

# Quantifying the Circularity of a Bioeconomy: A Case Study for Sustainable Aviation Fuel Pathways in the United States

Sabrina Summers<sup>1</sup> , Yuanhui Zhang<sup>1\*</sup> 

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## Abstract

Decarbonising the aviation sector remains a challenge because long-haul flights rely on liquid fuels. Hydrothermal liquefaction (HTL), a conversion process that utilises elevated temperatures and pressures to produce biocrude from wet biomass, is a potential pathway for sustainable aviation fuel (SAF). Through valorisation of biowaste, SAF pathways may improve circularity by increasing the use of renewable and recovered resources. However, standard lifecycle methods do not quantify resource circularity. Here, a scalable circularity index ( $0\% \leq CI \leq 100\%$ ) was applied to quantify the circularity of jet fuel production in the U.S. aviation industry between fossil fuels, hydroprocessed esters and fatty acids (HEFA, an approved SAF route), and HTL. CI showed that compared to fossil jet, HEFA and HTL increased carbon circularity by 6.80–12.70% and energy circularity by 17.95–31.58%. Uncertainty and sensitivity analysis showed that CIs in both SAF scenarios were highly correlated to feedstock supply and recovery, indicating further opportunities for improvement.

**Keywords** Circularity Index · Decarbonised Transportation · Hydrothermal Liquefaction · Sustainable Aviation Fuel · Waste Valorisation

## 1. Introduction

In the transition from a linear to a circular economy, goals to achieve net-zero emissions have motivated the decarbonisation of the transportation sector. Transportation is the largest producer of greenhouse gas (GHG) emissions by economic sector, accounting for 28% of the United States (U.S.) GHG emissions (United States Environmental Protection Agency, 2025). Specifically, long-haul transportation modes, such as aviation, are hard-to-abate sectors because they are difficult to electrify and require liquid fuels. Aviation fuel also has stringent fuel specifications, limiting the availability of alternative fuel sources. Sustainable aviation fuel (SAF) demand is expected to increase significantly because it is the only near-term solution to decarbonise existing aviation technology and infrastructure. Advancements in aircraft technologies and operations may contribute up to 30% of emissions reduction, with the remaining 70% addressed through the utilisation of SAF and market-based measures (Jensen et al., 2023). Compared to conventional jet fuel, SAF reduces carbon emissions by up to 80% (Prussi et al., 2021). The U.S. SAF Grand Challenge (Bioenergy Technologies Office, 2024; U.S. Department of Energy et al., 2022) aims to produce 11.36

<sup>1</sup> Department of Agricultural and Biological Engineering, University of Illinois Urbana-Champaign, 1304 W Pennsylvania Ave, Urbana, IL, 61801, USA

\* Corresponding author yzhang1@illinois.edu

billion litres of SAF per year by 2030 and 132.5 billion litres per year by 2050. Recently, SAF production capacity in the U.S. reached 4.8 million litres per day, but it still makes up less than 2% of daily jet fuel consumption (Troderman & U.S. Energy Information Administration, 2025).

Biomass feedstocks are expected to play a significant role in providing renewable carbon sources for energy. Municipal solid wastes, forestry, and agricultural sources are currently used for bioenergy, while other wastes and waste byproducts (plastic, paper, and cardboard), agricultural residues, and agricultural processing wastes are expected to contribute to near-term market scenarios (U.S. Department of Energy, 2024). Herbaceous and woody energy crops, and intermediate oilseeds are anticipated as potential biomass resources in mature market scenarios. Lastly, microalgae and macroalgae are emerging biomass resources.

Jet fuel is a mixture of n-alkanes, cycloalkanes, isoalkanes, and aromatics, with a stringent set of physicochemical fuel and handling properties. Eight SAF pathways are approved by the American Society for Testing and Materials (ASTM) in ASTM D7566 (ASTM International, 2024b), as well as three more co-processing pathways in ASTM D1655 (ASTM International, 2024a). The hydroprocessed fatty acids and esters (HEFA) pathway is the most mature and is anticipated to contribute a majority of SAF production (Calderon et al., 2024). Other pathways that convert waste, agricultural, and forestry residues, such as Fischer-Tropsch (FT) and alcohol-to-jet (ATJ), are also employed for SAF production, but at smaller scales.

HEFA utilises lipid feedstocks, such as vegetable oils, FOGs (fats, oils, and grease), and algae. Oil from those feedstocks undergoes catalytic hydrogenation, thermal hydrolysis, hydrodeoxygenation, hydroisomerisation, and hydrocracking to form n-alkanes and isoalkanes (Usman et al., 2023). However, low aromatics content in HEFA SAF may result in poor fuel operability and combustion characteristics, limiting the blending ratio to 50% with conventional jet fuel (Jet-A). ASTM D1655 requires the aromatics content of synthetic jet fuel to be within the range of 8-25% for proper seal-swelling performance (ASTM International, 2024a). While HEFA technology is not expected to be a barrier to significant scale-up, the availability of domestic feedstock is a major challenge due to flattening production (Fats and Oils: Oilseed Crushing, Production, Consumption and Stocks 2022 Summary, 2023; Rosales Calderon et al., 2024). Although a majority of HEFA fuels are produced from soybean oil, FOGs have lower carbon intensity, environmental impact, and competition with the food supply (Rosales Calderon et al., 2024).

Compared to other pathways, hydrothermal liquefaction (HTL) has increased feedstock flexibility because it can process wet biomass feedstocks (e.g., sewage sludge, food waste, and animal manure) without drying, which saves time and cost for feedstock pretreatment (Usman et al., 2023). Direct processing of wet biomass offers advantages to circularity because of greater feedstock availability, diversion from landfills, and reduced consumption of virgin resources. Food waste is a significant municipal waste stream in the U.S., with over 60 million tons lost or wasted each year (Kenny et al., 2023). Furthermore, food waste is an ideal feedstock for HTL, because its high lipid and protein content can be easily converted into biocrude oil (Aierzhati et al., 2019). HTL demonstrated high efficiencies in biocrude yields, carbon recovery, and energy recovery (Watson et al., 2020). HTL biocrude oil is suitable for upgrading to transportation fuels like gasoline, jet fuel, and diesel (Watson et al., 2021). HTL biocrude oil from food waste typically contains a high amount of fractions in the diesel range, which may require cracking to obtain molecules in the jet range (Summers et al., 2023). However, the overlap of carbon number and boiling point range for jet fuel and diesel allows flexible production in refineries (Calderon et al., 2024).

One challenge that the HTL-SAF pathway faces is catalyst deactivation due to the high content of inorganics, such as salt, metal, and ash, contained in HTL biocrude oil. Therefore, HTL biocrude pretreatment is required for inorganics removal prior to hydrotreating (Kilgore et al., 2023; Summers et al., 2024). Production of SAF from HTL biocrude oil was demonstrated for multiple feedstocks. A promising SAF candidate was produced by hydrotreating HTL biocrude oil from sewage sludge, containing 19% aromatics, 12% n-alkanes, 21% isoalkanes, and 47% cycloalkanes (Cronin et al., 2022). Hydrotreated HTL biocrude oil from microalgae *Picochlorum celeri* produced a jet fuel cut with 12% aromatics, 16% n-alkanes, 35% isoalkanes, and 36% cycloalkanes (Zhu et al., 2023). Notably, variances in feedstock composition and hydrotreating conditions may lead to differences in the hydrocarbon composition of HTL-SAF. Therefore, further scale-up and validation of HTL biocrude hydrotreating is needed to realise the HTL-SAF pathway.

Several LCA methodologies are used to evaluate the impact of SAF and other renewable fuels, such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSA) by the International Civil Aviation Organization (ICAO) (Prussi et al., 2021); Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model by the United States Department of Energy (DOE) Argonne National Laboratory (M. Wang et al., 2023); and ReCiPe (Huijbregts et al., 2017). These LCA metrics provide valuable metrics, such as GHG emissions/global warming potential (GWP), land use, water use, toxicity, acidification, and eutrophication (Carvalho et al., 2019; Osman et al., 2024).

For example, Wu et al. found that production of SAF from food waste-derived volatile fatty acids could reduce GHG by up to 71% compared to Jet A (Wu et al., 2024). Yoo et al. determined that Gevo Inc.'s ATJ SAF process reduced GHG emissions by about 17% compared to Jet A, but could be further reduced through the integration of renewable hydrogen, electricity, and heat, as well as carbon capture and storage, and sustainable farming practices during feedstock cultivation (Yoo et al., 2022). Capital and operational expenses related to HTL scale-up and feedstock logistics highly influence the minimum selling price, presenting challenges for HTL-SAF production (Summers et al., 2025). For example, a technoeconomic (TEA) and LCA study by Tzanetis et al. determined that SAF produced from HTL biocrude oil of forestry residues could reduce GHG emissions by up to 85%, but was also 2 times more expensive than fossil jet fuel because of feedstock costs (Tzanetis et al., 2017).

These results certainly support the lower environmental impacts of SAF, but they do not inherently measure resource circularity. There are also limitations to existing LCA methods, such as different approaches for midpoint and endpoint calculations. For example, midpoint categories are related to the cause/emission (e.g., GWP, water use), while endpoint categories are for a general area of protection (e.g., damage to human health, ecosystems, or resource availability) (Finnveden & Potting, 2014; Huijbregts et al., 2017). However, some midpoint impact categories, like fossil resources, do not have constant mid-to-endpoint factors (Huijbregts et al., 2017). Additionally, endpoint categories have higher uncertainty compared to midpoint categories, but are often easier to interpret for environmental relevance (Hauschild, 2019). Furthermore, LCA was designed for a “cradle-to-grave” approach, analogous to a linear economy (Samani, 2023). Therefore, a normalised system methodology that can be applied across different SAF technologies, scales, locations, and scenarios is still needed to complement LCA results for a circular economy.

Circularity of fuel production pathways can be improved by using renewable or recovered resources instead of fossil or virgin materials. As defined by the Ellen MacArthur Foundation, there are three aspects of a circular economy: reduce waste and pollution, circulate products and materials, and regenerate nature (Circular Economy Introduction, n.d.). Circularity reduces waste and extends resource use beyond “take, make, and waste”, through the recovery, remake, and reuse of conventionally disposed products. Essentially, circularity minimises material use and waste, which can help reduce negative environmental impacts associated with the depletion of natural and fossil resources. Established campaigns like the “3Rs” of waste management—reduce, reuse, and recycle—embody the concept of a circular economy. However, the conceptualisation and definition of a circular economy have been largely qualitative, lacking a cohesive definition and a quantitative metric. This has resulted in hundreds of definitions that fail to apply across different contexts (Kirchherr et al., 2023). Kristensen and Mosgaard compared 30 circularity indicators and found that they varied in definition and lacked flexibility in scale and scope, making it difficult to provide benchmarks and make direct comparisons (Kristensen & Mosgaard, 2020). Notably, claims of circularity and environmental friendliness may be overstated or misrepresented to benefit corporate profits (Kopnina, 2019; Kopnina et al., 2025). For example, airlines that tout the use of SAF often fail to clarify that although lifecycle emissions may be lower, burning SAF still emits CO<sub>2</sub> in comparable amounts to regular aviation fuel. Further, there are currently no realistic alternatives to conventional jet fuel, as fuel demand in the aviation industry largely outpaces the current supply of SAF due to insufficient scalability of feedstocks (Collins et al., 2024). Therefore, quantitative metrics for SAF must consider the context and limitations for a complete transition to a circular bioeconomy.

Some examples of existing circular economy indicators include the Material Circularity Indicator (The Ellen MacArthur Foundation & Granta Design, 2015), Multiple Criteria Decision Making (Garcia-

Bernabeu et al., 2020), and Zero Waste Index (Zaman & Lehmann, 2013). The development of new circular economy indexes, methods, and frameworks continues, with recent literature exploring indicators for industrial processes, regional sectors, waste recycling, and agriculture. Pilipenets et al. developed a process-level circularity framework to address the resource flows and environmental impacts of individual processes, producing a single index that comprises resource flow and emissions (Pilipenets et al., 2025). A quantitative analysis combining the use of the 6Rs (reduce, reuse, recycle, reclaim, recover, and restore) with the British Standard BS8001:2017 circular economy framework used an indicator scoring system to identify barriers to circular economy implementation in the Indian healthcare sector (Nath et al., 2025). Zhang et al. developed and applied a life-cycle cost (LCC) model to two different waste management techniques and found that the LCC results aligned with environmental impacts from LCA (J. Zhang et al., 2024). Brändström and Saidani also compared the results from circularity metrics and LCA, determining that circularity can be compatible with LCA metrics, highlighting reduced GWP (Brändström & Saidani, 2022). Kopnina et al. identified connections between frameworks for circular economy and Environmental, Social and Governance (ESG) to promote practical applications, proposing an updated R-hierarchy framework with new categories Regeneration, Rewilding, and Restoration for qualitative reporting and Circularity Scoring Model for quantitative reporting (Kopnina et al., 2025). Social impact assessment was compared with a ReSOLVE circularity framework and identified a negative correlation between circularity and social impacts, noting that the existing method could not assess trade-offs for decision making (Payne & Kwofie, 2024).

Zhang et al. developed a scalable circularity index (CI) that quantifies resource flows for systems of different scales, identifies weak links, provides benchmarks, and determines trade-offs (Y. Zhang et al., 2024). The identification of weak links provides insight into the barriers to transition (e.g., limited resource recovery). Furthermore, it enables actionable and measurable objectives to increase circularity. This CI was applied to determine the nitrogen circularity in a corn-soybean United States Midwest farm and the energy circularity of the United States national food and agricultural system, demonstrating improved CI through the integration of renewable and recovered resources in different scenarios (Y. Zhang et al., 2024). Circular economy indicators like CI are important for the development and scale-up of SAF because they can provide a single value for users and stakeholders to benchmark a process against a standard, rather than multiple environmental metrics (Saidani et al., 2019). Additionally, LCA alone cannot measure progress in the transition to a circular economy, as it fails to capture resource loops. For instance, commercial pathways like HEFA may achieve lower GHG emissions compared to fossil fuels, but the cultivation and diversion of edible feedstocks for SAF conversion may suggest lower circularity compared to the use of repurposed (i.e., non-edible or waste) feedstocks. This work showed that compared to existing SAF pathways like HEFA, an HTL pathway has the potential to further improve carbon and energy circularity of jet fuel production in the United States through the recovery and remaking of food waste.

## 2. Methods

The carbon and energy circularity of aviation systems was calculated using a scalable circularity index (CI, Eq.1), where CI = 0% represents a completely linear system, and CI = 100% represents a completely circular system (Y. Zhang et al., 2024):

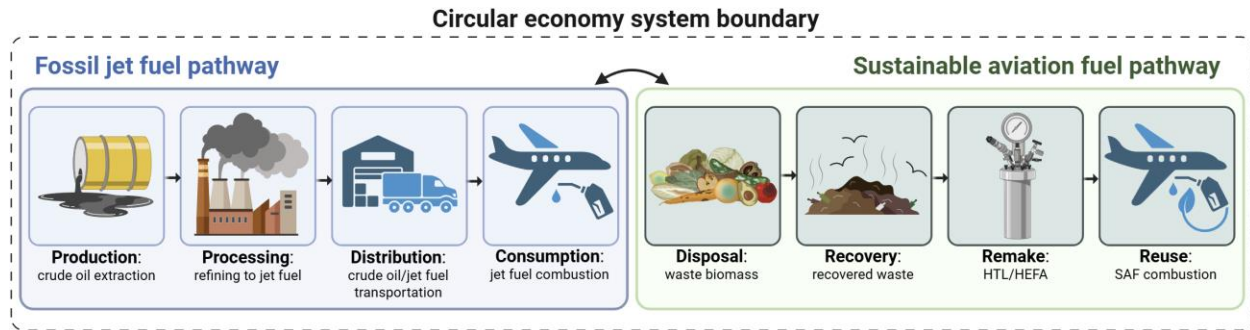
$$CI = \frac{Y_R}{Y} = \frac{\sum_{i=1}^n R_i X_i + [a_i][X_i]}{\sum_{i=1}^n (C_i + R_i) X_i} \times 100\%, (0\% \leq CI \leq 100\%) \quad \text{Eq. 1}$$

Where  $Y_R$  = total fraction of outputs from renewable and recovered resources,  $Y$  = total anthropogenic output of the system,  $R_i$  = renewable fraction of the  $i^{\text{th}}$  category,  $X_i$  = output of the  $i^{\text{th}}$  category,  $a_i$  = recovered fraction of the  $i^{\text{th}}$  category, and  $C_i$  = consumable fraction of the  $i^{\text{th}}$  category. Consumable resources are defined as non-renewable sources that are taken from natural sources and cannot be recycled naturally, such as fossil fuels and mined minerals. Renewable resources are defined as those derived from natural sources, such as solar or wind power, hydropower, and biofuel. Lastly, recovered resources are defined as those recoverable from residual or disposed waste streams. Examples of recovered resources include biocrude converted from waste, methane produced from waste digestion, and recycled nutrients. Notably, the difference between renewable and recovered resources is based on their source; renewable resources come from natural resources, while recovered resources come from anthropogenic waste streams. Details on how to define value-chain categories and resource fractions, collect data, and calculate the CI are described in previous work (Y. Zhang et al., 2024). For value-chain categories that contain multiple types of resource types, resource fractions are designated such that  $C_i + R_i = 1$ , and  $a_i$  represents recycled resources that could have reductive ( $a_i < 1$ ) or additive ( $a_i > 1$ ) contributions (Y. Zhang et al., 2024). Therefore, in a scenario where a system recovers more resources than it consumes, CI can be greater than 100%.

In this study, three scenarios were evaluated: 1) Jet fuel production and sustainable aviation fuel (SAF) consumption in the existing United States (U.S.) aviation industry; 2) Integration of hydroprocessed esters and fatty acids (HEFA) for SAF production from fats, oils, and greases (FOGs); and 3) Integration of hydrothermal liquefaction (HTL) for SAF production from food waste. FOGs were selected as the feedstock for HEFA to be comparable to food waste as a biowaste feedstock. The system scale was the United States (U.S.) aviation industry. For the existing aviation industry scenario, the system boundaries included crude oil extraction, refining, transportation and distribution, and consumption for petroleum-derived jet fuel production and existing SAF consumption every year. This existing scenario serves as a baseline for comparisons. For the HEFA scenarios, the feedstock considered was FOGs available in the U.S. each year, with a recoverable fraction for biofuels and a remake fraction for hydroprocessing. For the HTL scenarios, total food waste in the U.S. each year was considered, with a recoverable fraction from disposal streams, and a remake fraction via HTL and hydroprocessing. Eight value-chain categories were identified for the CI system analysis with designated resource types (**Table 1**). Data was collected from the U.S. Department of Energy, U.S. Energy Information Administration, Bureau of Transportation Statistics, U.S. Environmental Protection Agency, and U.S. Department of Transportation.

**Table 1.** Value-chain category descriptions and resource types for carbon and energy circularity in the U.S. aviation sector, where C = consumable, R = renewable, and a = recoverable.

| $X_i$ | Value-chain category | Description   | Resource type(s) |
|-------|----------------------|---|------------------|
| $X_1$ | Production           | Crude oil extraction for jet fuel   | C                |
| $X_2$ | Processing           | Crude oil refining to jet fuel  | C, R             |
| $X_3$ | Distribution         | Crude oil and jet fuel pipeline transportation                                    | C                |
| $X_4$ | Consumption          | Jet fuel combustion   | C, R             |
| $X_5$ | Disposal             | Biomass waste disposal (i.e. food waste, FOGs)                                    | R, a             |
| $X_6$ | Recovery             | Biomass waste recovery (i.e. landfilled food waste, FOGs designated for biofuels) | C, R, a          |
| $X_7$ | Remake               | Biomass waste valorisation (i.e. HTL and/or hydroprocessing)                      | C, R, a          |
| $X_8$ | Reuse                | SAF combustion  | C, R             |



**Figure 1.** Flowchart of system value-chain categories.

Data used in the CI calculations are described as follows, with example calculations in the Annexe. Each day, 1.77 billion kg of crude oil are produced in the U.S., with 9.42% of jet fuel accounting for finished petroleum products (U.S. Energy Information Administration, 2024c). Additionally, daily jet fuel refinery and blender production was 236 million kg per day, and jet fuel consumption was 225 million kg per day (U.S. Energy Information Administration, 2024c). The energy efficiencies of petroleum-based fuel-cycle stages were 98.0%, 95.3%, and 99.5% for crude recovery, jet fuel refining, and transportation and storage, respectively (M. Q. Wang, 1999a). In some refineries, renewable energy, such as solar, can provide up to 28% of operational power needs (Misbrenner, 2024). Each year, 18.9 billion kg of crude oil and 30.4 billion kg of jet fuel are transported through the Petroleum Administration for Defense Districts (PADDs) (U.S. Energy Information Administration, 2024a), with reported mileage of 135 thousand and 103 thousand kilometres (U.S. Department of Transportation, 2024), respectively. Assuming transportation mainly through pipelines, the GREET energy intensity for petroleum product transport of 0.292 kJ/km-kg was used (M. Q. Wang, 1999a). In 2022, it was reported that 2.15 billion kg of SAF were consumed (U.S. Department of Energy Alternative Fuels Data Center, 2023), representing <0.1% of jet fuel consumption.

For the HEFA-SAF pathway, 20.9 million metric tons of domestic HEFA feedstock are produced each year, with FOGs constituting 28% (~7 million tons) (Rosales Calderon et al., 2024). Furthermore, about 50% of FOG consumption was for biofuels, while the remaining feedstock was consumed by the food industry (e.g., feed, food, fatty acids) (Rosales Calderon et al., 2024). In a projected scenario that optimised the jet cut, HEFA conversion was 83%, while the jet fuel cut was 48% (Rosales Calderon et al., 2024). The energy content of FOGs is 36 MJ/kg (U.S. Department of Energy, 2024), and the energy content of HEFA-SAF is 44 MJ/kg (Huq et al., 2021). The carbon content of FOGs was 78% (Paiva Pinheiro Pires et al., 2023) and 85% for HEFA-SAF (Huq et al., 2021).

For the HTL-SAF pathway, 66.2 million wet metric tons of food waste were produced in 2019, with 59.84% of it sent to landfills (U.S. Environmental Protection Agency, 2025). A moisture content of 75% was assumed for the food waste. After landfilling, the next highest waste management pathways were combustion (14.57%), donation (7.76%), sewer/wastewater treatment (6.00%), and composting (4.99%). Additional pathways include animal feed (2.29%), bio-based materials and biochemical processing (3.53%), anaerobic digestion (0.81%), and land application (0.21%).

In this scenario, food waste was converted via HTL into biocrude oil under 300 °C, 11.0 MPa, and a space velocity of 3 h<sup>-1</sup> (Summers et al., 2023). The HTL biocrude oil was pretreated to remove moisture, salt, and ash (Summers et al., 2024). Then, pretreated HTL biocrude was hydrotreated using CoMo/Al<sub>2</sub>O<sub>3</sub> under 400 °C, 11.0 MPa, and a weight hourly space velocity of 0.5 h<sup>-1</sup>. The overall HTL pathway yields from food waste were 59.35% biocrude, with a 25.87% hydrotreating yield, and a 9.06% SAF yield on a dry basis (selected from preliminary data for a single scenario hydrotreating HTL biocrude oil). The energy content of food waste, HTL biocrude, and hydrotreated biocrude/SAF was 28.04, 38.37, and 27.15 MJ/kg, respectively. The carbon content of the same was 60.94%, 75.57%, and 85.65%, respectively. A value of 10% was assumed for process energy.

Uncertainty and sensitivity analysis were performed to determine the effect of food waste disposal and recovery, carbon content, energy content, and conversion yield on SAF CI. A 1,000-trial Monte Carlo

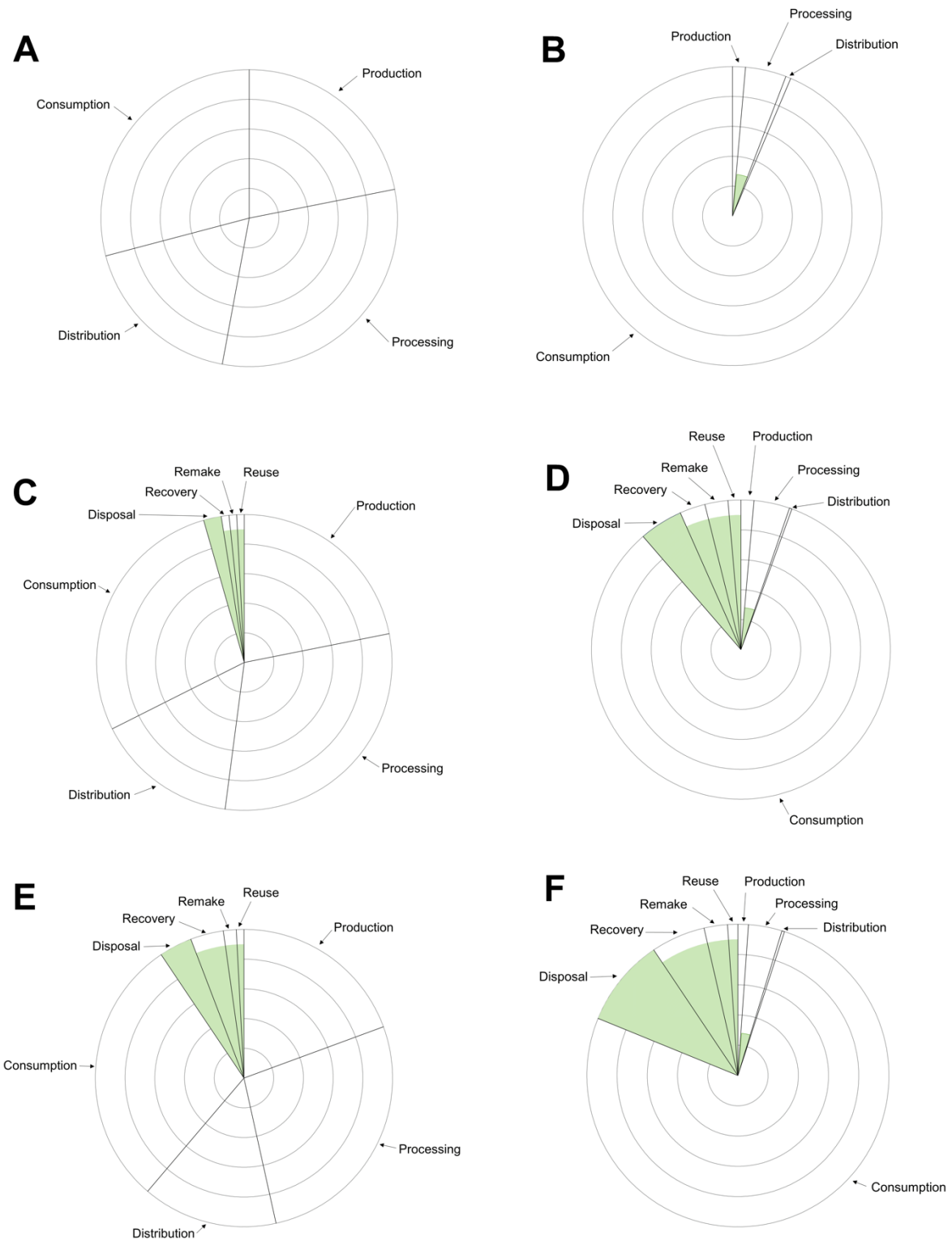
simulation was performed to randomly assign to values  $\pm 10\%$  of the model base data for all parameters except for feedstock recovery. A range of  $\pm 10\%$  was used due to the significant effect of food waste composition, HTL parameters, hydrotreating parameters, and catalyst selection on biocrude and SAF yields. For feedstock recovery, values ranged from  $-10\%$  of the base value to  $100\%$  recovery to simulate complete waste diversion. The Spearman's Rank Correlation Coefficient was determined for the sensitivity of each parameter. Additionally, deterministic sensitivity analysis was performed to display CI changes when significant parameters were set at the 10<sup>th</sup> and 90<sup>th</sup> percentiles of their uncertainty range. Key assumptions included that HTL and SAF yields from food waste were consistent across different compositions, generalised refinery performance for the whole country, and the feasibility of food waste collection from municipal solid waste.

### 3. Results and Discussion

#### 3.1. Circularity index of production pathways

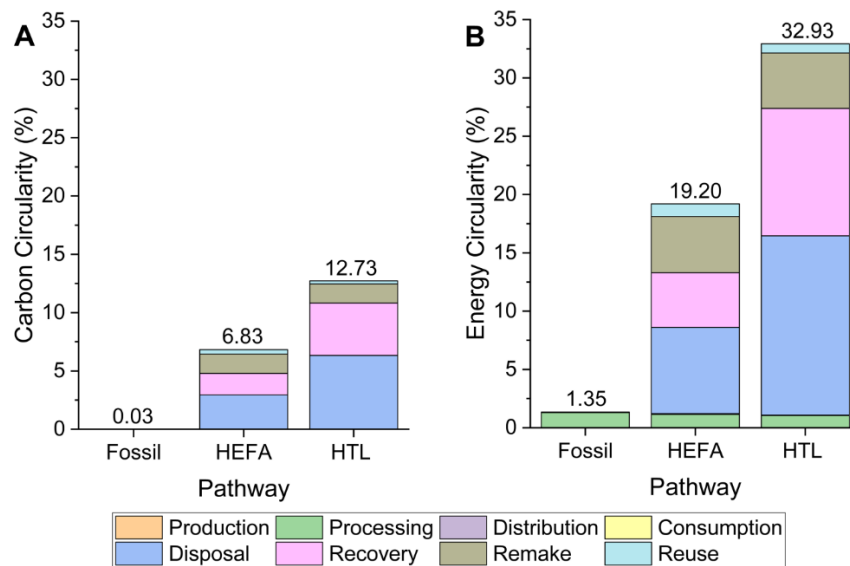
The carbon and energy circularity index (CI) was calculated for the fossil, hydroprocessed esters and fatty acids (HEFA), and hydrothermal liquefaction (HTL) pathways. Values assigned to the value-chain categories, and fractions of consumable, renewable, and recoverable resources were listed in data summary tables in the Annexe (**Tables A1** and **A2** for fossil carbon and energy, **Tables A3** and **A4** for HEFA carbon and energy, and **Tables A5** and **A6** for HTL carbon and energy). Radar pie diagrams depict the weak links and trade-offs present in each fuel pathway, with the pie sector representing the weight of each value-chain category, and the radar magnitude (0-100%) representing the renewable fraction (**Figure 2**). In the existing United States (U.S.) aviation fuel sector, production, processing, distribution, and consumption—which are notably the value-chain categories from a conventionally linear system—completely make up the pathway (**Figures 2A-B**), with a small portion of renewable energy used during processing.

Integration of HEFA-SAF from fats, oils, and greases (FOGs) into the fuel sector led to the presence of disposal, recovery, remake, and reuse value-chain categories, with increased renewable fractions (**Figures 2C-D**). Moreover, the utilisation of renewable and recovered resources in the HEFA pathway led to decreased weights of the “linear” value-chain categories. Similar trends were seen for the HTL pathway (**Figures 2E-F**), with further increases in renewable fractions. These increases reflected greater feedstock supply and recovery for food waste compared to FOGs. In terms of weak links, the lack of renewable resources used in the fossil pathway is evident. However, under the current infrastructure, these value-chain categories remain largely unchanged for the HEFA and HTL pathways. Therefore, further improvements can be made to incorporate the use of renewable resources in the production, processing, distribution, and consumption value-chain categories.



**Figure 2.** Radar pie diagrams depicting weighted value-chain categories of the circularity index for fossil a) carbon and b) energy, HEFA c) carbon and d) energy, and HTL e) carbon and f) energy.

It was demonstrated that the integration of SAF pathways for jet fuel production in the United States improved carbon and energy circularity. In the existing jet fuel production scenario, the carbon and energy CI were 0.03% and 1.35%, respectively (**Figure 3**). The existing circularity was attributed to the use of renewable energy during processing to power refinery operations and the current consumption levels of SAF. Meanwhile, SAF production from the HEFA pathway increased circularity by 6.80% and 17.85% for carbon and energy, respectively. As seen in the radar-pie diagrams, increased utilisation of renewable and recoverable resources was attributed to feedstock disposal and recovery. Furthermore, the remake of the FOGs into SAF enabled the production of renewable energy from recovered waste resources. In the HTL scenario, even further increases in CI were observed, achieving increases of 12.70% and 31.58% for carbon and energy circularity compared to fossil jet, respectively, due to increased feedstock supply. This demonstrated that SAF produced from the HTL of food waste consisted of about 13% renewable or recovered carbon, with a corresponding decrease in non-renewable or fossil carbon sources (i.e., petroleum crude). Increased carbon and energy CI align with the decreased environmental impacts of SAF LCA studies. HTL may serve an important role in the recovery of food waste and conversion into value-added products, leading to sustainable waste-management strategies needed to approach carbon neutrality (Dane et al., 2025).



**Figure 3.** Stacked bar chart of the A) carbon and B) energy circularity index (CI) of fossil, HEFA, and HTL jet fuel production pathways, where the contributions of individual value-chain categories to the overall CI are depicted.

Evidently, there is an opportunity to improve the last four value-chain categories, i.e., disposal, recovery, remake, and reuse, through increased feedstock recovery and expansion of the conversion technology to include other feedstock types. For example, only half of the FOGs supply in the U.S. is available for biofuels, with the other half consumed by the food industry (Rosales Calderon et al., 2024). Additionally, it is currently more profitable for biofuel facilities to produce renewable diesel instead of SAF, resulting in lower yield cuts. For instance, only 0.3% of California's Low Carbon Fuel Standard (LCFS) credits were sold for SAF in 2021, while 36% were sold for renewable diesel (Calderon et al., 2024). Other states, including Oregon (Oregon.gov, n.d.), Washington (State of Washington Department of Ecology, n.d.), Illinois (Harris, 2023), Minnesota (Minnesota Department of Revenue, 2024), and New Mexico (New Mexico Environment Department, 2025), have also provided SAF credits.

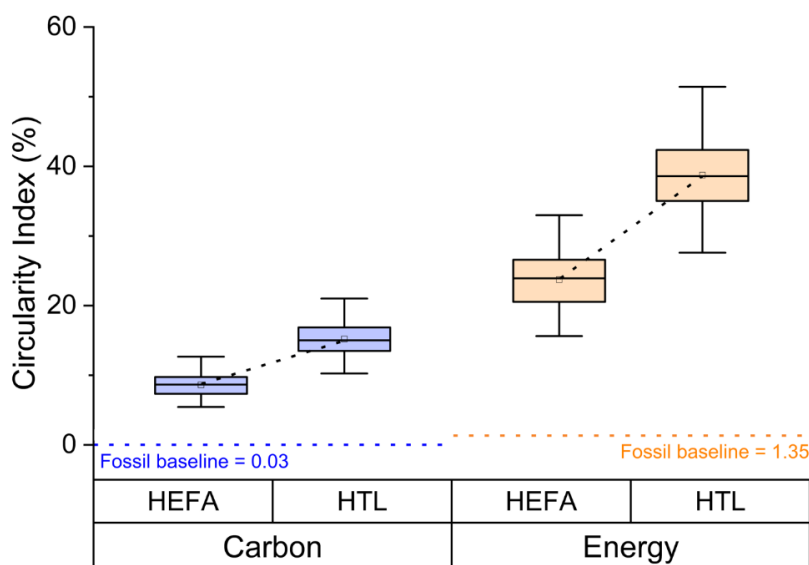
In the competition for feedstocks and end-products, increased selling price or incentives for SAF may encourage manufacturers to target SAF from FOGs over other products, thus increasing the remake and reuse value-chain categories. However, feedstock availability is a key constraint in the SAF circularity transition. For example, HEFA expansion is severely restricted by the availability of vegetable and waste

oils. Therefore, the disposal and recovery value-chain categories have limited room for growth in their current state. FOGs only make up 28% of HEFA feedstock, with most feedstocks coming from non-waste sources, including soybean oil (58%), corn oil (9%), canola, and vegetable oil (Rosales Calderon et al., 2024). Opportunities such as further expansion of HEFA technology for the conversion of other lipid-rich feedstocks like algae, along with engineered crops for increased lipid production, can help improve the overall circularity.

Meanwhile, similar weak links and opportunities were observed in the HTL pathway. Although a greater supply of food waste is available in the United States compared to FOGs, about 60% of it is recoverable from landfills (U.S. Environmental Protection Agency, 2025). Therefore, if food waste could be diverted from other waste treatment methods like combustion or composting, the disposal and recovery value-chain categories could be increased. HTL's main advantage over HEFA and other thermochemical conversion methods is its ability to convert a wider range of feedstocks, including those with high moisture, such as sewage sludge (Cronin et al., 2022), municipal solid waste (Rahman et al., 2022), and algae (Haider et al., 2021). Despite HTL's higher CI, weaknesses may exist with food waste and other waste feedstocks due to uncertainty in biocrude oil yield, due to variability in feedstock compositions. Therefore, optimisation of reaction conditions to increase HTL biocrude oil yield, pretreatment efficiency, and SAF yield may improve the remake value-chain category. Additionally, technical barriers like parameter tuning, catalyst development, and alternative methods for pretreatment, deoxygenation, denitrogenation, and desulphurisation all present challenges for HTL-SAF production and ASTM approval. Another factor that was not considered in the scope of this work was feedstock price, a key variable affecting production costs. SAF pathways that can utilise zero- or negative-cost feedstocks will have an economic advantage over typical feedstocks like seed oils and starch resources used by HEFA and ATJ.

In both SAF production pathways, the conventionally linear value-chain categories remained as weak links in achieving increased circularity. While neither HEFA nor HTL is at a large enough scale to fully replace fossil jet fuel, increased use of renewable energy, such as solar or wind, to power petroleum refining and transportation processes could improve the carbon and energy CI. As SAF production increases, the CI of the aviation sector will increase, representing decreased waste and improved resource circularity.

### 3.2. Uncertainty analysis



**Figure 4.** Box plots of the uncertainty range for carbon and energy circularity index in the HEFA and HTL SAF production pathways, compared to a baseline reference of the fossil jet fuel pathway.

It was observed that while the HEFA pathway had a lower average CI compared to HTL, it also had a smaller uncertainty range for both carbon and energy CI (**Figure 4**). In the HEFA pathway, the carbon CI ranged from 5.45 to 12.68%, with an average of  $8.61 \pm 1.56\%$ . Meanwhile, the carbon CI for the HTL pathway ranged from 10.27 to 21.02%, with an average of  $15.20 \pm 2.19\%$ . The average CI from the uncertainty distribution was slightly higher than that of the base case, due to the sensitivity of CI to feedstock supply and recovery. Similarly, the energy CI for HEFA ranged from 15.63 to 32.99%, with an average of  $23.75 \pm 3.88\%$ , while HTL ranged from 27.60 to 51.42%, with an average of  $38.76 \pm 4.78\%$ . The larger standard deviation for the HTL pathway reflected greater uncertainty compared to HEFA.

These uncertainty distributions again highlight the opportunity for increased feedstock supply and recovery to improve the carbon and energy circularity of SAF production pathways. Therefore, efforts to increase circularity should target under-utilised waste feedstocks with high recovery potentials. Additionally, improvements in biocrude yields, hydrotreating yields, and jet fuel cuts can lower uncertainty in the remake value-chain category and increase circularity. Additionally, reducing uncertainty in the chemical composition (e.g., carbon and energy content) of the feedstocks and SAF can also help reduce uncertainty in the CI.

### 3.3. Sensitivity analysis

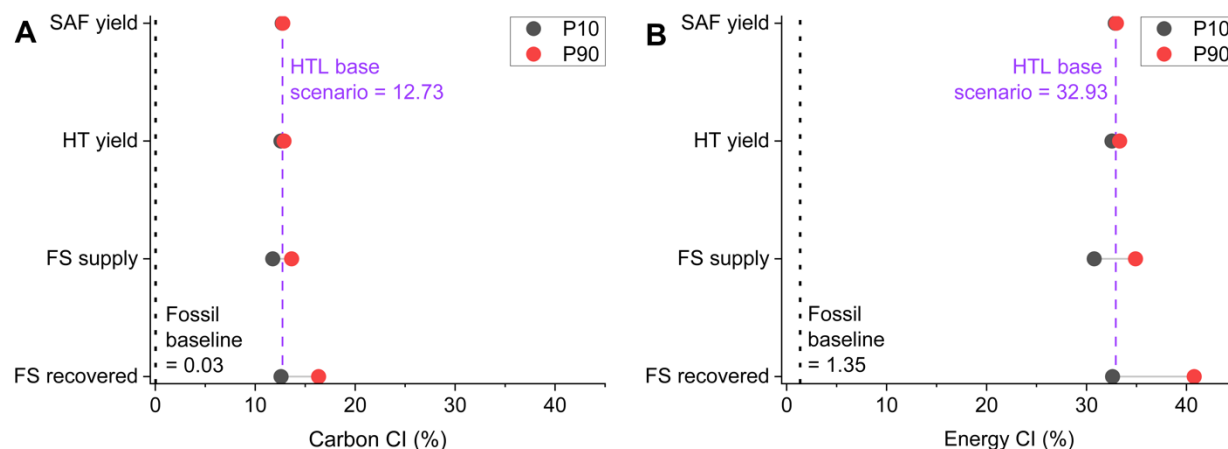
Based on the Spearman's Rank Correlation Coefficient (**Table 2**), carbon CI for the HEFA pathway was most sensitive to feedstock (FS) recovered > FS supply > FS carbon content, while the energy CI was also most sensitive to FS recovered > FS supply > FS energy content. In the HTL pathway, the same parameters had the greatest correlation to the CIs, with carbon CI most sensitive to FS recovered > FS carbon content > FS supply, and energy CI most sensitive to FS recovered > FS supply > FS energy content. Beyond feedstock parameters, hydrotreating yield had a greater impact on CI compared to the SAF yield for conversion. This demonstrated the importance of hydrotreating conditions on upgrading FOGs and HTL biocrude oil. This has also been reflected in recent research focused on hydrotreating HTL biocrude oil, with advances toward catalyst stability (Subramaniam et al., 2021), hydrotreating scale-up (Thorson et al., 2021), and deep denitrogenation (Haider et al., 2020).

**Table 2.** Spearman's Rank Correlation Coefficient of the HEFA and HTL pathway parameters for the carbon and energy circularity index, where FS = feedstock, SAF = sustainable aviation fuel, and HT = hydrotreating.

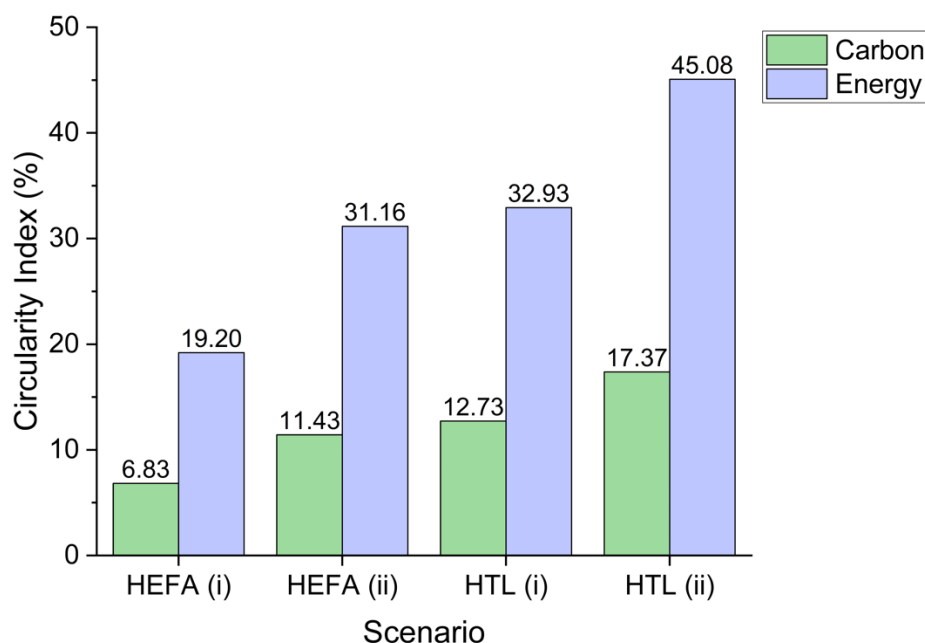
| Parameter                   | HEFA   |        | HTL    |        |
|-----------------------------|--------|--------|--------|--------|
|                             | Carbon | Energy | Carbon | Energy |
| FS supply (kg)              | 0.34   | 0.31   | 0.34   | 0.32   |
| FS recovered (%)            | 0.92   | 0.93   | 0.86   | 0.88   |
| Carbon content of FS (wt%)  | 0.17   | -0.03  | 0.36   | 0.05   |
| Energy content of FS (wt%)  | 0.01   | 0.21   | -0.02  | 0.27   |
| Carbon content of SAF (wt%) | 0.07   | -0.02  | 0.06   | 0.00   |
| Energy content of SAF (wt%) | 0.00   | 0.12   | -0.01  | 0.07   |
| HT yield (wt%)              | 0.06   | 0.06   | 0.08   | 0.08   |
| SAF yield (wt%)             | 0.00   | 0.00   | 0.03   | 0.03   |

Additionally, the HTL pathway has the additional steps of biocrude conversion and pretreatment prior to hydrotreating. The Spearman's Rank Correlation Coefficient was 0.11 and 0.09 for the HTL yield and PT yield with carbon CI, and 0.10 for both with the energy CI. The relatively high sensitivity of the CIs to HTL yield and pre-treating yield shows additional areas for monitoring and improvement. For example, switching to different feedstocks or even a new food waste source could affect the HTL yield, with increased yield correlated to increased CI, and decreased yield leading to decreased CI. Therefore, the use of kinetic models to predict biocrude yield based on feedstock composition and reaction parameters is useful in decreasing CI uncertainty. Furthermore, the use of other biocrude pre-treating methods may improve pre-treating yields through preservation of the heavy fraction, which is typically lost during distillation (Summers et al., 2024). Alternative treatments such as acid-assisted aqueous washes (Kilgore et al., 2023;

Xinru et al., 2006), solvent filtration, or ion exchange resins may improve pre-treating yields, but with the trade-off of additional costs. Furthermore, retaining the heavy oil fraction would require further hydrocracking of the biocrude oil, which may also increase hydrotreating costs due to more severe reaction conditions.



**Figure 5.** Sensitivity plot for A) carbon and B) energy circularity index (CI) of the HTL-SAF scenario for FS recovered, FS supply, HT yield, and SAF yield set at the 10<sup>th</sup> percentile (P10) and 90<sup>th</sup> percentile (P90) values of their uncertainty range, compared to the HTL base scenario and baseline of the fossil jet fuel pathway, where FS = feedstock, HT = hydrotreating, and SAF = sustainable aviation fuel.



**Figure 6.** Carbon and energy circularity index of different HEFA and HTL scenarios, where (i) represents existing feedstock recovery and (ii) represents maximum feedstock recovery.

Significant parameters, including feedstock recovered, feedstock supply, hydrotreating yield, and SAF yield, were varied at their 10<sup>th</sup> and 90<sup>th</sup> percentile (P10 and P90, respectively) values for deterministic analysis of the HTL-SAF scenario. As seen in the correlation coefficients, FS recovered and FS supply had the greatest effect on changes in the carbon and energy CI (**Figure 5**). For the feedstock supply, hydrotreating yield, and SAF yield, the CIs at the P10 and P90 values were symmetrical about the base

case. However, the P90 value of the feedstock recovered resulted in a much greater deviation from the base case, skewing the plot much further to the right compared to the P10 value. As seen in the CI value-chain categories and parameter sensitivity analysis, increased feedstock recovery is a major opportunity for increased carbon and energy CI.

Therefore, a second scenario for HEFA and HTL was modelled with maximum feedstock recovery (**Figure 6**). Compared to the existing feedstock recovery levels, the HEFA carbon CI increased by 4.60% and the energy CI increased by 11.96% after maximising feedstock recovery. Similar trends were observed for the HTL scenarios, with a 4.64% increase in carbon CI and 12.15% increase in energy CI with maximum feedstock recovery. In both the existing and maximum feedstock recovery scenarios, HTL has a clear advantage over HEFA in the conversion of waste feedstocks to SAF. However, future work may further evaluate other feedstocks beyond FOGs/food waste. Additionally, the CI model could also be expanded to determine the circularity of the overall HEFA or HTL process, including other fuels or bioproducts besides SAF, such as renewable diesel or gasoline.

### 3.4. Limitations and future opportunities

While the CI model provides a metric to quantify and benchmark transitions in resource circularity, there are several limitations and opportunities for further work. For example, the CI model has not yet been validated against conventional environmental and economic assessments for comparison. Although the CI is not directly comparable to LCA, future studies could compare relative changes in CI and LCA/economic viability results (e.g., does an increase in CI reflect a decrease in GHG emissions or lower break-even or carbon pricing points?).

The CI model for HTL-SAF can also be further developed to increase its robustness. For example, the biocrude yield could be determined as a function of feedstock composition and HTL parameters to account for different food waste types and conversion conditions. As is, the CI model gives a single scenario/one point in time result and could be expanded to accommodate dynamic modelling across time. Furthermore, evaluation of the entire pathway's products, i.e., including diesel and not just SAF, can provide a more holistic CI value for the conversion technology.

Additionally, future work may be interested in enhancing stakeholder use through the integration of CI results with existing LCA results or policy regulations. For example, CI could complement LCA metrics (e.g., carbon circularity ~ GHG emissions or carbon intensity). CI values could also be established as benchmarks for fuel credit standards (e.g., requiring  $\geq 10\%$  increase in carbon circularity). Lastly, a CI system-of-systems approach could be used to determine a multi-objective value by weighting resource CI with other circularities of concern, such as cost.

## 4. Conclusion

A quantitative, scalable circularity index (CI) was applied to the United States (U.S.) aviation sector to directly compare sustainable aviation fuel (SAF) pathways against the fossil jet fuel benchmark. It was shown that SAF production through the hydrothermal liquefaction (HTL) of wet biomass waste streams like food waste is a promising SAF pathway, which may increase carbon and energy CI by 13-30% compared to the fossil jet fuel and 6-14% compared to hydroprocessed esters and fatty acids (HEFA). Although HEFA had less uncertainty compared to HTL, it also had decreased CI potential due to its limited feedstock supply. HTL's greater feedstock flexibility may give it an advantage in the transition to a circular bioeconomy through the utilisation of waste biomass and reduced consumption of fossil resources.

To improve carbon and energy circularity during the scale-up of SAF production, increased waste recovery and feedstock expansion could be implemented to increase the use of renewable and recovered resources in value-chain categories. Future directions could include evaluation of other approved SAF pathways, like alcohol-to-jet (ATJ) and Fischer-Tropsch (FT), to provide more benchmarks for comparison

when characterising the CI of novel pathways like HTL. Additionally, incorporating spatial analysis through regional CI comparisons can account for location-specific feedstock availability, fuel consumption, etc., and provide targeted solutions. Overall, the CI successfully quantified circularity of resources in the U.S. aviation industry, providing a single metric for comparison between fossil jet fuel, HEFA-SAF, and HTL-SAF.

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## Declarations

**Competing Interests** The authors declare no competing interests.

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## Annex

**Table A1.** Carbon CI data summary for fossil scenario

| Value-chain category                      | $X_i$ (kg/yr)         | $X_i/Y$ | $C_i$ | $R_i$ | $a_i$ |
|---|-----------------------|---------|-------|-------|-------|
| $X_1$                                     | $5.16 \times 10^{10}$ | 0.22    | 1.00  | 0.00  | 0.00  |
| $X_2$                                     | $7.33 \times 10^{10}$ | 0.31    | 1.00  | 0.00  | 0.00  |
| $X_3$                                     | $4.09 \times 10^{10}$ | 0.18    | 1.00  | 0.00  | 0.00  |
| $X_4$                                     | $6.75 \times 10^{10}$ | 0.29    | 0.999 | 0.001 | 0.00  |
| $X_5$                                     | 0                     | 0       | -     | -     | -     |
| $X_6$                                     | 0                     | 0       | -     | -     | -     |
| $X_7$                                     | 0                     | 0       | -     | -     | -     |
| $X_8$                                     | 0                     | 0       | -     | -     | -     |
| Total system (kg/yr)                      | $2.33 \times 10^{11}$ |         |       |       |       |
| Total renewable, $R_i \times X_i$ (kg/yr) | $6.75 \times 10^7$    |         |       |       |       |
| Total recovered $a_i \times X_i$ (kg/yr)  | 0.00                  |         |       |       |       |

**Table A2.** Energy CI data summary for fossil scenario

| Value-chain category                      | $X_i$ (MJ/yr)         | $X_i/Y$ | $C_i$ | $R_i$ | $a_i$ |
|---|-----------------------|---------|-------|-------|-------|
| $X_1$                                     | $5.39 \times 10^{10}$ | 0.01    | 1.00  | 0.00  | 0     |
| $X_2$                                     | $1.78 \times 10^{11}$ | 0.05    | 0.72  | 0.28  | 0     |
| $X_3$                                     | $1.09 \times 10^{10}$ | 0.00    | 1.00  | 0.00  | 0     |
| $X_4$                                     | $3.62 \times 10^{12}$ | 0.94    | 0.999 | 0.001 | 0     |
| $X_5$                                     | 0                     | 0       | -     | -     | -     |
| $X_6$                                     | 0                     | 0       | -     | -     | -     |
| $X_7$                                     | 0                     | 0       | -     | -     | -     |
| $X_8$                                     | 0                     | 0       | -     | -     | -     |
| Total system (MJ/yr)                      | $3.86 \times 10^{12}$ |         |       |       |       |
| Total renewable, $R_i \times X_i$ (MJ/yr) | $5.22 \times 10^{10}$ |         |       |       |       |
| Total recovered $a_i \times X_i$ (MJ/yr)  | 0.00                  |         |       |       |       |

**Table A3.** Carbon CI data summary for HEFA scenario

| Value-chain category                      | $X_i$ (kg/yr)         | $X_i/Y$ | $C_i$ | $R_i$ | $a_i$ |
|---|-----------------------|---------|-------|-------|-------|
| $X_1$                                     | $5.14 \times 10^{10}$ | 0.22    | 1.00  | 0.00  | 0.00  |
| $X_2$                                     | $7.12 \times 10^{10}$ | 0.30    | 1.00  | 0.00  | 0.00  |
| $X_3$                                     | $3.67 \times 10^{10}$ | 0.16    | 1.00  | 0.00  | 0.00  |
| $X_4$                                     | $6.55 \times 10^{10}$ | 0.28    | 0.999 | 0.001 | 0.00  |
| $X_5$                                     | $4.56 \times 10^9$    | 0.02    | 0.00  | 1.00  | 0.50  |
| $X_6$                                     | $2.28 \times 10^9$    | 0.01    | 0.10  | 0.90  | 1.00  |
| $X_7$                                     | $2.06 \times 10^9$    | 0.01    | 0.10  | 0.90  | 1.00  |
| $X_8$                                     | $9.87 \times 10^8$    | 0.00    | 0.10  | 0.90  | 0.00  |
| Total system (kg/yr)                      | $2.35 \times 10^{11}$ |         |       |       |       |
| Total renewable, $R_i \times X_i$ (kg/yr) | $9.41 \times 10^9$    |         |       |       |       |
| Total recovered $a_i \times X_i$ (kg/yr)  | $6.61 \times 10^9$    |         |       |       |       |

**Table A4.** Energy CI data summary for HEFA scenario

| Value-chain category                      | $X_i$ (MJ/yr)         | $X_i/Y$ | $C_i$ | $R_i$ | $a_i$ |
|---|-----------------------|---------|-------|-------|-------|
| $X_1$                                     | $5.39 \times 10^{10}$ | 0.01    | 1.00  | 0.00  | 0.00  |
| $X_2$                                     | $1.73 \times 10^{11}$ | 0.04    | 0.72  | 0.28  | 0.00  |
| $X_3$                                     | $9.75 \times 10^9$    | 0.00    | 1.00  | 0.00  | 0.00  |
| $X_4$                                     | $3.51 \times 10^{12}$ | 0.83    | 0.999 | 0.001 | 0.00  |
| $X_5$                                     | $2.08 \times 10^{11}$ | 0.05    | 0.00  | 1.00  | 0.50  |
| $X_6$                                     | $1.04 \times 10^{11}$ | 0.02    | 0.10  | 0.90  | 1.00  |
| $X_7$                                     | $1.07 \times 10^{11}$ | 0.03    | 0.10  | 0.90  | 1.00  |
| $X_8$                                     | $5.12 \times 10^{10}$ | 0.01    | 0.10  | 0.90  | 0.00  |
| Total system (MJ/yr)                      | $4.22 \times 10^{12}$ |         |       |       |       |
| Total renewable, $R_i \times X_i$ (MJ/yr) | $4.95 \times 10^{11}$ |         |       |       |       |
| Total recovered $a_i \times X_i$ (MJ/yr)  | $3.15 \times 10^{11}$ |         |       |       |       |

**Table A5.** Carbon CI data summary for HTL scenario

| Value-chain category                      | $X_i$ (kg/yr)         | $X_i/Y$ | $C_i$ | $R_i$ | $a_i$ |
|---|-----------------------|---------|-------|-------|-------|
| $X_1$                                     | $5.15 \times 10^{10}$ | 0.21    | 1.00  | 0.00  | 0.00  |
| $X_2$                                     | $7.26 \times 10^{10}$ | 0.29    | 1.00  | 0.00  | 0.00  |
| $X_3$                                     | $3.94 \times 10^{10}$ | 0.16    | 1.00  | 0.00  | 0.00  |
| $X_4$                                     | $6.68 \times 10^{10}$ | 0.27    | 0.999 | 0.001 | 0.00  |
| $X_5$                                     | $9.82 \times 10^9$    | 0.04    | 0.00  | 1.00  | 0.598 |
| $X_6$                                     | $5.88 \times 10^9$    | 0.02    | 0.10  | 0.90  | 1.00  |
| $X_7$                                     | $2.14 \times 10^9$    | 0.01    | 0.10  | 0.90  | 1.00  |
| $X_8$                                     | $7.48 \times 10^8$    | 0.00    | 0.10  | 0.90  | 0.00  |
| Total system (kg/yr)                      | $2.49 \times 10^{11}$ |         |       |       |       |
| Total renewable, $R_i \times X_i$ (kg/yr) | $1.78 \times 10^{10}$ |         |       |       |       |
| Total recovered $a_i \times X_i$ (kg/yr)  | $1.39 \times 10^{10}$ |         |       |       |       |

**Table A6.** Energy CI data summary for HTL scenario

| Value-chain category                      | $X_i$ (MJ/yr)         | $X_i/Y$ | $C_i$ | $R_i$ | $a_i$ |
|---|-----------------------|---------|-------|-------|-------|
| $X_1$                                     | $5.39 \times 10^{10}$ | 0.01    | 1.00  | 0.00  | 0.00  |
| $X_2$                                     | $1.76 \times 10^{11}$ | 0.04    | 0.72  | 0.28  | 0.00  |
| $X_3$                                     | $1.05 \times 10^{10}$ | 0.00    | 1.00  | 0.00  | 0.00  |
| $X_4$                                     | $3.58 \times 10^{12}$ | 0.76    | 0.999 | 0.001 | 0.00  |
| $X_5$                                     | $4.52 \times 10^{11}$ | 0.10    | 0.00  | 1.00  | 0.598 |
| $X_6$                                     | $2.70 \times 10^{11}$ | 0.06    | 0.10  | 0.90  | 1.00  |
| $X_7$                                     | $1.18 \times 10^{11}$ | 0.03    | 0.10  | 0.90  | 1.00  |
| $X_8$                                     | $4.12 \times 10^{10}$ | 0.01    | 0.10  | 0.90  | 0.00  |
| Total system (MJ/yr)                      | $4.70 \times 10^{12}$ |         |       |       |       |
| Total renewable, $R_i \times X_i$ (MJ/yr) | $8.90 \times 10^{11}$ |         |       |       |       |
| Total recovered $a_i \times X_i$ (MJ/yr)  | $6.59 \times 10^{11}$ |         |       |       |       |

## Sample calculations for Energy CI of the existing U.S. aviation industry:

### $X_1$ – Production: Crude oil extraction

Data: 13,047,000 barrels/day of crude oil produced (U.S. Energy Information Administration, 2024c); 9.42% of crude goes to jet fuel production (U.S. Energy Information Administration, 2024c); 2% energy is consumed during crude oil extraction (M. Q. Wang, 1999b).

Conversions: 42 gal/barrel; 135,342 Btu/gal crude; 1 MJ/947.82 Btu; 365 days/yr

Calculation:  $(13.047 \times 10^6 \text{ barrels crude oil/day})(0.0942 \text{ jet fuel fraction})(42 \text{ gallons/barrel})(135,342 \text{ Btu/gallon crude oil})(1 \text{ MJ/947.82 Btu})(365 \text{ days/year})(0.02 \text{ energy consumed}) = 5.385 \times 10^{10} \text{ MJ/yr}$  consumed during crude oil extraction

### $X_2$ – Processing: Crude oil refining to jet fuel

Data: 1,738,000 barrels/day of jet fuel produced (U.S. Energy Information Administration, 2024c), 4.7% energy consumed during refining/blending (M. Q. Wang, 1999b).

Conversions: 42 gal/barrel; 135,000 Btu/gal jet fuel; 1 MJ/947.82 Btu; 365 days/yr

Calculation:  $1.738 \times 10^6 \text{ barrels jet fuel/day})(42 \text{ gallons/barrel})(135,000 \text{ Btu/gallon jet fuel})(1 \text{ MJ/947.82 Btu})(365 \text{ days/year})(0.047 \text{ energy consumed}) = 1.784 \times 10^{11} \text{ MJ/yr}$  consumed during jet fuel refining

**$X_3$  – Distribution: Crude oil and jet fuel transportation and storage**

Data: 139,102,126 barrels/yr of crude oil and 223,383,000 million barrels/yr of jet fuel were transported between the 5 Petroleum Administration for Defense Districts (PADD) regions (U.S. Energy Information Administration, 2024b); 0.5% energy consumption during distribution (M. Q. Wang, 1999b)

Conversions: 135,342 Btu/gal crude oil; 42 gal/barrel; 1 MJ/947.82 Btu; 135,000 Btu/gal jet fuel

Calculation:  $[139,102,126 \text{ barrels crude oil/year}(135,342 \text{ Btu/gallon crude oil})+(223,383,000 \text{ barrels jet fuel/yr})(135,000 \text{ Btu/gal jet fuel})] \times (42 \text{ gal/barrel})(1 \text{ MJ}/947.82 \text{ Btu})(0.005 \text{ energy consumed}) = 1.086 \times 10^{10} \text{ MJ/yr consumed during crude oil and jet fuel distribution}$

 **$X_4$  – Consumption: Jet fuel combustion**

Data: Average jet fuel consumption of 1.657 million barrels/day(U.S. Energy Information Administration, 2024c); 15.8 million gallons/yr of SAF consumed in 2022 (U.S. Department of Energy Alternative Fuels Data Center, 2023)

Conversions: 42 gal/barrel; 135,000 Btu/gal jet fuel; 1 MJ/947.82 Btu, 365 days/yr

Calculation:  $(1.657 \times 10^6 \text{ barrels jet fuel/day})(42 \text{ gal/barrel})(135,000 \text{ Btu/gal jet fuel})(1 \text{ MJ}/947.82 \text{ Btu})(365 \text{ days/yr}) + (15.8 \times 10^6 \text{ gallons SAF/yr})(135,000 \text{ Btu/gal jet fuel})(1 \text{ MJ}/947.82 \text{ Btu}) = 3.620 \times 10^{12} \text{ MJ/yr released during jet fuel and SAF combustion}$

**Energy CI Calculation:**

$$CI = \frac{\sum_{i=1}^n R_i X_i + [a_{ij}][X_i]}{\sum_{i=1}^n (C_i + R_i) X_i}$$

Where R = renewable fraction, X = resource chain category value, a = recoverable fraction, and C = consumable fraction.

For extraction and distribution, all energy is classified as consumable ( $C_i = 1$ ,  $R_i = a_{ij} = 0$ ). For refining, up to 28% of power can be supplied through renewable energy ( $C_i = 0.72$ ,  $R_i = 0.28$ ,  $a_{ij} = 0$ ). For consumption, the fraction of SAF was ~0.1% ( $C_i = 0.999$ ,  $R_i = 0.001$ ,  $a_{ij} = 0$ ).

$$CI = \frac{(1.784 \times 10^{10})(0.28) + (3.620 \times 10^{10})(0.001)}{5.385 \times 10^{10} + 1.784 \times 10^{11} + 1.086 \times 10^{10} + 3.620 \times 10^{12}} \times 100\% = 1.35\%$$

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