway (hydrolysis, hydroprocessing and isomerization) with a simpler one-step pathway (hydroconversion). They found that the three-step process, with its diverse product distribution, generated a higher by-product value, reducing the jet fuel MJSP, compared to the one-step process having only jet fuel as the main product. Similarly, Wright et al. [74] and Anex et al. [75] showed that using bio-oil (a pyrolysis process product) to produce on-site hydrogen for hydrotreatment lowers the biofuel yield, which affects the final fuel price.

3.1.2. Variances due to by-product estimation methods

By-product revenue (BPR) estimation methods were also found to vary significantly between studies. Barbera et al. [30] used wholesale prices for naphtha and diesel, while de Jong et al. [9] applied proportional cost allocation based on market value. Tanzil et al. [32,33] and Bann et al. [34], sourced historical prices for the produced by-products and performed a linear regression against the model-derived jet fuel selling prices to determine the by-product selling price, while Wang et al. [42] and Astonios et al. [44] relied on real-world pricing data. Diedrich et al. [24] assumed a 50 % increase in naphtha and diesel prices due to green premiums, while Lopez et al. [45] proposed higher prices for by-products (petrol, diesel, naphtha, and fuel oil) to ensure the economic viability of SAF compared to conventional fuel processes. In cases where a byproduct lacked an established market, alternative approaches have been adopted. For example, Neuling and Kaltschmitt [46] found the price ratio between biodiesel and fossil diesel to estimate by-product revenue for bio-based products like butane. Furthermore, IEA classifies co-products as generating revenues comparable to the main product and by-products as yielding lower revenues compared to main-product [76]. However, in the existing TEA literature there is the often synonymous use of the terms "co-product" and "by-product', highlighting the inconsistencies with methodological treatment of by-products [39,77].

3.1.3. Variances due to financial assumptions

Variations in financial assumptions across TEA estimations are also notable. Most studies assumed a financing structure of 30 % equity and 70 % debt, with an 8 % interest rate on debt over a 10-year loan term and a 10 % discount rate. The relative proportions of debt and equity also influence WACC. Pearlson et al. [78] found that eliminating debt could lower fuel gate costs, and higher discount rates are associated with higher MJSPs.

Income tax rates also vary by local policy and year [42]. The highest tax rate (40 %) was reported in a UK-based study [49], for 2017. The lowest tax rate (16.9 %) was used in US-based studies, e.g. [32,33,52], also for 2017. Crawford et al. [53] used a 0 % tax rate, evaluating MJSP in a pre-tax scenario and noting the ambiguity around biorefinery tax requirements. Other policy measures, such as decarbonization credits, as considered by [43,79], can reduce the MJSP, although such policy measures differ between countries. Fig. 3 shows the regions where the TEA studies compiled in this study were conducted. Many studies are USA and EU based, which is reflective of the current research landscape. Although all the data collected was standardized to 2022 USD to allow for a fair comparison, the geographical and technological concentration of available TEA studies may introduce selection bias. Future research with new TEA assessments, particularly those covering underrepresented regions and novel SAF pathways, may present additional insights

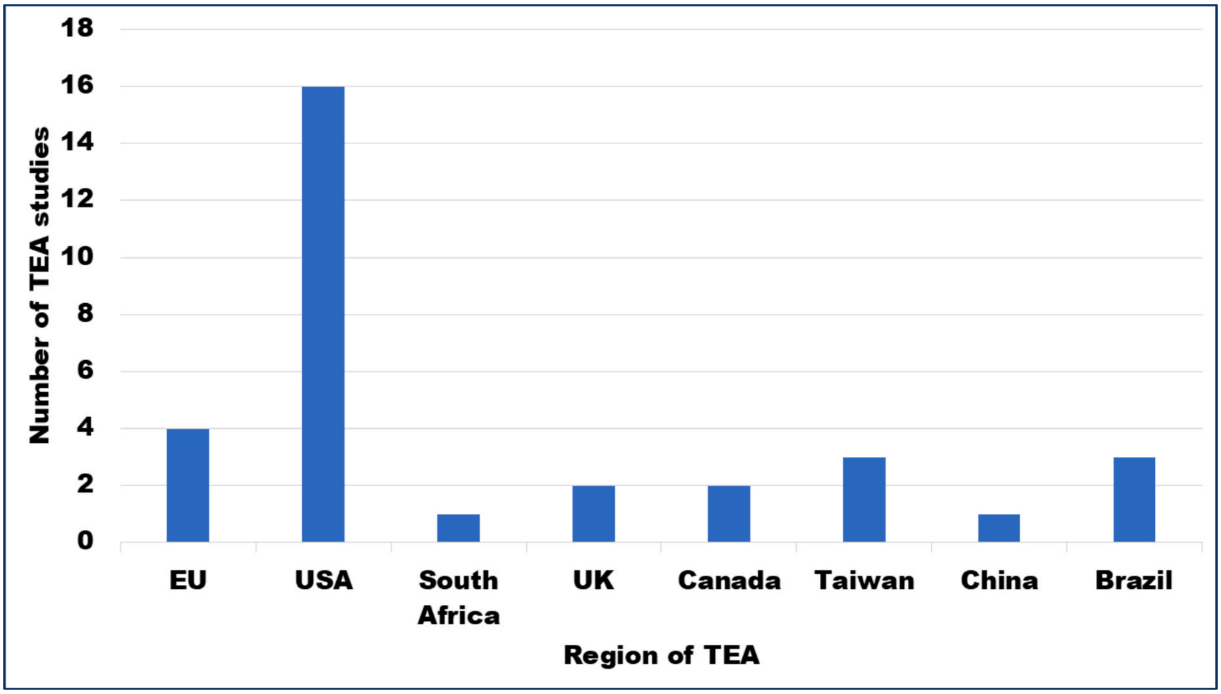

Fig. 3. Number of TEA (techno-economic analysis) publications considered in this study per country or region.

and refine the findings of this study.

Lastly, we noticed a general need for improved data quality and transparency in TEA studies on SAF. Incomplete disclosures regarding the derivation of intermediate cost components and discrepancies between supplementary materials and primary texts hinder comprehensive and accurate analysis, which is crucial for informed decision-making.

3.2. Cost findings for greenfield SAF production

Addressing the first objective, Figs. 4–7 illustrate the reported MJSPs, CAPEX, feedstock costs, and by-product revenue ranges for the 52 considered greenfield cases of HEFA, ATJ, FT, and PTJ across the different feedstock categories. Furthermore, Table 3 provides the average annual percentage contribution of cost variables to the MJSP for

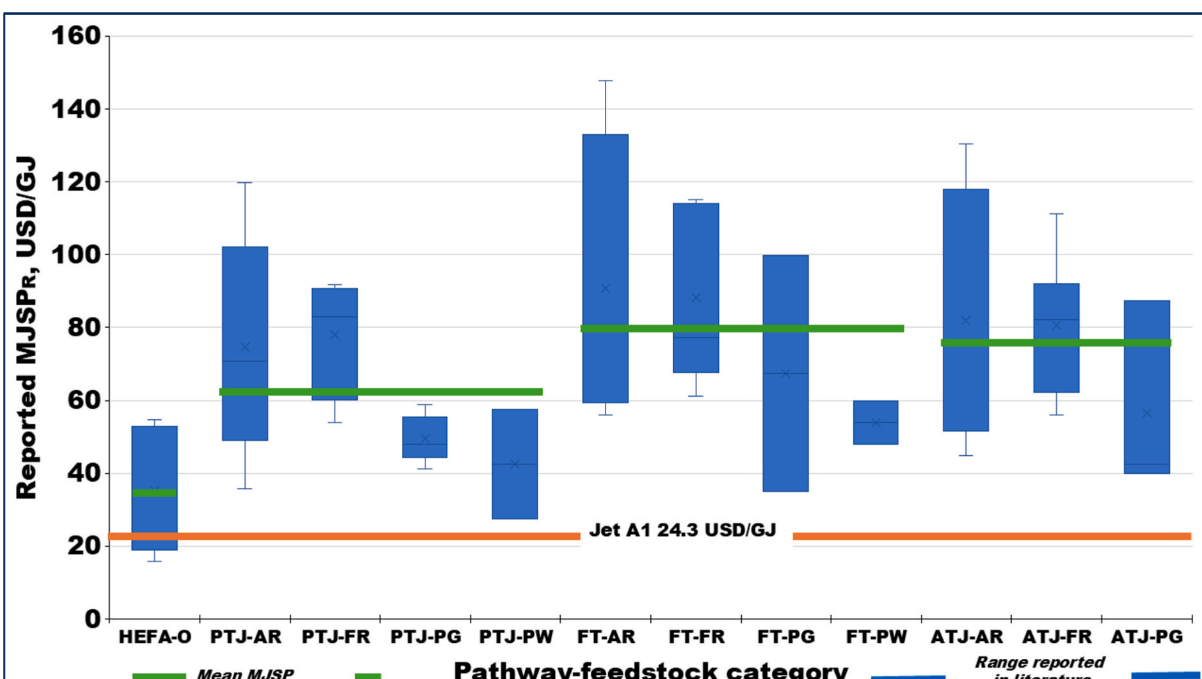

Fig. 4. Reported MJSP ($MJSP_R$) for SAF pathways for greenfield scenarios, presented in USD_{2022}/GJ and adjusted as per PPI 2022. The green horizontal lines indicate mean MJSP per pathway, across feedstock categories. The orange line indicate Jet A1 fuel price in 2022 reported by IATA [84]. HEFA = Hydrogenated esters and fatty acids, ATJ = Alcohol to Jet, FT = Fischer-Tropsch, PTJ = Pyrolysis to Jet, O = Oil based feedstocks AR = Agricultural residue, FR = Forest residue, PG = Purpose grown feedstocks, and PW = Process waste.

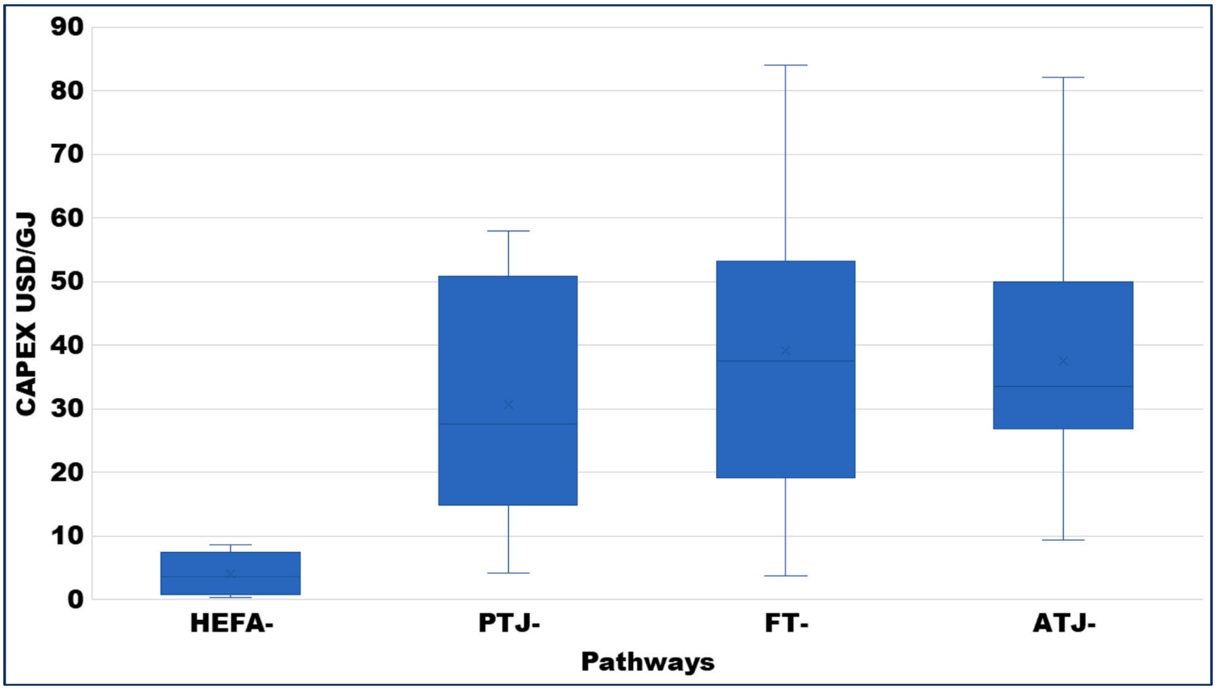

Fig. 5. CAPEX reported pathway-wise, annualized and adjusted as per CEPCI 2022.

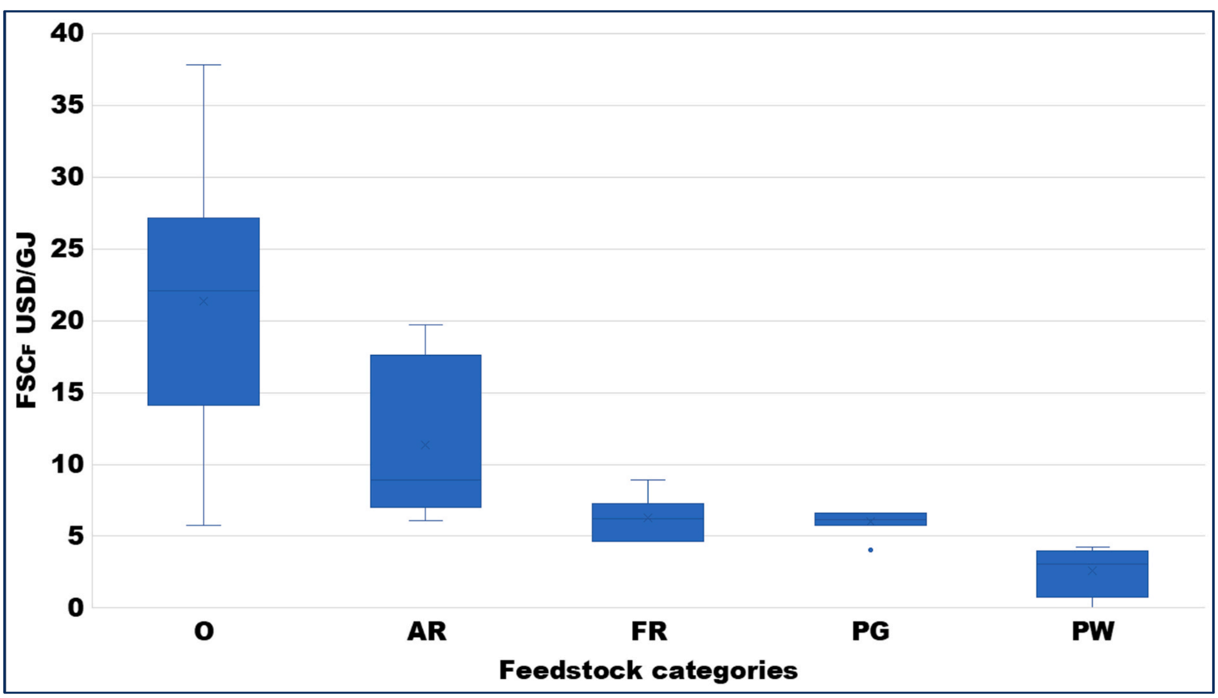

Fig. 6. Feedstock cost (FSC_F) $USD_{2022}/GJ_{LHV\ feedstock}$ adjusted as per PPI 2022. O = Oil-based feedstocks, AR = Agricultural residue, FR = Forest residue, PG = Purpose-grown feedstocks, and PW = Process waste.

each pathway. Appendix F contains additional figures referenced throughout this section.

The average MJSP for HEFA jet fuel based on UCO is 35 USD/GJ, which is significantly lower than all other pathways, confirming previous studies. HEFA benefits from the lowest CAPEX (Fig. 5 and Table 3) of all the pathways, as the production process has minimal complexity [80], is commercially practiced, and also backed by well-established biodiesel infrastructure and high fuel readiness level [81,82]. The PTJ pathway, with an average MJSP of 64 USD/GJ, is a promising near-term option. On the higher-cost end, ATJ (77 USD/GJ) and FT (80 USD/GJ) are comparable. However, all pathways are more costly than the Jet A1 fuel price of 24 USD/GJ. Pathways using process waste (PW) as feedstock (FT and PTJ) have lower MJSP due to zero or low feedstock costs (Fig. 6). Furthermore, by-product revenues contribute significantly to lowering the MJSP for PTJ and ATJ (Fig. 7, Table 3). In contrast, the HEFA's OPEX and BPR contributions to the MJSP are lower than for other pathways (Table 3), with jet fuel (primary product) constituting the majority of products [25,29,30] at an efficiency of 76 % [83]. HEFA

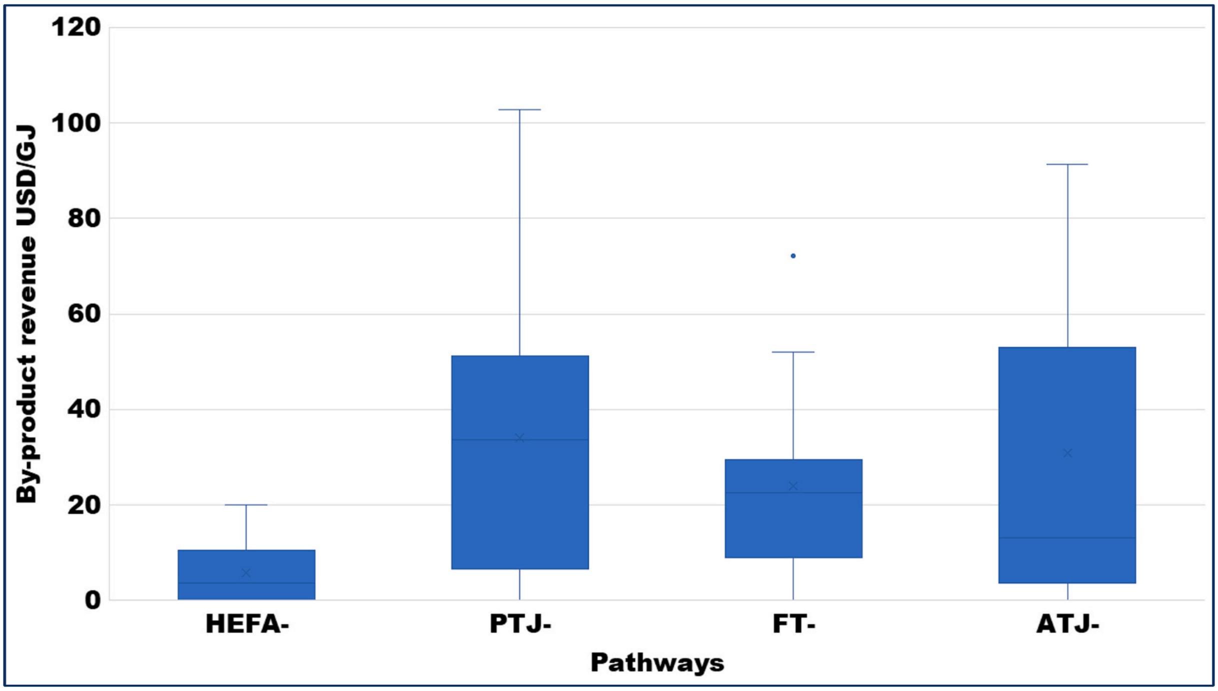

Fig. 7. By product revenue USD_{2022}/GJ of SAF pathway-wise and adjusted as per PPI 2022.

Table 3
Average annual percentage contribution of cost variables. The negative value of BPR indicates its total cost-offsetting potential.

Pathway-Feedstock	Capital expenditure CAPEX [a]	Operating expenditure OPEX	Feedstock cost FSC_J	By-product revenue BPR
HEFA-O	9.4 %	24.7 %	66 %	−14.5 %
PTJ	**30.7 %**	**41.4 %**	**27.9 %**	**−35.3 %**
PTJ-AR	30.9 %	41.3 %	27.8 %	−33.3 %
PTJ-FR	41.8 %	29.2 %	29.0 %	−33.4 %
PTJ-PG	41.8 %	29.2 %	29.0 %	−33.4 %
PTJ-PW	21.2 %	47.4 %	31.3 %	−34.0 %
FT	**36.9 %**	**37.0 %**	**26.1 %**	**−22.9 %**
FT-AR	38.2 %	38.8 %	23.1 %	−23.0 %
FT-FR	41.8 %	29.0 %	29.2 %	−15.4 %
FT-PG	24.3 %	48.0 %	27.7 %	−52.4 %
FT-PW	33.6 %	40.8 %	25.6 %	−15.3 %
ATJ	**34.5 %**	**43.2 %**	**22.3 %**	**−29.1 %**
ATJ-AR	39.4 %	39.2 %	21.4 %	−18.2 %
ATJ-FR	32.6 %	42.7 %	24.7 %	−23.8 %
ATJ-PG	36.0 %	47.9 %	16.2 %	−53.7 %

[a] Total capital investment (TCI) multiplied by the annuity factor (AF).

also has the highest yield among all pathways (Appendix F).

Sections 3.2.1–3.2.4 provide a detailed pathway-specific analysis, while Section 3.3 compares integrated and greenfield cases for the same pathways.

3.2.1. HEFA

Feedstock cost is a significant cost component for HEFA, in contrast to other pathways where CAPEX and OPEX tend to dominate (Table 3). HEFA from UCO shows an MJSP range of 18–57 USD/GJ (Fig. 4), while HEFA from first generation feedstocks and microalgae has an MJSP in the range of 30–407 USD/GJ [6,13,14,85]. Microalgae costs are higher due to the requirement for specific equipment and feed nutrients [85]. For comparison, palm oil, soybean oil, and rapeseed oil cost approximately 41 USD/GJ, 29 USD/GJ, and 64 USD/GJ, respectively (based on their respective LHV), as reported by Tiwari et al. [4], while UCO varies between 5–37 $USD/GJ_{LHV\ UCO}$ (Fig. 6).

UCO costs vary by region depending on culinary customs and market dynamics [29,86,87]. Chu et al. [29], for example, determined the price of UCO from the commodity market and used the spot price of UCO to determine the HEFA MJSP. In Asia, UCO exhibits lower prices due to higher supply [88]. For instance, UCO costs 22 $USD/GJ_{LHV\ UCO}$ in Taiwan [25] and 37 $USD/GJ_{LHV\ UCO}$ in the Netherlands [9], while in the USA, the UCO price is as low as 5.6 $USD/GJ_{LHV\ UCO}$ [26,30] due to a well-developed supply infrastructure [30].

By-products from UCO-based HEFA include naphtha, diesel, and LPG, whereas when using feedstocks like camelina or carinata, meal is generated as a by-product, which improves the economic viability of HEFA in such cases [29]. Besides the low contribution of BPR, OPEX is also a minor contributor to the MJSP (Table 3). Hydrotreating has a major influence on the OPEX [30], with hydrogen consumption accounting for 26 % of OPEX. Seber et al. found that hydrogen accounts for 12 % of the total costs, driving the operating costs during hydroprocessing [89]. Shahryar & Khanal [7] also noted the key contribution of hydrogen to OPEX and that the hydrogen module contributes to 50 % of CAPEX.

Overall, the widely accepted view that feedstock contributes significantly to HEFA's MJSP [6,7,79] is unlikely to change as Braun et al. noted that further major cost reductions are unlikely, making future prices increasingly dependent on feedstock costs [9].

3.2.2. Pyrolysis to jet (PTJ)

Among non-oleochemical feedstock-based pathways, PTJ appears promising, as highlighted by [8,60 9]. PTJ is also more feedstock versatile compared to HEFA. Dahal et al. [6] reported an MJSP range of 48–78 USD/GJ for PTJ, encompassing a wide range of feedstocks of relevance to this study (corn stover, wheat straw, and forestry residues), as well as a few estimates based on a first/second generation integrated sugarcane biorefinery using sugarcane and sweet sorghum as feedstocks from Santos et al. [90].

Our study finds that PTJ-AR exhibits the broadest MJSP range, from 36 to 120 USD/GJ, based on corn stover, wheat straw, and rice husk. Agricultural residues (AR) tend to have higher feedstock costs compared to forest residues (FR), purpose-grown feedstocks (PG), and process waste (PW) (Fig. 6). Similar to UCO, the cost of agricultural residues varies by location. For example, bagasse prices in Brazil depend upon the intensity of the dry season and the opportunity costs associated with electricity generation at sugarcane mills [49,91], while in the USA, corn stover is available at a lower cost due to the widespread presence of corn ethanol mills [33]. SAF produced via pyrolysis of MSW has an MJSP of 27 USD/GJ, making it the lowest-cost case for PTJ.

Feedstock type and characteristics, such as moisture content, impact the quality of bio-oil, the intermediate product of the pyrolysis process, as does pyrolysis process conditions such as the temperature [92]. The bio-oil quality in turn determines the upgrading techniques and the associated costs [35,39,40]. Bio-oil contains a high amount of oxygenated compounds, particularly phenols, which affect stability and SAF quality. The current state-of-the-art hydrotreatment processes cannot convert all compounds in bio-oil into valuable products [93]. However, phenols could be converted to aromatic ethers, as suggested by Ajam et al. [94] or separated as a by-product, as suggested by Sorunmu et al. [39]. The BPR revenue for PTJ in fact already contributes more to MJSP reductions than in other pathways, with diesel and gasoline constituting common by-products. Biochar was also reported by a few studies [38,39].

The quality of bio-oil can be improved by reducing its oxygen content through slurry-based processing, thus enabling further fuel upgrading with higher carbon recovery [95]. Rahman et al. [35] notices that fast pyrolysis is more cost-intensive compared to intermediate pyrolysis, which operates at lower heating rate and longer residence time, which leads to higher quality bio-oil with lower oxygen content, but at a lower bio-oil yield.

Bio-oil upgrading is the major cost driver for PTJ, due to in particular hydrogen consumption but also type and amount of catalyst, which significantly impacts both CAPEX and OPEX [9,35,39]. Yang et al. [40] and Crawford et al. [53] further highlighted CAPEX and OPEX interdependency on hydrogen sources, with hydrogen production through natural gas reforming being, in general, the cheapest option, while onsite coproduction of hydrogen increases TCI significantly [40]. Hydrogen produced through water electrolysis also increases costs, particularly when powered by renewable energy sources [96].

Stavros et al. [36] found that hydroprocessing requires more hydrogen than zeolite cracking (no hydrogen needed) or gasification, but it also yields higher jet fuel outputs. When upgrading through gasification, the bio-oil is gasified to syngas, which is then conditioned to syncrude via the FT process (resulting in nine times less hydrogen demand than the hydroprocessing technique and hence less OPEX). However, the FT upgrading process is more complex, which increases TCI as much as in the case of hydroprocessing upgrading (see also Section 3.2.3).

OPEX, specifically regarding maintenance costs, is also affected by coke formation, a known issue during hydrotreatment [94]. Unlike HEFA, where feedstock cost is the dominant cost component, OPEX is the most significant contributor to MJSP for PTJ (Table 3). Variations in hydrogen consumption have a greater impact on MJSP for pyrolysis than for other pathways, such as hydrothermal liquefaction (HTL), ATJ, or DSHC, due to the high oxygen content of bio-oil, as emphasized by de Jong et al. [9]. Catalytic pyrolysis produces bio-oil with low oxygen content, has the potential to reduce hydrogen demand during upgrading [11]. However, the bankruptcy of Kior, which had initiated the ASTM certification for catalytic pyrolysis, delayed further development of this process [11]. As of 2024, four new developers are pursuing ASTM certification for PTJ [97], with three using waste as feedstock (tires, plastic).

Overall, despite the challenges outlined above, PTJ exhibits better economic performance than ATJ and FT [8,9] due to potentially high conversion yield and relatively low equipment costs.

3.2.3. Fischer-Tropsch (FT)

Like PTJ, multiple feedstocks can be processed through the FT pathway for SAF production, and FT-based pathways are often recommended for processing MSW and other residual waste, as noted by Dahal et al. [6], Okolie et al. [8], and Shahriar and Khanal [7]. FT-PW, using MSW [34] and plastic waste [45], provides the most cost-effective option among FT pathways. Bann et al. [34] pointed out that MSW's zero feedstock cost is a key factor in making the pathway economically viable, and that feedstock could become a cost factor if MSW-based fuel production (SAF and other fuel products) becomes more prevalent, potentially leading to a 2.5-fold increase in SAF production costs compared to assuming zero-cost MSW [31].

The average MJSP for FT-PG is lower than FT-AR and FT-FR (Fig. 4), with significant BPR contributions that help lower the MJSP. Intan Fitriasari et al. [77] found that FT based on woody biomass performs better than FT based on rice husk and is comparable to PTJ based on hybrid poplar wood. The study highlighted that high SAF costs in FT-based pathways were mitigated by gasoline sales, which offset the costs by up to 40 % [77]. Naphtha, electricity, LPG, and diesel are commonly reported by-products in several studies, e.g., [9,24,32,41,44,46,49]. As discussed for PTJ above, BPR assumptions can impact MJSP significantly. Lopez et al. [45] constitute an outlier in the by-product revenue range, with selling prices at 3.47 those of conventional fossil fuel prices.

Like PTJ-AR, FT-AR demonstrates the broadest MJSP range, from 70 to 147 USD/GJ, based on feedstocks such as corn stover, wheat straw, and rice husk. Drying feedstocks (both AR and FR) is a significant cost driver, as noted by Okolie et al. [14], and Neuling and Kaltschmitt [46] found that FT based on willow and wheat straw with heat-induced pretreatment processes had higher OPEX than ATJ based on wheat straw and grains.

Neuling and Kaltschmitt [46] also found the FT process to be more capital-intensive, and several other studies highlighted CAPEX as a key challenge for FT pathways [9,42,98]. Syngas cleaning and conditioning, air separation, and upgrading units contribute the most to capital costs [24,44]. Multiple reactors and units are required for upgrading syngas and synthesis, further driving up CAPEX [49,99]. On average, FT has the highest upfront TCI, at 345 USD/GJ, among all studied pathways (Appendix F). For FT pathways, OPEX and CAPEX contribute almost equally to MJSP (Table 3).

Hydrogen costs are relatively low for FT compared to other pathways (in particular PTJ), while catalyst costs are notably higher [7,42]. Rogachuk and Okolie [100] emphasized that among all cost components, catalysts costs for fuel synthesis have the most significant impact on OPEX in FT pathways. Furthermore, catalyst durability and reusability affect overall costs [98]. The type of feedstock used determines the syngas clean-up process, which in turn determines the type of catalyst required [11]. Since FT can handle multiple feedstocks, syngas clean-up becomes a critical and costly step, as it must be tailored to the specific feedstock [11]. Fixed operating costs are also a major component of non-feedstock OPEX in FT, compared to their relative share in ATJ and PTJ pathways, as shown in [41,47]. In those studies, fixed operating costs for FT were reported at 77 % and 66 %, compared to 71 % and 61 % for ATJ, and 55 % and 41 % for PTJ. Since fixed operating costs are typically estimated as a percentage of FCI, this highlights the significant role of CAPEX in shaping the operating expenses for FT.

3.2.4. Alcohol to jet (ATJ)

ATJ is also a flexible pathway, capable of handling various feedstocks, including energy crops and lignocellulosic biomass, as highlighted by Okolie et al. [8]. Hybrid poplar biomass exhibits the lowest MJSP for the ATJ pathway [53], as ethanol is produced via acetic acid fermentation, which improves fuel yield, and enables for economies of scale to compensate for the additional capital costs incurred through more operation units used during the fermentation. ATJ tends to have higher carbon and thermal efficiency compared to FT, as noted by Atsonios et al. [44].

Dahal et al. [6] reported an MJSP range of 5–283 USD/GJ for ATJ, with the lowest costs found in studies focusing on the core ATJ process of upgrading alcohol to jet fuel, such as that reported by Geleynse et al. [28]. Highest MJSPs were attributed to first generation feedstocks used in advanced fermentation-based processes [91], where microorganisms carry out the sugar extraction process from switchgrass. This demonstrates that incorporating novel technology that affects process design in TEA studies can result in wider ranges of MJSP estimates.

The ATJ pathway generates multiple byproducts, including gasoline, diesel, LPG, and electricity, with an average BPR of 35 USD/GJ. Some studies also reported activated carbon and lignosulfonate as byproducts [50,52]. Furthermore, Okolie et al. [8] suggested poly-generation to improve the economics of the ATJ pathway.

In lieu of this context, methanol and butanol are emerging as promising alternatives to ethanol as feed for the ATJ [14,101–107]. The variation in MJSP was observed across different system boundaries and alcohol intermediates, which reflects the sensitivity of cost estimates to the alcohol feed [24,28,47,108]. For instance, additional costs are incurred for water recycling units during oligomerization for ethanol as the intermediate feed compared to in isobutanol-based pathways [24,28]. Conversely, the cost of isobutanol is a major contributor to the MJSP of butanol-based SAF production [109,110].

Although ethanol-based SAF is generally more cost-competitive than SAF derived from isobutanol [54,109], isobutanol upgrading is less expensive, as shown by Geleynse et al. [28]. Akter et al. included logging residue collection in the system boundaries and found that SAF-based isobutanol would result in lower MJSP compared to the ethanol-based alternative [111]. Cost findings for integrated SAF production.

Similar to the PTJ pathway, hydrogen is a significant contributor to total OPEX for the ATJ pathway, as shown in [52,53].

3.3. Cost findings for integrated SAF production

Several studies (e.g., [32,33,41,48,49,54,85,90]) have explored the potential for integrating SAF production with existing biorefinery plants or other industries, as integration can offer cost advantages over greenfield development, depending on the co-production strategy [9]. In this study, we compared the MJSP ranges between integrated and greenfield scenarios for ATJ, FT, and PTJ pathways. While the MJSP range for integrated scenarios remains higher than both the current Jet A1 price and the HEFA range (Fig. 8), it is lower than that of the corresponding greenfield production. As shown in Fig. 8, integration yields an average MJSP reduction of 9–29 % compared to greenfield SAF production. Among the pathways, FT shows the largest relative MJSP reduction through integration, followed by ATJ and PTJ.

The FT pathway can also be integrated with different host facilities, such as pulp and paper mills, leveraging black liquor from chemical pulp production. This can be achieved by retrofitting a gasifier unit, utilizing existing service facilities and buildings, and reducing contingency and labor costs through shared resources between two facilities [47,48,112,113]. Tanzil et al. [41] also investigated the repurposing of a petroleum refinery, utilizing in-place components within the battery limits, such as hydrotreaters, hydrocrackers, and steam methane reformers, as well as external components, like buildings, power substations, storage facilities, and waste disposal units, to produce SAF via FT synthesis. They found that this approach can generate more cost savings than co-processing renewable feedstocks with fossil ones.

Another option is integration with sugarcane mills, as explored by e.g. Klein et al. [48] and Real Guimaraes et al. [113]. Klein et al. demonstrated that FT-based SAF from sugarcane stalks and straw could reach an MJSP that is even competitive with fossil jet fuel prices. This is mainly due to shared use of the CHP (combined heat and power) unit and the production of by-products like naphtha and diesel, which generate additional revenue streams or cost savings. Klein et al. also emphasized that FT integration with ethanol distilleries can be economically advantageous, although incorporating it into existing sugarcane mills presents challenges due to complex mass and energy integration requirements [48]. Real Guimaraes et al. [113] similarly highlighted the superior economic performance of SAF production via FT in sugarcane mills, where dry lignocellulosic material from sugarcane serves as feedstock, compared to standalone configurations. Sugarcane or corn-based mills and pulp and paper mills are excellent host biorefinery options for ATJ pathways [32,33,48]. Compared to ATJ, FT benefits more from integration, as the cost savings in ATJ are offset by the higher equipment costs for additional complex upgrading units [48].

de Jong et al. [9] also noted that the wide range of feedstock costs,

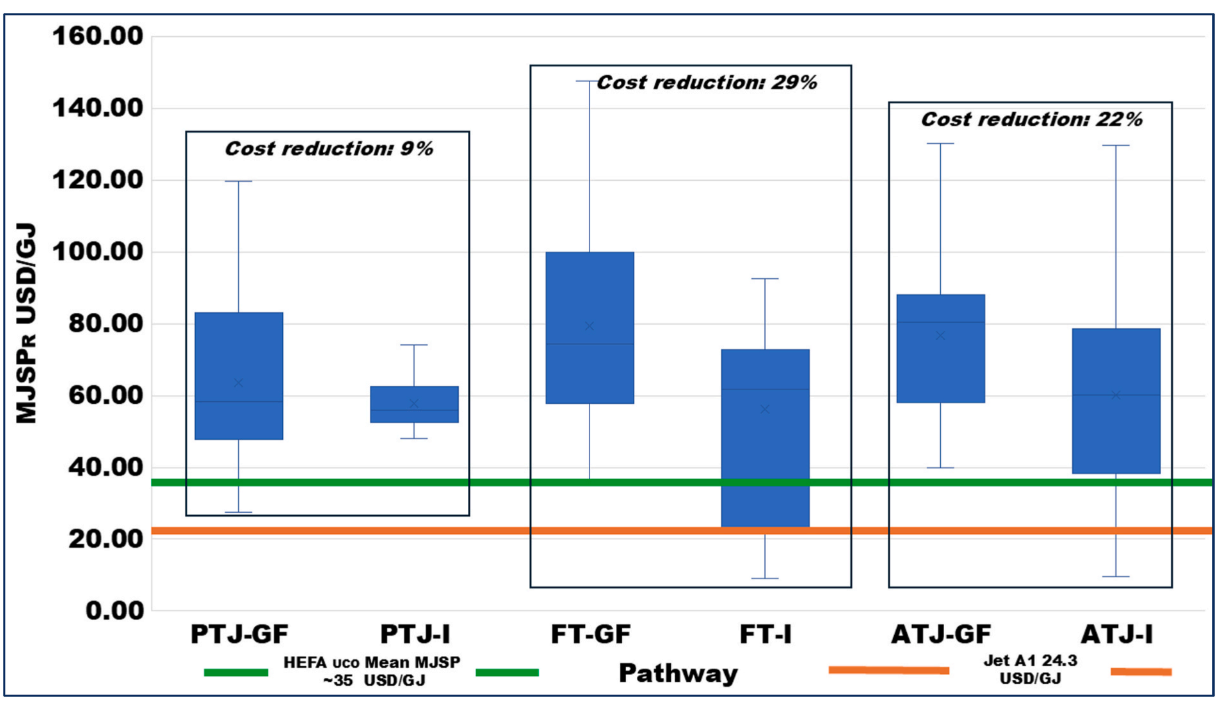

Fig. 8. Reported MJSP for studied SAF pathways for greenfield and integrated scenarios, presented in USD_{2022}/GJ and adjusted as per PPI 2022. GF = greenfield, I = integrated. Jet A1 fuel price based on the year 2022 reported by IATA [84].

particularly for straw, contributes to large variations in MJSP when the host biorefinery is a wheat ethanol facility. Overall, integrated FT production offers the most significant cost advantages compared to greenfield facilities among the integrated cases. However, integrated SAF production in existing systems also has limitations that may restrict efficiency and scalability. For PTJ, integration through co-location with a host biorefinery can lead to savings on feedstock transportation and allow for the utilization of excess electricity from biorefinery, as suggested by several studies [9,32,41]. Pyrolysis produces excess heat that can be utilized in a co-located industrial process (e.g. drying in sawmills) [114]. van Dyk et al. [115] also highlighted the potential of co-processing upgraded bio-oil with lipids at a petroleum refinery after partial upgrading by fluid catalytic crackers, the most feedstock flexible processing unit, which also allows for in-situ catalyst regeneration. Tanzil et al. [41] also explored the possibility of repurposing a petroleum refinery for SAF production via a pyrolysis pathway, which could reduce CAPEX by leveraging existing power and hydrogen generation systems. This kind of set-up benefits PTJ more than FT, as hydrogen requirement in FT pathway is minimal [7,42].

3.4. Regression analysis

Overall, the model's Root Mean Square Error of Estimation (RMSEE) for the 52 greenfield cases was 1.44 $USD/GJ_{Jet\ fuel}$, indicating high accuracy in predicting MJSP with $R^2 \sim 0.9956$ (Appendix C). Additionally, the Root Mean Square Error of cross-validation (RMSECV) was 1.53 $USD/GJ_{Jet\ fuel}$, suggesting good generalizability when applying the model to new data. Excluding TCI and annuity (represented by CAPEX, as previously described) from the regression model did not significantly affect the model's overall fit. RMSEE and RMSECV values for each pathway are listed in Table 4. Fig. 9 shows the magnitude of regression coefficients (uncertainty intervals calculated at a 90 % confidence level), illustrating the significance of CAPEX, FSC_J, OPEX, and BPR in explaining MJSP variability. The negative regression coefficient for BPR indicates its potential to offset MJSP. Positive coefficients represent direct relationships, and negative ones indicate inverse relationships. SIMCA displays coefficients based on scaled and centered data, which means that the coefficients reflect the relative influence of each variable independent of their units. As evidenced by the figures in Appendix D the coefficients are statistically significant (larger than the uncertainty), with confidence intervals that do not include zero.

Fig. 9 highlights high regression coefficients for FSC_J in HEFA, OPEX and BPR in PTJ, CAPEX and BPR in FT, and BPR and OPEX in ATJ, indicating how strongly MJSP correlates with these variables when they vary.

The loadings plot (Appendix E) shows minimal orthogonality for FSC_J across all pathways, suggesting that variations in FSC_J are strongly correlated with MJSP variation. Non-feedstock OPEX exhibits minimal orthogonality for FT, implying that its systematic variation aligns closely with MJSP. Section 3.2.3 suggests that fixed operating costs depend on FCI, and fixed operating costs are a significant component of non-feedstock OPEX for FT. Given this, we hypothesize that the strong predictability of non-feedstock OPEX is likely due to its dependence on FCI, further reinforcing the role of CAPEX in shaping the production cost structure in the FT pathway. It is noteworthy that different methodologies were used across TEA studies to calculate fixed operating costs. For example, maintenance and insurance and tax, were both set at 2 % of FCI in [63], while [64] used 3–5 % and 1–2 % of ISBL, respectively. Crawford et al. [53] used 20 % of the cash cost, following the methodology from [116]. Catalyst cost may also contribute to the predictive loading of OPEX, as the type of catalyst influences the product portfolio and, subsequently, MJSP.

In contrast, BPR showed maximum orthogonality for the FT case, and the VIP plot indicated that it contributes the least to MJSP variation. Variance in the FT model is primarily explained by CAPEX and OPEX. Further investigation of the scatter plot suggested that cases using gate or conventional market prices contributed to the high orthogonality of the BPR variable. Similarly, BPR shows substantial orthogonality for both PTJ and ATJ, indicating that much of its variation is not correlated with MJSP. High orthogonality was observed in cases where market prices were used for by-product credit assessment, as these values vary independently of jet fuel production costs. Lower orthogonality was noted in studies that employed other methods, such as regression analysis of historical fuel by-product prices (e.g., naphtha, diesel) correlated with jet fuel prices derived by the TEA model in each case.

Table 4
Standard errors (Root Mean Square Error of Estimation, RMSEE; Root Mean Square Error of cross-validation, RMSECV) with one model for each pathway/class of observation.

Pathway type/subset	RMSEE (USD/GJ)	RMSECV (USD/GJ)
HEFA	0.90	0.94
PTJ	1.41	1.61
FT	1.64	1.83
ATJ	1.63	1.76
All pathways	1.44	1.53

3.5. Harmonization analysis

Table 5 summarizes the effects of variable harmonization across different pathways. As expected, unless indicated by + sign, harmonization reduced the MJSP range (either significantly or marginally) across categories, as shown in the box plots for each case (representing MJSP pre- and post-harmonization) in Appendix G.

An increase in the 'MJSP range' indicates a notable shift in either the upper or lower quartile, driven by a significant increase or decrease in MJSP for that category. For illustration, one category (PTJ-FR) is discussed using a box plot in this section. The harmonization results provide complementary insights into the OPLS findings. Cases that drive changes in the MJSP range also tend to show low orthogonality and strong correlation with MJSP. However, multiple cases from a single publication may disproportionately influence specific findings, as seen with PTJ-PG.

HEFA showed little to no change in MJSP range post-harmonization. In contrast, for PTJ-AR, BPR harmonization led to a dramatic shift in the MJSP range, with a decrease in MJSP for de Jong et al. [9] and an increase for Tanzil et al. [33], as shown in Table 6. De Jong et al. reported no by-product credit and the highest SAF yield, while Tanzil et al. reported the highest BPR (estimated by correlating with historical jet fuel prices) and the lowest SAF yield in this category. The combined harmonization of OPEX + BPR counteracted this change in the MJSP range, indicating that interaction between OPEX and BPR significantly influences MJSP, which is consistent with the regression analysis results (Fig. 9).

For PTJ-FR (shown in Fig. 10),the lower quartile MJSP dropped considerably after BPR harmonization, driven by de Jong et al. [9], who reported no by-product revenue. Similarly, changes in MJSP range were observed for PTJ-PG and PTJ-AR, driven by Tanzil et al. [32] and Tanzil et al. [33], respectively. In these cases, OPEX + BPR harmonization counteracted the changes, as the harmonized OPEX was lower than the reported values. A similar pattern was observed for ATJ-PG [32]. ATJ-FR showed a similar trend to PTJ-AR, with the increase driven by Brandt et al. [52], who reported the highest SAF yield in this category. The MJSP range increased dramatically for PTJ-PG and ATJ-FR due to decreased MJSP for the cases by Tanzil et al. [32] and Brandt et al. [50], caused by lower harmonized OPEX compared to reported values.

For PTJ-AR, TCI harmonization increased the MJSP range, particularly in the rice husk-based case from Liu and Wang [38], where the harmonized TCI (168 USD/GJ) was significantly higher than the reported TCI (31 USD/GJ), based on Taiwanese vendor quotes for equipment costs. The MJSP range increased further after TCI + BPR

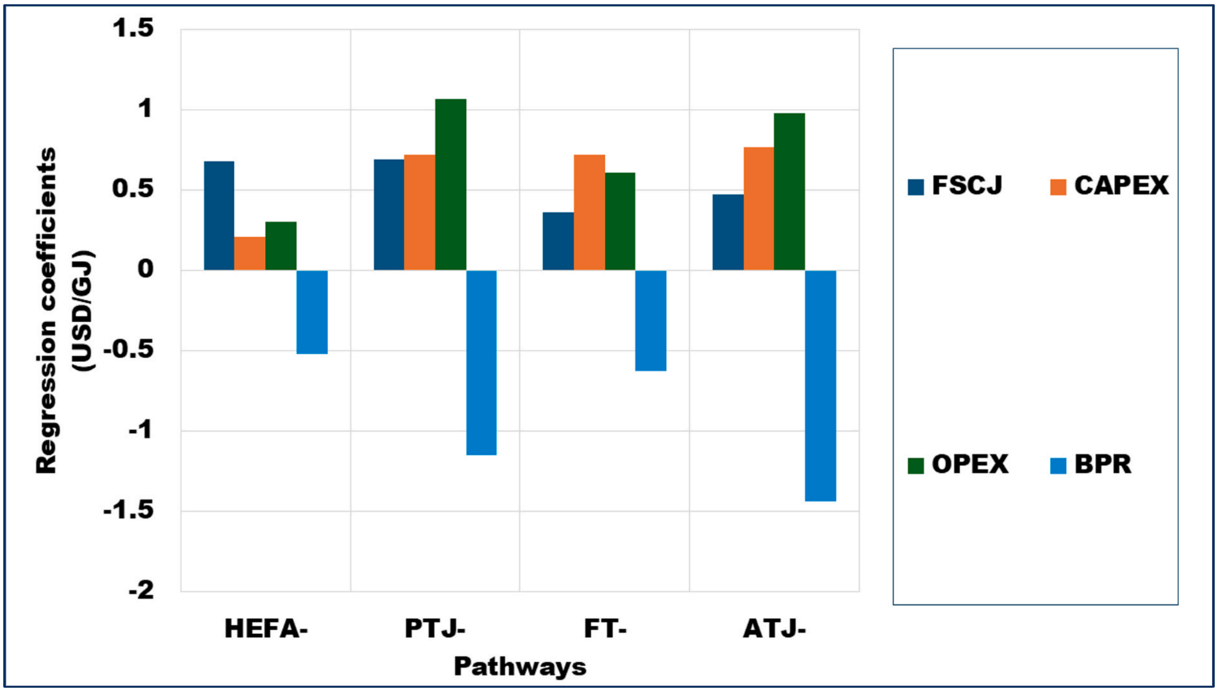

Fig. 9. Regression coefficients for each pathway for MJSP. CAPEX = Annualized Capital expenditure USD/GJ, BPR = By-product revenue USD/GJ, OPEX = Operational expenditure USD/GJ, FSC_J = Feedstock cost per GJ All costs are per GJ of jet fuel.

Table 5
Harmonization analysis results. + sign indicates a significant increase in the MJSP (USD/GJ) range (>2 unit increase).

Variables harmonized	HEFA	PTJ-AR	PTJ-FR	PTJ-PG	FT-AR	FT-FR	ATJ-AR	ATJ-FR	ATJ-PG
TCI		+					+		
OPEX				+				+	
BPR		+	+	+	+			+	+
OPEX + BPR				+					
TCI + BPR		+		+				+	

Table 6
Change in MJSP for PTJ-AR category to demonstrate the effect of single and combined variable harmonization. All values are in USD/GJ.

Study	de Jong et al.	Tanzil et al.
Original BPR and OPEX	0 and 17.26	73.98 and 63.9
Reproduced MJSP, $MJSP_P$	70	80
$MJSP_H$ post-BPR harmonization (Harmonized BPR: 37.04)	19	131
$MJSP_H$ post-OPEX + BPR harmonization (Harmonized BPR: 37.04; harmonized OPEX: 37.14)	46	94

harmonization, as the harmonized BPR was lower than the original BPR, but not enough to counteract the increase in MJSP. Similarly, PTJ-PG from Tanzil et al. [32] saw a drastic increase in MJSP range post-TCI + BPR harmonization, with MJSP rising from 62 USD/GJ to 98 USD/GJ in the upper quartile, due to having the lowest yield in this category.

For ATJ-AR, TCI harmonization changed the MJSP range primarily due to a significant decrease for the case from Tanzil et al. [41], where the original TCI was 251 USD/GJ, compared to the harmonized value of 174 USD/GJ, and with the lowest SAF yield in the category. For ATJ-FR, TCI + BPR harmonization led to a significant MJSP range increase, primarily driven by Atsosnios et al. [44], where the harmonized BPR (30 USD/GJ) was much higher than the reported value (5 USD/GJ), significantly reducing MJSP, even though the harmonized TCI (253 USD/GJ) was greater than the reported value (182 USD/GJ).

These findings highlight the strong interplay between BPR and OPEX in driving MJSP variation, compared to the more limited, independent effect of by-product variation alone, reinforcing the results from the OPLS analysis Notably, FSC_J harmonization consistently decreased the MJSP range across all categories, complementing the OPLS findings, which showed minimal orthogonal variation for FSC_J.

4. Conclusions

4.1. Insights and implications

Comparing TEA results of SAF pathways from the literature is challenging, as reported Minimum Jet Fuel Selling Prices (MJSP) often obscure the underlying assumptions embedded in techno-economic modelling. Factors such as the choice of capital estimation methods and SAF production process design, along with varying by-product estimation methods and associated cost-offsetting potentials, complicate direct comparisons and may skew conclusions about economic viability. Other contributors to MJSP variability include financial assumptions and location-dependent factors, such as feedstock prices, tax rates, labor, and energy costs. Some of these variances can be minimized through, for instance, improved capital estimation methods, clearer cost definitions, robust sensitivity analyses and using equipment costs estimates based on physical parameters or vendor quotes.

To enable fair comparison, we conducted a detailed and thematic literature review of SAF pathways and feedstock categories, supported by multivariate regression and variable harmonization analyses to

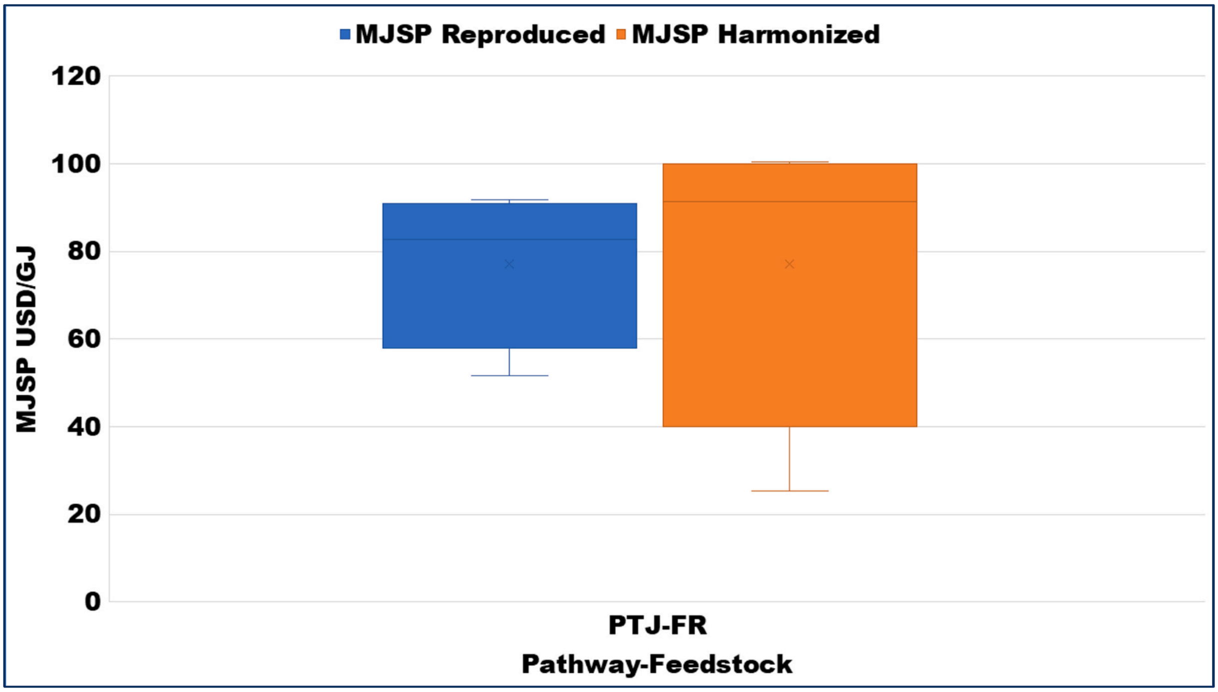

Fig. 10. Change in MJSP range for PTJ-FR to demonstrate the effect of variable harmonization (BPR in this case).

examine the relationship between key input variables and MJSP. Based on reported MJSP ranges for each greenfield pathway, we found that the average MJSP followed the order of HEFA < PTJ < ATJ < FT, confirming the general consensus that HEFA is currently the most commercially viable option (average MJSP of 35.3 USD/GJ). Among non-food feedstock pathways, PTJ emerged as the most promising alternative, with an average MJSP of 63.4 USD/GJ. Purpose-grown feedstocks (PG) and process wastes (PW) outperformed agricultural residues (AR) and forestry residues (FR), suggesting that these feedstock categories are key economically sustainable SAF development. While excluded from this study, other non-food feedstocks, such as microalgae, may represent a promising frontier for future SAF deployment.

Integrated cases consistently performed better than their greenfield counterparts, with the FT pathway showing the greatest MJSP reduction (up to 29 %). This implies that integrating SAF production into existing facilities may address economic feasibility challenges of SAF pathways, especially in the short term as technologies mature. Further research should explore how integration with existing biorefineries or other industrial facilities could provide cost advantages, and which SAF pathways that may synergize best with existing industrial infrastructure. In the short term, the PTJ and ATJ pathways could significantly contribute to net-zero goals. In the long term, emerging pathways that were outside the scope of this study, such as lignin-to-jet or power-to-liquid, may serve as viable drop-in aviation fuels.

The review also identified that hydrogen costs significantly affect MJSP for HEFA, PTJ and ATJ. For ATJ, the type of alcohol utilized for upgrading is also a key factor in the economic viability and integration potential. Beyond ethanol, alternatives like methanol could offer value chain flexibility and improved investor appeal. For PTJ, bio-oil upgrading technology and hydrogen sourcing methods, influence TEA results and overall economic viability.

Regression analysis revealed that MJSP variation is strongly influenced by specific feedstock cost (FSC_J) for HEFA, operational expenditure (OPEX) and by-product revenue (BPR) for PTJ, capital expenditure (CAPEX) and BPR for FT, and BPR and OPEX for ATJ. These findings were supported by the harmonization analysis. Furthermore, the OPLS analysis indicated that BPR values derived from market prices contributed to higher orthogonality, as they are less directly linked to jet fuel production costs. In the FT pathway, OPEX variation is closely correlated with MJSP, driven in large part by catalyst costs and fixed operating expenses. Catalyst selection directly influences the FT product portfolio and, consequently, MJSP. Additionally, fixed operating costs, which are often calculated as a percentage of FCI, further reinforce the role of CAPEX in FT cost structures. ATJ and PTJ pathways showed similar OPLS profiles for BPR, OPEX and FSC_J, suggesting similar relationships with MJSP. A focused comparative study between of these two pathways is recommended.

HEFA showed minimal changes in MJSP range after variable harmonization, supporting its status as the most commercially mature and techno-economically optimized pathway. FSC_J harmonization consistently reduced the MJSP range across all pathways, reinforcing its strong and predictable influence, as also highlighted in the OPLS analysis. Furthermore, MJSP range sensitivity to SAF yield underscores the importance of feedstock input rates and process efficiency in determining economic viability. While BPR variation alone did not explain MJSP variability, the harmonization analysis revealed that the combined effect of BPR + OPEX significantly impacted MJSP ranges, particularly for PTJ categories, FT-AR, and ATJ-FR/PG. This reinforces the importance of optimizing both by-product production and operational expenditures in enhancing techno-economic performance. Recognizing these complex interactions is critical for improving techno-economic modelling of SAF pathways. Future improvements in process design and market strategies will be crucial to enhancing the operational and economic feasibility of SAF production.

4.2. Limitations and future recommendations

This study is not without limitations. The scope does not fully capture the complete variability across TEA studies for SAF production, particularly due to the exclusion of certain feedstocks and emerging production pathways, such as power-to-liquid. These limitations underscore the need for continued research to broaden the understanding of SAF economic viability. Future studies could benefit from incorporating a wider range of feedstocks and production technologies, as employing more detailed regression models that account for additional variables.

Beyond addressing research gaps, there are also practical opportunities for optimization SAF economics. Reducing OPEX through process efficiency improvements, increasing BPR through market-aligned co-product strategies, and controlling FSC_J through targeted feedstock sourcing could all significantly reduce MJSP and improve the commercial attractiveness of SAF technologies.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors utilized the tool ChatGPT-4o to receive suggestions aimed at improving the readability and language of parts of the text. After using the tool, the authors thoroughly reviewed and edited the content as necessary and take full responsibility for the final content of the article.

CRediT authorship contribution statement

Zeenat Farooq: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elisabeth Wetterlund:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Sennai Mesfun:** Validation, Supervision, Methodology. **Erik Furusjö:** Supervision, Software, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Zeenat Farooq reports financial support was provided by Swedish Energy Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2025.120076.

Data availability

The data used is shared as supplementary file as Appendix F

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