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Harnessing Waste and Algae-Derived Sustainable Aviation Fuels: A Pathway to Circular Economy and Policy Integration for Decarbonising Aviation

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Research Question: To what extent can waste and algae be effectively utilized to produce sustainable aviation fuels (SAFs), thereby addressing both the unsustainability of aviation and current waste management practices?

Abstract
The reliance of the aviation industry on fossil-based jet fuels poses a major environmental challenge that demands innovative solutions to achieve carbon neutrality. This paper explores the viability of sustainable aviation fuels derived from solid waste and microalgae as renewable alternatives to conventional fuels. It analyses key technological pathways such as waste gasification followed by Fischer-Tropsch synthesis, plastic pyrolysis and algal conversion through transesterification and hydrothermal liquefaction. Beyond technological feasibility, the paper also examines the policy and implementation framework necessary to transition these solutions from research to real-world application, emphasising regulatory clarity, financial incentives and circular economy integration. Findings indicate that while both feedstocks demonstrate strong potential for decarbonisation, the capability and cost competitiveness depend heavily on robust policy support. Integrating waste management, carbon pricing and SAF certification mechanisms can enable the aviation sector to achieve meaningful sustainability and contribute to broader circular-economy goals.

Keywords: *sustainable aviation fuel, waste-to-fuel, algae biofuel, circular economy, aviation decarbonisation, environmental policy*

I. Introduction

The Aviation industry, encompassing a wide network for global operation of aircraft and airports, is the backbone of the economy by facilitating trade, enabling tourism, and providing numerous jobs. Globally, the Aviation industry supports $4.1 trillion, which amounts to 3.9% of the world's gross domestic product (GDP), and supports 86.5 million jobs (Persefoni, 2024). From pilots and traffic controllers to engineers and airline executives, the role that the Aviation industry plays today is vital.

However, there's a crucial drawback that the world fails to recognise: unsustainable fuel. This sector alone accounts for 2% of the global greenhouse gas emissions, and is constantly pressured to reduce them (IATA, 2022; Our World in Data, 2024). Not only are traditional sources of jet fuel unsustainable, but reliance on them also implies an underutilization of natural resources and waste. Increasingly, we can observe a rising trend in the amount of solid waste that is being produced, and this waste often contains valuable resources, like algae, that have immensely beneficial uses, but are wasted and dumped every day (ICAO, 2023).

Sustainable Aviation Fuels (SAFs) are types of aviation fuel that can solve these two issues simultaneously. They provide a sustainable alternative to traditional sources of jet fuel and can be an avenue to utilize waste that is not managed and discarded properly (PNAS, 2022; ICAO, 2023). For instance, these fuels can be drawn from non-exhaustive sources such as algae, which have a high oil content (Sharma et al., 2024).

However, while SAFs have garnered a lot of attention for being a promising alternative to unsustainable aviation fuels, significant challenges still remain. Additionally, the environmental implications of such processes and the incorporation of these fuels in the modern system need further exploration (Brennan & Owende, 2010; Venteris et al., 2014; Zhou et al., 2022). Therefore, this research paper aims to answer the following question: **To what extent can waste and algae be effectively utilized to produce sustainable aviation fuels (SAFs), thereby addressing both the unsustainability of aviation and current waste management practices?**

This paper examines the environmental and economic viability of implementing SAFs derived from solid waste and algae. It argues that such fuels can play a critical role in advancing sustainable development and fostering a circular economy by reducing dependence on conventional non-renewable jet fuels and mitigating their environmental impacts.

II. Background

Aviation is a key player across multiple areas, including tourism, trade, and healthcare. Aviation's dominance in the tourism sector is increasing exponentially; currently, 58% of all international tourists travel by air, underscoring the importance of Aviation in our lives (ATAG, 2023). To facilitate such large numbers, these aircraft consume a tremendous amount of jet fuel. In the USA alone, an average of 1,559 thousand barrels of jet fuel are utilised per day (TheGlobalEconomy.com, 2025). The Aviation sector relies heavily on fuel from unsustainable sources, such as fossil fuels with limited supply, which produce large amounts of carbon emissions (Shine, 2023). As seen in Figure 1, the world has already crossed the 880 million-ton threshold of global carbon dioxide emissions from the aviation sector, and scientists have predicted that this rate will grow even more rapidly as aviation becomes even more accessible (Air Transport Action Group, 2024). Moreover, studies have shown that the Aviation sector is the hardest to decarbonise due to its high energy requirements and the expense of alternative technologies; hence, finding a solution becomes even more essential. This highlights the need to curb this crisis as soon as possible, and the global importance of finding a more sustainable alternative to the current fuel sources.

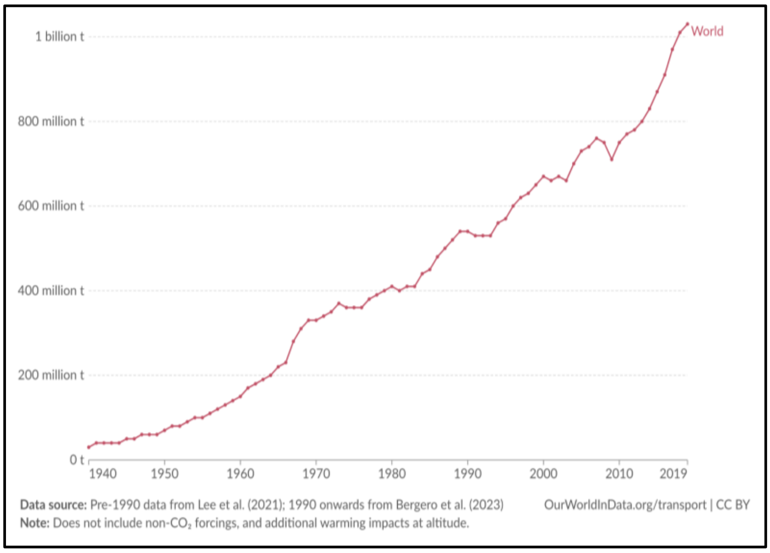

Figure 1: Global carbon dioxide emissions from aviation from 1940 to 2019

To minimise this unsustainable consumption, scientists have developed the concept of SAFs, or sustainable aviation fuels. SAFs are fuels that are composed of non-petroleum feedstocks that reduce emissions from air transportation. Unlike conventional sources, sustainable jet fuels are made of plant, animal material or waste, all of which have an unlimited supply and are biological sources that occur naturally. Not only do they rely on biomass, including algae, crop residue, animal waste, and forestry residue, but they are also highly viable to implement, as they can be used as "drop-in" replacements, meaning aircraft engines do not need to be modified to use them (Shine, 2023). Many countries have already begun implementing guidelines for the use of these fuels. Based on the ranked airlines' offtake agreements and the data publicly available by Eurocontrol, ICAO, airports and airlines, SAF is expected to be primarily available in European airports (60% of the airports with SAF), followed by North America (25% of airports with SAF), Asia (10% of the airports with SAF) and Oceania (less than 5% of the airports with SAF) (Transport & Environment, 2025).

However, the question remains: Why isn't SAF being used more? Although demand for bio-jet fuels has been rising, they still account for only 0.1% of total aviation fuel consumption (Shine, 2023). This is because implementing these fuels is not easy; it comes with various obstacles, such as the high costs associated with new technologies and production methods. The European Parliament says, "There's no sustainable aviation fuel that is cost-competitive yet with traditional jet fuel. The costs for incorporating this fuel are more than just massive, and in the current state, it is almost impossible for us to install it in any aircraft at all. Even if SAF production doubles every 2 years, it would still take over seven and a half years just for 10% of the total jet fuel to come from sustainable sources" (Shine, 2023). This directly highlights the severity of the problem and the need for a concrete solution.

While the aviation industry's dependence on fossil-based fuels is a clear threat to long-term sustainability, the problem of waste management highlights even more profound consequences – not just for biodiversity, but also for us humans. According to the International Finance Corporation, the world generates over 2 billion tons of municipal solid waste annually, and this is expected to increase by 70% by 2050 (IFC, 2024).

Most solid waste is either burned, buried in landfills, or dumped into the ocean, all of which contribute to pollution. It has been observed that a lot of valuable resources end up as a part of this waste, like algae, food scraps, forestry residue or even wasted plastics that could have been used to generate economic revenue and solve environmental issues. This undermines the idea that if waste management is made sustainable, it will not only reduce waste that ends up in landfills but also provide economic opportunities and reduce environmental depletion.

Figure 2: Municipal solid waste generated per year globally

Bringing these challenges together, it has become clear that the unsustainability of both the heavy reliance on traditional jet fuels in the aviation industry and the inefficiency of current waste management requires immediate solutions. Solid waste that is often discarded and algae can be transformed into SAF sources, eliminating both problems at once. This approach fosters a circular cycle in which materials that end up as waste are refurbished into potential fuel sources, injecting them back into the circular economy. By turning waste into a valuable resource, we can inch closer towards long-term sustainability and benefit the global economy.

Exploring Waste and Algae as Potential Resources for SAFs

Waste

Waste has become one of the most pressing challenges today, with billions of tons ending up in landfills every year. However, it is a double-edged sword; although waste significantly contributes to pollution and global warming, it remains a valuable resource that can be converted into aviation fuel. Recently, the role of waste in fuel generation has been subject to immense research and provides an excellent alternative to traditional aviation fuels that depend on fossil fuels.

One of the most established and well-researched methods is gasification followed by Fischer-Tropsch synthesis (Detsios et al., 2024). In this process, municipal solid waste, such as garbage, is heated and stored under extremely high temperatures in a limited supply of oxygen. Then, instead of combusting it, the waste undergoes a chemical process called gasification, producing carbon monoxide and syngas. This syngas is then passed through transition metal catalysts (like cobalt or iron) in the Fischer-Tropsch synthesis which produces large chains of hydrocarbons. These hydrocarbons are the sources of energy that, after further refining, act as aviation fuel.

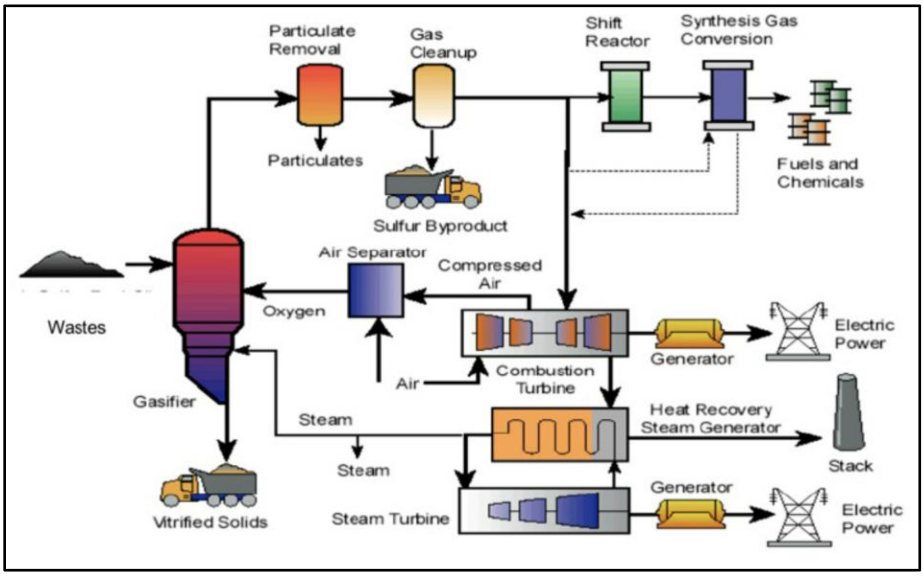

Figure 3: Waste to aviation fuel through gasification followed by Fischer-Tropsch synthesis

Within the realm of waste, over the past 70 years, plastic waste has increased nearly 230-fold, reaching 460 million tonnes in 2019 (Ritchie, Samborska, & Roser, 2023). Even just in the past two decades, plastic production has more than doubled. Amid this growing threat, researchers have been exploring unconventional methods to produce jet fuel from this plastic waste, mitigating both problems at once. Plastics are durable and resistant to degradation, so they can be used as substitutes for timber, iron or stone, highlighting their incorporation to foster scientific and economic advantages.

Although optimising the equivalence ratio of plastics for further utilization in internal combustion engines is not a viable option, the implementation of a pyrolysis system can be done (Al-Salem, 2019), especially for high-density polyethylene (HDPE), so that they can be transformed into liquid fuels compatible with aircraft engines (Huo et al., 2021). The plastic samples are decomposed at extremely high temperatures, and then operated isothermally at 500°C and 800°C which produces pyrogenic hydrocarbons. After pyrolysis, the vaporised hydrocarbons are passed through a two-stage condensation system designed to selectively recover the desired fuel-range hydrocarbons (C8 to C16). Finally, thermodynamic simulations are conducted using ideal turbojet cycles to assess parameters that enable this fuel to be available for commercial use (Deconstruction of HDPE into liquid hydrocarbon fuels, 2021).

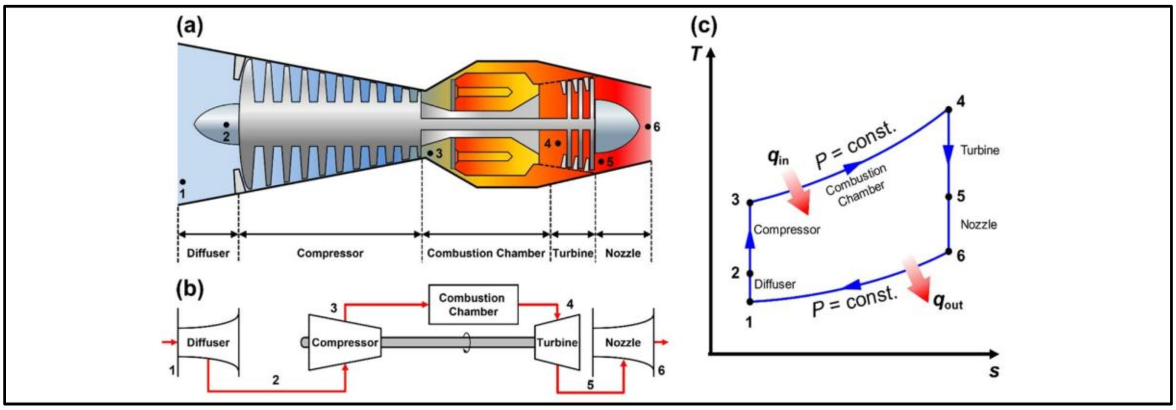

Figure 4: Production of aviation fuel via thermal cracking of plastic waste

Algae

Recent studies have shown that algae are a highly versatile and renewable feedstock for producing bio-based fuels, particularly SAFs. Algal biomass is rich in lipids, carbohydrates and proteins, making it suitable for conversion into valuable chemical compounds such as cycloalkanes, paraffins and other hydrocarbons that have significant industrial and energy applications. In the realm of aviation, microalgae can be converted into SAF through several processes, including lipid extraction, genetic engineering techniques, hydrothermal liquefaction (HTL) or transesterification (Ranjith Kumar, 2015; Zhu et al., 2023; Rai et al., 2025).

Many microalgae species have a naturally high lipid content, ranging from 70% to 77% of their dry weight, primarily stored as triacylglycerols (TAGs) (Sharma, 2023). These lipids are the key precursors for biodiesel and SAF production. Triacylglycerols are synthesised via the acylation of glycerol 3-phosphate in two enzymatic steps to produce phosphatidic acid. By targeting the first acylating enzyme and combining it with diacylglycerol acyltransferase activity, researchers have optimised TAG accumulation in algal strains such as Neochloris oleoabundans, thereby enhancing overall fuel yield. The resulting lipid-rich biomass is then harvested, typically via centrifugation or flocculation, before undergoing conversion into fuel.

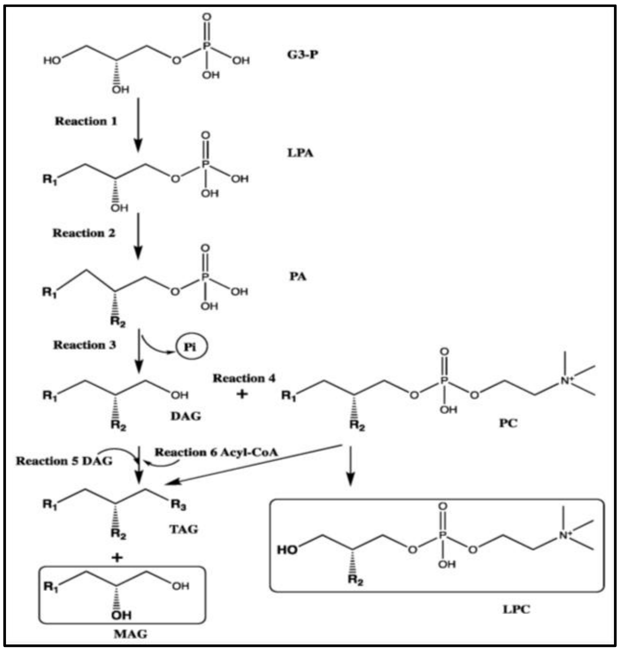

Figure 5: Biosynthesis of triacylglycerols in algae

Alternatively, after lipid extraction, transesterification can be employed to produce biodiesel. In this process, algal oils react with alcohol (usually methanol) in the presence of a catalyst to produce fatty acid methyl esters (FAMEs). Through hydroprocessing (HEFA - Hydroprocessed Esters and Fatty Acids), these esters undergo deoxygenation and hydrogenation, creating a "drop-in" fuel that is chemically and functionally similar to conventional Jet A-1 kerosene and compatible with existing aircraft engines.

Another emerging conversion route is hydrothermal liquefaction (HTL), where whole algal biomass, not just the lipids, is subjected to high temperatures (250-350°C) and pressures (10-25 MPa) in water. This process breaks down the biomass into a crude bio-oil, which can then be refined in conventional petroleum refineries into SAF and other hydrocarbons. HTL is particularly promising because it enables the use of wet algae, avoiding the costly drying steps required by other methods.

In addition to these thermo-chemical processes, advances in genetic engineering have also been pioneering in improving algae's potential as a biofuel source. Through gene editing and metabolic engineering, algae can be modified to have higher lipid productivity, faster growth rates and improved tolerance to environmental stress (Muñoz et al., 2021). For instance, through genetic alteration techniques (Kang et al., 2017), the accumulation of triglycerides, the precursors to hydrocarbon fuels, has increased substantially. Genetically modified strains are also engineered to produce longer-chain fatty acids (C14-C18), which are more compatible with jet fuel requirements and require less intensive hydroprocessing to convert into usable SAF.

Despite these advantages, several challenges continue to limit the large-scale commercialization of algae-based SAF. Algal cultivation requires significant amounts of water, nutrients (particularly nitrogen and phosphorus) and controlled conditions, all of which increase production costs. Scaling up from laboratory to industrial production also poses difficulties in maintaining productivity and preventing contamination. Moreover, energy input for harvesting and lipid extraction can sometimes offset the environmental benefits if not managed efficiently. According to recent life-cycle analyses, the current cost of producing algal SAF remains several times higher than fossil-derived jet fuel, though ongoing research into waste CO_2 utilization, wastewater-based cultivation and improved bioreactor designs may help bridge this gap in the coming decade.

Policy and Implementation Framework for Waste and Algae-Derived SAFs

In order to facilitate a shift from promising technologies to real-world impact, the successful deployment of SAFs derived from solid waste and algae will require a robust policy and implementation framework. Such a framework will need to address feedstock regulation, financial incentives, certification and standardisation, infrastructure integration as well as circular-economy linkage.

Firstly, feedstock regulation and classification are fundamental. For waste-derived SAFs, defining which waste streams qualify and how they are collected, pre-treated and integrated into fuel production systems matters. For instance, plastic converted via catalytic pyrolysis into jet-fuel-range hydrocarbons shows great technical promise, with up to 96% jet-fuel fraction from LDPE over Fe/AC catalysts (Li et al., 2022). But policy must clarify how much waste is diverted from landfills and accounted for in greenhouse gas inventories. Without clear regulatory incentives to divert waste into fuel production, the circular-economy benefits will remain purely theoretical.

Furthermore, financial incentives and carbon pricing are required to bridge the cost gap between novel SAF routes and conventional fossil jet fuel. Current techno-economic studies of microalgae-based SAF point to high production costs, including minimum fuel selling prices averaging €2.2 per litre for lipid-extraction routes (Concawe, 2025) and major upstream cost bottlenecks in cultivation and harvesting. Thus, policy measures including production tax credits, blending mandates or supportive carbon markets are important to de-risk investment and scale up.

Additionally, infrastructure and supply-chain integration play a key role in linking feedstock to production to end-use. For both solid waste and algae pathways, logistics of collection, transport, pre-processing, refining and blending must be coordinated. Alignment with the circular economy and linkages with waste-management policy are also essential. Waste-derived SAFs offer co-benefits: reducing landfill burden, plastics pollution and greenhouse-gas emissions. But policy must ensure that these co-benefits are realised – for example, through integration with municipal solid-waste systems, incentives for diverting plastics and capturing credits for plastic avoidance. Similarly, algae-based SAF systems may integrate wastewater treatment, CO_2 capture and nutrient recycling, strengthening the circular economy.

Overall, the effective utilisation of waste and algae for SAF production hinges not only on scientific processes, but also on well-designed policy frameworks that integrate regulation, incentives, certification, infrastructure and circular-economy linkages. Without these, the technologies may remain niche rather than mainstream.

III. Conclusion

The Aviation industry, despite being one of the most prominent industries on our planet that facilitates global connectivity, faces immense environmental challenges, and the most urgent one is its dependence on unsustainable fuel. This research ultimately focused on the prevalence of this issue and discussed optimal solutions that could curb this threat.

At its core, the study centres on SAFs as a potential solution, specifically exploring waste and algae as renewable resources that can be utilised to produce aviation fuel. By implementing these sources, the circular approach to sustainability can be achieved, where waste is transformed into valuable inputs that re-enter the production cycle.

The major findings highlight how solid municipal waste gasification and the Fischer-Tropsch synthesis produce hydrocarbons that can be processed into cleaner aviation fuel. Similarly, microalgae with high lipid content can also be converted into biodiesel through transesterification, hydrothermal liquefaction, or genetic modification, yielding optimised results. These scientific processes exemplify that both waste and algae can serve as viable alternatives to traditional fossil-derived sources, with immense potential to lead the world toward sustainable energy transitions.

Furthermore, the significance of these findings can also be attributed to economic and environmental contexts. Utilising both waste and algae not only addresses environmental degradation but also supports a circular approach, positioning the aviation industry as a leader in sustainable innovation and offering a blueprint for other industries to follow.

However, for these scientific advances to translate into real-world impact, supportive policy and implementation frameworks are indispensable. Establishing clear feedstock regulations, financial incentives and infrastructure integration mechanisms will be crucial to bridge the cost gap between SAFe and conventional fuels. Equally, linking these technologies to waste management and carbon reduction policies can ensure that the environmental and circular-economy benefits are fully realised.

To ratiocinate, while challenges such as high production costs and complex scaling processes remain, the potential that these options hold is no longer negligible. By investing in research, technological efficiency, and, critically, policy frameworks that enable their commercialisation, these SAFs can be the foundation of a cleaner future – one where waste is not an obstacle but a resource that powers progress.

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