Co-funded by the
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UNIVERSITÉ DE LORRAINE

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UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

Case Base Module

Decarbonizing Aviation: Evaluating Algae-Based Biofuels for Sustainable Aviation Fuel Production

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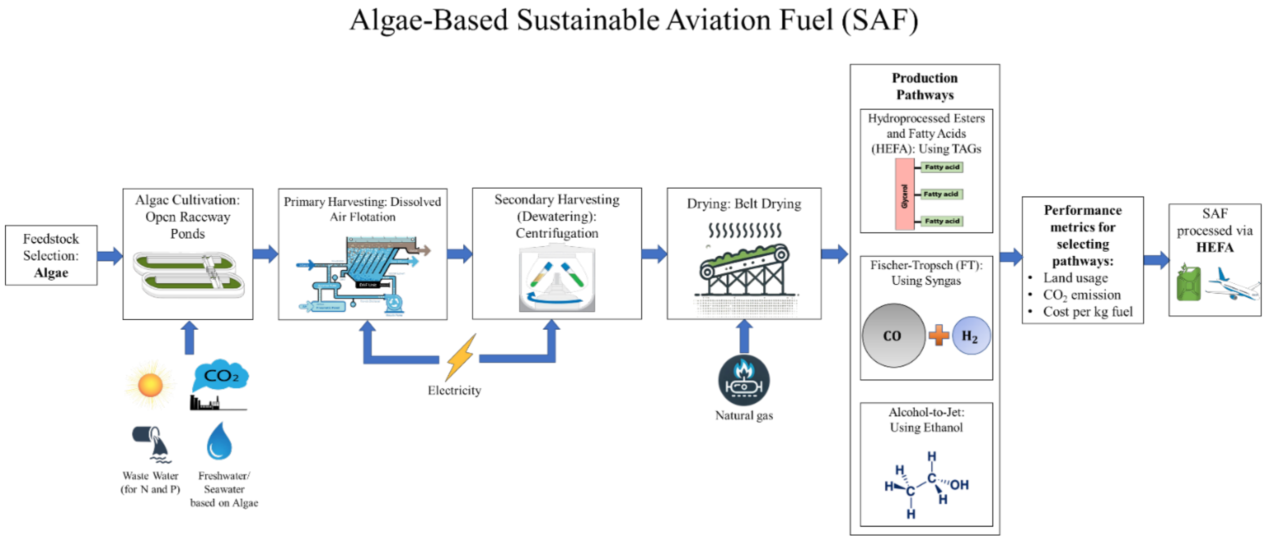
Date: 05/02/2025

Abstract

The aviation industry is a major contributor to global carbon emissions (2.5% of total), making the transition to sustainable aviation fuels (SAFs) essential for reaching the net-zero CO_2 emission goal. Among the various biomass options for SAF, algae-based biofuels stand out as a viable alternative, due to their high lipid content, rapid growth, and ability to utilize wastewater and industrial CO_2 emissions. This report evaluates three major SAF production methods—Fischer-Tropsch (FT), Hydroprocessed Esters and Fatty Acids (HEFA), and Alcohol-to-Jet (ATJ)—using the dry biomass obtained based on land use, greenhouse gas (GHG) emissions, and cost efficiency. These criteria are assessed by selecting *Nannochloropsis sp.* for HEFA due to its high lipid content, *Chlorella vulgaris* for ATJ because of its high carbohydrate content, and *Chlorella vulgaris* for FT due to its higher biomass yield, ensuring optimal efficiency for each conversion process. For large-scale production of algae, the use of an open raceway pond was proposed due to its simplicity and cost-effectiveness. *Nannochloropsis sp* is grown in a 50:50 mix of wastewater and seawater, whereas for *Chlorella vulgaris* the seawater is replaced with fresh water. However, while cultivation itself is relatively energy-efficient, drying remains the most CO_2-intensive step, accounting for 68% of total emissions—primarily due to its reliance on natural gas. By accounting the algae cultivation and the SAF production pathways, HEFA emerges as the most promising option, requiring 1,376.8 km² of land while achieving the lowest GHG emissions (32.6 gCO_2e/MJ), significantly lower than conventional jet fuel (85-95 gCO_2e/MJ). FT, despite requiring a similar land footprint (1,323.5 km²), emits 98 gCO_2e/MJ, making it less environmentally favorable. ATJ presents additional scalability challenges, demanding nearly double the land area (3,149.02 km²) and producing moderate emissions (69.6 gCO_2e/MJ). Cost analysis shows that HEFA (\$2.9/kg_{fuel}) is the most economical, while FT (\$6.7/kg_{fuel}) and ATJ (\$6.6/kg_{fuel}) remain costly due to their energy-intensive processing. However, HEFA is still 3.9 times more expensive than conventional jet fuel (\$0.74/kg_{fuel}), posing a challenge for widespread adoption. Overall, algae-derived SAF has the potential to significantly reduce aviation's carbon footprint. Future advancements in drying techniques, biofuel conversion, and policy incentives will be crucial for scaling up production and making algae-based fuels a commercially viable alternative to fossil-based jet fuel.

Graphical Abstract



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1 Introduction

The year 2024 was the first year to exceed the average global temperature by 1.5°C above the pre-industrial level [1]. We have already crossed our own limits and GHG emissions have not shown any sign of saturation [2]. GHG such as CO_2, CH_4, N_2O, CFCs, HCFCs, and HFCs are the contributors to this temperature rise. Out of these, CO_2 alone contributes to 70% of the global temperature rise [3]. 37.8 billion tons of CO_2 were released into the atmosphere due to the burning of fossil fuels in 2023 (1.1 % increase as of 2022) which is more than a 10-fold increase as compared to 1923 emissions [4]. Energy, transportation, and industrial processes are the major sources of carbon emissions. Power generation is the major contributor to this emission, accounting for 38.24%, followed by 21.1% by the transportation sector in 2023 [5]. To tackle this rising global temperature and cut down emissions, an agreement known as the Paris Agreement was formulated and signed by 196 parties to reduce global emissions and limit global warming below 2°C, preferably 1.5°C rise, compared to pre-industrial levels [6]. Under the agreement, each participating country submits a Nationally Determined Contribution (NDC), outlining their plans to reduce GHG emissions and adapt to climate impacts. France has also committed to the Paris agreement to reduce its GHG by 40% by 2030 and achieve carbon neutrality in 2050 [7]. Unlike the rest of the world, the energy industry only contributes to 11% of GHG emissions in France [8], thanks to its huge nuclear power industry. The major contributor to GHG emissions in France is the transportation sector accounting for 32% of GHG emissions [8]. While road transport is the most significant contributor to this, with the booming EV industry and insensitive government [9], it is expected to decline in the future. But hard-to-abate sectors such as aviation remain a challenge [10].

On average 175.8 thousand barrels per day of jet fuel was consumed in 2023 in France which passed the pre-COVID average of 170.8 thousand barrels in 2019 [11]. Considering 3.1 kg of CO_2 emission per kg of jet fuel combustion, 25.9 million tons of CO_2 was released into the atmosphere. Furthermore, more studies suggest that the global warming effect intensifies as this carbon is released high up in the air. Due to this effect, although 2.5% of CO_2 was released by the aviation sector in 2023, it has accounted for 4% of global warming [12] from pre-industrial areas. Although the aviation industry contributes less compared to other sectors such as road transport and the energy industry, there is a surging need for decarbonizing the aviation industry to meet the target of the Paris Agreement.

Decarbonizing the aviation sector presents a significant challenge due to the industry's reliance on fossil-based jet fuel and the specific safety, weight, and energy-density requirements of aviation fuels [13]. However, there are several technologies that can be crucial for decarbonizing the aviation industry. These solutions include sustainable aviation fuels, hydrogen propulsion, electric aircraft, and synthetic fuels. but all these technologies come with their challenges [13].

1.1 Overview of Technologies

1.1.1 Electric Aircraft

Electric aircraft have emerged as a promising solution for reducing aviation-related emissions, addressing the urgent need to decarbonize air travel. Battery-powered and hybrid-electric configurations offer significant environmental advantages, such as lower noise levels, reduced carbon dioxide emissions, and operational cost savings.

However, these benefits are currently limited by technological challenges, primarily the energy density and weight of batteries [14], [15]. For instance, lithium-ion batteries, despite their widespread use, provide energy densities far lower than conventional jet fuels [16]. Safety concerns were also examined in the analysis. Thus, safety challenges, such as thermal runaway, remain a critical problem for lithium-ion batteries and lithium-sulfur batteries. During the charging and discharging process of the battery, lithium dendrite growth creates risks of short circuits, leading to thermal runaway [17].

Solid-state batteries are safer due to their non-flammable, thermally stable solid electrolytes, which also resist dendrite formation. Table 1 details three key battery technologies available [18]. For the mass limitation, a case study was analyzed [19]. For the battery weight, the Alice electric plane is considered, with a maximum take-off weight of 6.67 kg and a payload capacity of 1.13 kg. The battery mass percentage relative to the total aircraft weight is calculated for different energy densities for the flight range of 392 km. This highlights the feasibility of operating such regional flights with modern battery technologies.

Table 1 Summary of the main battery properties and their limitations in aviation applications

Battery technology	Energy density (Wh/kg)	Safety	Long cycle life	Cell voltage (V)	Scalability	Battery weight
Lithium-ion	250	Medium	500-3000	3.7	Commercial scale (TRL 9) [20]	54% [19]
Lithium-sulfur	400	Medium	180-300	2.1	Small-scale prototype (TRL 4) [20]	38.83% [19]
Solid-state	500	Very high	1000-2000	3.8	Technology validation Small-scale prototype (TRL 3-4) [20]	28% [19]

Furthermore, different studies [21], [22] suggest that an energy density greater than 750 Wh/kg is required to make electric propulsion viable for regional and commercial aircraft, but another study [23] suggests that within the next 20 years, state-of-the-art battery technology could only achieve energy densities between 400 and 600 Wh/kg.

1.1.2 Hybrid-Electric Aircraft

Hybrid-electric aircraft provides a compromise by combining two power sources utilizing batteries during the less demanding cruise phase while conventional fuel is used for the energy-intensive phases such as takeoff and landing. The three main hybrid-electric aircraft architectures are series (where only electric motors connect to fans, with ICE driving a generator), parallel (where both ICE and electric motor shafts mechanically couple to drive fans), and series/parallel (combining both approaches with mechanical connections between ICE, motor, generator, and propeller) [24].

Since batteries remain one of the main elements of hybrid technology, their limitations in energy density and safety restrict hybrid systems' performance. Hybrid-electric aircraft propulsion faces three main technical challenges [25]. The integration of multiple power sources requires complex control and power management systems. The added weight of hybrid components demands more thrust during takeoff, creating performance tradeoffs. Additionally, electrical components need sophisticated cooling systems since, unlike traditional engines, they cannot easily release heat into the atmosphere [26].

1.1.3 Hydrogen

Another innovative approach to aviation decarbonization involves the development of hydrogen-powered aircraft. Hydrogen is a zero-emission fuel that produces only water vapor when combusted or used in fuel cells. The energy density of hydrogen, in terms of energy-to-weight ratio (MJ kg^{-1}), is three-fold that of conventional kerosene, rendering it suitable for longer flights in large planes supporting high payload capacity. Despite being lighter, hydrogen, in its cryogenic liquid form, has an energy-to-volume ratio (MJ L^{-1}) four-fold lower than fossil kerosene, which implies obvious storage challenges due to its need for cryogenic storage at -253°C and the bulkier and heavier fuel tanks compared to conventional fuel systems [20]. Furthermore, substantial investment is required to develop the necessary hydrogen refueling infrastructure at airports.

1.1.4 SAF

One of the most promising solutions is the use of sustainable aviation fuels (SAFs). SAFs are renewable, low-carbon alternatives to conventional jet fuel and can be used in existing aircraft engines without modifications. These fuels are typically derived from waste oils, agricultural residues, municipal solid waste, algae, and synthetic sources such as renewable hydrogen and captured carbon dioxide. When produced sustainably, SAFs can achieve up to 80% reduction in lifecycle carbon emissions compared to traditional fuels. However, current regulations permit up to 50% blending of SAFs with conventional jet fuels, emphasizing the necessity for further certification to increase this limit [27]. Despite their significant carbon reduction potential, SAFs face challenges such as high production costs, limited global availability, and the need for expanded supply chain infrastructure. However, the European Parliament seems positive about SAF. In a regulation published by the European Parliament in 2023 [28], the EU aims to have a minimum of 70% of SAF in 2050, with 35% from renewable hydrogen and captured CO_2.

1.2 Key Industrial Projects and Innovations

The aviation industry is increasingly adopting innovative solutions to address sustainability challenges, with leading companies pioneering projects in hydrogen propulsion, SAF and electric flight. Key leaders are represented below:

1.2.1 Airbus

Airbus is developing the ZEROe program in which three aircrafts are under consideration, each one incorporating hydrogen combustion technology to develop the first net-zero commercial aircraft by 2035. Both propellers and ducted fans are considered as thrust sources. Two conventional airframe configurations with liquid-hydrogen storage located behind the rear pressure bulkhead and propeller or fan propulsors as well as Blended-Wing Body aircraft with distributed turbofans and liquid-hydrogen storage underneath wings are being developed [29].

1.2.2 Emirates Airline

Emirates achieved significant milestones in SAF adoption, including a 2023 demonstration flight of a Boeing 777-300ER powered by 100% SAF in one engine and an Airbus A380 demonstration in November 2023. Additionally, Emirates has one of the world's youngest fleets and uses the latest GP7200 engines in its fleet, which allows it to save 500,000 L of fuel a year compared with comparable aircraft [30].

1.2.3 SAF Commitment by SE Asian Air Operators

Several airlines in the region including Singapore Airlines and Malaysia Airlines have demonstrated their first SAF flight since 2021. Most countries with major airlines in Southeast Asia have begun to develop their SAF strategy toward 2050. First SAF flights were conducted on October 27th, 2023, by Garuda Indonesia, on October 5th, 2022, by Cebu Pacific, on December 13th, 2023, by Thai Airways, on July 8th, 2022, by Singapore Airlines, on May 27th, 2024, by Vietnam Airlines [31].

1.2.4 Eviation

Eviation’s Alice, a fully electric nine-seater aircraft, successfully conducted its maiden flight in September 2022. Alice is designed for short-haul flights up to 250 nautical miles and aims for market entry by 2027 [19].

1.2.5 Air France - KL

Air France-KLM is the first airline in the world to use SAF biofuels and in 2011 was the world's first airline to carry out a commercial flight partly fueled by Sustainable Aircraft Fuel (SAF), committed itself to using 14% SAF of the total volume used in the Netherlands by 2030. By 2019, within a time range of 15 years, KLM has reduced its total CO_2 emissions by an absolute 4% and 31% per passenger per kilometer. For 2030, the target is 15% and 50% respectively [30]. The overview of the companies and their strategies is shown in

Figure 1.

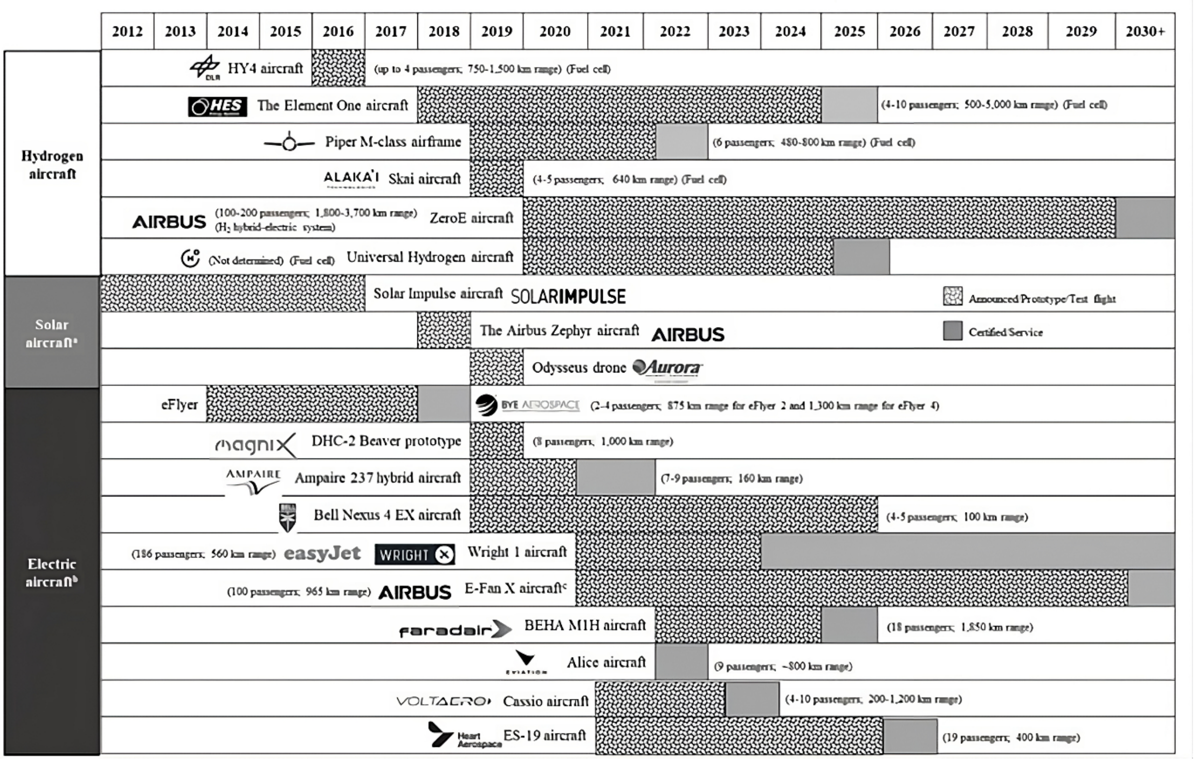

Figure 1 Examples of inventoried electric, hydrogen, and solar-based projects announced to date (by the end of the year 2021) [20]

1.3 Objectives

A comprehensive review of the four technologies highlights two fundamental challenges: low energy density and safety limitations. As a result, the aviation industry faces significant challenges in reducing CO_2 emissions while maintaining operational efficiency. Among the available alternatives, biofuels/SAFs offer a promising solution due to their compatibility with existing infrastructure and potential for carbon neutrality.

Thus, this study aims to assess the viability of SAFs as a long-term alternative to conventional jet fuel, focusing on feedstock potential, production processes, and key performance metrics. The study will access various biomass sources for sustainable aviation fuel (SAF) production, comparing their oil yield, carbohydrate content, land use efficiency, and environmental sustainability. These biomass sources include conventional crops, lignocellulosic materials, and microalgae. To effectively convert these feedstocks into viable SAF, various production pathways must be considered. American Society for Testing Materials (ASTM) has approved several pathways for SAF production, ensuring their viability and compatibility with existing aircraft engines and infrastructure. These pathways include processes such as Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch (FT), Alcohol-to-Jet (ATJ), Synthetic Isoparaffin (SIP), Catalytic Hydrothermolysis Jet (CHJ), Hydroprocessed Hydrocarbons (HC-HEFA), Synthesized Paraffinic Kerosene-Aromatics (SPK-A), and Co-processing of lipids. Among these, HEFA, FT, and ATJ are the most widely recognized and commercially feasible methods for SAF production and will be focused on in this project. To assess the feasibility of these production methods, this study compares SAF pathways based on three key evaluation metrics: land use, CO_2 emissions, and cost. The methodology is based on a systematic literature review to gather key numerical data providing the foundation for further calculations.

2 Feedstock for SAF

Biomass is a renewable feedstock with significant potential for biofuel production, as it captures solar energy through photosynthesis [32]. During this process, carbon dioxide from the atmosphere is converted into various carbon-based compounds within plants. As shown in Table 1, biomass possesses high volatile matter (59.2–83.2 wt%), low ash content (0.77–26.20 wt%), and moderate moisture content (5.00–12.45 wt%), along with substantial carbon content (35.6–52.2 wt%), making it an excellent candidate for bioenergy production. Biomass-derived bio-jet fuel offers a sustainable long-term solution for the aviation industry, with the potential to significantly reduce its environmental footprint [33].

Table 2 Proximate analysis, ultimate analysis, and HHV of biomass [34]

Biomass	Proximate Analysis (wt%, dry basis)				Ultimate Analysis (wt%, dry basis)					HHV (MJ/kg)
	Moisture	Ash	Volatile Matter	Fixed Carbon	C	H	N	O	S	
Corn cob	4.6	1.6	79.9	13.7	43.8	6.5	0.3	47.8	0	17.3
Corn stover	8.5	6.1	76.7	8.2	41.9	6.5	0.6	44.8	0.2	15.9
Risk husk	8.8	26.2	59.2	14.6	35.6	4.5	0.2	59.7	0.02	13.2
Palm shells	8.4	4.6	75.4	20	51.5	5.7	0.4	37.7	0.03	19.3
Palm fiber	5.0	11.8	79	9.3	52.2	7.1	0.7	28	0.07	22.0
Palm stem	9.1	3.5	81.2	15.3	47.5	5.9	0.3	42.5	0.13	17.4
Sugarcane bagasse	5.4	3.1	80.2	11.3	44.9	5.9	0.2	49.0	0.06	18
Cotton stalk	15.0	2.7	63.1	19.2	40.4	5.1	0.2	36.5	-	13.5
Pine needle	-	1.7	74.2	24.1	45.8	5.4	1	46.1	-	18.5
Banana leaves	7.9	6.2	78.2	15.6	43.3	6.2	1.0	49	0.49	17.1
Hazelnut shells	12.5	0.8	62.7	24.1	46.8	5.8	0.2	45.8	0.67	20.2
Olive pomacc	9.0	4.0	77	19	51	6	0.3	38	0.02	23.5
Microalgae (Chlorella sp.)	4.1	10.2	69.5	16.2	44.9	6.4	6.4	40.7	1.57	19.4
Microalgae (Nannochloropsis sp.)	5.0	5.0	79.7	10.6	49.1	7.6	6.3	35.6	1.42	18.2

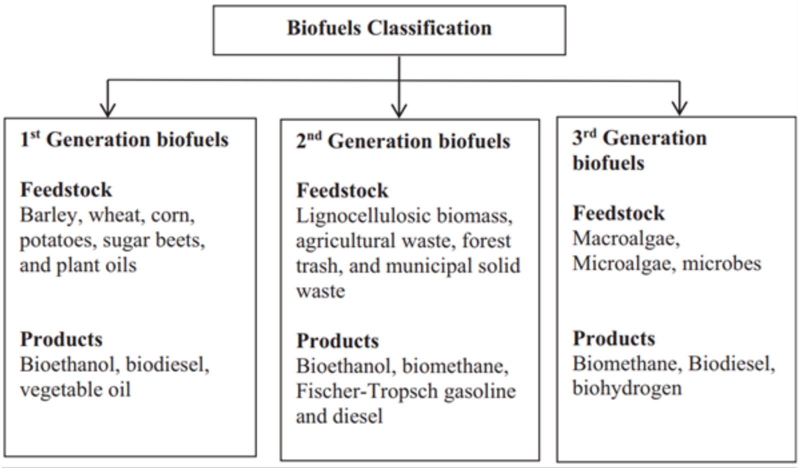

Figure 2 Biofuel classification

Energy production from biomass may be broadly classified as conventional or renewable, which can be further classified into three generations [35], [36].

Figure 2 illustrates the classification of biofuels. First-generation biofuels are derived from edible crops like barley, wheat, and corn; however, their increased production can compete with human diets and land use, posing a direct threat to food security [25], [37]. Second-generation biofuels utilize non-edible feedstocks such as agricultural waste, animal fats, used cooking oil, non-edible oilseeds, and lignocellulosic biomass. These feedstocks have high fatty acid content, making them suitable for bio-jet fuel production through hydroprocessing techniques or processes like gasification combined with Fischer-Tropsch [38]. Additionally, sugar-to-jet fuel pathways convert starch or sugar-rich biomass into alkane-type fuels with a need for pretreatment to extract fermentable sugars [39].

Third-generation biofuels are produced from microalgae, macroalgae, and microbes [40]. Microalgae are considered an exceptional feedstock due to their high growth rates, carbon fixation efficiency, and ability to store energy components like triacylglycerol and starch. According to Chisty [41], they can yield up to ten times more oil per acre than traditional crops, and their non-edible nature ensures no competition with food supply. Despite these advantages, microalgae-based biofuels face significant production challenges, including high costs, complex harvesting, processing pathways, and quality optimization. Advances in hydroprocessing, gasification Fischer-Tropsch, and sugar-to-jet pathways are addressing these challenges, with strategies focused on improving yield, quality, and cost efficiency [33]. The production of first-generation biofuels will likely have a direct impact on the food chain. While second-generation biofuels utilize non-edible waste and specialized lignocellulosic feedstocks, their adoption is hindered by the absence of efficient conversion technologies. In contrast, third-generation biofuels leverage macroalgae and microalgae as feedstocks, which can potentially overcome the limitations of earlier biofuel generations, without the controversial “food for fuel” argument [42]. Microalgae represents a promising alternative with the potential to replace conventional fossil fuels. More recently, research has focused on fourth-generation biofuels, which aim to enhance biofuel yield through genetically modified algae biomass [43].

2.1 Key Advantages of Algae-Based Feedstocks

From Table 3 and Table 4 the following observations can be made:

2.1.1 Yield Efficiency

Algae: Microalgae can produce up to 307 times more oil per hectare than soybeans or 23 times more than palm, translating into significantly higher biofuel output per unit area. Species like *Enteromorpha fasciata* and *Chaetomorpha linums* show lipid contents up to around 52.2 % and 60% dry weight, which is highly desirable for jet fuel.

HEFA Feedstocks: These feedstock are limited by crop yields, which are affected by climate, soil quality, and seasonal constraints. For example, soybean oil yield is approximately 446 liters/hectare/year, far less than algae’s potential.

FT Feedstocks: Relies on lignocellulosic biomass such as agricultural residues, forestry waste, or municipal solid waste. While abundant, these require energy-intensive preprocessing to extract useful hydrocarbons.

Sugar-rich Biomass: Corn (11 MT ha^{-1} in the USA) and sugarcane (82 MT ha^{-1} in Brazil) are the two main sugar-rich crops produced in the world. While the farming technology is extremely mature, the fermentation yield from the crop to bioethanol, which is the starting point for alcohol to jet (ATJ) technology, is only 28 % for corn and 8 % for sugarcane. Therefore, large land areas are required to use this feedstock for biofuel production [44].

Table 3 Classification of macroalgae and microalgae [45], [46]

Macroalgae	Lipid Content (%, w/w)	Microalgae	Lipid Content (%, w/w)
Red Algae		*Ankistrodesmus sp.*	24-31
Chondrus ocellatus	0.9	*Botryococcus braunii*	25-75
Porphyra perforate	5.8	*Chaetoceros muelleri*	33.6
Gloiopeltis fenax	33.4	*Chlorella emersonii*	25-63
Gracilaria crassa	11	*Chlorella protothecoides*	15-58
Brown Algae		*Chlorella sorokiniana*	19-22
Gracilaria corticata	10.9	*Chlorella vulgaris*	5-58
Hedophyllum sessile	6.4	*Crypthecodinium cohnii*	20-51
Saccharins japonica	1.2	*Dunaliella primolecta*	23
Nereocystics luetkeana	33.6	*Isochrysis sp.*	25-33
Sargassam sp.	1.6	*Monallanthus sauna*	<20
Green Algae		*Nannochloris sp.*	31-68
Caulerpa scalpelliformis	24.4	*Neochloris oleoabundans*	35-54
Ulva fenestrate	5.0	*Phaeodactylum tricornutum*	20-30
Chaetomorpha linum	60		
Enteromorpha fasciata	52.2		

Table 4 Type of biofuel production with oil yield content [47], [48]

S. No.	Crop	Oil Yield (L/ha/yr)
1	Corn	172
2	Soyabean	446
3	Canola	1190
4	Jatropha	1892
5	Coconut	2689
6	Oil Palm	5950
7	Microalgae	136900

2.1.2 Sustainability

Algae: Cultivating algae does not compete for arable land or freshwater resources. Algae can thrive in saline, brackish, or wastewater environments, allowing their growth on non-arable land, a crucial advantage given the global scarcity of agricultural land [49].

HEFA Feedstocks: The production of vegetable oils, such as palm and soybean, has been linked to deforestation, habitat loss, and intensive water usage, thereby exacerbating environmental challenges [50].

FT Feedstocks: Converting waste materials into energy through processes like the FT method can help reduce landfill usage. However, this approach involves complex logistics for the collection and preprocessing of biomass, which can be resource intensive.

Sugar-rich Biomass: The primary issue associated with sustainability for this feedstock is Food versus Fuel, which is the dilemma regarding the risk of diverting farmland or crops for biofuel production to the detriment of the food supply. It is estimated that for every million gallons of biofuel demand, an additional 2,345 hectares of land is required for corn production (1,167 ha for sugarcane).

2.1.3 Carbon Capture and Reduction

Algae: Algae actively sequesters CO_2 during photosynthesis, potentially achieving carbon-negative fuel production. In addition, algae can be grown on non-arable land such as deserts. Cultivation systems integrated with industrial CO_2 capture enhance environmental benefits [51].

HEFA Feedstocks: Carbon reduction depends on the type of feedstock, with limited lifecycle GHG benefits compared to algae.

Conventional FT Feedstocks: While FT fuels are cleaner-burning, the process itself is energy-intensive, potentially offsetting carbon savings unless renewable energy is used.

Sugar-rich Biomass: While crops such as corn and sugarcane also sequester CO_2 during their growth phase, studies show that expanding of croplands for bioethanol or biofuel production can cause more carbon emissions due to indirect land-use change (iLUC). Additional land, such as rainforests or grasslands, must be cleared up for the farms, and this results in an off-site change in the carbon stock of the soil and biomass. [52].

2.2 Selection of Algal Strains for SAF Production

Selecting the appropriate microalgal strain for jet fuel production is critical due to the need for specific fatty acid profiles that align with the hydrocarbon composition of aviation fuels. Jet fuel primarily consists of hydrocarbons with carbon chains ranging from C8 to C16, making microalgae rich in palmitic (C16:0) and palmitoleic (C16:1) acids ideal candidates [53]. In addition to the lipid composition, lipid content, carbohydrate content, biomass productivity, and growth rate are key factors in determining the suitability of an algal strain. The best algae strains for bio-jet fuel production also depend on the specific conversion pathways: FT, HEFA, and ATJ. HEFA requires high lipid-content algae since it involves hydroprocessing algal oils into jet fuel. ATJ requires algae with high carbohydrate or sugar content to maximize ethanol, butanol, or isobutanol production via fermentation. The FT process requires high biomass yield since it involves gasification of the whole algal biomass to syngas ($CO + H_2$), which is then converted into liquid fuels via catalytic synthesis. Table 5 compares the key characteristics of various microalgae species.

Table 5 Comparison of lipid content, carbohydrate composition, and growth characteristics of various microalgae species

Species	Lipid Content (% of DCW)	Carbohydrate Content (% of DCW)	Biomass Productivity (mg/L/day)	Growth Rate (day^{-1})	Reference
Nannochloropsis sp.	23.2 – 59.9	n.a	118*	0.30-0.54	[54]
Chlorella vulgaris	19.8–34.8	8.38–17.7	234.1 – 532.2	0.56	[55]
	34 - 40	26–40	340–410	0.34–0.54	[56]
Botryococcus braunii	20.85 – 48.65	n.a	43.87-145.12	0.014 - 0.043	[57]
Spirulina platensis	5.78-28.6	1.93–57.7	n.a	0.025 – 0.079	[58]
Scenedesmus obliquus	8.9 – 15.2	16.7-23.5	110-220	0.55-0.82	[59]
Dunaliella tertiolecta	n.a	7.1 -15.2	60 -133	n.a	[60]
Dunaliella tertiolecta	37	10	49.76	0.101*	[61]
Tetraselmis subcordiformis	13.9-27.4	3.7-48.6	416.5 – 740.1	0.2340-0.2997*	[62]

*obtained via calculation

Based on Table 5, *Nannochloropsis sp.* is the most suitable algae for HEFA due to its high lipid content, reaching up to 59.9% of dry cell weight (DCW), depending on cultivation conditions. Similarly, *Chlorella vulgaris* is an optimal choice for ATJ fuel production due to its high carbohydrate content (up to 40% DCW) and relatively high growth rate (0.56 day^{-1}). While *Spirulina platensis* has a higher carbohydrate content (up to 57.7% DCW), its lower growth rate (0.025–0.079 day^{-1}) makes it a less viable option. Additionally, *Chlorella vulgaris* exhibits high biomass productivity (410 mg/L/day), along with a relatively high carbon content (44.9 wt% dry basis) making it ideal for Fischer-Tropsch (FT) synthesis, which requires substantial biomass input [34].

2.3 Industrial-Scale Algae Cultivation and Processing for Biofuel Production

2.3.1 Algae Cultivation

Based on the study by Jiang et.al [54] an industrial-scale cultivation plan to grow *Nannochloropsis sp*. To scale *Nannochloropsis sp.* cultivation to an industrial level, open raceway ponds (ORPs) can be used, maintaining a depth of 20–30 cm for optimal light exposure. ORPs are cost-effective, with low operational costs, making them easier to set up compared to closed photobioreactor systems. Paddlewheel mixing can be employed to enhance circulation and nutrient distribution, improving productivity. Cultivation occurs in two phases to optimize lipid accumulation. In Phase I, microalgae are grown in a 50:50 mixture of municipal wastewater and seawater at 25°C. The nutrients essential for algae growth are absorbed from wastewater, which is naturally rich in nitrogen and phosphorus. A gas distribution system enables direct injection of flue gas, while wastewater supplies essential nutrients. A pH control system can be installed to prevent excessive acidification from CO_2 absorption. Additionally, salinity levels must be carefully managed, as *Nannochloropsis sp* does not tolerate prolonged exposure to low salinity or freshwater. This phase lasts for six days, reaching a biomass concentration of 0.7 g/L. In Phase II, wastewater supply is reduced to induce nitrogen starvation, triggering lipid synthesis. This phase lasts for 12 days resulting in increased lipid content, peaking at 59.9% and biomass yield of 2.23 g/L. If cultivated near industrial sites, residual heat from plants can be utilized to maintain optimal pond temperatures, further enhancing productivity [54].

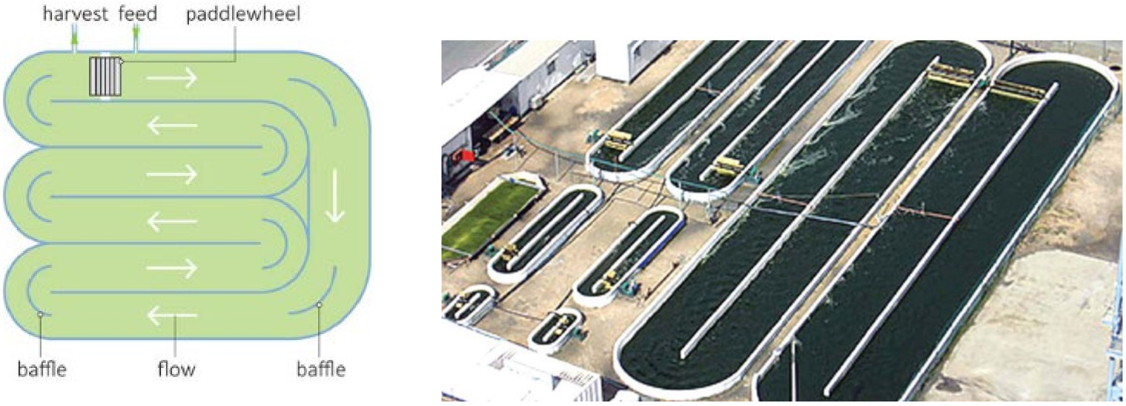

Figure 3 Schematic diagram (left) and industrial-scale open raceway pond system for microalgae cultivation [63]

Based on the criteria such as temperature (20°C to 30°C), access to seawater, proximity to industrial sites for flue gas supply, and large cities for municipality waste, the regions shown (plotted using QGIS) in the Figure 4 has been identified to grow *Nannochloropsis sp.*

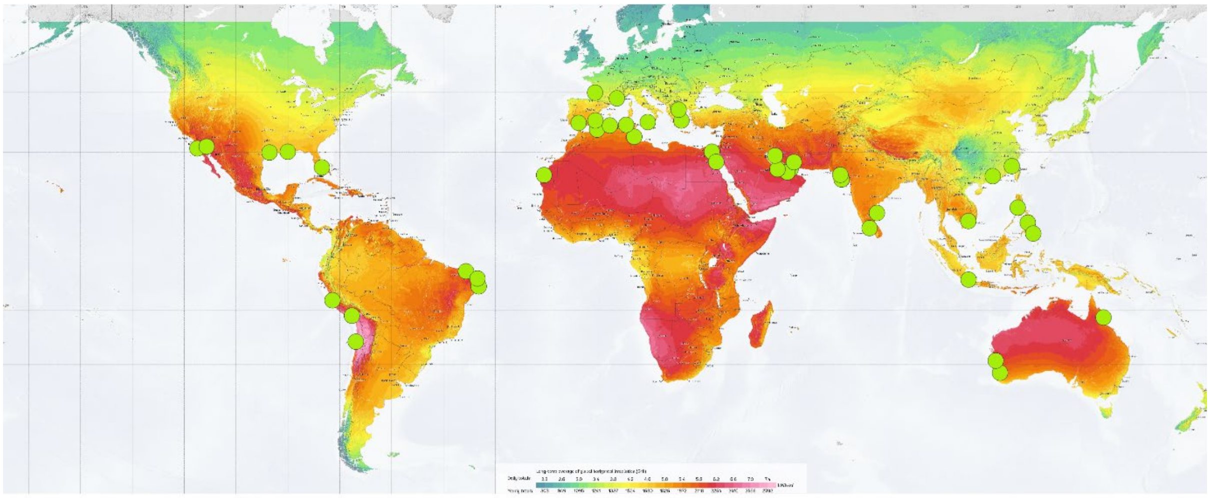

Figure 4 Global distribution of suitable regions for Nannochloropsis cultivation

For *Chlorella vulgaris*, since it has a low tolerance to salinity, the mixture can be replaced with freshwater. Here, Phase I (growth phase) would last for 6 days, while Phase II (nitrogen starvation) would continue from day 7 to day 10. Additionally, the pH must be maintained between 7 and 9, as *Chlorella vulgaris* is sensitive to acidification from CO_2 [56].

2.3.2 *Harvesting and Dewatering of Algae*

Algae harvesting is the process of separating microalgae biomass from the growth medium to concentrate it for further processing. To achieve efficient concentration, harvesting is carried out in two stages: primary harvesting and secondary harvesting. Primary harvesting methods include gravity sedimentation, flotation, and filtration, while secondary methods involve centrifugation, belt filter press, and filtration for further dewatering [64].

1. Primary harvesting

In gravity sedimentation, algae cells settle at the bottom of a tank due to gravity, but this method requires a long retention period and is only effective for larger algae species, making it unsuitable for *Nannochloropsis sp*. Flocculation enhances separation by aggregating microalgae into larger clusters through environmental factors (auto-flocculation), bacteria (biological flocculation), or chemicals like aluminum sulfate or lime (chemical flocculation) [63]. Flotation methods use gas bubbles to attach to algae cells, making them rise to the surface, where they can be skimmed off. Among flotation techniques, Dissolved Air Flotation (DAF) is the most effective for small algae like *Nannochloropsis*, as it uses microbubbles to push algae to the surface, forming a scum layer. Other flotation methods include Electrolytic Flotation, which generates gas bubbles through electrolysis, and Dispersed Air Flotation, which directly injects air bubbles into the system [63]. DAF consumes 2.24 - 3.0 kWh/m³, which is slightly higher or similar to flocculation (1.5 - 3.0 kWh/m³) but achieves a higher algae recovery rate of 80 - 90% compared to 60 - 85% for flocculation [64].

2. Secondary harvesting

Centrifugation separates algae from water through high-speed spinning and is most cost-effective when used after flocculation or flotation. There are two main types: disc centrifuges, which consume 2,070 kWh/m³, and decanter centrifuges, which consume 3,500 kWh/m³. Both achieve a high recovery rate of 95%, but disc centrifuges are more energy efficient [64]. A disc stack centrifuge uses a stack of closely spaced metal cones (discs) inside a rotating cylindrical bowl to separate materials based on density, applying forces between 4,000- and 14,000-times gravity, making it efficient for microalgae separation [65]. A decanter centrifuge is a solid bowl centrifuge that separates solids from liquids using a continuous rotating drum, suited for higher solid suspensions but with higher energy consumption [65]. Belt filter presses use mechanical pressure to remove water but are less effective for small-diameter algae like Nannochloropsis, resulting in lower recovery rates [64]. Filtration methods, including microfiltration, ultrafiltration, and microfiltration, work best for larger algae species but suffer from clogging and fouling issues [65]. Given its high recovery rate and lower energy consumption, the disc centrifuge is the most efficient secondary harvesting option [54], [64].

2.3.3 Drying

The pre-thickened algae must then be dried to reduce moisture content for efficient extraction and processing. The common drying methods include solar drying, spray drying, freeze drying, crossflow drying, vacuum shelf drying, and belt drying [64], [66]. Drying consumes the most energy in algae harvesting (up to 60%), unless solar drying is used, which relies on the sun for energy [67].

Solar drying utilizes natural sunlight to remove moisture and is the cheapest method. However, it requires large drying areas, causes degradation of organic compounds, and has a low yield per square meter. Spray drying produces high-value microalgae products by atomizing algae into fine droplets and rapidly drying them in hot air. However, it is highly energy-intensive and uneconomical for large-scale applications. Similarly, freeze drying, which involves freezing algae and removing ice through sublimation under a vacuum, preserves organic compounds and pigments, but the most expensive drying method, making it unsuitable for large-scale biofuel production. Roller drying spreads algae biomass on heated rollers for rapid evaporation but risks thermal degradation. Crossflow and vacuum shelf drying are alternative methods that reduce thermal damage; crossflow drying uses heated air, while vacuum shelf drying operates at low pressure to dry algae at lower temperatures. However, both methods are more expensive than other options, making them impractical for large-scale biofuel production [63], [66]. Belt drying is a continuous, low-temperature drying method where algae biomass is spread on a moving conveyor belt and gradually dried using hot air or waste heat, making it energy-efficient and suitable for large-scale algae production. While belt drying has a higher initial capital cost, it offers lower operational costs due to reduced heat usage and minimal maintenance. Additionally, it preserves biomass quality better than high-temperature methods like roller and spray drying, making it the most suitable option for large-scale algae biofuel production [64].

Ultimately, all drying processes require substantial energy input, with most relying on heat from natural gas, making drying the largest contributor to CO_2 emissions in the algae harvesting process. Therefore, selecting the most energy-efficient drying method is crucial for minimizing environmental impact and ensuring the sustainability of industrial-scale algae production.

Our proposed system utilizes open raceway ponds for algae cultivation, where Dissolved Air Flotation (DAF) serves as the primary harvesting method, followed by disc centrifugation for secondary dewatering. The concentrated biomass is then further dried using a belt dryer, achieving a high-solids content dry biomass for downstream processing.

3 SAF Production Methods

3.1 Fischer-Tropsch Synthesis (FT)

The Fischer-Tropsch (FT) process is a thermochemical conversion route that transforms syngas ($CO + H_2$) into long-chain hydrocarbons, which can be refined into synthetic fuels such as SAF, diesel, naphtha, and waxes. Different operating conditions, catalysts, and overall process designs are used with the Fischer-Tropsch (FT) reaction process based on the desired product, availability of the feedstock, available technology, economic feasibility, and environmental considerations [68], [69]. The input of the FT process is syn gas, which can be obtained by gasification or pyrolysis of the biomass. Research such as [70] shows that the gasification process has a higher mass yield, energy yield, and carbon yield than the pyrolysis process. This report focuses on the gasification-based FT process. FT process has been in the industry since the 1920s [71] and is predominantly used to produce diesel and gasoline using coal and natural gas as the feedstock [72]. However, in this report, the feedstock is biomass, and the desired output is ASTM D7566-specified synthetic jet fuel [73]. Hence, the process that shows higher selectivity towards hydrocarbons in the jet fuel range with no additional hydrogen required for the intermediate process is chosen. The overall process is shown below in Figure 5.

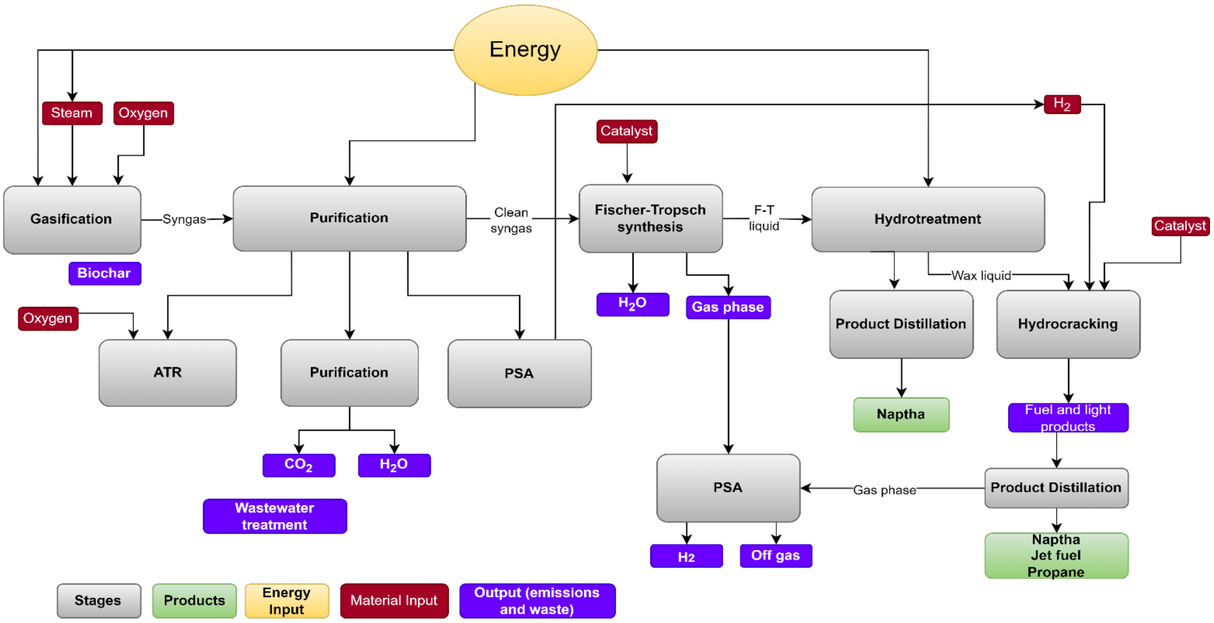

Figure 5 Schematic FT process diagram (adapted from [74])

3.1.1 Gasification/Syngas Production

Gasification breaks down biomass into a mixture of CO, H_2, CH_4, CO_2 and 2% biochar, and small amount of NH_3 at high temperatures of 1000°C and moderate pressures of 3 atm [74]. According to the experiments conducted by Snehesh et al. [75], the ratios of steam-to-feedstock and oxygen-to-feedstock were 0.66 and 0.23, respectively. The product gas, called syngas ($CO + H_2$), serves as the precursor for FT synthesis. The key reactions are below:

Decomposition of Biomass:

$$Biomass \rightarrow BioChar + Volatile\ gases$$

Cyclone Separation (Particulate removal): Remove char, ash, and solid particles. The method uses a cyclone separator to spin gas, forcing heavy solids to drop out.

Gasification reactions (syngas formation): Converts remaining solid carbon into a mixture of CO and H_2 (syngas).

- Boudouard Reaction (CO formation)

$$C + CO_2 \rightarrow 2CO$$

- Water-Gas Reaction (H_2 and CO Formation)

$$C + H_2O \rightarrow CO + H_2$$

- Methanation (Side Reaction – Produces CH_4)

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$

3.1.2 Syngas Purification

After gasification, the produced raw syngas contains impurities such as CH_4, CO_2, NH_3, and H_2S which must be removed to prevent FT catalyst poisoning and inefficiencies in FT synthesis. Methane reforming, which was selected to be auto thermal reforming (ATR) (decomposition of methane into carbon dioxide and water by oxygen [76]), was then used to convert the methane into the gasified products into carbon monoxide and hydrogen before entering the FT step. After the removal of methane and carbon dioxide, the pressure swing adsorption (PSA) was used to adjust the ratio of H_2 and CO to approximately 2.1 before entering the FT reaction [77]. Separate hydrogen can then be utilized in the hydrocracking or isomerization process.

CO_2 scrubbing (Carbon dioxide removal): Carbon dioxide was considered to have a negative impact on the F-T process due to the reduction of the selectivity of hydrocarbons with carbon numbers above 5. Therefore, it has to be removed before the FT process. Carbon dioxide can be separated from the syngas at low temperatures and high pressure, which was set at the pressure of 70 bar and the temperature of 10°C.

NH_3 Removal: Prevents unwanted side reactions in FT synthesis. Methods: Water Scrubbing is used as NH_3 is highly soluble in water, allowing most of it to be washed out.

3.1.3 Fischer-Tropsch Synthesis (FTS)

The FT is a catalytic process that converts syngas (CO + H_2) derived from microalgae gasification into liquid hydrocarbons, particularly SAF. This process operates at a moderate pressure of 30 atm and temperatures between 300°C. Catalysts like Fe, Co, Ni, and Ru have been utilized for alkane production in the FT process, with Co and Fe being the most studied. Research indicates that CO prevents the inhibition of carbon monoxide conversion to water. Additionally, Co catalysts exhibit greater stability and a longer lifespan compared to Fe catalyst [78], [79]. The FT reaction converts CO and H_2 into long-chain hydrocarbons through catalytic polymerization:

Primary FT reaction (forms hydrocarbon chains and water):

$$(2n + 1)H_2 + nCO \rightarrow C_nH_{2n+2} + nH_2O$$

This reaction produces liquid paraffin (alkanes), the primary component of jet fuel.

Methanation (Undesired side reaction – produces methane):

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$

Methane formation reduces fuel yield and should be minimized using cobalt catalysts.

3.1.4 Hydrotreament & Upgrading

The hydrotreatment process is a critical upgrading step in the FT synthesis pathway, where the raw FT products (paraffins, olefins, and oxygenates) are refined into high-quality Sustainable Aviation Fuel (SAF). This process involves hydrocracking and isomerization to improve fuel properties, stability, and performance. Hydrotreatment is essential for removing oxygen, sulfur, and nitrogen impurities, while also adjusting molecular structure to meet the ASTM D7566 certification standards for SAF. The primary goal is to increase jet fuel yield by selectively cracking and isomerizing long-chain hydrocarbons. The best catalyst choice for SAF Production: Pt/SiO_2-Al_2O_3, due to its high isomerization activity, which improves the freezing point and stability of jet fuel.

Hydrotreatment consists of two major reaction types, each playing a crucial role in fuel quality improvement:

Hydrocracking - Converts long-chain paraffins into shorter molecules:

$$C_{20}H_{42} + H_2 \rightarrow C_{12}H_{26} + C_8H_{18}$$

This reaction breaks down heavier FT waxes (C_{20+}) into jet fuel-range hydrocarbons (C_8-C_{16}).

Isomerization - Enhances cold-flow properties (reduces freezing point):

$$n - C_{10}H_{22} \rightarrow i - C_{10}H_{22}$$

This reaction improves fuel flowability at low temperatures, a key requirement for aviation fuel. The unreacted hydrogen and propane byproducts in the gas product are considered economically valuable. Propane can be separated via cryogenic distillation, after which the remaining gas is sent to a PSA unit for hydrogen separation. The liquid reaction products undergo distillation, where lighter components are removed from the top of the column, while the bottom product is SAF. Water generated during the process is directed to wastewater treatment, which includes coagulation, sedimentation, filtration, and disinfection steps [70].

3.2 Hydroprocessed Esters and Fatty Acids (HEFA)

The most common process to convert microalgae to SAF is by extracting the oils and lipids in the algae and chemically converting these into long-chain hydrocarbons. Generally, renewable fuels that are produced from the fats, oils, and lipids of plants and animals are termed Hydro-processed Esters and Fatty Acids or "HEFA." In the case of algae-derived HEFA, the overall process is shown below in Figure 6.

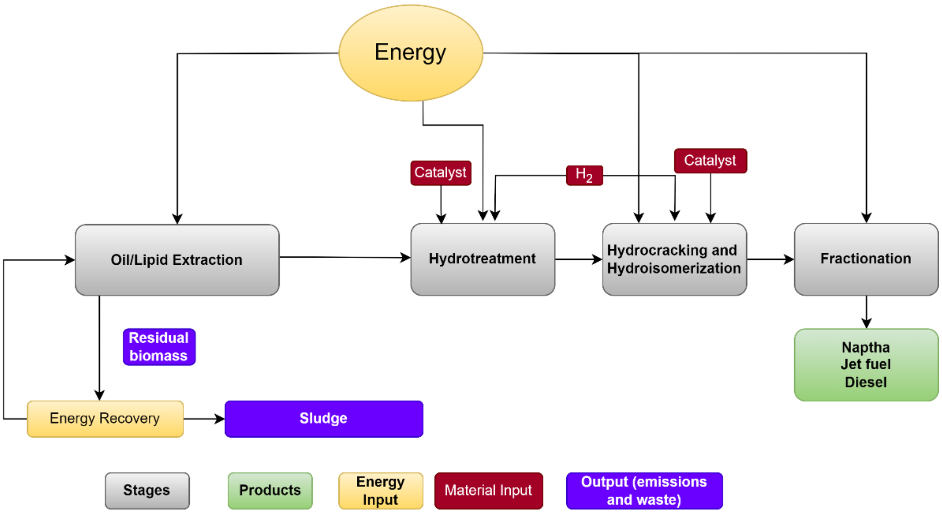

Figure 6 General process flow diagram for HEFA process from microalgae

3.2.1 Oil or Lipid Extraction

Extraction of the oil or lipid from the algae is the first step of the HEFA process. Direct extraction from dry biomass is considered a relatively easy process, but since algae is a wet biomass source comprising of at least 70% of water by weight even after filtration, drying becomes a more energy-intensive, more costly, but necessary procedure [80]. There are three common ways to perform the extraction:

1. Cell disruption and solvent extraction

Prior to extraction, the algal biomass can be pre-treated mechanically, via milling, to disrupt the cell membrane and allow the extracting solvent to enter the cell much more easily. After which, a combination of solvents with different polarities is used to ensure the extraction of both polar and non-polar lipids in a stage-wise process. The most common solvents used are hexane (non-polar) and methanol or chloroform (polar). After extraction, the solvents containing the lipids are separated from the residual solid, then the lipids are collected by distilling off the solvents. Unfortunately, this technique requires organic solvents that are potentially toxic or hazardous, but the solvents are cheap and volatile (therefore, it require less energy for distillation), and they can also be recycled after each use. At optimum conditions, this method can afford a near quantitative recovery of the total lipids from the biomass, as proven by experimental results [80]. The technology is also very well-established since it is very similar to soybean extraction. For these reasons, it is the most common extraction method [81]. Furthermore, the algal cake that is formed after the lipid extraction contains a non-negligible amount of biomass, which can be digested anaerobically to obtain biogas or used as fertilizer for algae cultivation.

2. Pyrolysis

It is a thermochemical process wherein any biomass is heated at high temperature and in the absence of air. Using high temperatures, such as 400-600°C, in a few seconds of residence time can yield bio-oil up to 80% weight of the original biomass. Catalysts may also be used to increase yields. However, this process requires high energy input. Additionally, the feedstock must be sufficiently dry for this process; otherwise, the energy requirement for drying and pyrolysis can be very high [82].

3. Hydrothermal liquefaction (HTL)

It can be performed in an aqueous medium, but still at moderate temperatures of 250-380°C and pressures of 2-20.6 MPa. At these conditions, chemical reactions take place to decompose the solid structure of biomass into oily components. HTL produces a bio-oil with a higher heating value (HHV) of 29-35 MJ kg^{-1} [34]. In a study by Biller, et al., liquefaction at a temperature of 350°C and 20.6 MPa of the *Chlorella sp.* microalgae reduced the oxygen content of the resulting bio-oil to 11% [83]. This value is to be further lowered in the next step of the process, deoxygenation. The summary of oil and lipid techniques is shown below in Table 6.

Table 6 Summary of oil and lipid extraction techniques

No.	Method	Mechanism	Type	Intermediate	Yield of Intermediate (% dry basis)
1	Solvent extraction	Solvent	Physical	Lipid	Up to 75% [84]
2	Pyrolysis	Heat	Chemical	Oil	Up to 60% [85]
3	HTL	Heat	Chemical	Oil	Up to 64% [84]

3.2.2 Hydrotreatment

In this step, the oxygen content in the lipids is removed by hydrogen to produce long-chain hydrocarbons, as well as by-products such as water, carbon dioxide, and carbon monoxide. A bifunctional catalyst composed of metal and acid sites is usually employed for this process, such as noble-metal-based ones (Pt, Pd, Ru, Rh), or molybdenum-based ones (NiMo, or CoMo). The reaction is carried out at high temperatures (260 to 405°C) and pressures (3 to 13.6 MPa). The general chemical reaction for this step is shown below [34].

$$C_{14}\ to\ C_{24}\ lipids + H_2 \rightarrow C_{14}\ to\ C_{22}\ hydrocarbons\ (diesel\text{-}grade) + H_2O + CO_2 + CO$$

Simply deoxygenating the algal lipids typically results in straight-chain paraffin having chain lengths similar to, or slightly shorter than, the fatty acid composition of the algal lipids. The fuel produced by deoxygenation meets the general specification for diesel fuel, but not for aviation fuel hence further processing by isomerization and selective hydrocracking is necessary [84].

3.2.3 Hydrocracking, Hydroisomerization, and Fractionation

During the hydrocracking and isomerization steps, the normal paraffinic hydrocarbons are converted to branched paraffins, while the higher carbon number paraffins are selectively cracked to form paraffins in the desired jet fuel range [86].

$$C_{14}\ to\ C_{22}\ hydrocarbons\ (diesel\text{-}grade) + H_2 \rightarrow C_8\ to\ C_{16}\ parrafins\ (jet\text{-}fuel\text{-}grade)$$

Similar to hydrotreatment, these reactions also require high temperatures, high pressures, hydrogen gas, and a catalyst. Finally, the output is separated into three outlet streams: naphtha, jet fuel, and biodiesel. The jet fuel fraction is typically 50-70% of the extracted lipid [34]. The summary of the refining step is shown below in Table 7.

Table 7 Summary of refining steps to produce SAF

Step	Hydrotreatment	Hydrocracking and hydroisomerization
Temperature	260-405°C	288-425°C
Pressure	3-13.6 MPa	2-20 MPa
Catalyst	Noble or Mo-based metals	Zeolite Y or amorphous silica alumina
Conversion	90-95%	90-95%
Output	Bio-diesel quality fuel	Jet fuel quality fuel

3.3 Alcohol-to-Jet (ATJ)

Another production route for the conversion of microalgae to SAF is to extract the carbohydrate from the algae, instead of its lipids. The carbohydrate can be converted into sugar, after which it can be fermented to an alcohol. Then, the established process of alcohol-to-jet fuel (ATJ) can be employed. The overall process is summarized below in Figure 7.

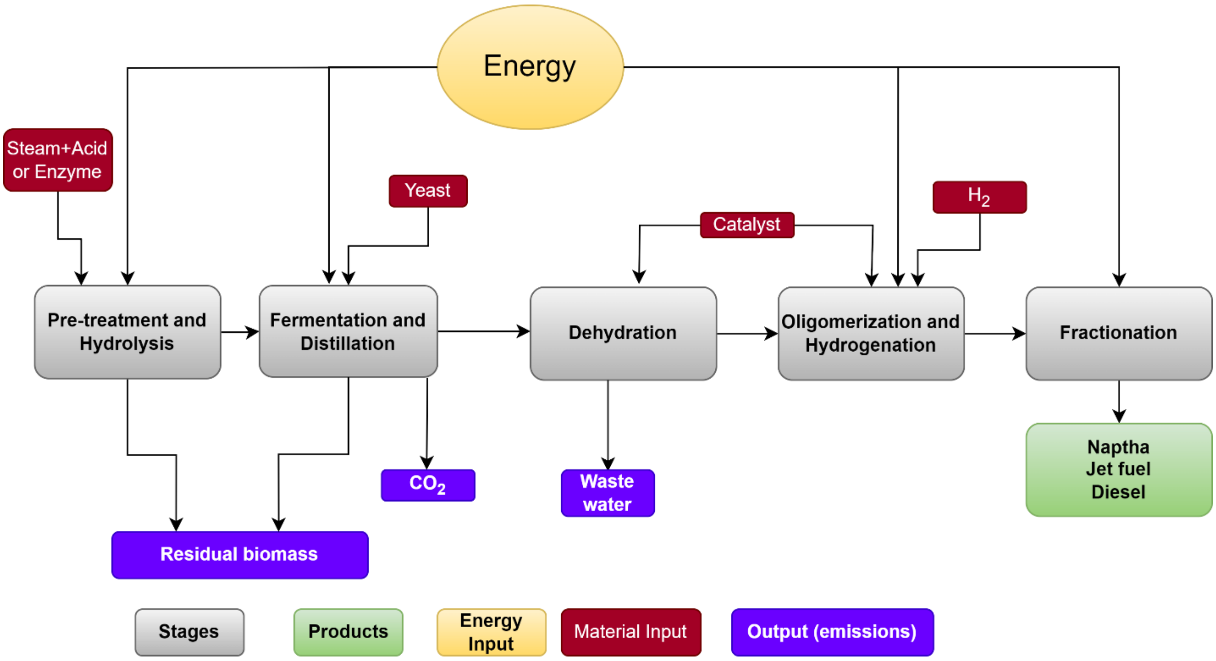

Figure 7 General process flow diagram for ATJ process from microalgae

3.3.1 Pre-treatment and Hydrolysis

To be able to use algae as a feedstock for alcohol production, it must be pre-treated first similar to other lignocellulosic materials. Pretreatment breaks down the crystalline structure of cellulose and releases the fermentable sugars, so that the hydrolysis of carbohydrates can be achieved more rapidly and with greater yields. The most common methods are described below [79].

1. Steam explosion and acid hydrolysis

Algae is mixed with steam at elevated pressures for a certain residence time, before the pressure is released abruptly, resulting in the evaporation of the water present within the biomass, causing the biomass structure to crack. This process is followed by the addition of an acid to catalyze the breakdown of cellulose. A study was able to successfully perform this treatment on algae using diluted sulfuric acid [87].

2. Enzymatic hydrolysis

An enzyme catalyzes the hydrolysis of cellulose to glucose to form shorter polysaccharides up to simple sugars. Using enzymes instead of acids results in a lower yield, but this treatment can be performed at milder temperatures and pH. However, studies with microalgal biomass are limited.

Table 8 Comparison of acid and enzymatic hydrolysis

Method	Steam explosion and acid hydrolysis	Enzymatic hydrolysis
Advantages	• High yields • Tested on algae	• Milder conditions
Disadvantages	• Harsher conditions • Requires steam	• Lower yields

3.3.2 Fermentation

Fermentation using yeast (*Saccharomyces cerevisiae*) is the worldwide accepted production process for bioethanol. Once the simple sugars have been obtained from the first step, the fermentation reaction for all biomass sources, algae included, is essentially the same as shown below. After fermentation, the ethanol is separated from the fermentation broth by distillation.

$$Sugar + Yeast \rightarrow Ethanol + 2\ CO_2$$

3.3.3 Dehydration, Oligomerization, Hydrogenation, and Fractionation

These four steps are a part of the general process route to obtain jet fuel from alcohol, as specified in ASTM D7566 [88], [89].

1. Dehydration

The hydroxy group is removed from the alcohol by forming water and this produces short-chain alkenes. This reaction typically takes place at elevated temperatures of around 400 to 550°C and moderate pressures of below 5 bars. The general chemical reaction for ethanol is shown below.

$$C_2H_5OH \rightarrow C_2H_4 + H_2O$$

2. Oligomerization

The alkene-rich product from dehydration is oligomerized to achieve a chain extension through the formation of carbon-carbon single bonds between the single alkenes. This oligomerization step is typically controlled by catalysts and takes place at moderate temperatures of 100 to 250°C and elevated pressures of at least 20 bars.

$$4\ C_2H_4 \rightarrow C_8H_{16}$$

3. Hydrogenation

Hydrogen is added to saturate the remaining double bonds and thus to produce alkanes. A noble catalyst such as platinum is used, as well as slight overpressure of less than 10 bars and at ambient temperatures.

$$C_8H_{16} + H_2 \rightarrow C_8H_{18}$$

Table 9 Summary of chemical reactions involved in ATJ

Step	Dehydration	Oligomerization	Hydrogenation
Input	Alcohol	Alkenes	Long-chain alkenes
Output	Alkenes	Long-chain alkenes	Long-chain alkanes
Typical catalyst	Nickel-HZSM-5	Nickel or Al_2O_3/SiO_2 zeolite	Noble metals on Al_2O_3 support
Temperature	400-550 °C	100-250 °C	Ambient or above
Pressure	5 bars	20 bars	10 bars

4. Fractionation

The resulting hydrocarbon mixture is separated into different products as per the fuel standards. This step is similar to the other processes.

4 **Results and Discussion**

For our case study, we are assuming a 35% blend on SAF for 2050 based on the EU Parliament directive [28]. Full details of the calculation and the data sources are explained in the appendix.

4.1 Comparison Metrics

Three key metrics were chosen for the comparison: Land use, CO_2 Emissions and Cost. The comparison metrics were evaluated based on sustainability and economic criteria.

4.1.1 Land Use

Land availability is a critical factor in biofuel production, as large-scale cultivation can compete with food production and natural ecosystems. First, in terms of productivity per area, microalgae were selected due to their superior performance compared to other biomass types (Section 2.1).

Environmental impact and efficient use of resources are a key factor for algae growth. Unlike other biofuel crops, algae can be grown in non-arable lands, such as deserts or near industrial areas where CO_2 emissions can be captured for algae growth. For instance, regions like the southern part of France, with high solar irradiance, could be ideal for open race-away ponds for algae cultivation. However, between 0.27% and 0.45% of French lands are adequate for deploying microalgae for biofuel production [90]. Considering the cost implication, the desert area adjacent to the sea with a flat topology without extreme temperature fluctuations. For instance, in Europe, only one area is designated as a desert, with an area of 258 km^2 located in Spain. Apart from the size limitation, the area is evaluated up to 900 m above sea level [91].

Land cost factors affect the overall feasibility of algae-based fuel production. France's cost of agricultural land was compared with the cost in Morocco due to the climate conditions, water resources, and land availability. The average cost of agricultural land in France in 2021 was 5940 euros per hectare compared to the average cost in Morocco of 3000-5000 euros per hectare [92]. Using the coastal areas close to industrial cities would have higher prices due to the tourism potential, which is relevant for both countries. However, major tourist destinations in Morocco are concentrated in coastal areas, while France balances its tourism sector.

The land use criteria demonstrate importance for various French stakeholders. The main stakeholders prioritizing land use are the NGOs associations and governments with 20.42% and 5.1% respectively among other criteria such as GHG, biofuel competitiveness, profit margin, feedstock availability, incorporation cost, security of supply, etc. [93].

The amount of land needed to meet the SAF requirement of France by 2050, which is taken as 35% of the projected jet fuel demand, is calculated [28]. This value is taken as 6.5 billion liters for France. For the worldwide SAF demand by 2050, the same percentage (35%) is applied to the projected world jet fuel demand, estimated to be 230 billion gallons [94]. Each process requires different amounts of algal raw material to be able to produce the same amount of SAF since each process has different algal strains, recovery efficiencies, and process yields. These values are summarized in Table 10.

Table 10 Summary of results for land calculations

Process	**FT**	**HEFA**	**ATJ**
Microalgae	*Chlorella vulgaris*	*Nannochloropsis sp*	*Chlorella vulgaris*
Overall conversion ($L_{fuel}\,kg_{algae}^{-1}$)	0.16	0.35	0.07
Algae growth [a] ($kg_{algae}\,m^{-3}_{media}\,cycle^{-1}$)	2.83	2.23	2.83
Algae growth cycle [b] ($days\ cycle^{-1}$)	10	18	10
Depth of pond [c] (m)	0.3	0.3	0.3
Land area for France's requirement (km^2)	**1,323.5**	**1,376.8**	**3,149.0**
Land area comparison	*Half the size of Luxembourg (2,586 km^2)*	*Half the size of Luxembourg (2,586 km^2)*	*1.25 times larger than Luxembourg (2,586 km^2)*
Land area for world's requirement (km^2)	**61,942.7**	**64,437.7**	**147,386.0**
Land area comparison	*Half the size of Greece (131,957 km^2)*	*Half the size of Greece (131,957 km^2)*	*Half the size of Italy (301,340 km^2)*

[a] [54], [56]

[b] This value assumes that mature algae must be harvested, and fresh algae must be grown every n days. [54], [56]

[c] The pond depth of 0.3 meters is chosen since this is the maximum pond depth that allows light to reach the bottom of the pond [64].

As mentioned above (Section 2.2), the microalgae strains are chosen based on their compatibility with each process' requirements. For example, *Nannochloropsis sp* is chosen for its high algal lipid content (maximum of 59.9% [95]), which is critical to achieve a productive HEFA process. Consequently, the overall conversion for HEFA will be dependent on the lipid content, as can be seen in the formula below.

$$\begin{matrix} Overall \\ conversion_{HEFA} \end{matrix} = \begin{matrix} Harvesting \\ recovery\ rate \end{matrix} \times \begin{matrix} Lipid \\ content \end{matrix} \times \begin{matrix} Lipid\ recovery \\ efficiency \end{matrix} \times \begin{matrix} Lipid\ to\ jet\ fuel \\ yield \end{matrix} \tag{1}$$

The overall conversion of ATJ is the lowest among the three processes, wherein ~15 kg of dry algae is needed to produce 1 liter of jet fuel. This is expected, since the ATJ process begins with the ethanol molecule, which is composed of only two carbon atoms. To form the long-chain hydrocarbons of kerosene, several molecules of ethanol are needed to oligomerize. Fortunately, this drawback is partially offset by the superior algae growth and cycle rate of the ATJ microalgae strain. However, ATJ still requires the largest land area (2.4 times larger than HEFA or FT).

4.1.2 CO_2 Emissions

The carbon footprint of algae-based jet fuel is significantly lower than fossil fuels due to its natural CO_2 absorption. During cultivation, algae directly capture CO_2 from industrial sources, making this stage nearly carbon neutral. In algae, the primary source of carbon is carbon dioxide (CO_2). The atomic mass of carbon (C) is 12 g/mol, while the molecular mass of CO_2 is 44 g/mol. The amount of CO_2 required to produce 1 kg of dry algae biomass can be calculated using the formula:

$$O_2\,required\ = Carbon\ Content\ \times \frac{Molecular\ weight\ of\ CO_2}{Atomic\ weight\ of\ C} \tag{2}$$

Table 11 Carbon content and CO_2 sequestration potential of selected algae strains

Species	Carbon content [34]	CO_2 seq per kg of algae
Nannochloropsis sp.	49.07	1.795
Chlorella vulgaris	44.93	1.626

When comparing the three SAF production pathways—ATJ, HEFA, and FT—their emissions remain relatively low, primarily dependent on energy sources used in processing. While grid electricity and natural gas for steam heating contribute some emissions, these are minimal compared to fossil-derived fuels. Additionally, the combustion of SAF in aircraft engines is also carbon-neutral since the CO_2 released was originally absorbed by the algae during growth, creating a closed carbon cycle.

The GHG emissions of each process are estimated from literature. In some cases, these values are directly stated in studies, while in others, the calculation is performed from the energy requirement (in MJ kg_{algae}^{-1}) of individual steps in the process. In this scenario, the corresponding CO_2 emissions associated with the energy source (natural gas, steam, or grid electricity) is considered. Since different countries have different carbon intensities for their electricity grids, two calculations are presented: (1) using the France electricity grid (56 g CO_2 per kWh), which represents a low carbon intensity grid, and (2) using the worldwide average electricity grid (481 g CO_2 per kWh).

Table 12 Summary of GHG emissions estimations

Process	**FT** ($gCO_2e\ MJ_{fuel}^{-1}$)	**HEFA** ($gCO_2e\ MJ_{fuel}^{-1}$)	**ATJ** ($gCO_2e\ MJ_{fuel}^{-1}$)
Algae cultivation	3.0	1.4	3.5
Algae harvesting	1.4	0.6	1.6
Algae drying	56.3	56.3	34.5
Feed transportation	0.6	0.6	0.6
Extraction	-	12.9	19.8
Upgrading/Conversion	36.1	12.8	9.0
Fuel transportation	0.6	0.6	0.6
Total life cycle	**98**	**85.2**	**69.6**
Credits	*0*	*-52.6*	*0*
Net CO_2 emissions (case: France grid)	**98**	**32.6**	**69.6**
Net CO_2 emissions (case: world grid)	**131.6**	**47.9**	**108.2**

In the case of HEFA, a combined heat and power unit that utilizes the residual biomass after lipid extraction as the fuel can be incorporated into the process (Figure 8). This process is achieved via an anaerobic biodigester, which converts the residue to biogas and sludge. This biogas, mostly methane, is then used to provide heat energy for other processes, such as drying or distillation. As a result, HEFA is able to achieve some form of carbon credit, since a portion of the total algae biomass is used as fuel prior to its final conversion to CO_2. Because of this advantage, the net GHG emission of HEFA is the lowest among the three processes.

Notably, without this credit, the life cycle emission of HEFA is almost the same as that of petroleum-based kerosene (85-95 $gCO_2e\ MJ_{fuel}^{-1}$) [96]. Breakdown analysis shows that the drying step contributes to 68% of total emissions, consistent with many literatures that cites the same challenge [67]. This is because HEFA requires sufficiently dry algae (10% moisture) as feedstock for its extraction process, which utilizes non-polar solvents. For the solvent molecules to effectively penetrate the interior of the cell and reach the lipids, there should be as little water as possible remaining in the algae [97]. Therefore, belt drying is performed to reduce the moisture content from 90% to 10%, which requires a large amount of energy provided by burning natural gas.

If this heat energy can be replaced with a renewable source, such as biogas or synthetic fuel, this major GHG contribution can be totally removed from the calculation, which then lowers the gross CO_2 emissions of HEFA down to 26.7 $gCO_2e\ MJ_{fuel}^{-1}$. However, since natural gas is presently the primary source of energy for drying, these findings demonstrate another reason as to why microalgae to jet fuel processes are not yet a reality. Alternatively, a carbon capture unit can be installed to collect the CO_2 produced from natural gas combustion. Another promising option is to perform lipid extraction without prior drying. This technology is being investigated as well. Several works have successfully reported working models, but since these works are few and have only been performed on a laboratory scale, this method was not considered in the study [98], [99], [100], [101].

In the case of ATJ, the hydrolysis of the algae to extract sugar involves the use of steam and acid and is performed in an aqueous medium (Figure 9). Therefore, the GHG emissions associated with the drying step (34.5 $gCO_2e\ MJ_{fuel}^{-1}$) are relatively lower compared to the other two processes. However, the extraction and fermentation steps release substantial carbon emissions (19.8 $gCO_2e\ MJ_{fuel}^{-1}$) due to the energy-intensive distillation involved [102].

In the FT process, biomass gasification is conducted using steam and oxygen at elevated temperatures (approximately 1000°C), rendering it an energy-intensive procedure. To maintain the reaction and supply the requisite energy at such high temperatures, natural gas (NG) is combusted at a rate of 0.089 kg CH_4 per kg of biomass [103]. The combustion of NG emits approximately 50 g CO_2 equivalent per kg of NG, contributing to the overall carbon intensity of the FT process compared to alternative pathways. Furthermore, during the FT process, approximately 52% of the carbon originally present in the algae biomass is released as CO_2 across various stages, resulting in a carbon efficiency of 21% with respect to jet fuel production [103]. However, the CO_2 emitted during the process is not considered a net emission, as it was initially sequestered by the algae during its growth phase. If the use of NG could be replaced with direct electric heating or electricity-derived fuel such as green methane, it can minimize CO_2 emissions.

4.1.3 Cost

The economic feasibility of algae-based jet fuel is a major consideration. Production costs are influenced by cultivation, extraction, and refining processes, with high infrastructure and energy costs being a challenge. Compared to fossil-based fuels, algae-derived fuel requires a significant initial investment, which impacts the final price of jet fuel and, subsequently, airline ticket costs. Sensitivity analysis suggests that cost reductions could be achieved through improved lipid extraction and economies of scale.

Table 13 Summary of cost estimations

Process	**FT** (\$ kg_{fuel}^{-1})	**HEFA** (\$ kg_{fuel}^{-1})	**ATJ** (\$ kg_{fuel}^{-1})
Algae cultivation, harvesting, and drying	5.5	2.3	5.5
Extraction	-	0.4	0.5
Upgrading/Conversion	1.3	0.2	0.6
Total estimated cost	**6.7**	**2.9**	**6.6**

The estimated cost of jet fuel production using each process is determined from the literature. The cost of algae cultivation, harvesting, and drying stands out as the largest contributor.

Notably, the FT process has the highest production cost compared to HEFA and ATJ processes. Maintaining target product generation requires the development of the selective and active catalytic system, which combined with the energy-intensive nature of the process, results in the highest conversion cost of \$1.3/kg among all three processes—significantly higher than ATJ (\$0.6/kg) and HEFA (\$0.2/kg). The current state of catalyst design is focused on the development of Fe and Co-based catalysts, while the price as well as the mining of cobalt under socially and ecologically critical conditions give rise to the search for catalyst materials with lower social and ecological impacts [104].

While more expensive than iron-only catalysts, Fe-Co bimetallic catalysts are still more economical than pure cobalt catalysts. Co-Ni-based alloys showed similar activity as pure Co systems. As the Co cost is higher, it can be used with some cheaper metals (Ni) and yields similar activity.

However, finding the right alloy combination and composition is very challenging. In addition, the long-term stability of the Co-Ni alloy must be studied to yield higher selectivity and activity [105].

Recent research has focused on developing iron-based catalysts as a more cost-effective alternative to cobalt for the FT process. Iron catalysts offer several advantages, including higher olefin selectivity and flexibility in product distribution. The cost of iron is significantly lower than cobalt, with iron ore priced at around $100-150 per ton compared to cobalt at $30,000-50,000 per ton. This substantial price difference makes iron catalysts economically attractive for large-scale FT operations. The stability of the iron-based catalyst is sensitive due to the facet of iron carbides which is one of the challenges [105].

The processing cost for HEFA is the least expensive, mainly because HEFA is regarded as the most economically viable and technologically ready out of the three processes. It also has the best overall conversion, so the sizing of all its equipment and reactors, as well as energy consumption, are all relatively smaller. In contrast, the overall conversion of ATJ is the lowest, so this results in an opposite effect on its capital and operating costs. Additionally, obtaining alcohol is a two-step process (hydrolysis and fermentation) for ATJ, while it is a one-step process (lipid extraction) for HEFA. These reasons contribute to the higher processing cost for ATJ [106].

Reducing the amount of algae to produce one kilogram of jet fuel is crucial for reducing the total production cost. Several strategies can be implemented to enhance the efficiency of algae cultivation, harvesting and drying. One of the approaches involves genetically modified algal strains and optimization of the growth conditions to improve scalability in biofuel production [107]. Developing energy-efficient harvesting methods, such as enhanced flocculation, co-cultivation with other microorganisms, and the use of biofilm reactors to reduce costs and improve overall process efficiency is also possible [108].

Additionally, government subsidies, tax incentives, and other financial support are essential to making SAF from microalgae commercially viable. Most bio-jet fuel production technologies incur costs that are at least 120% higher than conventional fossil-based jet fuel, while achieving emissions reductions of at least 27%. Despite these high costs, only 38% of existing policies provide monetary incentives to SAF producers, resulting in SAF production operating at only 3.5% of its total potential capacity [108]. Therefore, future research and development efforts should focus on further optimizing cultivation conditions, enhancing genetic engineering techniques, and developing cost-effective harvesting and processing methods.

4.2 Discussion

The performance of three SAF methods was analyzed based on land use, GHG emissions, and cost. The estimated performance metrics for France and global projections are summarized in Tables 14 and 15.

Table 14 Summary of performance metrics (France, 2050 jet fuel demand)

Process	**FT**	**HEFA**	**ATJ**
Total Land area requirement (km^2)	1,323.45	1,376.76	3,149.02
GHG emissions ($gCO_2e\ MJ_{fuel}^{-1}$)	98	32.6	69.6
Estimated cost ($\$\ kg_{fuel}^{-1}$)	6.7	2.9	6.6

Table 15 Summary of performance metrics (global demand, 2050 projection)

Process	**FT**	**HEFA**	**ATJ**

Total Land area requirement (km^2)	61,942.7	64,437.7	147,386.0
GHG emissions (gCO$_2$e MJ$_{\text{fuel}}^{-1}$)	131.6	47.9	108.2

Table 14 summarizes the estimated performance metrics for the three microalgae-to-jet technologies considering France's 2050 jet fuel demand and France's electricity grid. Currently, HEFA has the lowest GHG emissions (32.6 gCO$_2$e/MJ), and the lowest cost ($2.9/kg fuel) compared to FT (98 gCO$_2$e/MJ, $6.7/kg) and ATJ (69.6 gCO$_2$e/MJ, $6.6/kg). HEFA has lower emissions as lipid extraction and hydrotreatment are relatively lower energy intensity compared to the gasification (FT) and fermentation (ATJ) processes. However, HEFA requires slightly more land than FT (~1376.76 km^2 vs. ~1323.45 km^2 by 2050), but significantly less than ATJ (~3149.02 km^2) making HEFA the most realistic, sustainable, and cost-effective method to convert microalgae to jet fuel.

On a global scale, the carbon footprint of SAF production depends on the energy grid mix. The average global electricity grid emits 481 gCO$_2$/kWh due to its reliance on fossil fuel (60.65%), while France's grid emits only 56 gCO$_2$/kWh due to its heavy reliance on nuclear energy (65.29%) and other renewables [109], [110]. Since algae cultivation and processing require electricity (e.g., paddle wheels, dissolved air flotation, centrifugation), the choice of energy source significantly impacts total emissions. Hence, countries with cleaner electricity grids will inherently produce lower-emission SAF.

Cost, however, remains a major barrier to SAF adoption. From Tables 14 and 15, it can be observed that HEFA is the most cost-competitive option for large-scale deployment. However, currently, conventional jet fuel costs ~$0.743/kg$_{\text{fuel}}$ (equivalent to $94.93 per barrel) making all microalgae-derived SAF pathways significantly more expensive [111]. To bridge this gap and make SAF economically viable, policy interventions such as carbon taxes, subsidies, and mandates for SAF blending will be necessary.

One of the most energy-intensive steps in SAF production is drying, which is typically powered by natural gas, significantly contributing to the overall emissions. However, transitioning to renewable energy technologies—such as biofuels, biogas, e-fuels, or carbon capture and sequestration (CCS)—can substantially reduce emissions. Table 16 demonstrates the potential GHG reductions achieved by switching to renewable energy sources for drying.

Table 16 Impact of renewable drying on GHG emissions (gCO$_2$e MJ$_{fuel}^{-1}$)

Process	**FT**	**HEFA**	**ATJ**
Baseline (Natural Gas Drying)	98	32.6	69.6
Renewable Drying	32.6	-23.7	35.1

Transitioning to renewable energy sources significantly reduces emissions across all SAF production pathways, with HEFA even achieving negative emissions (-23.7 gCO$_2$e MJ$_{\text{fuel}}^{-1}$). However, this shift presents challenges, particularly in securing sufficient and cost-effective biofuels or synthetic fuels. A key concern is the competition between biomass for fuel and food production, which could drive up costs and strain agricultural resources, making these processes less financially viable. Addressing these economic and environmental trade-offs will be crucial to ensuring a sustainable and scalable transition to algae-derived SAF.

4.3 Scaling Algae-Based SAF: Integration, Land Use, and Deployment (2025–2050) to Meet French Requirements

This plan outlines the scaling of algae-based SAF production through HEFA as it is the most cost-effective and lowest-emission pathway. By 2050, Algae-based SAF will achieve 35% blending, ensuring net-zero aviation emissions.

1. 2025–2030: Early Deployment & SAF Commercialization (SAF Blending: 2% → 6%)

By 2030, aviation SAF demand will reach ~756 million liters, requiring ~160 km² of land for HEFA, slightly higher than FT (~154 km²) but significantly lower than ATJ (~366 km²). Expansion will focus on high-density algae farms, CO_2 capture, and wastewater recycling to optimize land use. ASTM D7566 certification, tax incentives, and airline offtake agreements will support early adoption. Airlines will blend 2% HEFA SAF in 2025, increasing to 6% by 2030, backed by carbon credit and lower SAF taxation to drive adoption.

2. 2030–2040: Scaling HEFA Production (SAF Blending: 6% → 24%)

By 2040, HEFA production must meet ~3.74 billion liters of SAF demand, requiring ~792 km² of land, slightly higher than FT (~762 km²) but far lower than ATJ (~1812 km²). Land use efficiency will improve with photobioreactors, vertical farms, and saline cultivation to avoid competition with food crops. HEFA production will fully integrate renewable electricity, further lowering emissions and costs. Policies will mandate higher SAF blending, securing long-term airline contracts. By 2040, HEFA blending will rise to 24%.

3. 2040–2050: Full Commercialization & Net-Zero Aviation (SAF Blending: 24% → 35%)

By 2050, SAF demand will reach ~ 6.51 billion liters, requiring ~1377 km² of land for HEFA, still slightly higher than FT (~1324 km²) but far lower than ATJ (~3149 km²). HEFA production will be fully powered by renewable energy, making it cost-competitive at less than \$2.5/kg_{fuel}. Direct Air Capture (DAC) will be integrated with algae bioreactors to achieve carbon-negative fuel production. Regulatory mandates will enforce a minimum of 35% SAF blending.

The plan for scaling of algae-based SAF production and projected land requirement is represented in Figure 8.

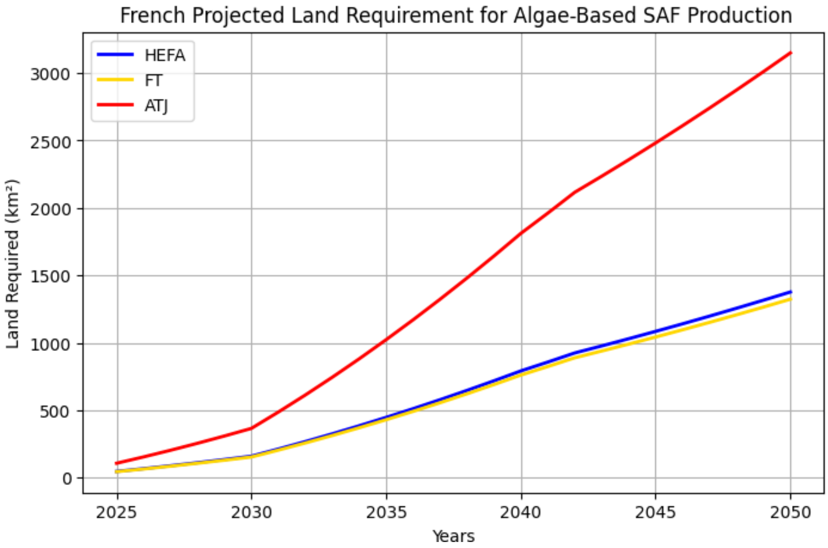

Figure 8 Projected land requirement for algae SAF production

5 Summary and Conclusion

Decarbonizing the aviation sector is one of the biggest challenges in sustainability because of the difficulty in finding alternatives to the energy-dense, petroleum-derived kerosene. The objective of this report is to assess the different options and strategies that the sector can undertake in order to mitigate its GHG emissions. Initially, a brief investigation was done to consider the potential of up-and-coming forms of energy storage technologies, such as hydrogen, batteries, or a hybrid between the two. However, these options are deemed to be unrealistic in present conditions since their technology readiness level has not matured enough. On the other hand, sustainable aviation fuel (SAF) is a carbon-neutral jet fuel that is chemically converted from biomass or synthetically produced from water and carbon dioxide. Since the chemical composition and properties of SAF are similar to that of kerosene, blending of SAF into the present operations can be easily done without requiring any additional installation or changes to the aircraft, hence they are also termed "drop-in fuel." Therefore, SAF is considered to be the most feasible option to achieve short-to-medium-term decarbonization of the sector and is the focus of this study.

To further narrow the scope, biomass is chosen as the feedstock to produce SAF. In our analysis, the specific biomass source was first selected by comparing possible options in terms of yield efficiency, sustainability, and carbon emissions. In order to address the jet fuel demand in the next decades, a stable, productive, alternative biomass source must be obtained that will not compete with food or any other sector. The underexplored potential of microalgae was investigated due to its fast growth rate, high biomass content, and ability to take in CO_2 and wastewater during cultivation. Therefore, the techno-economic feasibility of microalgae to jet fuel production was studied in detail.

The conversion of microalgae to jet fuel was modeled and analyzed based on three established processes: FT, HEFA, and ATJ. Each process requires different characteristics from the algae that will maximize yield efficiency. After the best strains had been identified, the algae cultivation, harvesting, and drying processes were discussed in detail. In addition, the possible locations of algae cultivation were suggested based on geography, proximity to wastewater sources, and sunlight availability. Following this, the three processes were discussed and evaluated based on three metrics: land requirement, CO_2 emissions, and estimated cost. It was found that algae drying is the most energy-intensive step and therefore releases the most GHG in the entire life cycle analysis. Algae growth and treatment were also found to be the biggest contributor to cost, attributed mainly to the processes' low overall yields, wherein 3-15 kg of algae is needed to produce just one kg of jet fuel. This is consistent with other SAF-related studies in literature, frequently citing those raw materials contribute to over 75% of the final SAF production cost, regardless of biomass source.

To conclude, it was found that microalgae-derived SAF produced via the HEFA process is the most cost-effective and sustainable option, utilizing all the information available presently. Calculations yielded an estimated price of 2.85 $\$/kg_{fuel}$ and emissions of 32.6 gCO_2e/MJ_{fuel}. The price is considerably higher than fossil-fuel-derived kerosene, but the merit of reducing the carbon footprint of the aviation sector should be weighed more heavily. Furthermore, to supply the commitment of France that 35% of its jet fuel demand in 2050 is to be addressed by SAF, a land area of 1,377 km^2 is needed to grow the algae *Nannochloropsis sp.* just for SAF production. It is important to note that these are the estimates as of today, and as technological engineering continues to improve in the coming years, the yields and efficiencies will also increase. Furthermore, SAF produced via different processes and from different biomass sources can all contribute to meeting this requirement. Therefore, it is important to continue research and development in the area of sustainable aviation, to be able to attain the goal of zero carbon emissions in the sector by 2050 and beyond.

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7 Appendix

7.1 Land Area Calculation

For the calculation of land area requirement, the overall conversion for each process from wet algae to jet fuel is first determined.

- **FT:**

$$\begin{matrix}\mathit{Overall}\\ \mathit{Conversion}_{FT}\end{matrix} = \begin{matrix}\mathit{Harvesting}\\ \mathit{recovery\ rates}\end{matrix} \times \begin{matrix}\mathit{Dry\ algae\ to}\\ \mathit{jet\ fuel\ ratio}\end{matrix} \tag{a}$$

Table A1. Values for calculation of overall conversion for FT *[112]*

Yield or recovery efficiency	Value	Source
Primary harvesting recovery efficiency	0.85	[64]
Secondary harvesting recovery efficiency	0.95	[64]
Dry algae to jet fuel yield	0.19	[84]
Overall conversion for FT	**0.16 L_{fuel} kg_{algae}^{-1}**	-

- **HEFA:**

$$\begin{matrix}\mathit{Overall}\\ \mathit{Conversion}_{HEFA}\end{matrix} = \begin{matrix}\mathit{Harvesting}\\ \mathit{recovery\ rates}\end{matrix} \times \begin{matrix}\mathit{Lipid}\\ \mathit{content}\end{matrix} \times \begin{matrix}\mathit{Lipid\ recovery}\\ \mathit{efficiency}\end{matrix} \times \begin{matrix}\mathit{Lipid\ to\ jet\ fuel}\\ \mathit{yield}\end{matrix} \tag{b}$$

Table *A2. Values for calculation of overall conversion for HEFA*

Yield or recovery efficiency	Value	Source
Primary harvesting recovery efficiency	0.85	[64]
Secondary harvesting recovery efficiency	0.95	[64]
Lipid content for *Nannochloropsis sp.*	0.599 kg_{lipids} kg_{algae}^{-1}	[54]
Lipid recovery efficiency	0.95	[80]
Lipid to jet fuel yield	0.58 L_{fuel} kg_{lipids}^{-1}	[84]
Overall conversion for HEFA	**0.35 L_{fuel} kg_{algae}^{-1}**	-

- **ATJ:**

$$\begin{matrix}\mathit{Overall}\\ \mathit{Conversion}_{ATJ}\end{matrix} = \begin{matrix}\mathit{Harvesting}\\ \mathit{recovery\ rates}\end{matrix} \times \begin{matrix}\mathit{Sugar}\\ \mathit{content}\end{matrix} \times \begin{matrix}\mathit{Sugar\ recovery}\\ \mathit{efficiency}\end{matrix} \times \begin{matrix}\mathit{Fermentation}\\ \mathit{yield}\end{matrix} \times \begin{matrix}\mathit{Alcohol\ to}\\ \mathit{jet\ yield}\end{matrix} \tag{c}$$

Table A3. Values for calculation of overall conversion for ATJ

Yield or recovery efficiency	Value	Source
Primary harvesting recovery efficiency	0.85	[64]
Secondary harvesting recovery efficiency	0.95	[64]
Sugar content for *Chlorella vulgaris*	0.4 kg_{sugar} kg_{algae}^{-1}	[56]
Sugar recovery efficiency	0.90	[79]
Fermentation yield	0.47 $kg_{alcohol}$ kg_{sugar}^{-1}	[79]
Alcohol to jet fuel yield	0.37 L_{fuel} $kg_{alcohol}^{-1}$	[113]
Overall conversion for ATJ	**0.07 L_{fuel} kg_{algae}^{-1}**	-

The land area is calculated by:

$$Land\ area\ [m^2] = \frac{SAF\ demand\ \left[\frac{L_{fuel}}{yr}\right] \times \frac{1\ yr}{365\ days} \times n\ \left[\frac{days}{cycle}\right]}{Conversion\ \left[\frac{L_{fuel}}{kg_{algae}}\right] \times \underset{concentration}{Algal} \left[\frac{kg_{algae}}{m^3\text{-}cycle}\right] \times \underset{depth}{Pond}\ [m]} \tag{d}$$

Table A4. Values for calculation of land area

Process	FT	HEFA	ATJ	Source
SAF demand of France in 2050 [a] (L_{fuel} yr^{-1})	6.5 billion	6.5 billion	6.5 billion	[114]
Conversion (L_{fuel} kg_{algae}^{-1})	0.16	0.35	0.07	Tables A1-A3
Algal concentration (kg_{algae} m^{-3} $cycle^{-1}$)	2.83	2.23	2.83	
Pond depth [b] (m)	0.3	0.3	0.3	[64]
n [c] (days $cycle^{-1}$)	10	18	10	[54], [56]
Land (km^2)	**1,323.5**	**1,376.8**	**3,149.0**	-

[a] For the calculation of the land area for the entire world's SAF requirement in 2050, the demand is simply replaced accordingly, and the land is calculated using the same equation.

[b] The pond depth of 0.3 meters is chosen since this is the maximum pond depth that allows light to reach the bottom of the pond [64].

[c] This value assumes that mature algae must be harvested, and fresh algae must be grown every n day.

7.2 GHG Emissions Calculation

The GHG emissions are estimated in grams of CO_2 equivalent per megajoule of fuel (gCO_2e MJ_{fuel}^{-1}). This calculation considers other forms of GHG aside from CO_2, such as methane, nitrogen and sulfur oxides. The value is estimated in two ways: (1) directly lifted from literature, or (2) calculation of energy consumption (MJ or kWh per kg_{fuel}), followed by application of the carbon intensity of the energy source (gCO_2e kWh^{-1}). Presently, the energy source is assumed to be either grid electricity or natural gas.

- For electricity:

$$CO_2\ emission\ \left[\frac{gCO_2e}{MJ_{fuel}}\right] = Energy\ consumption\ \left[\frac{kWh}{kg_{fuel}}\right] \times CI_{electricity} \left[\frac{gCO_2e}{kWh}\right] \times \frac{1\ kg_{fuel}}{44.1\ MJ_{fuel}} \tag{e}$$

- For natural gas:

$$CO_2\ emission\ \left[\frac{gCO_2e}{MJ_{fuel}}\right] = Energy\ consumption\ \left[\frac{MJ}{kg_{fuel}}\right] \times CI_{natural\ gas} \left[\frac{gCO_2e}{MJ}\right] \times \frac{1\ kg_{fuel}}{44.1\ MJ_{fuel}} \tag{f}$$

Table A5. Values of carbon intensities of energy sources

Carbon intensity	Value	Source
$CI_{electricity,\ France}$ (gCO_2e kWh^{-1})	56	[110]
$CI_{electricity,\ world}$ (gCO_2e kWh^{-1})	481	[110]
$CI_{natural\ gas}$ (gCO_2e MJ^{-1})	50	[115]

Note: In the case that energy consumption is provided in the units of [MJ kg_{algae}^{-1}], the following calculation must be performed to make the units consistent.

$$\begin{matrix}Energy \\ consumption\end{matrix}\left[\frac{kWh\ or\ MJ}{kg_{fuel}}\right] = \begin{matrix}Energy \\ consumption\end{matrix}\left[\frac{kWh\ or\ MJ}{kg_{algae}}\right] \div \left(\begin{matrix}Overall \\ Conversion\end{matrix}\left[\frac{L_{fuel}}{kg_{algae}}\right] \times 0.77\left[\frac{kg_{fuel}}{L_{fuel}}\right]\right) \quad \text{(g)}$$

This implies that the overall conversions of each process (as calculated above in Tables A1-A3) is necessary to convert it to [MJ kg_{fuel}^{-1}]. Therefore, the GHG emissions for algae cultivation, harvesting, and drying will vary per process, depending on the number of algae needed.

- Algae cultivation and harvesting:

Table A6. Values for calculation of GHG emissions in algae cultivation and harvesting [64]

Process	**Energy Usage (kWh kg_{algae}^{-1})**
Paddle Wheel	0.66
Initial Pumping and Filling	0.06
Makeup Water Pumping	0.23
On-site flue gas distribution electric	0.32
DAF + Centrifugation	0.60
Total	**1.87**

- FT:

$$CO_{2,FT} = CO_{2,algae} + CO_{2,drying} + CO_{2,transportation} + CO_{2,Process} \quad \text{(h)}$$

Table A7. Values for calculation of GHG emissions of FT

Step	**Energy requirement**	**Energy source**	**CO_2 emissions (gCO_2e MJ_{fuel}^{-1})**	**Source**
Algae cultivation and harvesting	1.9 kWh kg_{algae}^{-1}	Electricity	4.4	[64]
Algae drying	16.5 MJ kg_{algae}^{-1}	Natural gas	56.3	[64]
Transportation			1.2	[64]
Process			37.1	[113]
Total	**-**		**98**	**-**

- HEFA:

$$CO_{2,HEFA} = CO_{2,algae} + CO_{2,drying} + CO_{2,lipid\ extraction} + CO_{2,upgrading} - CO_{2,credits} \quad \text{(i)}$$

Table A8. Values for calculation of GHG emissions of HEFA

Step	**Energy requirement**	**Energy source**	**CO2 emissions (gCO2e MJfuel-1)**	**Source**
Algae cultivation and harvesting	1.9 kWh kg_{algae}^{-1}	Electricity	2.0	[64]
Algae drying	16.5 MJ kg_{algae}^{-1}	Natural gas	56.3	[64]
Transportation			1.2	[64]
Lipid extraction	-		12.9	[84], [116]
Upgrading	-		12.8	[84], [116]
Credit			-52.6	
Total	-		32.6	-

Credits

From Table 11, every 1 kg of harvested *Nannochloropsis sp* (the algae strain for HEFA) sequesters 1,790 g of CO_2 during its growth. After extraction, only 0.57 kg of the algae becomes lipids (due to the lipid content and extraction efficiency), while the balance (0.43 kg) turns into sludge. This sludge is fed to the digester to obtain a nutrient-rich cake that can be used as fertilizer (solid) and biomethane that can be used as fuel for the dryer (gas). The total amount of CO_2 present in this sludge is computed by linear scaling of the original sequestered CO_2, equal to 771.4 $gCO_2\ kg_{algae}^{-1}$. Converting to the units of $gCO_2\ MJ_{fuel}^{-1}$, it is approximately 52.6 $gCO_2\ MJ_{fuel}^{-1}$ which is considered CO_2 that is reused in the process.

- ATJ:

$$CO_{2,ATJ} = CO_{2,algae} + CO_{2,drying} + CO_{2,E\&F} + CO_{2,upgrading} \tag{j}$$

Table A9. Values for calculation of GHG emissions of ATJ

Step	**Energy requirement**	**Energy source**	**CO_2 emissions ($gCO_2e\ MJ_{fuel}^{-1}$)**	**Source**
Algae cultivation and harvesting	1.9 kWh kg_{algae}^{-1}	Electricity	5.10	[64]
Algae drying	4.0 MJ kg_{algae}^{-1}	Natural gas	34.5	[102]
Extraction and fermentation			19.8	[102]
Transportation			1.2	[64]
Upgrading			9.0	[117], [118]
Total			**69.6**	**-**

7.3 Cost

For cost estimates, all values are directly or indirectly derived from literature values. Sources of the data are indicated in the main text.