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# MICROALGAE: A POTENTIAL RESOURCE FOR AVIATION BIOFUEL AND THE DECARBONIZATION OF THE AVIATION SECTOR

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**Abstract.** Along with technological development and the effects of globalization, concern about climate change caused by anthropogenic action has been increasing over the years. The aviation sector is responsible for emitting large amounts of carbon dioxide into the environment, and this fact has contributed to the increase in research seeking solutions to mitigate the environmental impact. Aviation biofuels based on algae have been studied and have shown high potential as an alternative for the total or partial replacement of conventional petroleum-based fuels. For this reason, the present study gathers data available in the literature on microalgae as feedstock for the aviation sector, the methods of converting bio-oil into bio-kerosene studied so far, compares the properties of aviation biofuel and conventional fuel, and identifies the technical, economic, and environmental challenges faced in implementing this alternative to conventional kerosene.

**Keywords:** aviation biofuels, microalgae, conversion methods, renewable feedstock, sustainability

## 1. INTRODUCTION

Aviation increasingly plays a significant role in transporting people and goods, connecting various parts of the world and boosting the global economy. However, the growing popularity of air travel has raised concerns about the environmental impact of this sector, particularly the fuel consumption responsible for exacerbating the greenhouse effect. Aviation's reliance on fossil fuels has been one of the main challenges for the industry and science, as the emission of gases from the combustion of these fuels contributes significantly to climate change and global warming (Said *et al.*, 2022).

For illustration, it was reported that in 2013, the aviation industry emitted approximately 705 Mt of CO<sub>2</sub>, representing an estimated share of 2 to 3% of global CO<sub>2</sub> emissions during that period. This percentage tends to grow considerably, as studies point to a future estimated increase of 1000 to 3100 Mt of CO<sub>2</sub> to be released by aviation (Bwapwa *et al.*, 2017). In 2018, a study was conducted comparing different forms of transportation and their global greenhouse gas (GHG) emissions. As shown in Fig. 1 below, among the modes of transport, the aviation sector was responsible for about 12% of the emitted CO<sub>2</sub> (Umenweke *et al.*, 2023).

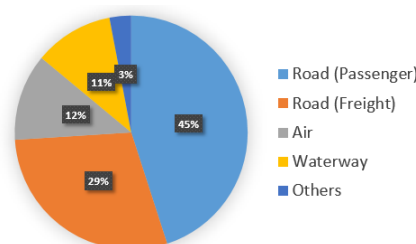


Figure 1. Global GHG emissions from transportation in 2018. Adapted (Umenweke *et al.*, 2023)

In this context, the aviation industry is primarily focusing its efforts on the development of carbon-neutral biofuels, widely known as Sustainable Aviation Fuels (SAF), which aim not only to reduce but also to neutralize carbon emissions associated with air operations. The goal is to achieve net-zero carbon emissions by 2050, representing a significant step towards sustainability and mitigating the environmental impacts of this sector. This alternative fuel, SAF, aims to convert renewable raw materials, such as biomass, into a sustainable aviation fuel (Umenweke *et al.*, 2023; Mofijur *et al.*, 2022).

Biomass, mentioned above as a potential input, is organic material with high potential for use as a renewable energy source. It is formed by the accumulation of various residues and can originate from both plant and animal sources (Arévalo *et al.*, 2017; Lim *et al.*, 2021). Due to its organic origin, biomass generally has a high carbon value and low sulfur content in its composition, making it promising as a raw material for obtaining bioenergy (Lim *et al.*, 2021).

One of the pathways biomass can provide is for the production of biofuels. Due to its organic and biodegradable

nature (Sajjadi *et al.*, 2014; Estevam *et al.*, 2022), the combustion produced from this alternative is considered clean, given that conventional petroleum-derived fuels emit polluting gases such as sulfur compounds and contain toxic compounds in their composition, such as aromatic and metallic substances (Sajjadi *et al.*, 2014). For this reason, biofuels point to a solution for the aviation sector with the production of SAF, also known as bio-jet fuel (Wang and Tao, 2016).

The keen interest in microalgae and their many possibilities is due to their wide range of applications. In this context, "biofuel" is a general term that encompasses biodiesel, biohydrogen, and aviation biofuel (Bwapwa *et al.*, 2017; Rony *et al.*, 2023). Additionally, with biomass from microalgae, it is possible to produce biobutanol, bioethanol, and methane gas. The co-products generated by them are also beneficial, such as proteins, carbohydrates, and even the residual biomass generated after bio-oil extraction, which can be used in animal feed and fertilizers (Lim *et al.*, 2021).

The great energy potential of microalgae lies in their inherent energy due to photosynthesis, which occurs through the capture of sunlight. In this process, CO<sub>2</sub> biofixation occurs for glucose production. Biofixation is also known as biological carbon sequestration, making the cultivation of microalgae for biofuel production even more interesting (Mata *et al.*, 2010; Mofijur *et al.*, 2022), aiming to meet the decarbonization goals of the aviation sector mentioned earlier.

Therefore, with the intention of achieving the highest quality of the final product, besides the concern with the characteristics of the extracted bio-oil from microalgae, there is also interest in discussing the best method for converting this lipid into aviation biofuel. For this reason, this bibliographic research aims to aggregate knowledge about microalgae for the production of bio-jet fuel, bringing comparisons between the different methods of converting bio-oil into bio-kerosene available in the literature, as well as identifying the technical, economic, and environmental challenges faced in implementing this alternative to conventional kerosene.

## 1.1 Conversion Methods

The conversion of lipids present in microalgae into biofuels suitable for aircraft use involves a range of distinct approaches, such as pyrolysis, hydrothermal liquefaction, transesterification, gasification, hydroprocessing, and sugar-to-jet conversion (Rony *et al.*, 2023; Bwapwa *et al.*, 2017; Lim *et al.*, 2021).

The diversity of these conversion routes represents the continuous efforts of the industry and researchers to develop viable and efficient alternatives that meet the stringent quality and safety standards of aviation (Mofijur *et al.*, 2022). Some of these routes have already obtained ASTM certification, given the maturity of development, availability of fuel, and their potential to drive the aviation sector towards greater sustainability (Lim *et al.*, 2021).

The conversion of microalgae oil into aviation biofuel requires reducing the number of carbon chains to be within the expected range; for example, between 8 and 16 carbons for commercial and military jets. By using operational processes defined by temperature control, pressure, and/or catalysts, these conversion methods can break long carbon chains to achieve the desired final properties of the biofuel (Bwapwa *et al.*, 2017) — properties that will be discussed later in section 8 of this work.

It is worth noting that despite recent advances, the ongoing search for improvements has not ceased, as many current studies aim to reduce the costs of biofuel without compromising its efficiency. However, detailed knowledge about the different conversion routes, their cost-benefit, and environmental aspects are not yet widely disseminated in the literature, which could be relevant to the general public and particularly to those interested in producing SAF from microalgae (Bwapwa *et al.*, 2017).

## 2. PYROLYSIS

Pyrolysis is a thermal process in which organic molecules are decomposed in the absence of oxygen, producing various by-products such as water, gas, oil, and charcoal, depending on the process parameters used. Generally, in this procedure, gases are generated at the highest temperatures of the process (which can reach up to 800 °C), and charcoal is generated at the final, moderate, and low temperatures (equal to or below 450 °C). For biomass, this process is known as fast pyrolysis, usually occurring at temperatures between 400 and 600 °C—a working range reached rapidly. After this process, the gas is cooled through quenching or taken to a condenser, the final step to obtain bio-oil (Bwapwa *et al.*, 2017; Rony *et al.*, 2023).

Applied to biomass, this process can generate an efficiency of around 80% by weight of bio-oil obtained. The catalyst used in this procedure, whose influence also improves the oil quality, is zeolite, with the potential to reduce oxygen content and increase the proportion of aromatic compounds in the obtained bio-oil (Bwapwa *et al.*, 2017; Rony *et al.*, 2023), which is interesting for improving the biofuel's properties (Lim *et al.*, 2021). When catalytic pyrolysis is compared to non-catalytic pyrolysis, it is observed that the former produces higher quality oil without the need for many upgrading stages, thereby reducing the process cost compared to the latter (Rony *et al.*, 2023).

Lim *et al.* (2021) reported that in a study on the effect of catalytic pyrolysis on *Chlorella Vulgaris*, the bifunctional catalyst HZSM-5LS was used during the process. It was observed that with its use, the activation energy (EA) required for the reaction and enthalpy showed lower results, 133.26 kJ/mol and 129 kJ/mol, respectively. This confirmed that using catalysts reduces the energy needed during the process, making it a promising thermochemical pathway compared

to non-catalytic pyrolysis.

Thus, pyrolysis shows potential benefits and is an acceptable method for obtaining oil. However, it presents challenges concerning temperature regulation, which occurs in very high ranges. Additionally, due to the by-products generated during the process, the produced oil may contain a high amount of water and oxygen, even with the use of catalysts. Therefore, to improve the obtained oil quality, hydroprocessing and hydrocracking steps may be added (Rony *et al.*, 2023), or even a pre-process dehydration step can improve results — a factor that should be considered, as it adds cost to the methodology (Lim *et al.*, 2021; Bwapwa *et al.*, 2017).

Moreover, the development and optimization of low-cost alternatives are necessary, such as improving existing processes like hydrodeoxygenation and deoxygenation. Thus, studies on the suitability of catalysts aiming to improve the process, adapting their life cycle, reducing hydrogen intake during operation, and even using deoxygenation in conventional refineries for bio-oil co-processing, may be future alternatives that are currently in laboratory-scale applications (Bwapwa *et al.*, 2017).

### 3. HYDROTHERMAL LIQUEFACTION

Hydrothermal liquefaction is a promising approach used in the production of aviation biofuel. Similar to pyrolysis, this thermochemical process occurs under high pressure and medium temperature conditions to transform algal biomass into bio-oil, which can then be converted into biofuel. In this process, macromolecules present in the biomass undergo hydrolysis, breaking into smaller molecules (Bwapwa *et al.*, 2017). Additionally, dehydration and decarboxylation processes occur during this process to remove a substantial amount of oxygen present in the biomass to improve the fuel's performance (Bwapwa *et al.*, 2017; Lim *et al.*, 2021).

The hydrothermal liquefaction method offers notable advantages over others, such as high conversion efficiency provided by the properties of sub/supercritical water as the reaction medium, and there is no need for a pre-processing drying step, reducing energy consumption. Moreover, studies have shown that microalgae with low lipid content can be transformed into oil through hydrothermal liquefaction (Gai *et al.*, 2015).

However, this technology's use is still quite limited to laboratory scale and pilot projects, as industrial application needs to overcome challenges (Rony *et al.*, 2023). One of the main obstacles relates to the reaction mechanism of the hydrothermal liquefaction process. Many studies have focused on single model compounds, which do not fully reflect biomass behavior during the process, as the different fractions of microalgae interact during the process, potentially leading to the production of crude bio-oil from various substrates (Gai *et al.*, 2015).

Gai *et al.* (2015) proposed investigating the influence of reaction temperature and raw material properties on the liquefaction pathway. Thus, *Chlorella pyrenoidosa* and *Spirulina platensis* species with different lipid contents were selected to obtain a more comprehensive understanding of basic reaction pathways. For this purpose, spectral analysis and molecular identification of these strains were used to help interpret the interactions between reaction intermediates generated from different substrates.

### 4. TRANSESTERIFICATION

Transesterification, also called alcoholysis, is one of the processes used to obtain biodiesel—which is a mixture of methyl and ethyl esters of fatty acids (FAME) — from oil. In this chemical reaction, an ester is obtained from another ester: the triglycerides that compose the bio-oil produced from microalgae react with alcohol (usually methanol) in the presence of a catalyst (a strong base or acid), producing fatty acid esters with glycerol as a by-product—which is positive, as glycerin has commercial value (Sajjadi *et al.*, 2016; Kumbhar *et al.*, 2022).

One of the objectives of performing transesterification with short-chain alcohols is precisely to reduce the viscosity of the oil and meet the requirements set by standards, as viscosity is considered a major hindrance regarding the properties of biofuels (Sajjadi *et al.*, 2016; Bwapwa *et al.*, 2017).

Aiming at the production of aviation biofuel, the transesterification process is followed by decarboxylation and deoxygenation to increase the fuel's energy density, and then isomerization to reduce the carbon chains into smaller chains. Thus, the final product is a high-purity fuel (Rony *et al.*, 2023; Bwapwa *et al.*, 2017).

The great advantage is that transesterification itself is an efficient and economical process; however, the freezing point obtained may be higher than the reference value for aviation biofuel (Bwapwa *et al.*, 2017), in addition to the difficulty related to the stability of the catalysts (Estevam *et al.*, 2022). Furthermore, the combination of all the additional processes to transesterification mentioned above, aiming at purification, makes this process quite expensive, making it necessary to conduct more associated studies, both laboratory and pilot, for better optimization (Bwapwa *et al.*, 2017).

### 5. GASIFICATION/FISCHER-TROPSCH

Gasification with Fischer-Tropsch synthesis (GFT) is considered a promising route for converting microalgae biomass into biofuel, particularly for producing synthetic paraffinic kerosene (SPK) (Lim *et al.*, 2021). This method consists of

first subjecting the biomass to a thermochemical conversion process called gasification, at a temperature between 150°C and 300°C and under controlled pressure ranging from 10 to 40 bar, transforming it into synthesis gas (CO, CO<sub>2</sub>, CH<sub>4</sub>, and H<sub>2</sub>). Subsequently, Fischer-Tropsch synthesis is carried out on this gas while it reacts with hydrogen in the presence of a catalyst, typically iron, cobalt, or nickel (Lim *et al.*, 2021; Bwapwa *et al.*, 2017). The catalytic action occurring up to this point produces a liquid, and then the fractionation technique can be applied to produce the necessary aviation fuel fractions (Lim *et al.*, 2021).

Initially, microalgae have a high moisture content, which impairs the efficiency of the gasifier and results in synthesis gas with low energy content (the calorific value ranges between 3.45 and 5.9 MJ/kg) (Lim *et al.*, 2021). However, it is possible to solve this problem by performing a drying step before the gasification process. Drying occurs at temperatures ranging from 150°C to 500°C, aiming to reduce the moisture content, thereby improving the gasifier's performance (Rony *et al.*, 2023). It is worth noting that aviation fuel produced from this route based on ASTM certification is called Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK), which is considered suitable for converting various types of biomass, such as lignocellulosic, woody, agricultural, and microalgal. However, despite the positive prospects, the process still requires significant optimization and improvements to promote large-scale implementation (Bwapwa *et al.*, 2017).

## 6. HYDROPROCESSING

The hydroprocessing method is one of the most mature techniques for producing aviation biofuel today (Umenweke *et al.*, 2023), a step commonly following pyrolysis and hydrothermal liquefaction. The bio-jet fuel produced from hydroprocessing is called hydroprocessed esters and fatty acids (HEFA) (Lim *et al.*, 2021) and has been widely adopted by the industry (Umenweke *et al.*, 2023), as it presents properties similar to fossil fuels, but with some environmental advantages, such as reducing greenhouse gases including nitrogen oxides (NO<sub>x</sub>), carbon dioxide (CO<sub>2</sub>), carbon monoxide (CO), hydrocarbons (HC), and particulate matter. Furthermore, HEFA has lower aromatic and sulfur content, high thermal stability, high cetane number, and low exhaust emissions (Lim *et al.*, 2021).

This route begins with the extraction of lipids from microalgae to obtain triglycerides, then these triglycerides, in the presence of a catalyst, are subjected to conditions of high pressure and temperature to transform them into linear chain hydrocarbons. During the deoxygenation or decarbonization stage, the oxygen content of the triglyceride raw material is removed, generating a range of by-products, including water, carbon dioxide, and carbon monoxide. At the end of this stage, the carbon chain length of the fatty acid undergoes isomerization and cracking processes to obtain fuel with the desired properties (Lim *et al.*, 2021).

Other notable characteristics of HEFA aviation fuels include the ability to be stored for long periods due to their stability and resistance to microbial growth, high energy content, allowing direct application in aircraft engines without the need for blending with fossil fuels. It is worth mentioning that, although this practice is viable, blending with conventional aviation fuel is recommended to improve lubricity (Lim *et al.*, 2021; Kumbhar *et al.*, 2022).

It should be noted that although hydroprocessing represents an extremely promising route for producing biofuels, there are significant challenges that need to be overcome. One of these challenges is the hydrodeoxygenation reaction, which, as mentioned earlier, requires conditions of high pressure and temperature, making the process costly. Furthermore, the use of problematic catalysts and the relatively high cost of raw materials, such as fats and oils, are also important issues to be addressed.

## 7. SUGAR-TO-JET

The biochemical route for converting microalgae into aviation biofuel, sugar-to-jet, is a highly promising approach that involves using the carbohydrate biomass found in microalgae to produce alcohols, such as ethanol and butanol, which are then transformed into biofuels. The first step in executing this technique consists of extracting the starch present in the cells of microalgae cultures to convert them into sugars. Next, the obtained sugars undergo a fermentation stage to produce alcohols, such as ethanol and butanol (Lim *et al.*, 2021). Fermentation is characterized by being a process in which enzymes are used to trigger specific biochemical reactions, functioning as catalysts for the reaction (Rony *et al.*, 2023). Finally, these alcohols undergo a series of chemical reactions such as dehydration, oligomerization, hydrogenation, and distillation to be converted into biofuel (Lim *et al.*, 2021).

Among the various species of microalgae, the strains of *Chlorella*, *Chlamydomonas*, *Dunaliella*, and *Scenedesmus* sp. have shown to be some of the most promising for obtaining alcohol, as these microalgae have demonstrated the ability to produce more than 50% of their dry cell weight in the form of starch, which, as previously mentioned, can be converted into alcohol through fermentation. It is important to note that due to the low energy density, flash point, and temperature-related properties, the direct use of bioalcohol as fuel is an unfeasible practice (Lim *et al.*, 2021). Therefore, to meet the stringent international specifications for aviation biofuel, it is essential for the alcohol to undergo stages such as dehydration, oligomerization, hydrogenation, and distillation.

An interesting fact to mention is that the fuel produced from this route has already been used as biofuel for test flights in an A-10 aircraft (USAF) and an F/A-18 Hornet fighter jet (US Navy) in 2012 and 2014, respectively (Lim *et al.*, 2021).

However, fuel production via this route is still in the development and improvement phase, considering that continuous research and the development of more efficient technologies are essential to maximize the yield and productivity of these biofuels to make them competitive with fossil fuels.

## 8. COMPARISON OF CONVENTIONAL AVIATION KEROSENE AND AVIATION BIOFUEL FROM MICROALGAE

The table presented in this section compares the properties of conventional aviation kerosene and aviation biofuel. The standards shown in the table were adapted from Resolution ANP No. 856, dated October 22, 2021 (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2021b). This Resolution defines the specifications that aviation kerosene must meet, as well as quality control obligations that must be fulfilled by economic agents for the fuel to be commercialized in the national territory.

According to the Resolution (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2021b), aviation kerosene types are divided into four major groups:

JET A: fossil-based aviation kerosene, with a maximum freezing point of  $-40^{\circ}\text{C}$ , exclusively for use in aircraft turbines;

JET A-1: fossil-based aviation kerosene, with a maximum freezing point of  $-47^{\circ}\text{C}$ , exclusively for use in aircraft turbines;

Alternative aviation kerosene (JET alternative): fuel derived from alternative sources such as biomass, vegetable oils, animal fats, waste gases, solid waste, coal, and natural gas, produced by processes that meet the requirements set forth in this Resolution;

Aviation kerosene C (JET C): fuel exclusively for use in aircraft turbines, composed of a single type of alternative JET blended with JET A or JET A-1 in proportions defined in this Resolution.

Within the definition of alternative JET, the Resolution (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2021b) specifies a type of bio-kerosene produced from the microalgae *Botryococcus Braunii* – which will be used as an example to represent the physicochemical properties of kerosene produced by microalgae according to the standard. It is defined as follows:

Synthetic paraffinic kerosene derived from bio-derived hydrocarbons, fatty acids, and hydroprocessed esters (SPK-HC-HEFA): synthetic paraffinic kerosene obtained by hydrogenation of bio-derived hydrocarbons from the microalgae *Botryococcus braunii*, fatty acid esters, and free fatty acids.

Therefore, Tab. 1 below compares the physicochemical properties between JET A, JET A-1, and JET C aviation fuels with SPK-HC-HEFA (the alternative JET made from microalgae), as laid out in Resolution ANP No. 856 (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2021b), in addition to showing properties obtained from studies in the literature, where cultivation and conversion methods of microalgae bio-oil into aviation bio-kerosene varied between hydroprocessing and transesterification.

Table 1. Properties of conventional aviation kerosene and aviation biofuel.

PROPERTIES	JET A, JET A-1, JET C	JET-C (Additional requirements)	SPK-HC-HEFA	Microalgae Biofuel Produced by Hydroprocessing	Microalgae Biofuel Produced by Transesterification
LHV (MJ/kg)	42.8	-	-	44	35 to 41
Freezing point ( $^{\circ}\text{C}$ )	-47 (Jet A-1), -40 (Jet A)	-	-40	-30	Close to 0 (zero)
Flash point ( $^{\circ}\text{C}$ )	38	-	38	68	115
Density ( $\text{kg}/\text{m}^3$ )	771.3 to 836.6 (at $20^{\circ}\text{C}$ )	-	725.9 to 796.5 (at $20^{\circ}\text{C}$ )	1380 (at $15^{\circ}\text{C}$ )	864 (at $15^{\circ}\text{C}$ )
Viscosity ( $\text{mm}^2/\text{s}$ )	8.0 (at $-20^{\circ}\text{C}$ )	12.0 (at $-40^{\circ}\text{C}$ )	-	2.8 (at $-20^{\circ}\text{C}$ )	7.5 (at $-20^{\circ}\text{C}$ )
Total surfur	0.3% by mass	-	15 mg/kg	0.27% by mass	0.05% by mass
Aromatic compounds	25% volume, max	8% volume, min	0.5% (m/m), max additives	-	-
Water, max	-	-	75 mg/kg	-	-
REFERENCES	(Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2021b)	(Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2021b)	(Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2021b)	(Lim <i>et al.</i> , 2021)	(Bwapwa <i>et al.</i> , 2017)

The properties of aviation biofuels can vary based on several factors, including the chosen strain of microalgae as raw material, the cultivation method—which can affect lipid production and oil composition—and the method used to convert bio-oil into aviation bio-kerosene. These operational processes define characteristics such as carbon chain length, which significantly influence key physicochemical properties required to meet standard specifications, including viscosity,

density, and freezing point. As mentioned earlier in subsection 1.1 (on conversion methods), the carbon chain length of the biofuel can affect important physical and chemical properties necessary to meet standard specifications, such as viscosity, density, and freezing point — factors that can affect fuel injection into the engine, automatic ignition, and fuel flow point (Moraes, 2008).

According to Tab. 1, the lower heating value (LHV) is not specified for SPK-HC-HEFA (alternative JET produced from microalgae). However, the results of the aviation biofuel production presented in the literature show that the bio-kerosene obtained from hydroprocessing met the standard, with a value higher than the minimum required. Only the bio-kerosene produced by transesterification showed a slight variation below.

For freezing point — where a low value is essential to prevent fuel crystallization at high altitudes (Lim *et al.*, 2021; Rony *et al.*, 2023) — the SPK-HC-HEFA standard matches JET A at  $-40^{\circ}\text{C}$ . However, both hydroprocessed and transesterified bio-kerosenes did not meet the standard, showing higher values of  $-30^{\circ}\text{C}$  and  $0^{\circ}\text{C}$ , respectively. For this case, an anti-freeze additive can be added to lower the freezing point temperature (Lim *et al.*, 2021).

Regarding density values — which should remain stable to avoid compromising the ideal fuel mass injected into the combustion chamber (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2021a) — there is variation between conventional kerosene standards (JET A and JET A-1) and SPK-HC-HEFA (alternative JET). However, even considering this difference, neither hydroprocessed nor transesterified bio-kerosenes met the standard; both values were above the specified limit, with the latter being closest to the standard.

Viscosity — which, if too high, can affect fuel flow (Moraes, 2008) — for microalgae obtained by hydroprocessing and transesterification was within the standard, with values not exceeding the maximum of  $8\text{ mm}^2/\text{s}$ .

Flash point — which indicates the lowest temperature at which a fuel can ignite, with higher values being safer (Moraes, 2008) — is not defined for SPK-HC-HEFA. The literature reported significantly higher values for bio-kerosene production compared to the minimum standard for conventional aviation fuel, which is  $38^{\circ}\text{C}$ , showing reliability regarding flammability.

The literature found did not present the amount of water obtained by bio-kerosene produced from hydroprocessing or transesterification. However, SPK-HC-HEFA has a limit of  $75\text{ mg/kg}$ . This is because the presence of water and other compounds from contamination or degradation can promote oxidation and influence fuel oxidative stability (Caldeira *et al.*, 2017).

The sulfur content of biofuels from hydroprocessing and transesterification was below the maximum limit required by the standard, a positive outcome as it will result in low emissions of sulfur compounds during combustion (Rony *et al.*, 2023).

The Tab. 1 also shows that for the SPK-HC-HEFA standard, there is a maximum limit on aromatic content, whereas conventional JET fuels have a maximum composition limit. This indicates that biofuels from microalgae have a low aromatic content — a beneficial feature regarding combustion products. However, it is important to note that complete absence of aromatic compounds in aircraft engines can lead to issues such as fuel leakage and low combustion heat (Lim *et al.*, 2021).

Mofijur *et al.* (2022), in their conclusion, reported that among the 17 strains analyzed, none met the density, heating value, and freezing point required by international aviation standards for any of the strains. Therefore, studies are being developed to modify the use of this raw material for bio-kerosene production, such as blending with conventional fuel or with a solvent or additive derived from petroleum, for example.

## 9. TECHNO-ECONOMIC AND ENVIRONMENTAL ASPECTS

Techno-economic analysis involves assessing the economic viability of a process, analyzing each part until reaching the final product (Muhammad *et al.*, 2021). However, for the production of aviation biofuel from microalgae, the literature still lacks a detailed comparison between different possible methodologies, specifying cost-benefit parameters and environmental impact with actual numbers and costs for each pathway (Rony *et al.*, 2023; Muhammad *et al.*, 2021).

The data available in the literature for the pathways presented in this work are more general and qualitative, providing only indications of results, which show that conversion methods can be expensive due to the high energy demand of some processes. Additionally, there is the possibility of greenhouse gas emissions (GHG) — albeit much lower than emissions from petroleum-derived fuels — due to the combination of various necessary processes to achieve high-quality bio-kerosene according to established standards for subsequent commercialization.

For improving the quality of aviation biofuel, for instance, hydrothermal processes (such as hydrothermal liquefaction) and pyrolysis — mentioned earlier in this work — require extensive deoxygenation, which can add significant costs to the processes; a factor analyzed as a hurdle for scalability and efficiency in bio-kerosene production (Bwapwa *et al.*, 2017). Furthermore, the pyrolysis process has environmental impacts due to the potential emission of greenhouse gases from the energy needed for raw material drying and coproduct combustion (Lim *et al.*, 2021), while the use of catalysts can increase the cost of hydrothermal liquefaction (Rony *et al.*, 2023).

As mentioned in section 4, the transesterification process can also become expensive due to additional processes required for obtaining aviation fuel, along with the potential emission of considerable amounts of  $\text{CO}_2$  during decar-

boxylation, depending on the volumes of biofuel produced (Bwapwa *et al.*, 2017). Among hydroprocessing processes, sugar-to-jet, and GFT, the former is the cheapest conversion method but requires longer operation time. Seeking better selectivity of C8-C16 hydrocarbons (Lim *et al.*, 2021), GFT has proven suitable for aviation fuel production, albeit at a high cost and intensive energy use (Bwapwa *et al.*, 2017; Lim *et al.*, 2021). Meanwhile, sugar-to-jet process, despite still in development, has shown promise in replacing other methods, being a cost-effective route that requires relatively less energy (Lim *et al.*, 2021).

Although the use of bio-oil produced by microalgae is environmentally safe, the processes related to its extraction and subsequent aviation biofuel production present techno-economic and environmental challenges, requiring further studies on technologies that make them viable in all aspects (Ağbulut *et al.*, 2017).

## 10. DISCUSSION

Taking all points into consideration, it is understood that achieving efficiency in biofuel production, while adhering to its clean energy production principle, requires that techniques, operations, and parameters be ecologically sound. Therefore, many studies focus on improving processes so that aviation biofuel production techniques, from the selection of microalgae strains for cultivation to the conversion of bio-oil into bio-kerosene, are enhanced and demonstrate scalability with environmental and cost-effectiveness, making this alternative commercially attractive (Muhammad *et al.*, 2021).

For this reason, it is crucial that the development of microalgae-based biofuel industries receives governmental support. After all, the first and second generation biodiesel is only economically viable because of the government policies that encourage commercialization through subsidies, tax exemptions, import tariffs and allocation. Similar efforts must be made to support third generation biofuels. Here in Brazil, the National Biodiesel Production and Use Program (PNPB) has implemented a policy of incentives, with a reduction in biodiesel production taxes from various raw materials. This fact can increase producers' interest in the use of microalgae as raw materials for biofuel production (Muhammad *et al.*, 2021).

The challenge of producing biofuels that comply with established standards and regulations is undeniable (Bwapwa *et al.*, 2017). Thus, investments in improvement technologies for application in processes, as well as studies on the use of Machine Learning for predicting the properties (and therefore quality) of biofuels obtained, for example, are gaining momentum and can help achieve this goal effectively (Suvarna *et al.*, 2022). Studies on genetic modifications in microalgae also emerge as an interesting option for achieving desired properties (Mofijur *et al.*, 2022; Bwapwa *et al.*, 2017).

Furthermore, other alternatives to achieve the desired biofuel profile have been mentioned in section 8 of this work, such as blending the bio-kerosene obtained from algae with some petroleum product or additive (Mofijur *et al.*, 2022). It is known that the ultimate goal is the complete substitution of fossil-based fuel by aviation biofuel; however, it is necessary to consider that the change is gradual, and according to the progress of technologies to improve bio-kerosene, it is possible to transform it into a self-sufficient option to fully replace petroleum-based fuel. Although not the ideal scenario, this blending alternative mitigates the exclusive need for petroleum, thus delaying the depletion of this source.

## 11. CONCLUSION

Due to the scenario of finite oil availability and the environmental impacts caused by its use, the demand for diversification and expansion of energy supply is gaining more attention. Aviation bio-kerosene produced from microalgae shows enormous potential for future substitution of conventional aviation fuel (Rony *et al.*, 2023), but with existing technologies, the processes for its production are not always economically viable to be competitively commercialized against fossil origin kerosene. For this reason, research aims to improve and optimize these processes to increase their techno-economic and environmental viability, aiming to make this alternative feasible on a large scale (Nascimento *et al.*, 2013; Bwapwa *et al.*, 2017).

Emphasis should also be given to the importance of political structures to improve economic and production viability, aiming to make aviation bio-kerosene a long-term total substitute for petroleum-based kerosene. Furthermore, enriching the literature with research on process scalability, energy use, and processing routes, along with greater availability of techno-economic data with quantitative analyses of the entire process until obtaining biofuel, can help guide future improvements (Muhammad *et al.*, 2021).

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