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# Pragmatic assessment of meeting the 2030 U.S. sustainable aviation fuel goal

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ABSTRACT

Sustainable aviation fuel (SAF) production is essential for decarbonizing the aviation sector in the short and mid-term as well as maintaining the global competitiveness of U.S. airlines, supporting job creation, and ensuring U.S. energy independence. The near-term U.S. SAF target, set by the SAF Grand Challenge, is 11.4 billion liters (3 billion gallons) of domestic SAF production by 2030, with a minimum 50 % reduction in lifecycle greenhouse gas emissions. In 2024 U S. SAF production was less than 2 % of the stated goal, demonstrating that the remaining production growth is significant. Barriers to scale-up include technological readiness, feedstock availability, and delays in facility development. This study uses a database of U.S. SAF production announcements to assess the feasibility of attaining the 2030 targets by analyzing production potential, construction paradigms, feedstock availability, and $CO_2$ abatement cost. Our analysis indicates that the hydroprocessed esters and fatty acids pathway will dominate U.S. SAF production through 2030, with notable contributions from alcohol to jet and co-processing. However, probable U.S. production of SAF is predicted to fall short of the current goal by 3.6-billion liters although there are scenarios that meet the goal. Existing U.S. policies favor on-road transportation fuels and are insufficient to drive necessary SAF production scale-up. Additional measures, such as non-government scope 3 emission purchases, long-term incentives, a national low-carbon fuel standard, or volume mandates, are options to close the gap. These measures are needed to ensure the profitability of SAF production and competitiveness with renewable diesel.

Abbreviations

| | |
|---|---|
| AEZ-EF | Agro-ecological Zone Emission Factor |
| ASCENT | Aviation Sustainability Center |
| ATJ | Alcohol to Jet |
| BLY | Billion liters per year |
| CARB | California Air Resources Board |
| CCLUB | Calculator for Land Use and Land Management Change from Biofuels Production |
| CFP | Clean Fuel Program |
| CH | Catalytic Hydrothermolysis |
| CI | Carbon intensity |
| COD | Commercial operation date |
| CORSIA | Carbon Offsetting and Reduction Scheme for International Aviation |
| DAC | Direct air capture |
| DCO | Distillers corn oil |
| EIA | Energy Information Administration |
| EPA | Environmental Protection Agency |
| FID | Final investment decision |
| FOG | Fats, oils and greases |
| FT | Fischer-Tröpsch |
| GHG | Greenhouse gases |
| GREET | Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model |
| HEFA | Hydroprocessed esters and fatty acids |
| ICAO | International Civil Aviation Organization |
| ILUC | Induce land use change |
| IRA | Inflation Reduction Act |
| LCA | Life cycle assessment |
| LCFS | Low Carbon Fuel Standard |
| MLY | Million liters per year |
| MSP | Minimum selling price |
| RD | Renewable diesel |

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| | |
|---|---|
| RFS | Renewable Fuel Standard |
| RIN | Renewable identification number |
| SAF | Sustainable aviation fuel |
| TEA | Techno-economic analysis |
| UCO | Used cooking oil |
| U.S. | United States |
| | |
| Units | |
| t | metric ton |
| t/year | Metric ton per year |
| MM $ | Millions of U.S. dollars |
| MM $/year | Millions of U.S. dollars per year |
| $/t | U.S. dollars per metric ton |
| g $CO_2$e/MJ | Grams of carbon dioxide equivalent per mega Joule |
| $/t $CO_2$e | U.S. dollars per metric ton of $CO_2$e |
| MLY | Million liters per year |

## 1. Introduction

Sustainable Aviation Fuel (SAF) presents an important short and medium-term option to decarbonizing the aviation sector. In the United States (U.S.), SAF is also key to maintaining the global leadership position of U.S. airlines, extending U.S. energy independence, and creating jobs, mainly in rural communities [1,2]. The U.S. SAF Grand Challenge, led jointly by the U.S. Department of Transportation (DOT), U.S. Department of Energy (DOE) and U.S. Department of Agriculture (USDA), aims to enable industry to expand domestic SAF production with a minimum 50 % life cycle emissions reduction compared to conventional petroleum jet fuel [3,4]. The near-term production goal is 11.4 billion liters (3 billion gallons) in 2030, followed by 132.5 billion liters (35 billion gallons) in 2050 [4]. In 2024, U.S. SAF production was 146 million liters (38.7 million gallons), an impressive increase compared to the 2023 value of 99.5 million liters (26.3 million gallons) [5,6]. In this period, SAF selling prices were one and a half to six times the petroleum jet fuel price, with the European Union Aviation Safety Agency (EASA) reporting estimated 2024 SAF production costs of $1.0–6.4/L [5,7–10]. In spite of the significant growth between 2023 and 2024, only 1.2 % of the U.S. 2030 volume goal of 11.4 billion liters has been domestically produced, with less than six years remaining to scale up to the near-term goal [11–14].

A variety of SAF production pathways are qualified or in the qualification process under the ASTM D7566 and D1655 standards, which ensure the fuel meets the performance and safety specifications for its use in current aircraft and fuel handling systems [15–19]. Production limitations hindering industry scale-up and meeting U.S. goals include technology maturity of new pathways, the time required to plan, permit, build, and start a facility, as well as the physical quantity and ecological limitations of feedstocks [16,18,20]. Potential producers also need to secure capital, financing, and revenue, often while relying on market-based policies to provide a significant portion of their income [21–23]. The capital costs associated with biorefineries can be prohibitive to biorefinery success, especially for unproven technology [8,24]. Although the U.S. government has provided both capital grants and loan guarantees, capital costs remain a significant barrier to industry expansion [25–27]. In the U.S., federal and state policies are primarily focused on increasing the supply of renewable fuels for road transportation while setting emission reduction criteria including estimations of induced land use change (ILUC) [28–32]. SAF-specific policies are novel and are currently applicable for short durations. Policy, costs, demand volume, and supply chain readiness will impact the fuel distillates that producers choose since SAF and renewable diesel (RD) can be produced in the same facility, with volumes between the distillates adjusted based on market conditions [14,17,33–36]. These factors influence both the SAF minimum selling price (MSP) and the cost of abated emissions.

Various mechanisms have been attempted to place a cost on emitting fossil carbon. The "social cost of carbon" is an estimated monetary value of worldwide damage from emitting one additional ton of anthropogenic $CO_2$e into the atmosphere. However a precise assessment is complicated by variations in the risks and costs analyzed [37–39]. Carbon pricing is a policy instrument that aims to hold producers and consumers accountable for greenhouse gas (GHG) emissions while shifting current systems to options with lower emissions [40]. Theoretically, the carbon price should equal the "social cost of carbon", but carbon pricing is inconsistent. In 2017, a global carbon pricing of $50–100/t $CO_2$e by 2030 was suggested to meet the goals set by the Paris Agreement [41]. However, the cost of carbon often exceeds this estimate with markets trading carbon credits between $10–1000/t$CO_2$e, with nature-based options generally less expensive than technology-based solutions [42]. Some companies elect to include internal charges for $CO_2$e emissions, with values varying within and between industries and regions and with some companies differentiating by activity type [43]. For example, in 2022, Microsoft released an internal carbon price of $100/t $CO_2$e for business travel [44]. Abatement costs reflect the price paid to reduce emissions by one ton of $CO_2$e and this value varies by emission source and intervention, but facilitates normalized comparisons [38]. For SAF, abatement cost estimates range between $130–3680/t CO2e [24,45,46] some of which exceed the carbon market.

Developing a new industry provides opportunities, tempered with challenges, both of which need to be explicitly understood for successful growth. Using the volume and time goals set by the U.S. SAF Grand Challenge, the opportunity is the unfulfilled potential market. Challenges could include difficulty procuring feedstock, the time required to fund, site, permit and build facilities and the MSP required to ensure financial solvency. To the best of the authors' knowledge, data on the U.S. SAF industry development including project implementation ratios, project timelines, including delays, and comprehensive feedstock volumes, are not widely available in public sources. This paper seeks to assess the U.S. SAF production potential in the near-term by: 1) developing the concept of a production implementation ratio to determine the likely success of announced plants to achieve production, 2) assessing the near-term feedstock availability to supply the announced production plans, 3) evaluating the time required from announcement to production, and 4) estimating $CO_2$ abatement costs, including the impact of existing U.S. policy. Challenges of reaching SAF production goals by 2030 based on our analysis are presented.

## 2. Methods

Quantifying potential U.S. SAF production and the associated barriers including feedstock, production, and uptake was completed for six conversion technologies:(1) hydroprocessed esters and fatty acids (HEFA), (2) alcohol to jet (ATJ), (3) Fischer-Tröpsch (FT) with either biomass or $CO_2$ as the carbon source, (4) pyrolysis with biomass (process under consideration by ASTM), (5) catalytic hydrothermolysis (CH), and (6) co-processing lipids at a petroleum refinery. These processes were selected as they are the most frequently included in our database of SAF production announcements (section 2.1).

### 2.1. Announced production database

A database of publicly announced U.S. renewable fuel facilities with the potential to produce SAF or RD was compiled. Relevant production and technology information of the facility capabilities was collected over multiple years through internet searches, direct marketing announcements, internet key-word alerts, industry outreach, and verification with other databases. The database includes entries from the years 2000–2023 which was regularly updated as additional details and/or changes became available. No privately shared information is considered in this analysis. Facilities with production greater than 3.8 million liters per year (MLY) were categorized as: (1) built and operational, (2) under construction, (3) in development but not yet under construction, (4) built and shuttered, or (5) abandoned. Facilities are considered "verified" if they belong to category (1), (2), or (3) and "inactive" if they were categorized as (4) or (5). Evidence of inactivity includes bankruptcy, facility closure, a public statement indicating the project was abandoned, liquidating essential equipment/assets, and/or at least five years without public information updates.

Jet fuel and diesel have overlapping chemical compositions, so facilities producing RD can also produce SAF. Therefore, RD facilities are included in the production database with estimated potential SAF volumes. Each renewable fuel producer will decide how much SAF and RD to produce, mainly based on financial criteria, and it is unlikely that all RD facilities will choose to produce SAF [16,36,47–50]. To address this uncertainty, two scenarios were considered: (1) all technically feasible facilities for producing SAF, and (2) only biorefineries that have publicly stated an interest in SAF production.

SAF can also be produced by co-processing lipids sources at existing petroleum refineries. Lipids are limited to 5 % for refineries co-processing jet fuel if they are to comply with ASTM D1655 Annex A [51]. An ASTM task group is investigating increasing the current 5 % maximum co-processing rate to 30 %, but approval has not been issued at the time of this writing [52].

#### 2.1.1. Announced production volumes

The list of verified announcements includes only entries with: (a) stated fuel conversion technology, (b) nameplate production capacity, and (c) commercial operation date (COD). The most recent information was utilized when multiple CODs were found. Pilot and demonstration plants, as defined in their announcements or a scale of less than 3.8 MLY total production, were not included in calculations. For each announcement, two potential SAF production scenarios, labeled "baseline" and "high" were calculated because distillate cuts vary by conversion technology, equipment, catalyst type, and market strategies. The announced total distillate nameplate capacity was converted to estimate SAF production volumes using baseline or high distillate cut ratios. However, if the public announcement included a SAF-specific volume, that volume was used in both scenarios (Table 1).

The U.S. Energy Information Administration (EIA) reported that four refineries co-processed RD as of January 1, 2023 [53], producing 765 MLY of RD [53]. One of these refineries has since completed an expansion, increasing the industry production total to 1226 MLY [54]. Co-processing is included in the potential SAF volume using the historical values; however, no announced volumes were identified for future implementation.

SAF distillate fractions as a function of total distillate for the studied technologies were collected from literature (Table 1). HEFA is the most commercially advanced SAF production technology and has seen the greatest process refinement over time, especially with regard to distillate yield and cuts. As such, three industry partners were consulted to validate whether the literature values selected could reasonably be expected at an existing RD facility for the baseline and high scenarios. Likewise,

**Table 1**
Baseline and high scenario mass fraction SAF distillate cuts for each conversion technology.

| Conversion Technology | Baseline | High | References |
|---|---|---|---|
| HEFA | 0.4 (0.3–0.5)[a] | 0.80 (0.5–0.85)[a] | [55–57] |
| Co-processing | 0.1 | 0.1 | [58,59] |
| ATJ | 0.7 | 0.90 | [60–62] |
| FT-biomass | 0.4 | 0.73 | [63–65] |
| FT-$CO_2$ | 0.4 | 0.73 | [65] |
| CH | 0.48 | 0.48 | [66,67] |
| Pyrolysis | 0.44 | 0.52 | [64,68] |

[a] Range from industrial partners.

ATJ SAF cut selections were compared to industry values. For co-processing, the distillate cut in Table 1 was applied to the reported RD volume to estimate potential the SAF volume. Literature values without industry validation were used for the remaining four technologies.

#### 2.1.2. Implementation ratios

Not all commercial announcements lead to a successful construction and start-up [36]. Expected future values were estimated using a calculated "implementation ratio" for combined or individual technologies. The implementation ratio is defined as the fraction of announced facilities that achieved production, computed using the verified and inactive projects in the historical database following the process outlined in Fig. 1. Technology specific implementation ratios are used unless a conversion technology has less than ten verified announcements. The threshold of ten was chosen at a natural break in the verified counts and is also high enough to prevent the success or cancellation of a single facility from unduly influencing the implementation ratio. Thus, the combined implementation ratio was employed for FT-$CO_2$, pyrolysis, and CH pathways.

#### 2.1.3. Potential cumulative SAF volumes

When calculating potential SAF production values, announced nameplate volumes were adjusted to account for the historic implementation ratio and potential SAF distillate cut as outlined in Fig. 2. For each year, the cumulative SAF production volume is the sum of the previous year's volume and the current year's expected operational volume, adjusted by implementation ratios and distillate cuts.

Cumulative volumes over time using high and baseline SAF distillate cuts were estimated for the defined scenarios: prioritization of SAF (inclusion of all HEFA facilities), public interest (inclusion of announcement with publicly stated interest in SAF production). HEFA announcements that include both total distillate and SAF volumes were used to calculate an announced SAF distillate cut, which was used for comparison with the values in Table 1.

#### 2.1.4. Construction paradigms

Biorefineries can be designed and built using multiple construction paradigms. This work characterizes each entry as one of four paradigms: a greenfield facility built on bare land, an expansion of an existing facility, co-location with an existing facility, or conversion of an existing petroleum refinery into a biorefinery (Fig. 3). Project costs and timelines were compared using announcements sorted by construction paradigm.

#### 2.1.5. Announced project costs

Project costs are reported in the database for verified announcements when values are available. Project costs are most often found in press releases, however these do not explicitly state what the costs include (total capital investment, fixed capital investment, etc.). Even with the uncertainty in reported values, this data helps determine generalized trends for project costs.

The reported costs are normalized to dollars per liter of fuel and sorted by construction paradigm. Construction paradigms match company reporting. The scale of some expansions align well with greenfield. Reasons for this choice include a potentially streamlined permitting process and increased community acceptance.

#### 2.1.6. Project timelines

The time required to build a biorefinery and begin fuel production is influenced by construction logistics, technology maturity, permitting, and the time required to reach final investment decision (FID). FID can take years and may be delayed by changes in crude oil prices, the biofuel market, policy uncertainty, permitting, and feedstock cost inflation.

Permitting can have significant influence on project timelines. It occurs on municipality, city, county, state, and federal levels, and is commonly required before FID [69,70]. Rosales Calderon et al. (2024) identified permitting as a "substantial barrier" to increasing SAF

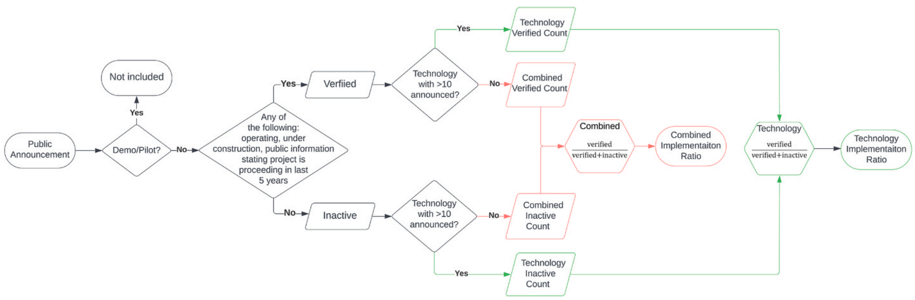


**Fig. 1.** Flow chart for estimating implementation ratio.

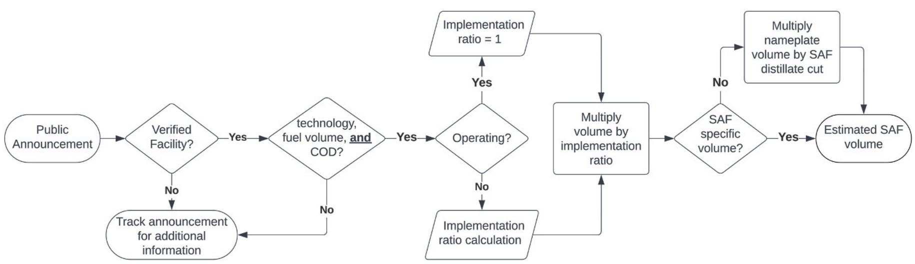


**Fig. 2.** Flow chart describing the method employed to estimate potential SAF volume.

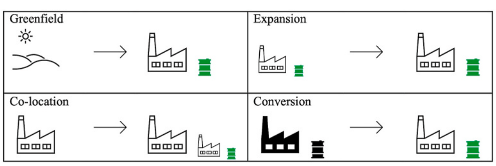


**Fig. 3.** Diagrams of generalized biorefinery construction paradigms.

production, with permit timing taking months or years from application submission. Timelines can extend when technology is new, public comment is extensive, the application needs revision, and/or as agencies are overwhelmed with applications. The average timeline to complete a National Environmental Protection Act environmental impact statement increased from 3.5 years in 2010 to 4.5 years in 2018, measured as the time between the notice of intent until the record of decision is issued, with time increasing each year by approximately one month [71,72].

Delays are a common challenge in industrial facility development, including SAF production facilities [73]. The average time between the first public announcement and the initial stated COD was calculated. Delays were then calculated as deviations from this timeline using updated or actual CODs.

### 2.2. Feedstock

Feedstock availability is a critical variable when assessing the potential production ramp of SAF. Volumes of lipid, ethanol, biomass, and gaseous carbon for SAF feedstock were estimated. Quantification of the feedstock available is the first step in determining whether specific feedstock can be used for SAF production. A detailed assessment would also include logistics requirements and cost limitations that are not in the scope of this work.

To evaluate U.S. lipid feedstock availability for biofuels, domestic lipids and biofuels production statistics, trade data, and published literature were collated. To date, the primary feedstocks for U.S. RD and biodiesel are fats, oils, and greases (FOGs), and vegetable oils [7,74]. Additional details are included in Supplementary Material 1.

FOGs are waste lipids that include used cooking oil (UCO), rendered animal fats, and distillers corn oil (DCO). UCO production is conventionally tied to regional eating habits and reported on a per capita basis [75–77]. UCO volumes were estimated by combining trade data and reported consumption from renewable fuel production [74,78]. Animal fats, including beef tallow, choice white grease, and poultry fat were estimated using herd, slaughter, consumption, and trade data [78–83]. DCO, a byproduct of dry milling corn, is not intended for human consumption. Reporting of corn oil is not consistently categorized as edible or inedible. DCO supply surpasses the corn oil consumption for biofuels, thus this study assumes that biofuels use DCO, not edible corn oil.

Vegetable oil use is reported separately for RD and biodiesel fuels, but disaggregated FOGs data are not provided [74,84]. To parse out biodiesel and RD FOGs consumption, state and federal government data were combined with private data [85–89]. RD and biodiesel vegetable oil and FOGs consumption was estimated for 2018 through 2023 using the methodologies detailed in Supplementary Material 1.

The volume of ethanol for ATJ, biomass for FT or pyrolysis and gaseous carbon for FT were taken from literature [7]. The published values were compared with the required mass needed to meet the demands from announced SAF production.

### 2.3. Abatement costs

The relative economic viability of each SAF pathway was quantified using minimum selling price (MSP) and abatement cost. Abatement cost, defined in Equation (1), is the cost of each unit of avoided emissions in $/t$CO_2$e. Abatement costs can be covered by government programs, fuel purchasers, and/or companies looking to reduce their environmental impact.

$$Abatement\ Cost = \frac{MSP_{SAF} - Jet\ A\ Price}{CI_{jet\ A} - CI_{SAF}} \qquad \text{Equation 1}$$

#### 2.3.1. Minimum Selling Price (MSP) of Fuels

Harmonized, open-sourced techno-economic analysis (TEA) models were used to estimate MSP [63,66,68,90,91] for SAF produced using different technologies. Two assumed weighted-average rates of return, denoted “rates of return” in this paper, were used in this analysis to allow comparisons with academic literature (10 %) and represent the return needed for investment (20 %) [92]. The TEA methodology is detailed elsewhere [93,94] and in Supplementary Material 2. MSP values that assume mature processes that have been proven and replicated commercially, denoted nth plant, are included for all pathways. However, many SAF production technologies are largely unproven, making pioneer costs more relevant for technologies other than HEFA and co-processing [16]. Pioneer MSPs are higher as a result of greater capital costs per unit of production, lower initial productivity, and smaller facility scale. As each technology is proven in commercial applications, costs will transition from pioneer to nth plant values.

MSP for co-processed SAF was not found in public documentation. Refinery details vary greatly, affecting the viability and cost of co-processing, making MSP estimates difficult. This work estimated co-processed SAF MSP by reducing HEFA operating costs, except for feedstock, hydrogen, and catalysts, by 45 % [95]. In addition, little to no capital costs are expected for this conversion technology [96–98]. Talmadge et al., 2021 investigated the cost of co-processing pyrolysis oil and reported capital costs for a 5 % co-processing rate, which were adapted for facility scale in this work. This was assumed to be a low-cost option as [99] did not include capital costs for feedstock pre-treatment nor infrastructure to receive feedstock. The capital cost for this scenario corresponds to 3 % of a greenfield biorefinery. Refinery needs will vary; thus, an assumed value of 25 % was evaluated as a higher-cost option. The difference in estimated SAF MSP between these options is less than 2 %, so the [99] value was used in the abatement cost calculations.

#### 2.3.2. Carbon intensity

The “default life cycle emissions values” from the International Civil Aviation Organization (ICAO), which include ILUC, were used to calculate generalized abatement costs [100] (Table 2). FT-$CO_2$, CH, and pyrolysis do not have ICAO values, so literature values were applied [101–103]. It is important to note that companies with lower CI processes, including crop-based feedstocks grown with non-standard practices, can choose to use actual values.

### 2.4. U S. Policy

In the U.S., abatement costs are addressed with government-supported incentives legislated at the state and federal levels. This work focuses on the effectiveness of three such legislative policies: the Renewable Fuel Standard (RFS), the Clean Fuel Production Credit, denoted 45Z, included in the Inflation Reduction Act (IRA) and revised in the One Big Beautiful Bill Act (OBBBA), and California’s Low Carbon Fuel Standard (LCFS) (Table 3). California’s LCFS was selected over similar policies in Oregon and Washington as it issues more credits [106]. State policy legislation has also passed in Minnesota, Illinois, and Nebraska, each with details that limit the value to a fuel producer [107–109].

The ASCENT U.S. Policy Applicability and Value Estimation Tool, a spreadsheet-based tool, was used to determine policy applicability and to estimate the value of existing U.S. policies [106]. Market-based incentive values were estimated as the mean values from 2019 through 2023. The number of LCFS credits was calculated by comparing the fuel CI to the 2025 target CI.

**Table 2**
CI, $gCO_2e/MJ$, for fuel production pathways from Ref. [100] unless otherwise cited. Total values in parenthesis are alternate CI values accepted by the U.S. government [104].

| Conversion Pathway | Core LCA Value | ILUC | Total |
|---|---|---|---|
| Petroleum Jet A | | | 89 |
| HEFA (UCO) | 13.9 | 0 | 13.9 |
| HEFA (soybean oil) | 40.4 | 24.5 | 64.9 |
| Co-Processing (UCO) | 16.7 | 0 | 16.7 |
| Co-Processing (soybean oil) | 40.7 | 24.5 | 65.2 (44.5) |
| ATJ (corn ethanol) | 65.7 | 25.1 | 90.8 |
| ATJ (sugarcane) | 24.1 | 8.5 | 32.6 |
| FT-biomass (forest residues) | 8.3 | 0 | 8.3 |
| FT-$CO_2$ (wind) | 11 [105] | 0 | 11 |
| CH (UCO) | 18.4 [102] | 0 | 18.4 |
| CH (soybean oil) | 28.2 [102] | 24.5 | 52.7 |
| Pyrolysis (forest residues) | 26.0 [103] | 0 | 26.0 |

## 3. Results and discussion

A set of analyses were conducted on the announced SAF production database. These include quantification of implementation ratios, potential production volume, the time and capital required to build facilities, and the delays that should be expected. Potential volumes are compared to feedstock availability to determine the practical viability of reaching the SAF volumes for the 2030 goal. This section also quantifies SAF MSP, conversion technology abatement costs and the effectiveness of U.S. policy to cover those costs. Barriers to meeting the 2030 goal are identified so that they can be addressed in support of the developing U.S. SAF industry.

### 3.1. Potential production volume

Data presented in this section includes calculated implementation ratios, potential SAF production volumes, construction paradigms, announced project costs, and project timelines.

#### 3.1.1. Implementation ratio

Using the historic and verified commercial scale project counts, technology-specific implementation ratios were calculated for HEFA, ATJ, and FT-biomass (Table 4). The combined value of 0.5 was applied to all other technologies.

The evolution of implementation ratios can be represented in a progressive curve by plotting against facility count with successive announcements (Fig. 4). Successful conversion technologies will have an increasing trend in the implementation ratio after initial low values early in technology development. Announcements made in or after 2020 are represented with a dashed line, as these facilities still have an uncertain status and thus this section of the curve is more likely shift.

HEFA has the longest history of verified announcements, and the implementation ratio evolution follows the expected transitions from a lower to higher values. The initial shape of the ATJ implementation ratio curve is similar to HEFA, with a sharp upward trend at six facilities. This trend may be a result of insufficient time after the ATJ announcements to determine if projects proceed. Additional time is needed to see if follows trends similar to HEFA.

Using data frozen at the end of 2023, the FT-biomass curve follows the ATJ curve until the 6th facility, where FT-biomass continues to fall before leveling out. A second FT-biomass curve is shown for data updated in the third quarter of 2024. This includes a bankruptcy and closure, which impacted the implementation ratio. This shift demonstrates the volatility of this value during technology maturation. The plotted implementation ratio values are approximations based on current data and will continue to change over time as both the SAF industry and individual technologies develop.

#### 3.1.2. Production volume

Fig. 5 shows the potential SAF volumes over time for the baseline and high SAF cut scenarios. For the baseline scenario, the potential SAF volume curve flattens out after 2027, 0.2-billion liters short of the U.S. 2030 target. This plateau could be due to production announcements with a COD beyond 2027 not yet released to the public or facilities might be paused in construction from policy, feedstock and/or fuel demand uncertainty. The high SAF cut scenario, however, meets the target in 2024. It should be noted that achieving these volumes depends on facilities continuing to operate at full capacity, new facilities starting up on-schedule, and RD facilities maximizing SAF production instead of only RD.

**Table 3**
Details of selected U.S. policies.

| Policy | RFS | 45Z | LCFS |
|---|---|---|---|
| Jurisdiction | Federal | Federal | California |
| Scope | Production of biogenic renewable fuels for road transportation | US production of clean transportation fuel. Non-biomass-based fuels are eligible | Decarbonization of road transportation. Non-biomass-based fuels are eligible |
| Duration | 2005-No expiration year | 2025–2029 | 2009-No expiration date |
| Unit | Renewable identification number (RIN) issued for each gallon ethanol equivalent produced (1.6 RINs per gallon SAF, 1.7 RINs per gallon RD)<br>Fuel pathways determine which of the four RIN classification applies | Gallon of fuel produced | Credit issued per t $CO_2e$ not emitted below the annual state target |
| Compensation | Market value, different value for each RIN classification<br>D3/D7: cellulosic biofuel<br>D4: biomass-based diesel<br>D5: advanced biofuels<br>D6: renewable fuel | $0-$1, starting at 50 kg$CO_2e$/MMBtu linearly to 0 kg $CO_2e$/MMBtu for fuels that legislated requirements | Market value |
| CI requirement | Threshold for each RIN classification<br>D3/D7: 60 % reduction<br>D4: 50 % reduction<br>D5: 50 % reduction<br>D6: 20 % reduction | Below 50 kg $CO_2e$/MMBtu | Below annual target |
| CI methodology | U.S. Environmental Protection Agency (EPA), Indirect emissions factors based on the Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB) | Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)<br>Analysis for this work assumes GREET and EPA acceptable following precedent set by the ruling for Sustainable Aviation Fuel Credit (40B). Empirical carbon flux emission factors from the Agro-ecological Zone Emission Factor (AEZ-EF), does not include land use change | CA GREET3.0 Empirical carbon flux emission factors from the Agro-ecological Zone Emission Factor (AEZ-EF) |
| CI used in analysis | Threshold from applicable RIN designation | Lowest from CORSIA, EPA, GREET | Median reported value |
| References | [23,110–115] | [31,100,111,116,117] | [28,86,114,118,119] |

**Table 4**
Historical and verified commercial scale project count and estimated implementation ratios by SAF conversion technology.

| Conversion Technology | Historical Count | Verified Count | Implementation Ratio |
|---|---|---|---|
| Combined | 144 | 70 | 0.5 |
| HEFA | 59 | 40 | 0.7 |
| ATJ | 18 | 11 | 0.6 |
| FT-biomass | 39 | 11 | 0.3 |
| FT-$CO_2$ | 3 | 3 | 0.5[a] |
| Pyrolysis | 5 | 1 | 0.5[a] |
| CH | 4 | 2 | 0.5[a] |
| Other/Not Indicated | 19 | 2 | 0.5[a] |

[a] Values are the combined implementation ratio.

The potential HEFA SAF volume in 2023 is approximately 92 % of the total baseline scenario and 96 % of the total high scenario with nearly all of the remaining SAF from co-processing. By 2030, HEFA's contribution drops to 77 % for the baseline scenario and 82 % for the high scenario. HEFA's dominance is a result of technology that is considered mature as demonstrated by a relatively high implementation ratio and larger facility scales compared to developing technologies. These market shares will change if and when other technologies mature, but are unlikely to shift appreciatively by 2030.

The subset of public announcements that express interest in SAF production were compared to the assumption that all facilities will produce SAF for both the baseline and high scenarios, split into HEFA production and production from all other technologies (Fig. 6). The larger number of HEFA facilities in the data set allowed for the calculation of announced SAF cuts to confirm distillate assumptions. The range is 15–50 %, with a mean of 34 %, confirming the range encompasses the baseline scenario.

For comparison, actual and projected EIA values and the U.S. 2030 SAF goal are included in Fig. 6 [120]. The EIA values are similar to the baseline SAF cut for facilities with announced SAF interest for 2023. However, by 2024–2025 the EIA values are lower. This scenario reaches 7.8 billion liters by 2030, two-thirds of the 2030 U S. goal. The 2030 SkyNRG projection is slightly less optimistic at 7.2 billion liters per year (BLY), a decrease from the previous 2030 prediction of 8.3 BLY [73,121]. Potential changes to implementation ratios for FT-biomass and ATJ may alter the total volume. Although the 2030 U S. goal is attainable it will require a combination of high SAF distillate cuts, participation from facilities that have not expressed interest in SAF and no negative changes to currently operating facilities throughput or SAF intentions. The baseline SAF is the most likely scenario, and it identifies a shortfall in potential SAF production compared to the 2030 goal.

#### 3.1.3. Construction paradigms

Greenfield construction accounts for well over half of the verified production database entries, followed by conversion and expansion at 31 % (Fig. 7A). Co-location has the fewest entries and includes the addition of HEFA production to existing petroleum refineries or corn ethanol facilities or ATJ to be constructed at existing ethanol facilities. When production volume is considered instead of facility count, greenfield and conversion still accounts for 80 % (Fig. 7B). This is likely a result of expansions that are more akin to greenfield facilities built where demonstration or pilot facilities were originally located.

#### 3.1.4. Project costs

One barrier to increasing SAF production is the difficulty in securing funding for commercial-scale facilities due to high capital investment requirements. Although project costs vary significantly, generalized trends can be identified. Fig. 8 shows that public announcements of project costs are generally lower and less variable for the conversion of existing petroleum refineries compared to greenfield construction. Project costs for expansion overlap with greenfield; however, the scale for expansion does not reach that of conversion or greenfield. Expansion project costs include facilities much larger than the original scale and thus costs may mimic greenfield.

#### 3.1.5. Project timelines

Fig. 9 shows the mean time between a facility announcement and

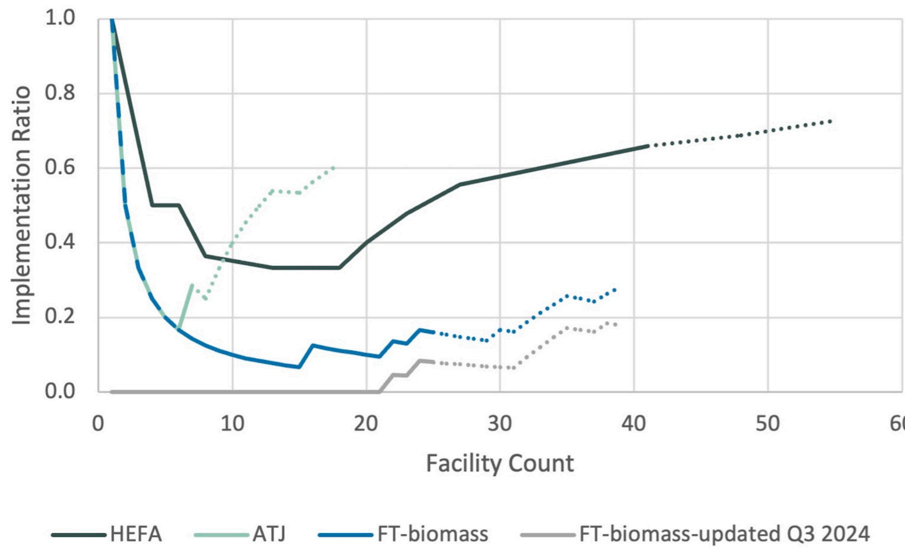


**Fig. 4.** Evolution of SAF technology implementation ratios versus U.S. facility count, added in chronological order. Dashed lines correspond to announcements made in or after 2020.

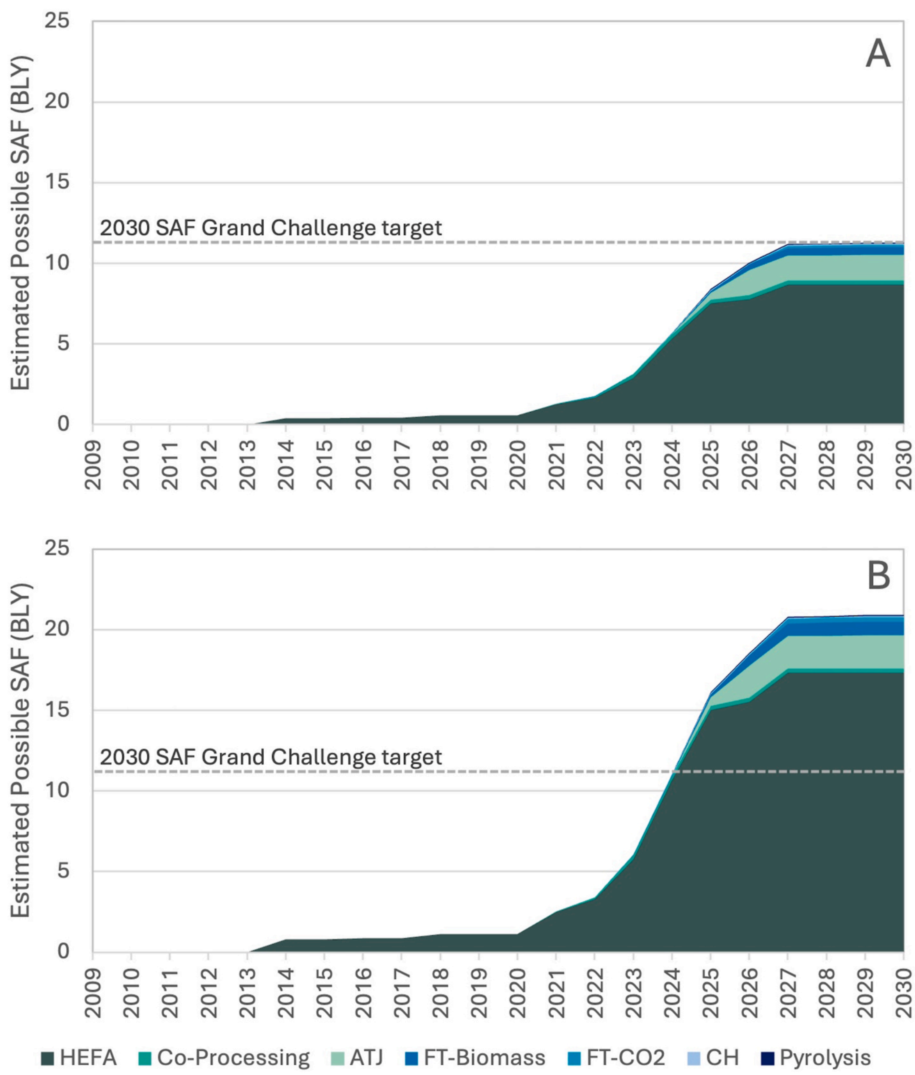


**Fig. 5.** Expected SAF production through 2030 for two scenarios. A is for the baseline SAF distillate cuts and B is for the high SAF distillate cuts found in Table 1.

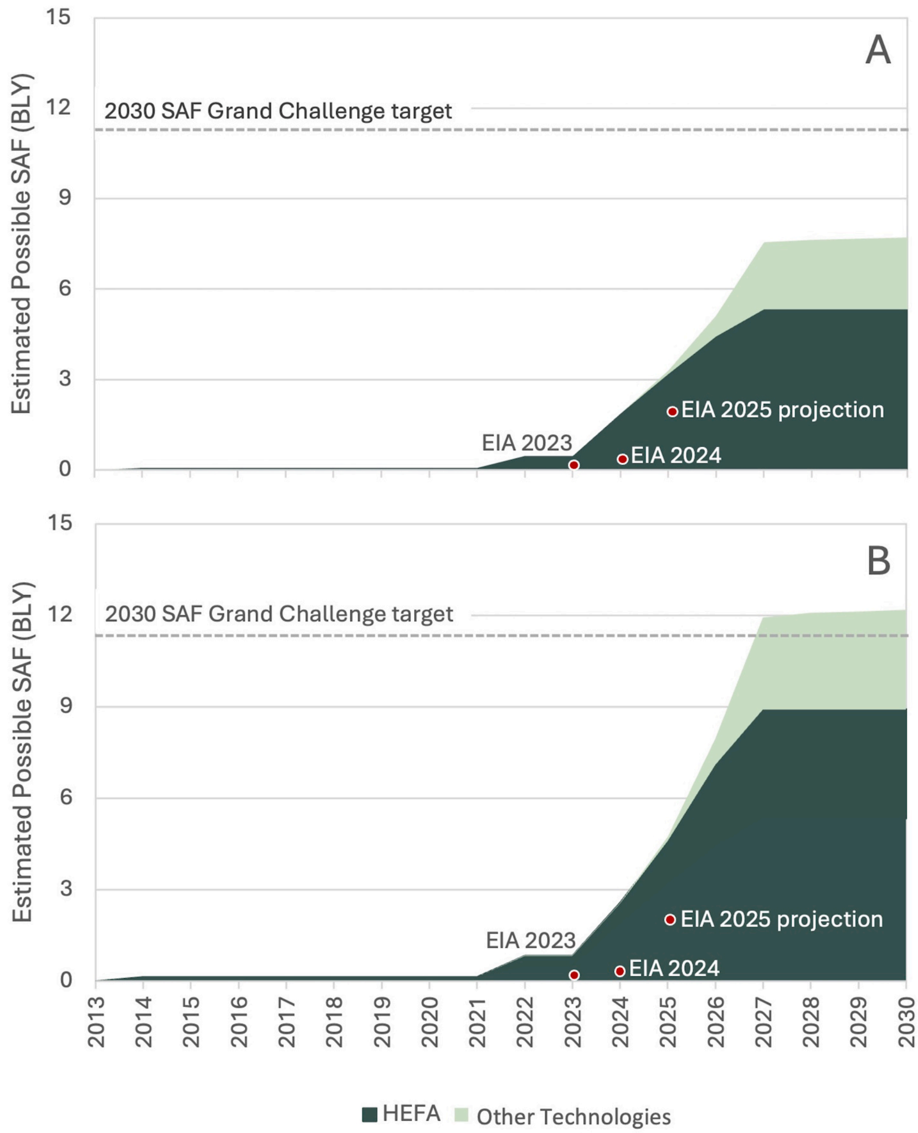


**Fig. 6.** Potential SAF volumes for active announcements that specifically include SAF for two scenarios. A is for the baseline SAF distillate cuts and B is for the high SAF distillate cuts found in Table 1.

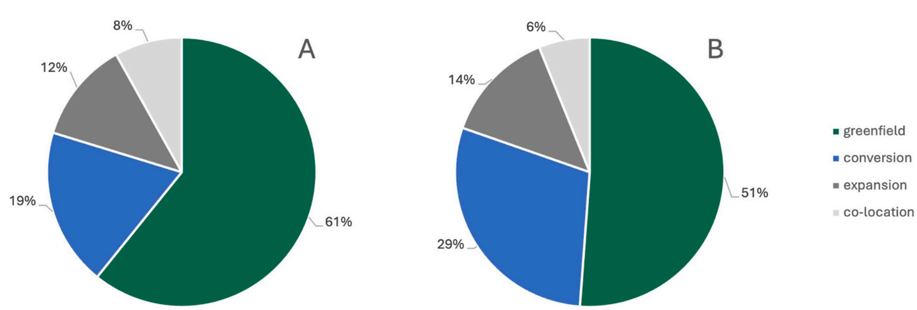


**Fig. 7.** Percent of verified announcements for each construction paradigm by (A) count and (B) volume.

COD for each conversion technology, along with mean start-up deviations. For FT-$CO_2$, CH, and pyrolysis, there are fewer than 5 data points, making the data less reliable. HEFA and FT-$CO_2$ have the shortest mean time between announcement and COD, both under 4 years. HEFA data includes operational facilities, with a mean time from announcement to COD of 3.1-years with a 0.7-year delay. In contrast, FT-$CO_2$ data is limited, with few announcements and no operational facilities. The recent nature of these announcements could also imply that delays have yet to occur or to be communicated. Delay data ranged from zero to ten years, with an overall average of 1.6 years. HEFA facility conversions have a slightly shorter mean delay of 0.9-years compared to a greenfield delay of 1.2-years. Companies that publicly discuss delays cite reasons like permitting, financing, delays in FID, feedstock uncertainty, market uncertainty, and company restructuring/sale. With 2030 rapidly

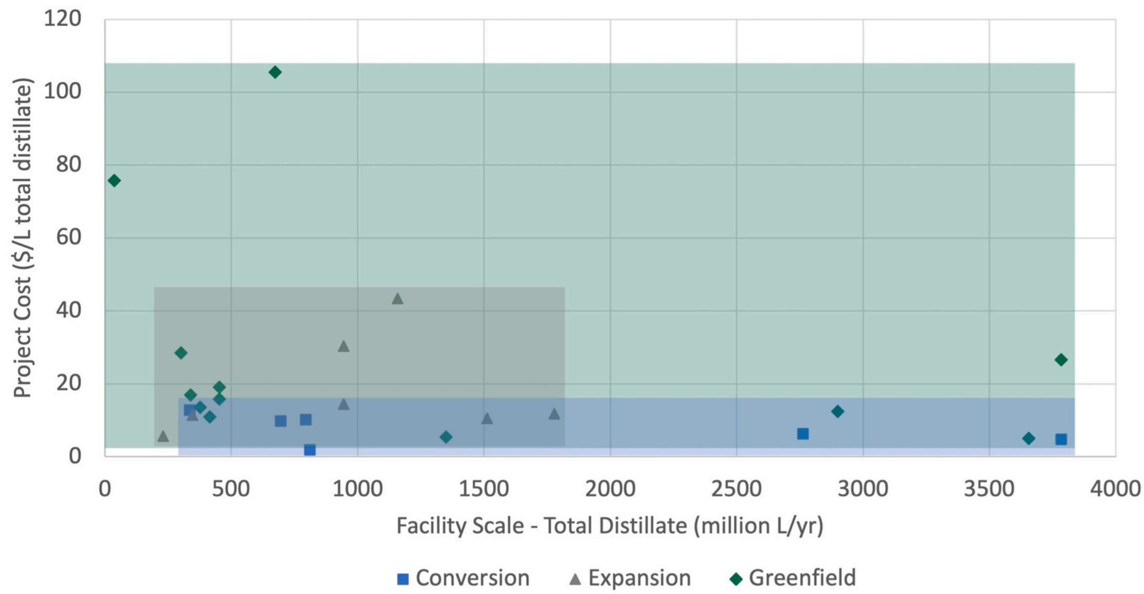


**Fig. 8.** Normalized project costs by construction paradigm. Data includes costs for both mature and pioneer facilities.

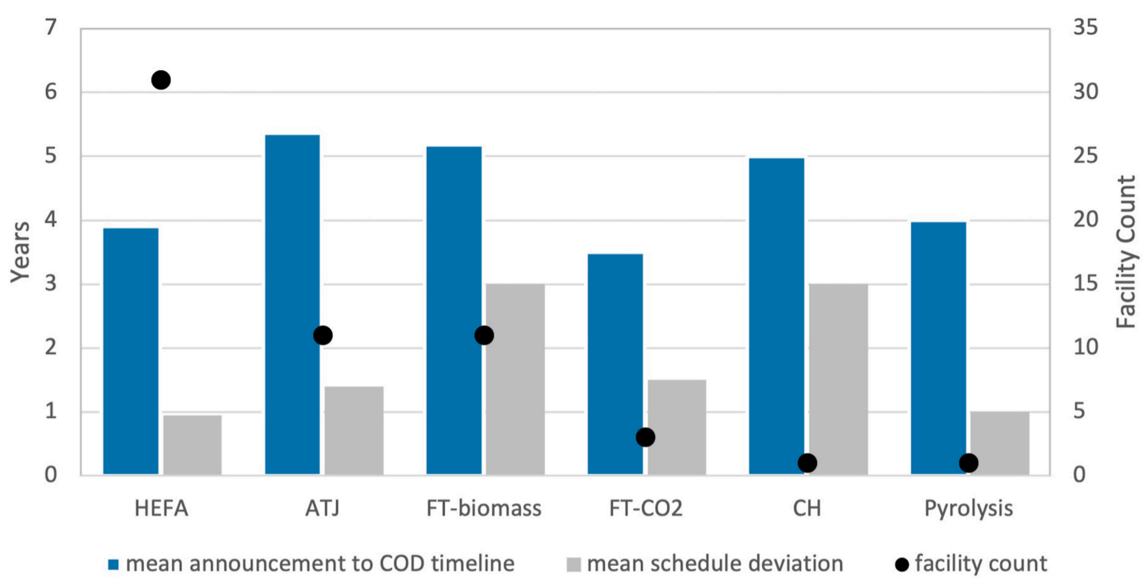


**Fig. 9.** Mean timeline in years from first announcement until COD or announced COD slated to begin, mean timeline deviation, and the count of facilities for each conversion technology.

approaching, the collated data suggest most of the volume to meet the near-term target will come from already announced facilities.

### 3.2. *Feedstock*

Feedstock data for each conversion technology were compiled and compared to demand based on potential production volumes, with a focus on lipids. HEFA uses lipid feedstocks and is the dominant technology in both count and scale in the database. In addition, co-processing utilizes lipid feedstocks and has the potential to produce a notable volume of SAF.

The lipid supply and consumption from both domestic and imported sources for 2022 is summarized in Table 5. Types of FOGs and vegetable oils are listed separately for clarity. Individual volumes are rounded, as a result the sum of columns and rows may not match delineated values. It is interesting to note that the total 2022 lipid consumption for biofuels (10.2 million t) is within 1 % of the values in the 2023 Billion Ton Report (10.1 million t) [7].

In 2022, 10.2 million tons of lipids were used for biofuels, with approximately half allocated to RD and half to biodiesel. The RD industry expanded in 2023 consuming an additional 3.8 million t/year of lipid, shifting the split to one-third to biodiesel and two-thirds to RD (Fig. 10). Some of this feedstock shift could be the result of the contraction in biodiesel production, following the 11 % reduction from 2018 through 2022 [18]. The 2030 projected HEFA production will require 14.2 million t/year of lipid feedstocks [91]. Even with a drop in biodiesel production, it is unlikely that a significant portion of existing facilities and supply chains will halt operation and switch to HEFA production by 2030. Further, the 10.2 million t of lipids that used for biofuels is still 4 million t/year short of the projected demand. Meeting that demand from biodiesel feedstock is not a realistic solution to the expected lipid shortfall.

Animal fats provide a small fraction of slaughter revenue, making substantial growth unlikely as a result of increase biofuel demand [79,

**Table 5**
2022 U S. lipid production, import, consumption and export volumes (million t) [7,78–83,88,122].

| | Supply | | | Consumption | | |
|---|---|---|---|---|---|---|
| Feedstock | Production | Imports | Total | Biofuels | Other | Exports |
| Vegetable Oils (no corn oil) | | | | | | |
| Soybean | 11.9 | 0.2 | 12.1 | 4.8 | 6.7 | 0.6 |
| Canola | 0.8 | 4.0 | 4.9 | 0.6 | 4.3 | 0.0 |
| Other | 0.5 | 3.4 | 3.8 | 0.0 | 3.7 | 0.1 |
| **Total** | **16.0** | **7.7** | **23.6** | **6.7** | **16.0** | **0.9** |
| Corn Oil | | | | | | |
| **Total**[a] | **2.8** | **0.1** | **2.8** | **1.5***| **1.1** | **0.2** |
| FOGs | | | | | | |
| Tallow | 2.8 | 0.6 | 3.4 | 0.9 | 2.1 | 0.3 |
| Choice White Grease | 0.8 | 0.1 | 0.8 | 0.3 | 0.5 | 0.0 |
| Poultry Fat | 0.9 | 0.0 | 0.9 | 0.1 | 0.8 | 0.0 |
| UCO | 2.2 | 0.4 | 2.6 | 2.3 | 0.0 | 0.4 |
| **Total** | **6.7** | **1.0** | **7.7** | **3.5** | **3.4** | **0.8** |
| All Lipids | | | | | | |
| **Total** | **22.7** | **8.7** | **31.4** | **10.2** | **19.5** | **1.6** |

[a] Values include both edible corn oil and DCO. Details are only available for production of corn oil with 0.8 million t of edible corn oil and 1.9 million t DCO. This work assumes that the 1.5 million t used biofuel production is DCO.

123–127]. DCO production is expected to remain stable as ethanol production stays steady over the next ten years [128]. However, vegetable oil supply can increase with biofuel demand. In fact, it is predicted that the soybean crop will have an annual growth rate of 1.2 % over the next decade [129]. However, supply changes may be limited by demand for the protein meal that is an important co-product of oilseed crushing and used primarily in livestock feed. The value of soybean and canola meal is crucial for financial success, making up 63 % and 32 % of total revenue, respectively [88,130].

To achieve the projected fuel production, lipid feedstocks need to increase by an estimated 54 %, which will require a combination of imports, additional domestic production, and/or changes in current lipid allocation. To date, feedstock imports have been the area of greatest growth (Fig. 11). However, with uncertain tariff scenarios as well as new and potential changes that limit government support of imported feedstocks, the cost of importing feedstock may prohibit this as an economically viable solution [117,131]. Adjusting feedstock allocation for the biodiesel production decline and increased domestic soybean production may be able to cover a portion of the needed feedstock growth by 2030. However, with the limited time to meet this demand, the industry will likely depend heavily on imports. During 2018 through 2021, most UCO imports came from Canada. Imports from Australia and Brazil began contributing to the U.S. supply in 2022 and by 2023, UCO imports from China increased, accounting for 31 % of total imported FOGs [78]. While China's supply presents a significant opportunity as a UCO source, accusations of fraud involving cutting the UCO with palm oil have led to an EPA investigation [132]. In addition [133], assessed six leading Asian UCO exporters to estimate the potential for increasing UCO exports. In 2019, the total potential volume increase from Asian nations, including China, for global use was 1.5–2.5 million t/year. The potential unused UCO volume is well short of demand. Second crop oilseeds are another potential source of feedstock. The Billion Ton Report estimates that potentially 9.5 million t/yr of lipids could be

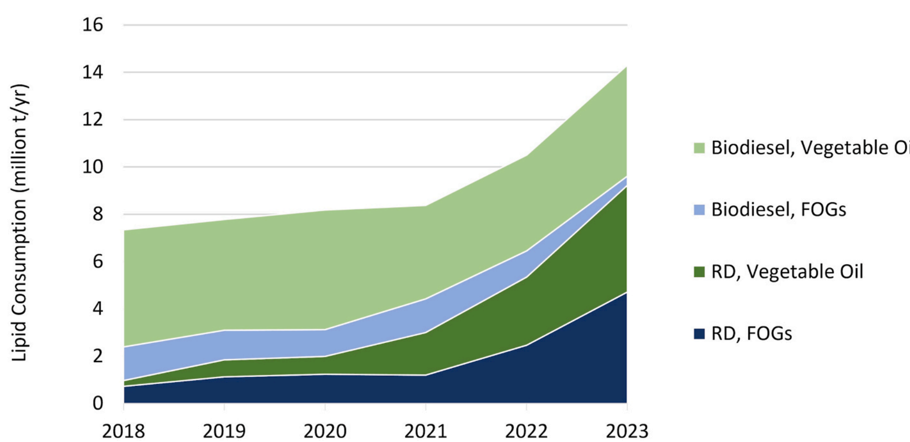


**Fig. 10.** Feedstock category used for domestic production of biodiesel and RD.

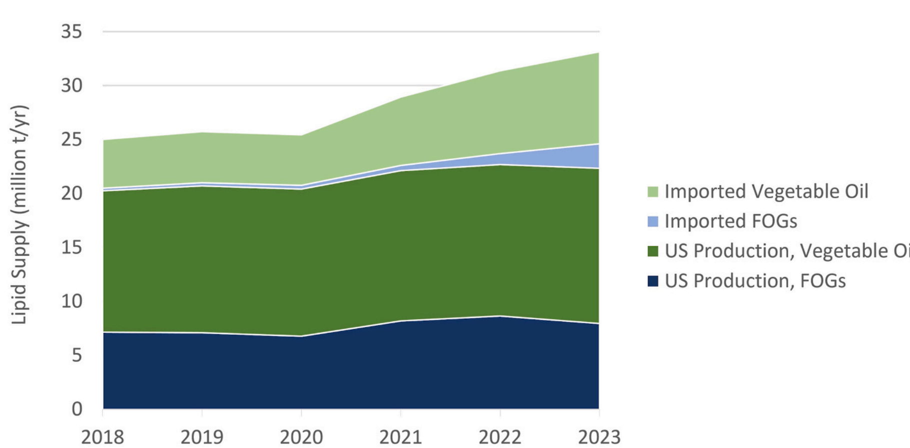


**Fig. 11.** Total U.S. lipids market, divided into U.S. production and imports for vegetable oils and FOGs.

available when the market is mature (modeled as the year 2041) [7]. However, developing second crop oilseed industry will require additional research and outreach to growers to overcome barriers such as the lack of crop insurance, market uncertainty, unknown best practices for growth in coordination with existing crops, equipment availability, and overcoming reluctance from past failures [134–138]. Growth in co-processing and possible maturation of the CH conversion technology will further stress the lipid supply. In summary, there is not a clear, realistic pathway to expand low-CI lipid feedstocks to meet the current production estimates.

The estimated SAF volume from ATJ announcements represents the second-largest projections after HEFA and co-processing. While this pathway can utilize various feedstocks, ethanol is a prominent option. In 2022, U.S. ethanol production was between 54.5 and 58.3 billion liters [7]. Not all of this ethanol will meet the required 50 % reduction in CI, but with process changes at ethanol production facilities as well as climate-smart agricultural practices, this feedstock could be a competitive option [139,140].

If calculated ATJ SAF volume were derived from ethanol, this demand would account for 5 % of the total 2022 U S. production. Even if ATJ production increases significantly, it is unlikely that ethanol availability will limit this pathway by 2030. However, demand for low CI ethanol may encourage producers to import sugarcane-based ethanol, particularly if U.S. corn farmers and/or corn ethanol producers do not make changes to meet the 50 % GHG reduction target, as demonstrated by the LanzaJet Freedom Pines ATJ facility [141].

The potential SAF volume and required feedstocks for FT-biomass, pyrolysis and FT-$CO_2$ are low. Public announcements show that neither biomass nor gaseous carbon will provide large SAF fuel volumes by 2030. The combined biomass feedstock requirements for FT-biomass and pyrolysis to meet the estimated SAF production volumes in 2030 is 9.3 million t/year, and FT-$CO_2$ will need only 4.4 million t/year [63,68]. The required biomass volume is well below the near-term estimates for "potential forestland resources" (28 million t) or "potential agricultural land resources" (127 million t) [7]. The expected gaseous carbon demand of 4.4 million t is 10 % of the 43 million t of low-cost point source $CO_2$ available, without the need utilize more expensive direct air capture (DAC) $CO_2$ [7].

### 3.3. Abatement costs

SAF MSP values were estimated for nth and pioneer facilities and two rates of return (Table 6). The MSP values calculated using the higher rate of return likely reflect with the return needed to mitigate the risk of new technology. Therefore, using the pioneer MSP at a 20 % rate of return is suggested for all but the HEFA estimates. The SAF MSP values listed in Table 6 could change as a result of emerging trade issues, including tariffs. Trade uncertainty increases financial risk, resulting in higher prices. Prices increase to offset increased costs of feedstock and equipment from policies like tariffs and/or from indirect impacts such as hedging against potential future changes. If, for example, a feedstock price increase of 25 % is analyzed for HEFA (soybeans), a pathway highly reliant on feedstock price, the SAF MSP increases 19 %. If the feedstock analyzed is UCO, the SAF MSP rises by 21 %. However, if trade issues instead escalate TCI by 10 % the SAF MSP for HEFA (soybeans), HEFA (UCO), and ATJ (corn ethanol) all increase by a modest 1 %. However, if a more capital-intense pathway like FT (forest residues) incurs a 10 % increase in TCI, the SAF MSP grows by 4 %.

**Table 6**
SAF MSP ($/L) for nth and pioneer plants assuming a 10 % or 20 % rate of return. Bolded values correspond to current technology maturity.

| Conversion Pathway | 10 % rate of return | | 20 % rate of return | |
|---|---|---|---|---|
| | nth | pioneer | nth | pioneer |
| Petroleum Jet A[a] | **0.5** | | | |
| HEFA (UCO) | **1.0** | – | **1.0** | – |
| HEFA (soybean oil) | **1.2** | – | **1.2** | – |
| ATJ (corn ethanol) | 0.7 | **0.8** | 0.7 | **0.9** |
| ATJ (sugarcane) | 0.7 | **0.9** | 0.7 | **1.0** |
| FT (forest residues) | 2.0 | **3.5** | 2.2 | **3.9** |
| FT ($CO_2$) | 3.6 | **4.1** | 3.8 | **4.3** |
| CH (UCO) | 1.2 | **1.4** | 1.2 | **1.4** |
| CH (soybean oil) | 1.6 | **1.8** | 1.6 | **1.8** |
| Pyrolysis (forest residues) | 1.6 | **2.3** | 1.7 | **2.6** |
| Co-processing (UCO) | **0.8** | – | **0.9** | – |

[a] 2021 EIA wholesale price, does not correspond to the discount rates or plant maturity.

Table 7 presents abatement costs based on the respective MSP values, the average 2021 wholesale petroleum jet fuel price, and the CI values from Table 2 [142]. FT-forest residues and FT-$CO_2$ are the lowest CI options. However, their corresponding MSPs cannot be overcome by CI alone, resulting in the highest abatement costs of $1070 and $1330/t $CO_2$, respectively. Superior options are represented by co-processing with UCO ($140/t $CO_2$), HEFA with UCO ($180/t $CO_2$), ATJ with sugarcane ethanol ($210/t $CO_2$), and CH with UCO ($350/t $CO_2$) (Table 7). Comparisons to available literature data adapted to a 2021 cost year, without harmonization for other economic and process assumptions, overlap many of the presented values. The literature abatement cost for co-processing is much higher than the value from this paper, likely as a result of the authors using miscanthus bio-oil as feedstock. The ATJ literature values are much higher for ATJ with sugarcane, this could be from location-specific carbon intensity values and disparate economic assumptions. If the MSP for a given pathway decreases with technology maturation, the abatement cost will change following the curves in Fig. 12. Addressing both the MSP and CI is critical to minimize abatement costs and maximize the environmental benefit per dollar spent.

### 3.4. U S. Policy

Stacking state and federal incentives helps cover abatement costs, but policies often fail to close the price gap. The monetary value of market-based policies can vary widely over time; thus, minimum, maximum, and median values are presented for 2019–2023, converted into $/t $CO_2e$ (Table 8). The variability of RIN and LCFS credit prices is apparent in Table 8 through the reported max and min values. The RFS was not designed to focus solely on fuel CI reduction; however, it has the highest median abatement values due to strong market values, relatively low CI reduction thresholds, and the 1.6 equivalence value used for SAF.

**Table 7**
SAF abatement costs ($/t$CO_2e$) for nth and pioneer plants assuming a 10 % or 20 % rate of return. Bolded values correspond to current technology maturity. Literature values were adapted to 2021 cost year.

| Pathway | 10 % rate of return | | 20 % rate of return | | Literature Values |
|---|---|---|---|---|---|
| | nth | pioneer | nth | pioneer | nth |
| HEFA (UCO) | **180** | – | **190** | – | 160-430 [45, 143–145] |
| HEFA (soybean oil) | **470** | – | **480** | – | 710-1530 [45, 143–145] |
| ATJ (sugarcane) | 110 | **210** | 120 | **230** | 500-520 [45,143, 144] |
| FT (forest residues) | 540 | **1070** | 600 | **1230** | 250-640 [45, 143–146] |
| FT ($CO_2$) | 1170 | **1330** | 1210 | **1390** | 1430-1740 [45, 145] |
| CH (UCO) | 270 | **350** | 290 | **380** | 206[a] [147] |
| CH (soybean oil) | 870 | **1000** | 900 | **1060** | |
| Pyrolysis (forest residues) | 490 | **850** | 550 | **970** | 460 [45] |
| Co-processing (UCO) | **140** | – | **140** | – | 470-480[b] [148] |

[a] Literature CH abatement cost for carinata oil.
[b] Literature value for co-processing is for miscanthus bio-oil as a feedstock.

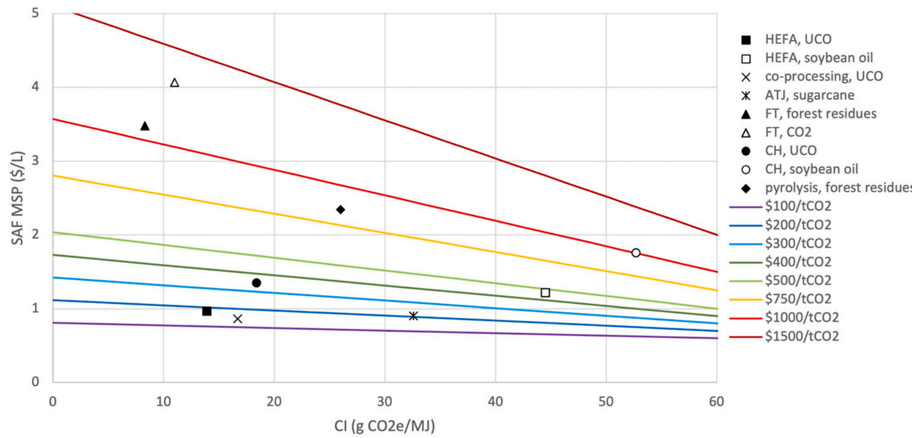


**Fig. 12.** Abatement cost curves for various CI scores over a range of MSP values with SAF pathways plotted. Plotted pathways are for current technology maturity (nth for HEFA and co-processing, pioneer for all others).

**Table 8**
Estimated U.S. federal and state policy support values.

| Policy | | Value (\$/t $CO_2$e) median (min, max) | Reference |
|---|---|---|---|
| RFS | D3/D7 | 360 (68, 519) | [149] |
| | D4 | 233 (39, 523) | |
| | D5 | 244 (18, 523) | |
| | D6 | 476 (4, 854) | |
| IRA/OBBBA | 40B[a] | 220–156 | [31] |
| | 45Z[b] | 16–84 | |
| LCFS, CA[c] | | 185 (70, 206) | [150] |

[a] 40B range reported is for fuels with 50 %–100 % GHG reduction, two-year duration that expired at the end of 2024, values assume that wage and labor requirements are met.
[b] 45Z range reported if for fuels with CI reduction of 49–81 g$CO_2$e/MJ, applicable 2025–2029, inflation adjusted, values assume that wage and labor requirements are met.
[c] LCFS ruling from November 2024 limits RD support to fuels with company average virgin oil consumption to 20 % or less of total feedstock use [151].

The D3/D7 RIN designation provides the most support on a volume basis, while the 20 % reduction needed to earn a D6 RIN provides this RIN category the highest abatement cost support. Tax credits included in the IRA/OBBBA can be generous, but the support is only available for a short period of time.

For policies tied to a sliding CI scale, the feedstock, pathway, and process details are irrelevant, assuming legislated criteria are met. Fig. 13 shows median policy values for six pathways. RFS and LCFS are market-based policies, which means their values can vary significantly. The error bars show the range of values without including 45Z and the yellow bands show the required abatement costs for pioneer and nth plant assumptions. Only co-processing has sufficient support to meet abatement needs when the minimum values are applied. With median values and nth plant assumptions, ATJ with sugarcane ethanol, FT with forest residues, HEFA with UCO, and co-processing with UCO have enough support (Fig. 13). HEFA with soybean oil does not have sufficient support with median policy values, although this would change with a lower soybean oil price or if the CI of this pathway is lowered through farming, transportation, and processing choices. FT with DAC and offshore wind does not currently qualify for RFS support and has a very high abatement cost requirement, falling well short regardless of the policy value scenario. If MSP values from a pioneer plant are used, ATJ with sugarcane ethanol has enough support with median policy values, but FT with forest residues falls short, even with the maximum policy scenario.

The median abatement costs covered by existing U.S. policy are insufficient for current technology maturity for FT (forest residues), HEFA (soybean oil) and FT ($CO_2$) by 41 %, 7 % and 80 %, respectively. The monetary values of these short-falls range from \$33/t$CO_2$e to

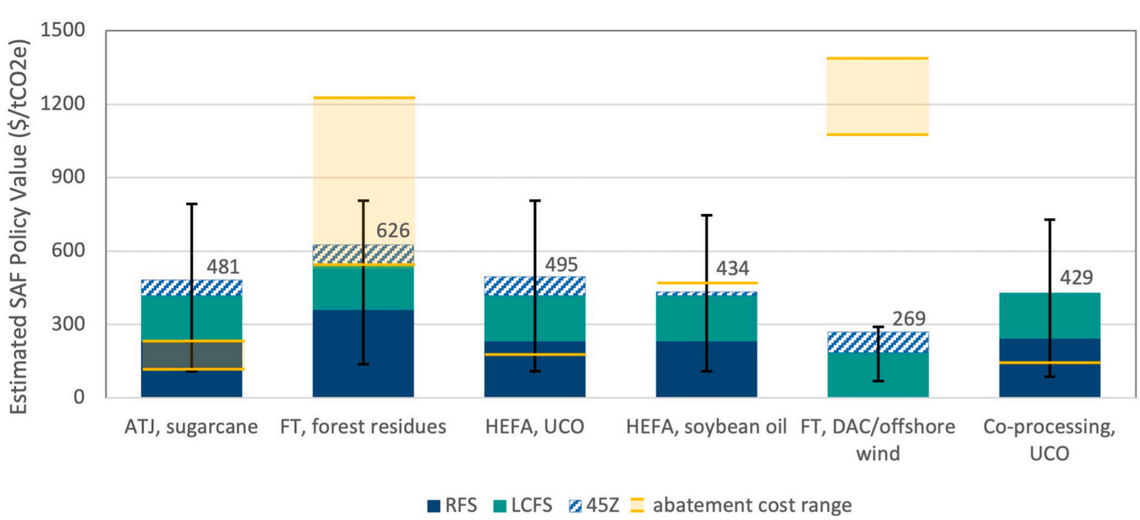


**Fig. 13.** Estimated support of abatement costs from state and federal U.S. policy. Error bars represent minimum and maximum market values for RFS and LCFS. The minimum also removes 45Z (five years). Numerical median values include RFS, LCFS and 45Z.

$1056/t$CO_2$e. FT ($CO_2$) is outside of the current private-pay abatement cost range while HEFA (soybean oil) is well within the range and FT (forest residues) hovers at the higher end of reported ranges [152,153].

## 4. Conclusions

This paper addresses the literature gap by comparing announced SAF volumes with U.S. SAF production goals. This analysis was achieved by integrating data from the announced production database with harmonized TEAs and the ASCENT U.S. Policy Applicability and Value Estimation Tool to assess practical and financial barriers for the emerging SAF industry. These include the time and capital required to build and start up facilities, limited lipid feedstocks, and insufficient policy to overcome abatement costs for many pathways, especially for pioneer technology.

In 2030, potential SAF production will be dominated by HEFA, with additional volumes from co-processing and ATJ. The baseline analysis estimates 11.2 billion liters/year in 2030, just shy of the near-term U.S. goal of 11.4 billion liters/year, while the high scenario estimates 20.9 billion liters/year, surpassing this goal. However, reaching the high scenario will require significant financial and logistical support. The baseline scenario that includes facilities that have specifically discussed SAF and the other technologies sums to 7.8 billion liters/year, nearly of 70 % of the 2030 goal.

Building and starting new facilities take years, with a mean just over 4 years from initial announcement to COD. Findings highlight that facilities are affected by frequent delays, averaging 1.5 years. Although conversion and expansion construction paradigms may be a lower-cost alternative to greenfield construction, the required capital is still daunting. For the 2030 U S. SAF target, most of the volume is expected from existing and already under-construction facilities. Co-processing appears to be a cost-effective alternative, but feedstock shortages and competition from the RD and biodiesel markets need to be resolved.

Insufficient SAF policy and comparatively higher RD support from the RFS and LCFS may cause SAF volumes to stagnate. The effectiveness of stacked state and federal policies is not simply the total dollar value, but instead the ability of the total value to cover the corresponding abatement cost. Additional support from the supply side, demand side, or both, could assist in growing this emerging industry. Providing extended market certainty is critical to reduce risk for producers. Short-duration policies do not provide the reliable support that encourages industry growth through derisking investments.

Think tanks including Third Way have suggested creating a federal low-carbon fuel standard for aviation that combines CI reductions with mandated volumes [154]. In British Columbia, Canada, a provincial mandate that starts at 1 % in 2028 and grows to 3 % in 2030 and is combined with a low carbon fuel standard with both penalties ($445/t$CO_2$e) and payments (average value of $346/t$CO_2$e from 2022 through mid-2024) [155,156]. This policy, though new, can be further stacked with the Canadian federal low carbon fuel standard, making British Columbia one location to watch for the impact of supply and demand side incentives [157].

In the European Union, ReFuelEU has mandated SAF volumes that increase over time with embedded feedstock and technology requirements. Mandates ensure uniform volumes across the industry. Financial support is available through the EU Emissions Trading Scheme [158]. Another option is to pass the abatement cost to air travelers via increased ticket prices (SAF levy), as planned in Singapore [159]. Other supportive measures include loan guarantees, green bonds, research grants, take-or-pay offtake agreements, and corporate emission offsets [23].

Current U.S. policies are unlikely to incentivize production to meet the 2030 SAF goal, as they fall short of estimated abatement costs for most pathways. The decision made by each producer to sell SAF will be made to ensure that they align with individual economic analyses, sustainability goals, and government compliance. The intention to produce SAF will transition to actual SAF production on a large scale when SAF production is profitable and more lucrative than RD. Increased production will likely require additional support that may include one or more of the following: (1) valuation of environmental and social services, (2) private purchase of scope 3 emissions, (3) long-term, high-value incentives, (4) national SAF-specific policies similar to LCFS or RFS, or (5) volume mandates. Further research is needed to determine which additional support mechanisms could catalyze the U.S. SAF industry.

As the near-term deadline for the U.S. SAF goal approaches and the SAF industry matures, continued monitoring of production announcements and recalculating the implementation ratios and potential volumes are required.

## CRediT authorship contribution statement

**Kristin Brandt:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lina Martinez-Valencia:** Writing – review & editing, Validation, Software, Methodology, Formal analysis. **Dane Camenzind:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation. **Alessandro Martulli:** Writing – review & editing, Visualization, Methodology, Data curation. **Robert Malina:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Florian Allroggen:** Writing – review & editing, Software, Methodology, Formal analysis. **Michael Wolcott:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2025.108516.

## Data availability

Data will be made available on request.

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