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Agricultural Residue Impact on Fuel Production via Anaerobic Digestion: A Systematic Assessment

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Abstract

This study investigates how feedstock characteristics of agricultural residues influence optimisation strategies and techno-economic-environmental performance for anaerobic digestion (AD) based sustainable aviation fuel (SAF) production. Quantitative analysis of 33 engineering studies (methane yield: 29.7-312 mL CH_4/g VS) was combined with qualitative synthesis to link feedstock properties-lignocellulosic composition outcomes. Results demonstrate that feedstock characteristics are primary determinants of optimisation pathways. High-lignin feedstocks (15-25% lignin, e.g., rice husks, oil palm residues) require intensive pretreatment (torrefaction, hydrothermal, alkaline), achieving yield improvements of 137-209% but with energy penalties of 15-30% of total system energy. High-carbohydrate feedstocks (low lignin, e.g., cassava peels) respond better to pH and totaanial solids optimisation (20-25% TS), achieving moderate yield improvements (41-75%) with lower energy input. Optimal C:N ratio of 20-30:1 is achieved through co-digestion, enhancing stability and yield by 20-50%. Techno-economic analysis shows that high-intensity pretreatment achieves lower minimum fuel selling price ($15.4/GJ) only under favourable policy conditions, while moderate strategies achieve better energy return on investment (EROI > 3). Environmental assessment demonstrates emission reductions of 77% and carbon-negative operation (-4.58 g $C0_2$e/MJ) with optimised methane capture, though high-intensity pretreatment can increase net emissions if energy inputs exceed methane gains. This study demonstrates that feedstock-informed, multi-objective optimisation-rather than universal yield maximisation-is essential for sustainable AD-based SAF deployment.

Keywords: Anaerobic digestion; Agricultural residues; Lignocellulosic biomass; Sustainable aviation fuel; Pretreatment; Techo-economic analysis; Life cycle assessment.

1 Introduction

Agricultural residues are easily accessibility and economical renewable lignocellulosic fibre resources that can be used as an alternative to woody lignocellulosic biomass (Shah et al., 2025). This residue have similar structure, content and characteristics to those of other plant fibres (Faruk and Mohini Sain, 2015; Sikiru *et al.*, 2024). Agricultural residues such as cassava peels, rice husks, and oil palm residues represent significant sources of lignocellulosic biomass with high potential for bioenergy production (Ramalingam et al., 2025; Sikiru et al., 2024). Adhikari, Nam and Chakraborty (2018) underlined that these lignocellulosic biomass typically comprises of 35%–55% cellulose, 25%–40% hemicellulose, and 15%–25% lignin with small amount of extractives, protein, and ash. Pattanaik et al. (2019) and Babu et al. (2022) opined that agricultural residues contains considerable lignocellulosic components, totalling 30–50% hemicellulose, 30–40% cellulose, and 8–21% lignin. It also offers significant substances, including proteins, fatty acids, dietary fibers, tastes, and bioactive elements, useful in the food, pharmaceutical, and cosmetic sectors. These residues are generated in large quantities in agrarian economies and are often underutilised or disposed of through environmentally harmful practices. Cassava peels are rich in carbohydrates but may contain cyanogenic compounds that require careful handling. Rice husks are characterised by high silica and lignin content, which limits biodegradability. Oil palm residues, including empty fruit brunches and palm kernel shells, exhibit high lignocellulosic complexity but substantial energy potential (Miskat et al., 2025). The primary agricultural materials utilised in the manufacturing of biofuel are the residuals of wheat, corn, rice, sugarcane, and sugar beetroot. Their compositions are 19–24% lignin, 27–32% hemicelluloses, 32–44% cellulose, and 4.5–9.0% ashes (sugarcane bagasse); 5–24% lignin, 19–27% hemicelluloses, 32–47% cellulose, and 19% ashes (rice straw); 15–20% lignin, 20–25% hemicellulose, and 33–40% cellulose (wheat straw); 11.9 ± 2.3% lignin, 44.4 ± 5.2% hemicellulose, and 38.8 ± 2.5% cellulose (corn cob); and 1–2% lignin, 25–36% hemicellulose, and 20–25% cellulose (sugar beet pulp) (Puligundla and Mok, 2021; Zielińska and Bułkowska, 2024). The diversity of these feedstocks introduces variability in anaerobic digestion performance, necessitating tailored pretreatment and optimisation strategies.

Feedstock availability and consistency are major difficulties in AD-based SAF systems. Agricultural residues are fundamentally seasonal, with supply flunctuating based on harvest cycles and meteorological circumstances (Sikiru et al., 2024). This fluctuation impacts affects process stability and demands robust storage and logistics systems. Transportation and handling of biomass also add to operational expenses and energy consimption, particularly for low-density wastes such as rice husks. Inadequate infrastructure in poor nations further exacerbates these problems, restricting large-scale implementation (Afolabi et al., 2021). Additionally, feedstock heterogeneity causes uncertainty in process performance, requiring adaptive optimisation systems capable of handling varying input circumstances. This underscores the necessity for comprehensive system-level modelling and optimisation in AD-based SAF manufacturing.

Feedstock characteristics can be optimized through various decision variables that influence biodegradability and methane production efficiency. Key adjustments include reducing particle

size, which enhances surface area and hydrolysis rates. Saelor et al. (2024) noted that particle size may considerably impact the speed and stability of anaerobic digestion, hence matching the choice of particle size reduction equipment to digester type can thus decide the success or failure of the operation. Lu et al. (2025) emphasised that reducing the particle size of feedstocks, particularly lignocellulosic biomass, increases the surface area available to microbial enzymes thereby accelerating hydrolysis rates. While smaller particles (0.088-0.40mm) generally increase methane yield, excessive reduction (below a certain threshold) can lead to the accumulation of volatile fatty acids (VFAs) and process inhibition (Joolaei et al., 2024). Controlled pre-treatment severity is also essential for breaking down lignin and releasing biodegradable components. Optimisation of these methods (thermal alkaline) is necessary to ensure significant lignin removal and high methane yields up to 4.3-fold increases compared to untreated biomass. Furthermore, managing blending ratios for co-digestion of multiple substrates, which improves nutrient balance and carbon-to-nitrogen (C/N) ratio and provides required micronutrients, which addresses nutrient deficiencies and improves overall stability (Ma et al., 2021). A C/N ratio in the range of 20-25/1 is generally identified as optimal to prevent ammonium inhibition and ensure high methane yields (Lv et al., 2026). These factors significantly impact the overall efficiency of biogas production Including higher methane output by 20-50% through optimised feedstocks, better process stability by effective blending and particle size control, and improved biodegradability, which enhances volatile solids conversion into energy (Sikiru et al., 2024). This study advances existing anaerobic digestion (AD)-based sustainable aviation fuel (SAF) literature by developing a feedstock-informed multi-objective optimisation framework integrating technical performance, economic feasibility, environmental sustainability, and energy efficiency.

Unlike previous studies that evaluate optimisation strategies independently or focus primarily on methane yield enhancement(Usman, 2020; Milicevic et al., 2025; Mamimin, O-Thong and Reungsang, 2024), this study systematically synthesises evidence from multiple agricultural residue categorises to demonstate that feedstock physicochemical characteristics fundamentally determine optimisation pathways and sustainablity.

1.1 **Research Objectives**

The study contributes original insights in five major ways.

i. It provides one of the first systematic cross-study quantitative syntheses linking lignocellulosic composition, C:N ratio, volatile solids, and moisture content to optimisation intensity requirements for AD-based SAF production.
ii. It demonstrates that methane yield maximisation alone may reduce overall system sustainability through declining Energy Return on Investment (EROI), described in this study as the “EROI trap.”
iii. The study integrates techno-economic analysis (TEA), lifecycle assessment (LCA), and optimisation trade-off analysis within a unified framework rather than treating them as separate evaluations.

iv. It quantitatively compares optimisation pathways across high, moderate, and low-lignin agricultural residues to identify feedstock-specific sustainability thresholds.
v. The study proposes practical feedstock-informed optimisation guidelines for sustainable deployment of AD-based SAF systems in both developed and low-and middle-income economies.

These contributions address significant methodological and conceptual gaps within existing AD-SAF literature, where optimisation studies are frequently fragmented, feedstock-specific, and insufficiently integrated across environmental, technical and economic dimensions.

2 Literature Review

Decision variables are parameters that are configurable that have an impact on system outputs such as methane yield, energy efficiency, and fuel generation. These variables are present at several phases of the AD-based SAF system. The operational parameters critically influencing the performance of Anaerobic Digestion (AD) systems include temperature, hydraulic retention time (HRT), and organic loading rate (OLR). AD can function under mesophilic conditions (30-40°C) or thermophilic conditions (50-60°C) (Goswami et al., 2016; Nandi et al., 2020; Gyadi et al., 2024). Utilizing thermophilic digestion enhances reaction rates but may compromise stability (Khalid et al., 2011; Kumar et al., 2024). HRT indicates the duration that biomass remains in the reactor, with longer HRT facilitating better degradation at the cost of throughput. OLR denotes the volume of organic material introduced per reactor unit; while higher OLR can enhance productivity, it also poses risks of system overload and instability (Kumar et al., 2024). Thus, optimization of these variables is essential for maximizing methane yield while maintaining process stability.

2.1 Biogas Upgrading Decision Variables

Optimisation of biogas upgrading systems to high purity biomethane (CH_4) is contingent upon three key decision variables: operating pressure, membrane selectivity, and absorption efficiency to minimise energy consumption while maximising methane recovery. This interplay of these factors is pivotal, as they dictate both the investment (CAPEX) and operating (OPEX) costs of the upgrading plant (Soto et al., 2022). Operating pressure affects the efficiency of gas separation.Tomczak et al. (2024) underlined that high pressure is critical for driving gas seperation, particulaly in membrane systems (6-20 bars) and presure swing absorption (PSA). Bozorg et al. (2020) noted that while higher pressure increases the driving force and improve separation, they also significantly raise energy consumption and compressor costs. Optimal pressure selection involves a trade-off between energy input and methane loss. Membrane selectivity determines the purity of methane. Lawson et al. (2021) identified that high- selectivity materials reduce the need for multi-stage processes and recycling loops thus lowering compression costs and reducing energy consumption. Hence, materials with higher selectivity allow for higher methane purity in the retentate. Absorption efficiency influences the rate of CO2 removal. Abejón et al. (2024) identified that in chemical or physical absorption, this governs the rate of removal and is influenced by solvent flow rates, column design and temperature. Increasing the absorbent flow rate increases

removal efficiency but may increase the energy needed for subsequent solvent regeneration. These factors play a crucial role in energy consumption and product quality, highlighting their importance for system-level optimisation (Perera et al., 2025).

2.2 Performance Metrics in AD-Based SAF Systems

Anaerobic digestion (AD)-based sustainable aviation fuel (SAF) systems are evaluated using a set of quantitative performance parameters that measure technical efficiency, economic feasibility, and environmental sustainability. These measurements provide a foundation for comparing optimisation strategy and evaluating overall system efficacy.

Technical performance metrics evaluate the AD process's efficiency and stability, as well as its capacity to generate high-quality intermediates for SAF synthesis. Methane yield (m3 CH4/kg VS) is the most commonly used metric of AD efficacy is methane yield, which is the amount of methane produced per unit of volatile solids (VS) in the feedstock. It reflects the efficiency of converting biological materials into useful energy (Inayat et al., 2021). Higher methane yield suggests better substrate utilisation and process effectiveness. However, it is heavily reliant on feedstock composition, pre-treatment, and operating conditions. Conversion efficiency (%) is the percentage of feedstock carbon or energy converted to methane or downstream fuel products. It provides a larger system-level perspective than methane yield alone, taking into account losses at various phases of the process (Ma et al., 2021). In AD-based SAF systems, conversion efficiency must go beyond digestion to encompass upgrading and fuel synthesis stages. Process stability represents the AD system's capacity to work consistently under a variety of operating situations. pH balance, VFA buildup, and ammonia inhibition levels are examples of indicators (Kumar et al., 2024). Stable systems ensure continuous methane production while preventing reactor failure. Optimisation solutions must therefore strike a balance between yield maximisation and system robustness.

Economic Performance Indicators assess the financial sustainability of AD-based SAF production systems, which remains a significant obstacle to widespread adoption. The Minimum Fuel Selling Price (MFSP) is the minimum price at which SAF must be sold to achieve economic viability, taking into account capital expenditure, operating costs, and expected returns (Huang et al., 2025). It is an important statistic for comparing various production methods and optimisation tactics. Lower MFSP values suggest more competitive systems compared to fossil-based aviation fuels. Capital and operating costs include feedstock procurement, energy usage, maintenance, and labour (Maggi, Wenzel, and Sundmacher, 2020). Optimisation strategies seek to lower these costs by increasing efficiency, process integration, and resource utilisation.

Economic performance is directly related to technical efficiency; for example, increased methane yield can reduce feedstock requirements while increasing cost efficiency. However, optimising (such as high-temperature operation) can raise energy expenditures, emphasising the importance of balanced optimisation.

Environmental Perforance Indicators compare the sustainability benefits of AD-based SAF systems to traditional fossil fuels. Lifecycle emissions (Gco2e/MJ) are the total greenhouse gas emissions associated with fuel production, which includes feedstock collection, processing,

upgrading, and combustion (Wang, Ting, and Zhao, 2024). AD-based SAF has the potential to dramatically cut emissions by using waste biomass and capturing methane that would otherwise be discharged into the atmosphere. The Energy Return on Investment (EROI) is the ratio of energy input in the manufacturing process. A greater EROI suggests a more energy-efficient system (Huang et al., 2025). Energy inputs in AD-based systems include pretreatment, reactor operation, and the upgrading process. Optimisation aims to improve EROI while preserving fuel quality and yield. Environmental performance is becoming increasingly crucial for policy support and regulatory compliance, especially in the aviation industry, where carbon reduction requirements are rigorous.

3 Materials and Methods

3.1 Study Design and Analytical Framework

This study utilized a systematic quantitative literature synthesis that combined techno-economic assessment (TEA), lifecycle environmental assessment (LCA), and comparative optimization analysis to determine how agricultural residue characteristics affect optimization outcomes in anaerobic digestion (AD)-based sustainable aviation fuel (SAF) systems. Following the PRISMA framework for improved methodology transparency, the analysis comprised five components: feedstock physicochemical characterization, AD optimization analysis, techno-economic performance evaluation, LCA, and multi-objective optimization trade-off analysis, focusing on agricultural residues for biomethane-based SAF production pathways involving anaerobic digestion, biogas upgrading, and downstream fuel synthesis..

3.2 Literature Search Strategy

A systematic literature search was conducted across three major scientific databases such as Scopus, Web of Science core collection and ScienceDirect. The search covered studies published between January 2010 and February 2026 to capture recent developments in AD optimisation, biomethane upgrading, and SAF conversion technologies.

Search strings combined Boolean operators and thematic keywords including “anaerobic digestion” AND “sustainable aviation fuel”, “agricultural residues” AND “methane yield”, “anaerobic digestion” AND “sustainable aviation fuel” ,“anaerobic digestion” AND “sustainable aviation fuel”, “agricultural residues” AND “methane yield”, “biogas upgrading” AND “lignocellulosic biomass”, “pretreatment” AND “methane production”, “techno-economic analysis” AND “biomethane”, “techno-economic analysis” AND “biomethane”, “co-digestion” AND “agricultural waste”, “life cycle assessment” AND “SAF”.

3.3 Study Selection and Eligibility Criteria

3.3.1 Inclusion Criteria

i. Studies investigating agricultural residues as AD feedbacks
ii. Included quantitative methane yield outcomes
iii. Reported physicochemical feedstock characteristics
iv. Studies evaluating pretreatment or optimisation strategies
v. Studies reporting economic and/or environmental indicators

vi. Were peer-reviewed journal articles published in English

3.3.2 Exclusion Criteria

i. Studies focused exclusively on municipal or food waste
ii. Studies lacking methodological transparency
iii. Studies that did not provide quantitative AD performance outcomes
iv. Were conference abstracts, editorials, or grey literature

The database search initially identifies 412 studies. Following duplicate removal and title-abstract screening, 76 full-text studies were assessed for eligibility. A final total of 33 studies met the inclusion criteria and were included in the quantitative synthesis.

3.4 **Data Extraction and Standardisation**

A structured extraction framework was developed to ensure consistency across studies. Extracted variables were grouped into four categories. Data from selected studies will be systematically extracted and organised using Zotero and Microsoft Excel. The following variables will be extracted:

Feedstock Data

- Type (cassava peels, rice husk, oil palm residues)
- Lignin content (%)
- Cellulose content (%)
- Hemicellulose content (%)
- Moisture content (%)
- Volatile solids (% TS)
- Carbon-to-nitrogen ratio (C:N)

Economic Indicators

- Minimum Fuel Selling Price (MFSP)
- Internal Rate of Return (IRR)
- Operational costs
- Pretreatment energy demand

Technical Performance Metrics

- Methane yield (m_3CH_4/kg VS)
- Volatile solids reduction (%)
- Hydrolysis enhancement
- Yield improvement relative to untreated control (%)

Environmental and Energy Indicators

- Emission reduction relative to fossil jet fuel (%)
- Methane leakage estimates
- Energy Return on Investment (EROI)
- Lifecycle emissions (Gco_2e/MJ)

To improve comparability across studies methane yields were standardised to mL CH_4/g VS, lifecycle emissions were standardised to g CO_2e/MJ, economic values were inflation-adjusted to

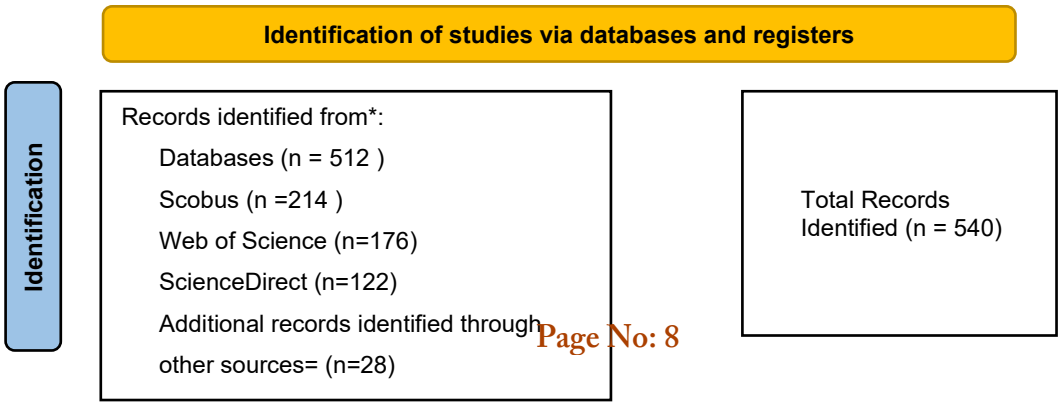
2025 USD equivalents and energy metrics were normalised relative to untreated feedstock baselines.

3.5 **Feedstock Categorisation**

Agriculture residues were categorised according to lignin content and structural recalcitrance. Category A include High-Lignin Feedstocks (15-25%) with examples such as rice husks, wheat straw and palm empty fruit bunches characterised with high structural complexity, low biodegradability and intensive pretreatment requirement. Category B include Moderate -Lignin Feedstocks (10-15%) with examples such as oil palm mesocarp fibre, corn stover with characterised by moderate recalcitrance and responsive to moderate pretreatment intensity. Category C include Low- Lignin Feedstocks (<10% lignin) with examples such as cassava peels, sugar beet pulp characterised by high biodegradability and minimal pretreatment requirement. This classification enabled comparative assessment of optimisation pathways across structurally distinct feedstock groups.

3.6 Review Approach

The review aligned with review protocols, informed by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. The review process will entail structured stages including identification of relevant literature, screening titles and abstract , full- text eligibility assessment, and final inclusion and synthesis. A PRISMA 2020 flow diagram was used to document the screening and selection process, ensuring trasparency and reproducibility. The figure below is a PRISMA 2020 flow diagram.



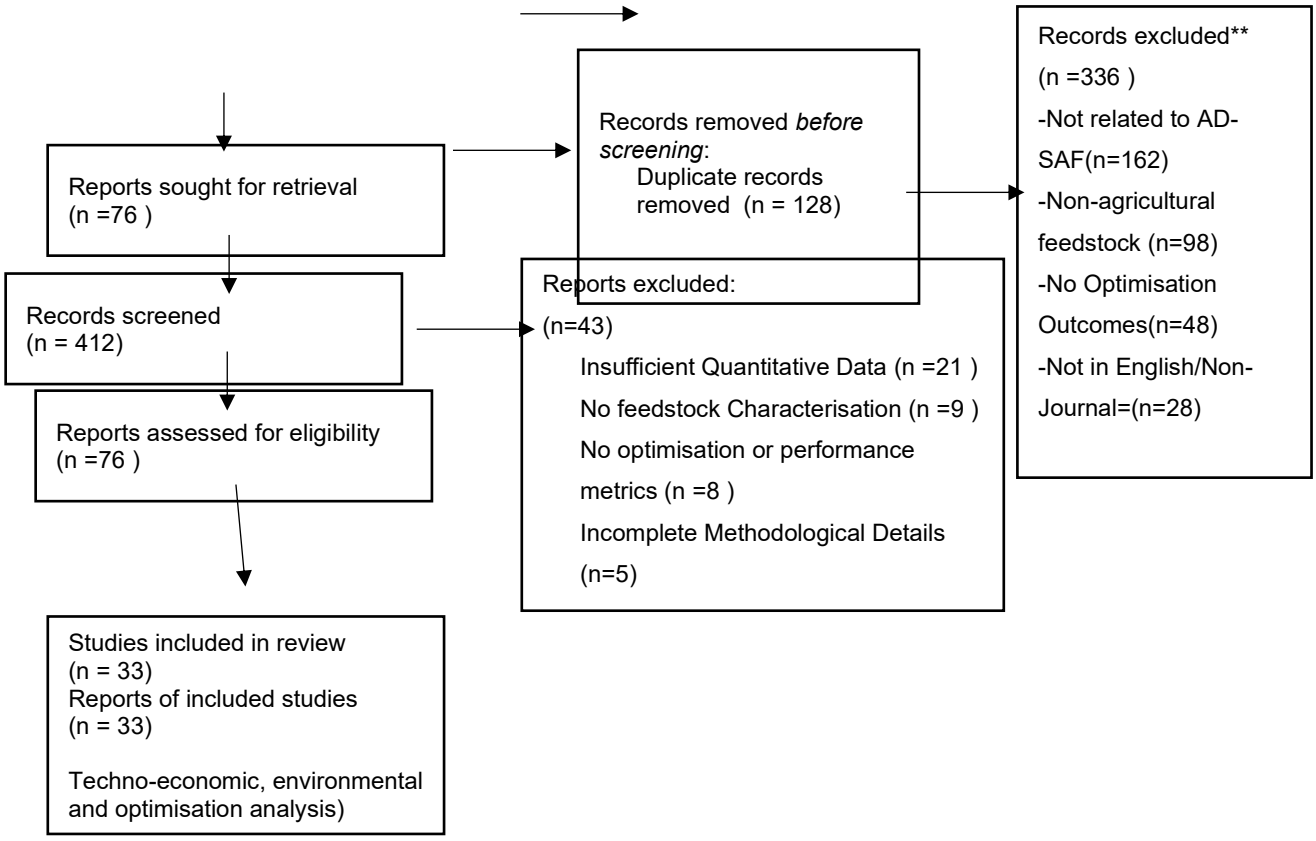


Figure 1: PRISMA 2020 flow diagram.

3.7 **Quantitative and Statistiscal Analysis**

Descriptive, comparative, regression-based analyses were performed to evaluate relationships between feedstock properties and optimisation outcomes.

3.7.1 Methane Yield Improvement

Methane yield improvement was calculated as:

$$\text{Yield Improvement (\%)} = \frac{(Optimised\ Yield - Baseline\ Yield)}{\text{Baseline Yield}} \times 100$$

This standardisation enabled direct comparison across studies with different reactor configurations and operational conditions.

3.7.2 Regression Analysis

Linear regression analysis was conducted to evaluate the relationship between lignin content and methane yield enhancement potential.

The coefficient of determination R^2 was used to assess explanatory strength.

A strong positive relationship was observed:

$$R^2 = 0.89,\ p < 0.001$$

Indicating that lignin content strongly predicts pretreatment intensity requirements and potential methane yield improvement.

3.8 Trade-Off Ratio Analysis

Optimisation efficiency was evaluated using trade-off ratios:

$$\text{Trade-Off Ratio} = \frac{\%\textbf{Yield Improvement}}{\%\textbf{Increase in Energy input}}$$

Higher ratios indicate more energy-efficient optimisation strategies.

3.8.1 Energy Return on Investment (EROI)

EROI was estimated as:

$$\textbf{EROI} = \frac{\textit{Energy Output}}{\textit{Energy Input}}$$

Energy inputs included pretreatment, upgrading, compression, and operational energy demands.

3.8.2 Tecno-Economic Assessment

Techno-economic analysis assessed the economic feasibility of various optimization pathways using metrics such as MFSP, IRR, pretreatment costs, hydrogen demand, upgrading energy needs, and infrastructure dependence. The evaluation took into account regional energy prices, policy incentives, and feedstock availability, identifying hydrogen cost as a significant economic driver for the viability of biomethane-to-SAF conversion viability.

Lifecycle Environmental Assessment

Environmental performance was evaluated through lifecycle assessment based on ISO 14040/14044 standards, using 1 MJ of produced SAF as the functional unit. The system boundaries encompassed feedstock collection, pretreatment, anaerobic digestion, biogas upgrading, fuel conversion, and methane leakage effects. Lifecycle emissions were compared to conventional fossil jet fuel baselines.

3.8.3 Multi-Optimisatiom Framework

A multi-objective optimisation framework was created to assess trade-offs between maximising methane yield, reducing lifecycle emissions, ensuring economic feasibility, and enhancing EROI performance. Pareto optimisation principles were conceptually applied to identify balanced optimisation pathways where no single objective could improve without worsening another.

This framework demonstrated that the technically optimal strategy was not always the most environmentally or economically sustainable.

4 Results

4.1 Feedstock Characteristics and Structural Variability

Table 1: Representative feedstock characteristics by category

Parameter	Category A (High Lignin)	Category B (Moderate Lignin)	Category C (Low Lignin)
Lignin (%)	15-25	10-15	5-10

cellulose (%)	30-40	40-50	35-45
Hemicellulose (%)	20-30	25-35	20-25
C:N ratio	30-60:1	20-40:1	15-25:1
Moisture (%)	10-20	60-80	60-70
VS (% TS)	70-85	80-90	85-95
Example feedstocks	Rice husk, wheat straw, EFB	Oil palm fibre, corn stover	Cassava peel, sugar beet pulp
Representative studies	Milicevic et al., 2025; Usman, 2020	Mamimin et al., 2024	Al-Zuhairi et al al., 2026; Lu et al., 2025

Significant variability was noted among agricultural residues for lignin concentration, moisture content, volatile substances, and carbon-to-nitrogen ratio. High-lignin feedstocks, including rice husks and wheat straw, shown lignin concentrations between 15-25%, leading to enhanced structural recalcitrance and reduced biodegradability. Conversely, cassava peels and sugar beetroot pulp contained less than 10% lignin and exhibited markedly greater biodegradation capacity. Volatile solids were 70-95% of total solids, signifying substantial diversity in methane generation capability among feedstocks. The results indicate that the physiochemical composition of feedstock profoundly affects optimisation requirements and the attainable methane yield outcomes.

4.2 Optimisation Strategies by Feedstock Category

Table 2: Optimisation strategies and methane yield improvement by feedstock category

Feedstock Category	Primary Optimisation Strategy	Secondary Strategies	Methane Yield Improvement Range	Mean Improvement
Category A (High lignin)	Intensive pretreatment (torrecfaction, hydrothermal, alkaline)	Co-digestion (manure), biochar addition	137-209%	175%
Category B (Moderate lignin)	Moderate pretreatment (thermal, chemical) and Co-digestion	TS optimisation (20-25%)	74-137%	105%

Category C (Low lignin)	pH and TS optimisation (pH 8.29,TS 20-25%)	Co-digestion for C:N balance	41-75%	58%

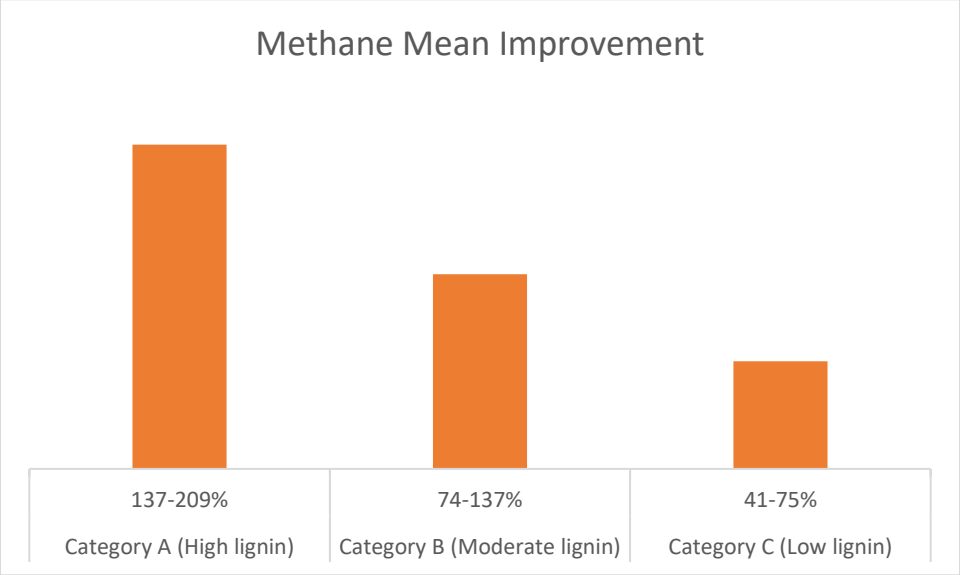


Figure 2: Relationship Between Feedstock Lignin Content and Methane Yield Improvement

Methane yield varied from 29.7 to 312 mL CH4/g VS based on feedstock and optimisation. High-lignin feedstocks showed the greatest improvement (137-209%, mean 175%) with pretreatment methods like torrefaction, hydrothermal processing, and alkaline pretreatment. Moderate-lignin feedstocks improved 74-137% (mean 105%), benefitting from moderate pretreatment and co-digestion. Low-lignin feedstocks had a 41-75% improvement (mean 58%). Operational optimisations like pH adjustment and total solids optimisation enhanced sustainability and performance. The chart demonstrated a strong relationship between lignin content and methane yield enhancement potential. Feedstock lignin content is the single strongest predictor of required pretreatment intensity and potential yield improvement ($R2=0.89$, $p < 0.001$) indicating that lignin content is the strongest predictor of pretreatment intensity requirements. High-lignin feedstocks achieve the largest absolute yield improvements but require the most energy-intensive interventions.

4.3 Influence of Carbon-to-Nitrogen Ratio and Co-Digestion Performance

Table 3: Methane yield as a function of C:N ratio (data compiled from 15 studies)

Parameter	**C:N ratio**	Methane Yield Improvement Range
Category A (High Lignin)	30-60:1	137-209%

Category B (Moderate Lignin)	20-40:1	74-137%
Category C (Low Lignin)	15-25:1	41-75%

Tab. 1 indicates that methane yield is maximized at C:N ratios of 20-30:1. Ratios below 15:1 cause ammonia inhibition, while those above 35:1 hinder microbial growth. Co-digestion of agricultural residues, by mixing high-carbon materials like rice husk (C:N = 60:1) with nitrogen-rich sources such as manure (C:N = 15:1), helps achieve optimal ratios. This approach can enhance yield by 20-50% compared to mono-digestion, with specific optimal mixing ratios varying by feedstock (e.g., 2:3 vinegar residue to cattle manure; Lu et al., 2025). Co-digestion is recommended as a fundamental optimisation strategy.

4.4 Techno-Economic Performance

Table 4: Economic performance metrics by feedstock category and optimisation strategy

Feedstock Category	**Optimisation Strategy**	**MFSP ($/GJ)**	**IRR (%)**	**Key Cost Drivers**
Category A (High lignin)	Torrefaction pretreatment	15.4	Not reported	Pretreatment energy (high)
Category A (High lignin)	Alkaline pretreatment	Not reported	36.19% (under incentives)	Chemical costs
Category B (Moderate lignin)	Hydrothermal and co-digestion	Not reported	Not reported	Operational energy
Category C (Low lignin)	pH + TS optimisation	143 € /MWh (biomethane)	Not reported	Upgrading (H_2 cost)

Economic performance across optimisation pathways varied significantly. High-intensity pretreatment strategies resulted in the lowest Minimum Feedstock Price (MFSP) values, achieving $15.4/GJ and up to a 36.19% Internal Rate of Return (IRR) under supportive conditions, although they faced notable energy penalties. In contrast, low-lignin feedstocks showed benefits such as lower capital expenditures, reduced operational energy demands, and enhanced economic stability. Moreover, hydrogen demand in biomethane upgrading was identified as a key economic constraint across various studies. Hydrogen cost is the key economic factor for converting biomethane to sustainable aviation fuel (SAF), with gas scrubbing optimization reducing this cost by approximately 51%, thereby enhancing economic viability regardless of feedstock type (Brands et al., 2025). In Sao Paulo, an optimized SAF production presents an internal rate of return of 36.19%, although its feasibility relies significantly on regional infrastructure, energy expenses, and policy

incentives; without these, its standalone feasibility remains limited (Infante Cuan et al., 2025; Deuber et al., 2023).

4.5 Lifecycle Environmental Performance

Table 5: Environmental performance metrics by feedstock category

Feedstock Category	Optimisation Strategy	Emissions (g CO_2e/MJ)	Emission Reduction vs. Fossil	Carbon-Negative Achieved?
Category A (High lignin)	Intensive pretreatment and methane capture	-4.58 to 16.11	94-105%	Yes (with capture)
Category B (Moderate lignin)	Hydrothermal and co-digestion	Data limited	73-82%	Not reported
Category C (Low lignin)	pH and TS optimisation	3.12	96%	No (but near-zero)

Lifecycle emissions ranged from carbon-negative values of -4.58 g CO2e/MJ to positive emissions exceeding 16.11 g CO2e/MJ, influenced by methane capture efficiency and pretreatment energy intensity. The study highlights that methane capture efficiency is crucial for achieving carbon-negative operations, with optimised systems achieving emission reductions of up to 105% and enabling carbon-negative SAF pathways. In contrast, methane leakage significantly diminishes environmental benefits. Methane capture is essential for achieving carbon-negative operations, with Munar-Florez et al. (2025) demonstrating -4.58 g CO2e/MJ from optimized methane capture, compared to 16.11 g CO2e/MJ without capture. Emissions reductions of up to 77% are possible under optimal conditions (Khalifa, 2026), with variations reported between 21-62% (Zaborowska et al., 2026) and 73-82% (Deuber et al., 2023). Additionally, high-intensity pretreatment can lead to increased net emissions if energy inputs surpass methane gains, highlighting a critical trade-off for environmental benefit.

4.6 Energy Return on Investment (EROI)

Table 6: EROI Analysis by pretreatment intensity

Pretreatment Intensity	Yield Improvement	Energy Input	Net Energy Gain	EROI
None (control)	Baseline	1.0	Baseline	2.5-3.0
Low (biochar)	74.5%	1.2	45% gain	3.2
Moderate (alkaline)	180%	1.5	87% gain	3.5
High (torrefaction)	209%	2.2	40% gain	1.8

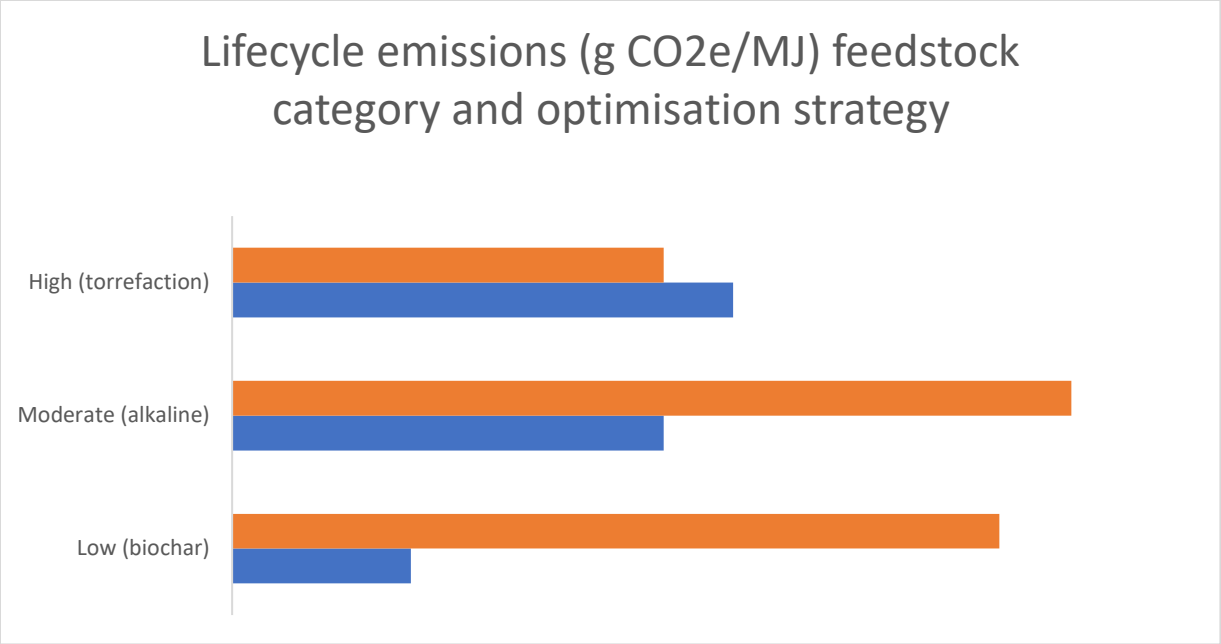


Figure 3: Lifecycle emissions (g CO2e/MJ) feedstock category and optimisation strategy

Table 5: EROI analysis highlighted sustainability trade-offs in optimization strategies. High-Intensity Pretreatment achieved a 209% yield improvement with an EROI of 1:8, while Moderate Pretreatment yielded a 180% improvement with an EROI of 3:5. Despite the significant methane yield increase from aggressive pretreatment, high energy demand compromised net energy efficiency, leading to the concept of the "EROI trap," where the highest methane yield does not align with optimal sustainability performance. There exists an optimal pretreatment intensity for maximizing yield without significantly increasing energy inputs, which ultimately reduces overall Energy Return on Investment (EROI). Moderate-intensity pretreatments, such as alkaline and hydrothermal, achieved the highest EROI of 3.5, while high-intensity torrefaction lowered EROI to 1.8 compared to a control of 2.5-3.0. This underscores the key insight that maximizing methane yield does not equate to maximizing net energy gain, which is essential for sustainable system design.

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4.7 Multi-Objective Optimisation Trade-Offs

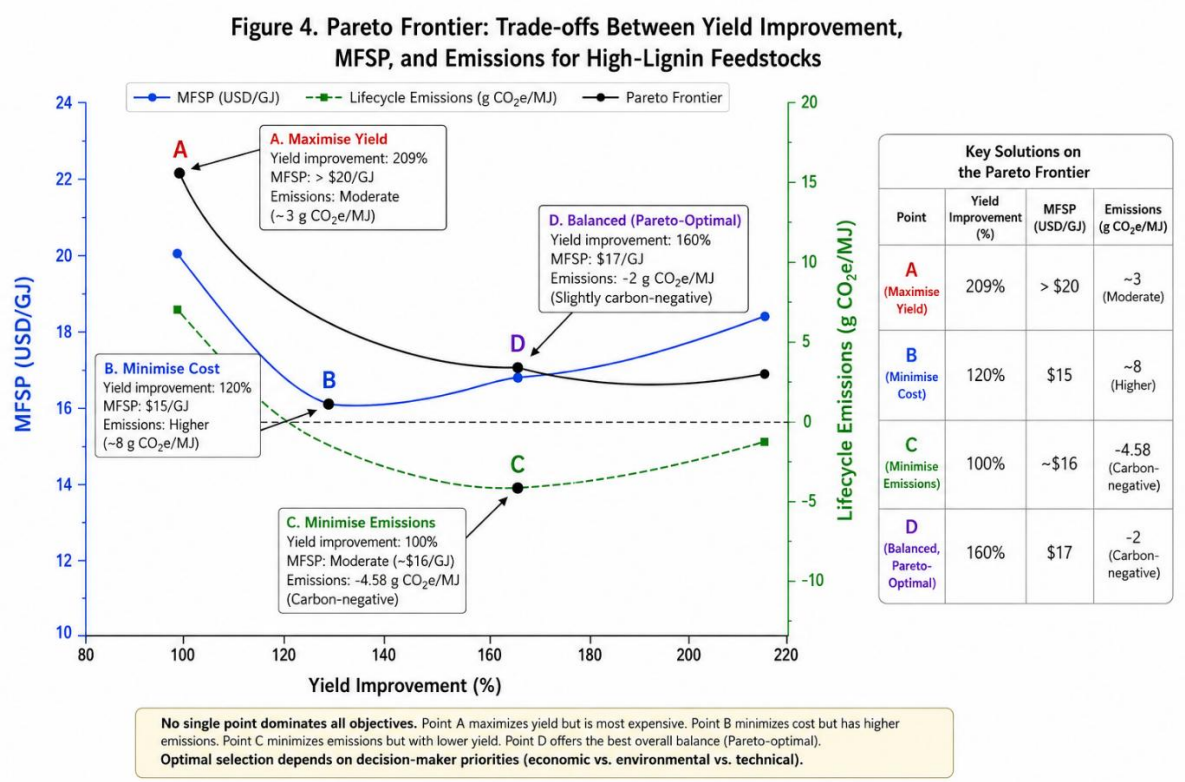


Figure 4: Pareto frontier visualising trade-offs between yield improvement, MFSP, and emissions for high-lignin feedstocks

The Pareto optimisation analysis revealed that it is impossible to maximize methane yield, economic feasibility, environmental performance, and energy efficiency simultaneously. Balanced optimisation pathways resulted in better overall sustainability compared to yield-maximisation strategies. This supports a shift from single-objective optimisation to adaptive multi-objective frameworks informed by feedstock. Fig 4 illustrates multi-objective optimisation results: Point A aims to maximize yield with a 209% improvement; however, it has a marginal fuel supply price (MFSP) greater than $20/GJ and moderate emissions. Point B focuses on minimizing cost, achieving a 120% improvement with an MFSP of $15/GJ but higher emissions. Point C targets emission reduction with a 100% improvement, resulting in a carbon-negative output of -4.58 g CO2e/MJ and moderate cost. Point D represents a balanced, Pareto-optimal choice with a 160% improvement, an MFSP of $17/GJ, and -2 g CO2e/MJ. No single point is superior across all objectives; the optimal choice is contingent on the decision-maker's priorities regarding economic, environmental, and technical factors.

5 Discussion

The study reveals that optimisation outcomes in anaerobic digestion (AD)-based sustainable aviation fuel (SAF) systems are limited by the physiochemical characteristics of feedstock. It critiques existing studies for focusing on methane yield maximisation while neglecting energy penalties, lifecycle emissions, and economic feasibility. The introduction of the "EROI trap"

concept highlights that high methane yields may lead to energy demands that decrease net energy performance and environmental benefits. Importantly, methane capture efficiency is essential for carbon-negative operations. The study advocates for prioritising integrated methane management and tailored optimisation for specific feedstocks, moving away from one-size-fits-all strategies towards approaches that balance efficiency, economic feasibility, and environmental sustainability.

5.1 Feedstock Characteristics as Primary Optimisation Determinants

The results indicate that feedstock characteristics, particularly lignin content, C:N ratio, and volatile solids, are critical to the optimization process. For high-lignin feedstocks (Category A), intensive pretreatment is essential to achieve acceptable methane yields, offering substantial yield improvements (137-209%) but incurring energy penalties (15-30% of system energy). Economic feasibility relies on policy incentives (IRR 36% under favorable conditions), and carbon-negative operation necessitates integrated methane capture. Conversely, low-lignin feedstocks (Category C) do not require intensive pretreatment, which can diminish net energy gain. Optimizing pH and total solids (20-25% TS, pH 8.3) offers a 41-75% improvement, with lower capital and operational costs, though absolute methane yields may be lower compared to optimized high-lignin systems. This analysis reinforces that a universal operational strategy is ineffective, emphasizing the need for feedstock characterization prior to optimization design.

5.2 The Methane Capture Imperative for Carbon-Negative SAF

A critical finding indicates that methane capture is essential for achieving carbon-negative operations, rather than yield maximization. Munar-Florez et al. (2025) reported emissions of 16.11 g CO2e/MJ (450%). Key implications include the potential for AD-based SAF to achieve negative emissions if biogas collection and upgrading are optimized to prevent methane leakage. Given that methane's global warming potential is 28-84 times that of CO2 over 20-100 years, even minor leakage can offset benefits. Therefore, policies should incentivize methane capture infrastructure rather than solely focusing on SAF production volumes.

5.3 The EROI Trap: When Yield Maximisation Reduces Sustainability

The EROI analysis indicates that high-intensity torrefaction yields a gross methane increase of 209% with an energy input of 120%, resulting in a net energy gain of 40% and an EROI of 1.8, which is below the control range of 2.5-3.0. In contrast, moderate alkaline pretreatment yields a gross methane increase of 180% with only a 50% energy input, leading to a net energy gain of 87% and an EROI of 3.5, above the control. This suggests that while torrefaction optimizes yield, it is less energy efficient, highlighting the need for a balance in sustainable AD-based SAF objectives. Co-digestion is effective across all feedstocck categories for two reasons: 1. Optimizing the C:N ratio involves mixing high-carbon residues (C:N = 30-60) with nitrogen-rich materials (C:N = 15-20) to achieve an optimal range of 20-30:1. 2. Nutrient supplementation, such as manure and other co-substrates, provides essential trace elements for methanogen activity. 3. Co-digestion should be a standard strategy due to its consistent 20-50% yield improvement and enhanced process stability.

5.4 Practical Guidelines for Feedstock-Informed Optimisation

Based on the synthesis, guidelines for different lignin feedstocks are proposed as follows: For high-lignin feedstocks (such as rice husks, EFB, wheat straw), intensive pretreatment is required, co-digestion with manure is recommended, methane capture infrastructure needs optimization, and a trade-off approach is acknowledged for yield versus EROI. For moderate-lignin feedstocks (e.g., oil palm fibre, corn stover), moderate pretreatment is required, with pH and total solids optimized for expected yield improvements of 74-137%. For low-lignin feedstocks (such as cassava peels, sugar beet pulp), minimal pretreatment is required, pH and total solids should be optimized, co-digestion is optional, and yield improvements of 41-75% are expected.

6 Limitations and Future Research

Limitations in the current research on EROI and net energy balance include insufficient reporting, geographic concentration in developed economies, and a lack of standardized metrics for pretreatment energy inputs. Future research priorities focus on establishing standardized EROI reporting, expanding geographic study areas to tropics and subtropics, conducting lifecycle assessments with uncertainty quantification, and integrating renewable hydrogen to mitigate upgrading emissions.

7 Conclusion

This study provides a comprehensive evaluation of how the characteristics of agricultural residues influence the optimization of anaerobic digestion (AD) for sustainable aviation fuel (SAF) production.

The research highlights that the properties of feedstock are critical factors impacting optimization pathways, methane yield potential, environmental performance, and energy efficiency. Four major conclusions are drawn:

First the Lignin Content Impact. The lignin content of feedstocks plays a significant role in determining the intensity of pretreatment needed and the potential for methane yield improvement. High-lignin feedstocks necessitate more intensive pretreatment to overcome issues related to structural recalcitrance, whereas low-lignin feedstocks can achieve better sustainability performances through moderate optimization strategies. Second the Importance of Methane Capture Efficiency; For carbon-negative SAF production, the efficiency of methane capture is more vital than merely maximizing methane yield. Achieving carbon-negative operations relies heavily on controlling methane leakage effectively. Third, the challenges of Aggressive Pretreatment; The study identifies a phenomenon termed the "EROItrap," where aggressive pretreatment can inadvertently reduce overall sustainability performance by diminishing the Energy Return on Investment (EROI). This indicates that pursuing the highest methane yield may not align with the most sustainable optimization approach. Fourth, Feedstock-informed Multi-objective Optimization; A more robust framework for the deployment of sustainable AD-based SAF lies in the use of feedstock-informed multi-objective optimization, which is preferred over traditional yield-focused optimizations.

Based on these insights, the study recommends that future AD-SAF systems implement adaptive optimization frameworks that simultaneously consider feedstock characteristics, lifecycle emissions, energy efficiency, and economic viability. These findings contribute valuable methodological and conceptual insights aimed at enhancing sustainable aviation fuel systems within the context of circular bioeconomy transactions.

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