The Environmental and Economic Performance of Camelina-Derived HEFA Sustainable Aviation Fuels: A Secondary Data Attributional Lifecycle Analysis

Background

The already large aviation industry is poised for incredible growth in coming years. The jet fuel market alone is expected to more than double its value from 2020, as outlined by the Department of Energy, or DOE (n.d.-b). However, this growth will bring with it a surge in the aviation industry's environmental footprint. Currently, around 11% of all transportation greenhouse gas (GHG) emissions originate from aviation (D'Ascenzo et al., 2024). This constitutes around 2-3% of all human carbon emissions, in addition to emissions from other GHGs such as water vapor and methane. Even apart from these gases, aviation releases other environmentally detrimental substances into the atmosphere, such as soot and sulfur (Chireshe et al., 2025).

The severe environmental impacts of aviation pose a serious issue, especially when considered in conjunction with the coming growth of the aviation industry. Recently, research has focused on the use of sustainable aviation fuels, or SAFs, to resolve this issue. Sustainable aviation fuels are defined as jet fuels that can be produced from renewable sources of energy, such as biomass or hydrogen. SAFs are crucial to aviation because they pose the potential to reduce the environmental footprint of the industry – both in manufacturing and emissions – without the need for significant structural changes to existing aircraft and infrastructure. Additionally, while other methods for aircraft environmental sustainability do exist, such as electric or hydrogen power, there are numerous technical barriers faced by these nascent methods (Song et al., 2024), further contributing to the importance of SAFs.

Purpose

Environmental performance is inevitably a major point of concern for sustainable aviation fuels; however, economic performance is also of paramount importance. Today, fuel represents around 20-30% of the operating costs of an airline (DOE, n.d.-b). As such, for sustainable aviation fuels to be practical in real world application, they must be capable not only of decreasing the environmental footprint of aviation, but also of being produced at feasible costs relative to existing fuels.

At the moment, there are numerous developed SAF production pathways, including: Hydroprocessed esters and fatty acids, alcohol-to-jet, hydroprocessing of fermented sugars, Fischer-Tropsch, pyrolysis, aqueous phase reforming, and power-to-liquid. Of these existing routes, the hydroprocessed esters and fatty acids route, or HEFA, is currently the most mature (Bauen et al., 2020). HEFA makes use of renewable feedstocks to obtain oils and fats, which are then hydroprocessed to create fuel. Being the most mature existing SAF pathway, HEFA poses the greatest potential for sustainable aviation fuel implementation. Despite its overall significance, however, an immensely important consideration for the HEFA process is the feedstock implemented. In this regard, the camelina crop is a feedstock with incredible potential, because it requires little energy to grow, contains high amounts of non-food oil, and can be grown without interfering with other agriculture as a cover crop (Wang et al., 2020). The goal of this paper is to analyze existing literature to obtain secondary data values, then present a full environmental and economic lifecycle analysis of the HEFA production route given camelina as a feedstock, and thus provide a robust analysis of the HEFA pathway.

Literature Gap

There is currently a gap in the literature surrounding SAFs in research focused on the lifecycle environmental and economic performance of the HEFA route. Various recent works in the field have focused exclusively on the lifecycle environmental performance of sustainable aviation fuels. For example, Kurzawska-Pietrowicz (2023) reviewed the lifecycle emissions of various sustainable aviation fuels, Abayo et al. (2024) compared the environmental impact of various SAF pathways, and Zemanek et al. (2020) analyzed the emissions from using oilseeds in the HEFA route. However, such works have not examined the lifecycle economic impacts of SAFs, although in some instances they may be directed specifically at the HEFA. In contrast, other literature has focused on the lifecycle economic performance of sustainable aviation fuels; for instance, Pearlson et al. (2013) created estimates for the economics of the HEFA route. However, such literature similarly fails to present the lifecycle environmental performance of SAFs, although it may also focus solely on HEFA.

Resolving this issue with works focusing exclusively on either the lifecycle environmental or economic performance of SAFs, some literature has also focused on both of these factors. Grim et al. (2022), for instance, reviewed the lifecycle environmental and economic aspects of the power-to-liquids SAF production pathway. Similarly, Gonzales-Garay et al. (2022) reviewed the lifecycle environmental and economic feasibility of the Fischer-Trophsch and methanol-to-fuels given different energy sources. Additionally, Braun et al. (2024) analyzed various SAF production methods, including HEFA, to determine lifecycle environmental impact and pricing. Yet, the vast majority of papers in this domain do not focus exclusively and comprehensively on the HEFA pathway to SAF production, although very rarely, as in the case of Braun et al. (2024), the method may be analyzed alongside others. In other words, while papers analyzing the lifecycle environmental or economic performance of SAFs sometimes focus specifically on HEFA, papers that present both the lifecycle environmental and economic performance of SAFs are rarely directed towards HEFA.

Finally, there are some papers that resolve even this literature gap, and provide an environmental and economic analysis focusing specifically on the HEFA pathway. Seber et al. (2014), for instance, looked at the lifetime environmental and economic impacts of HEFA fuel production given waste oils and tallows as feedstocks. Nevertheless, literature in this highly specific domain is minimal, and, as in the case of the paper from Seber et al. (2014), not always recent, as is important particularly in the realm of economics. As a result, the precise focus of this paper on the environmental and economic performance of the HEFA pathway given a lifecycle analysis is beneficial by contributing to the research gap surrounding this specific domain.

Research Question and Hypothesis

To summarize the aforementioned explanations, the question that this paper seeks to answer is: What is the economic and environmental performance of sustainable aviation fuels produced from camelina via the HEFA pathway, when considering full lifecycle analysis? The initial hypothesis regarding this question is that HEFA SAFs produced from camelina have an environmental footprint approximately 20% less than traditional fuels, while still roughly matching the costs of these fuels.

Methodology

To prove this hypothesis, the body of this secondary analysis was chronologically structured around the various stages of the HEFA route: Feedstock production, transport and oil extraction, HEFA conversion, and combustion. In each stage, the paper tracked two measures of SAF performance: CO_2 equivalent emissions for environmental performance, and cost in dollars for economic performance. Also for each step, the magnitude of these two measures was placed in relation to the “input” quantity for that stage. For example, for the oil extraction step, emissions and costs were given per kilogram of feedstock, as feedstock was the input quantity for oil extraction.

The paper followed these two measures of performance by drawing any discovered quantitative values for emissions and cost in each stage, and synthesizing them to produce overall values for that stage. Such synthesis was performed as values were used to corroborate others, or as mathematical arithmetic and unit conversions were done to combine values and align them with the input unit for each step. This secondary method of analysis was particularly beneficial given the presence of some research on either the lifecycle environmental or lifecycle economic HEFA performance, by allowing the synthesis of existing literature to fill the gap in research on both forms of analysis. Additionally, a stage by stage analysis was performed as opposed to a synthesis of final lifecycle values from papers given the lack of extensive literature even on either environmental or economic HEFA analysis, and an absence of definitive conclusions for either aspect.

Once values for each step of the process were derived applying the analysis, they were combined through further unit conversion to produce final values for emissions and cost. These values were then compared to those of traditional fuels, as obtained from credible and corroborated sources, to establish improvement or deterioration in both categories. This form of analysis produced the secondary analytical nature of this paper, and the conditions and assumptions established produced its attributional quality.

In terms of information sourcing, sources analyzed within this research paper were found using the following search terms: Sustainable, aviation, lifecycle, environmental, fuel, economic, and HEFA, as well as other search terms tangential to the field of sustainable aviation fuels.

These search terms were used in research databases, such as JSTOR and Google Scholar, as well as in ordinary search engines such as Google. Furthermore, only sources from 2000 and onward were considered. Under these conditions, the research paper considered a total of 70 sources, of which 47 sources were used within the body of the paper. The sources used were chosen for the scope of relevant information they covered, and the credibility and expertise they offered. Specifically, sources considered for the analysis of the paper were excluded if they did not provide quantitative data regarding the HEFA pathway. Similarly, sources considered for the introduction were rejected if they did not present expertise in their subject field. Of the sources used in the body of the paper, 39 were academic research papers, 7 were government or otherwise credible reports, and 1 was a credible website.

A highly important note should also be made in regard to the way that calculations were performed throughout the entirety of the paper. Throughout the paper, data from sources was taken in exact specificity as originally found when used in calculations. In the same way, calculated numbers from original source values were stored to exact specificity for further computation. However, when original figures or calculated values were presented, they were rounded to three decimal places (and identified as approximates unless in the appendixes), or left with their original number of decimals if not present in this specificity. Furthermore, even if original figures were identified as approximated in the sources from which they came, they were not identified as such in the paper, and used according to the rules above. These choices were made to improve the understanding and ease of the reader.

Key Abbreviation Definitions

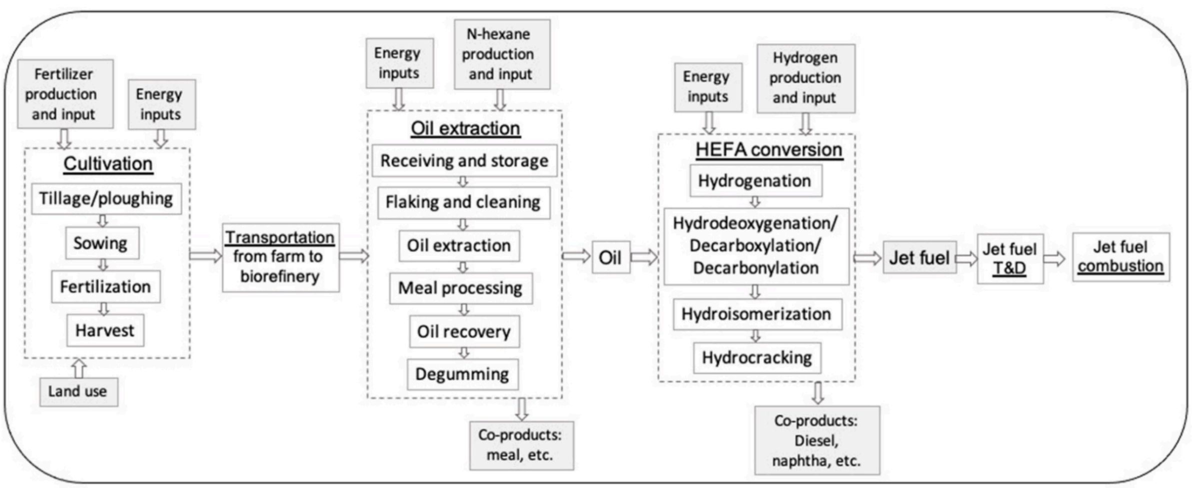
- metric kilogram = kg
- metric kilometer = km

- $CO2$ equivalent = CO_2e
- metric megajoule = MJ
- metric gigajoule = GJ
- metric kilowatt-hour = kWh
- metric ton = ton
- imperial pound = lb
- imperial mile = mi
- metric gram = g

Analysis

Figure 1

Lifecycle HEFA Fuel Production Pathway



Note. Figure from Seber et al. (2022).

Feedstock Growth

The first stage of the HEFA process is the growth of a feedstock (Seber et al., 2022); for the purposes of this paper, camelina. Feedstock growth is an exceedingly important consideration in the HEFA lifecycle, because it can sequester significant volumes of atmospheric carbon dioxide. However, feedstock growth is also an incredibly complex factor, because feedstocks themselves require energy to grow, and may have impacts on other agriculture. Camelina as a feedstock is grown for its oilseeds, from which oil can be extracted to create SAFs (Li & Mupondwa, 2016). The goal of this section is to analyze camelina growth within the HEFA process, to determine its environmental and economic impacts.

As explained previously, the environmental impacts of camelina growth must be considered by analyzing both the resources needed to grow the crop, and the resulting greenhouse gas sequestration. This paper will consider typical to marginally conservative growing conditions for camelina, to obtain the most accurate and broadly applicable results. One value for camelina's environmental impact can be found in a study from Krzyzaniak and Stolarski (2019), which calculated that under reduced tilling conditions, growing one hectare of camelina produced a net release of between 1732 and 1772 kg of CO_2e (in regards to climate impact) gas. However, this study ignored carbon sequestration within the soil in which the camelina was grown. Krzyzaniak and Stolarski (2025) later incorporated this factor into a separate study in which they used the SimaPro 9.6 software to simulate plant growth, allowing them to refine their figure down to 762 kg of CO_2e per hectare, with a 0.95 confidence interval ranging from approximately 140-1700. This figure is supported by other previously performed studies such as that of Krohn and Matthias (2012), which found between 650 and 950 kg of net CO_2 emissions given low input growth conditions. An important point to note regarding these studies is that each analyzed camelina as the only crop growing on a plot of land, but did not consider the potential environmental benefits or drawbacks of other crops that might otherwise be grown on that land. As such, the figures in each of these studies should be taken at value only if camelina is considered as being grown in its most common form; as a cover crop, during a time when most others cannot feasibly be grown. Using the above figures with this in mind, it can be concluded that net carbon emissions from camelina growth, when considering input resources and carbon sequestration, lies approximately around 750 kg of CO_2e per hectare grown. Finally, dividing this value by the the average camelina yield of around 1900 kg of oilseed per hectare (Li and Mupondwa, 2016; Zhang et al., 2021) gives that the carbon emissions from camelina growth lie around 0.395 kg of CO_2e per kg of oilseed. However, the question of the associated costs of this growth still remains.

In regard to answering this question, this paper will focus on various factors that affect the cost of camelina growth for HEFA, such as machinery costs, farming resources, and land use. In a paper by Li and Mupondwa (2016), the average cost for camelina growth was cited as $463 per hectare, given the average yield of 1900 kg of camelina oilseed per hectare found by the authors, and corroborated by Zhang et al. (2021). This figure took into account numerous production variables, including fertilizer cost, machinery, repair, depreciation, land investment, labour, and more. Additionally, Li and Mupondwa (2016) also found that the cost to grow camelina varied depending on the yield per hectare, with low yields of around 700 kg per hectare costing $0.66 per kg of oilseed, and high yields of 3300 kg per hectare costing only $0.14 per kg of oilseed. Nevertheless, the authors' cost-value for an average yield of camelina oilseed is more broadly applicable to various circumstances, and is thus a significantly more accurate figure for the purposes of this paper. As such, dividing $463 per hectare by the average camelina yield of 1900 kg per hectare gives an accurate cost of approximately $0.244 per kg of oilseed. An important point to note regarding camelina oilseeds is the economic impact of camelina meal, which is derived from the oilseeds after the oil has been extracted, and can be sold for a profit (Li & Mupondwa, 2016). However, this impact will be analyzed in a later section, as it falls under the oil production stage of HEFA rather than under feedstock growth. Overall, it can be concluded that the cost to grow camelina for the HEFA route is approximately $0.244 per kg of oilseed.

Transportation And Oil Extraction

The second step of the HEFA process involves two stages: The transport of a feedstock to a biorefinery, and the subsequent extraction of oil from that feedstock (Seber et al., 2022). In terms of environmental and economic impacts, both of these stages are incredibly important to consider. Freight transport releases greenhouse gases that damage the environment (Congressional Budget Office, 2022), and also adds costs to the lifecycle of HEFA. Similarly, oil extraction requires energy that generates both GHGs and furthers the costs of the process.

Firstly, the transportation of feedstocks to biorefineries for oil extraction is an important player in the emissions associated with HEFA. According to statistics from the Congressional Budget Office (2022), trucking - the primary method of freight transportation - produces 0.4 lb of CO2 per ton-mi (transporting one ton a distance of one mile). This figure is incomplete without a transport distance, but a study by Li and Mupondwa (2016) found that feedstock transportation to processing plants within a 200 km radius took an average distance of 133 km. This paper will assume transport distances under 200 km, and accordingly apply the 133 km average. Combining this value with the trucking emissions figure (see *Appendix B*), it can be reasonably concluded that transportation emissions amount to around 0.015 kg of CO_2 per kg of camelina. It is important to note that this figure is an estimate, not an exact calculation by any means, especially given the variability of trucking emissions highlighted by the Congressional Budget Office (2022). Nevertheless, it is a reasonable estimate given the information, and thus merits a continuation to consider costs.

For the aforementioned 200 km radius, Li and Mupondwa (2016) also found that feedstock transportation had an average impact of $12.29 per ton of oilseed transported. Converting this figure from per ton of oilseed to per kilogram of oilseed (see *Appendix A1*), it can be concluded that transportation costs add around $0.012 per kg of camelina. Moving on, the next relevant consideration in this stage is the impact of oil extraction itself.

There are currently two major recognized methods of feedstock oil extraction: Mechanical pressing, and solvent extraction, although enzymatic extraction may also be considered in this regard (Pikula et al., 2020). Of these two methods, mechanical pressing is less expensive (Pikula et al., 2020), more time efficient (Ofori-Boateng et al., 2012), and is the only method used in small scale facilities (Veljkovic et al., 2022). In addition, solvent extraction may result in negative environmental impacts (Pikula et al., 2020). For these reasons, this paper will consider only the mechanical pressing method of oil extraction. However, there are nevertheless important concerns with mechanical pressing, including the need for oil filtration and purification (Popa et al., 2017), and a reduced oil extraction efficiency as compared to solvent extraction (Ofori-Boateng et al., 2012). The method itself consists of cleaning oilseeds, pressing them to extract oil, and purifying the oil to prepare it for HEFA conversion (Seber et al., 2022).

For the mechanical pressing method, the environmental impacts of camelina oil extraction mainly come from the electricity needed to execute oilseed crushing, as this is the stage that naturally requires the most energy. A thorough empirical study from Dangol et al. (2015) reported that such emissions amounted to 0.043 kg of CO_2e per lb of refined oil produced by mechanical pressing. Given that this study also reported extracting 27.4% of camelina input mass as oil, calculations (see *Appendix C1*) show that the emissions from oil extraction are approximately 0.026 kg of CO_2e per kg of input oilseed. To reiterate, this value assumes negligible contributions from the cleaning and purification processes, given the low energy input and lack of environmentally damaging substances involved with these stages. However, while the environmental impacts of camelina oil pressing can be considered in this way, the costs of the process involve numerous other factors.

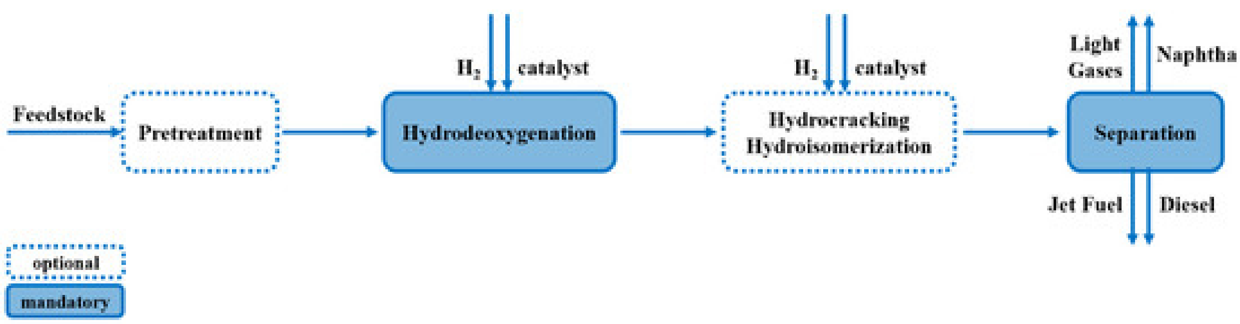
For the purposes of this paper, the costs of camelina mechanical oil extraction will be considered using two factors: The energy required for oil pressing, and the by-product (meal) produced by the extraction. The energy for oil extraction is naturally an important factor for cost, and relevant mainly to the actual oil pressing stage itself. The by-products, however, are also important to consider, because they can be sold to offset other costs (Veljkovic et al., 2022). First looking at oil pressing, the energy required to press oilseed typically falls at 0.05 kWh per kg (Singh & Bargale, 2000). Furthermore, the U.S. Energy Information Administration, or EIA (n.d.-a), cites current average industrial prices for electrical energy as $0.083 per kWh. Multiplying these figures gives a relatively minute value of about $0.004 per kg of oilseed. However, this cost can be offset by selling the camelina meal left behind by the oil extraction. As aforementioned, Dangol et al. (2015) found that mechanical pressing can extract 27.4% of inputted camelina oilseed mass as actual oil. The remaining 72.6% of input camelina mass is therefore left behind as meal. Combining this value with the price of camelina meal, $0.25 per kg (Bertacchi et al., 2020), and further accounting for the approximately $0.004 per kg for electrical energy (see *Appendix C2*) demonstrates that the final oil extraction cost value is around $0.177 per kg of oilseed in cost offset (revenue).

HEFA Conversion

The third and perhaps most complex stage of the HEFA process is the actual conversion of feedstock oils into HEFA fuel (Seber et al., 2022). Ignoring the pretreatment stage that this paper covered in the previous section, HEFA conversion begins with reacting feedstock oil and H_2 at a high temperature and pressure to remove oxygen; a process known as hydrotreating (DOE, n.d.-b). Once this step is completed, the resulting substance becomes functional fuel (Monteiro et al., 2022). However, to meet the various requirements of jet fuel, it is hydrocracked and hydroisomerized again using H_2 as a catalyst (DOE, n.d.-b). Finally, after these steps, the upgraded fuel is separated from the other products of the reaction, resulting in usable biofuel. This section will analyze both the emissions and cost of this HEFA conversion step, with camelina as a feedstock in mind.

Figure 2

Simplified and Complete Visual of the HEFA Process



Note. Figure from Monteiro et al. (2022).

The environmental impacts of HEFA conversion are a large consideration for the process as a whole. This is due to the large amounts of energy, H_2, and natural gases needed for this stage. According to Han et al. (2013), the net HEFA conversion related emissions for camelina are approximately 0.021 kg (20.5 g) of CO_2e per MJ of SAF produced. Han et al. (2013) considered various factors in this figure, such as hydrogen input and energy requirements. Given the calorific value of camelina HEFA biofuel; 44.1 MJ per kg of SAF, and the fact that 1 kg of input camelina oil converts via HEFA into only 0.75 kg of biofuel (Han et al., 2013), it can be concluded that HEFA conversion releases about 0.678 kg of CO_2e per kg of input camelina oil (see *Appendix D1*).

Regarding costs, HEFA conversion is relevant due to the energy associated with hydroprocessing, but also because of the by-products that are produced through conversion, namely naphtha and a propane mix (Monteiro et al., 2022); which can also be sold to offset energy costs. An important note is that diesel can also be a by-product (Seber et al., 2014), but will be ignored for the purposes of this paper, as the studies used for economic analyses - such as that from Han et al. (2013) - also do not consider it. First regarding energy, there are three major concerns: H_2, natural gas, and electricity. According to Han et al. (2013), hydrogen use for camelina HEFA processing lies at 4734 MJ of H_2 per ton of produced biofuel. Similarly, natural gas use is 7818 MJ per ton of biofuel, and electricity use makes up 61 kWh per ton of biofuel. For H_2 use, implementing hydrogen's energy density of 120 MJ per kg (DOE, n.d.-a), and a reasonable cost assumption for electrolysis produced hydrogen, $5 per kg (Vickers et al., 2020), shows that hydrogen use in HEFA conversion constitutes $197.25 per ton of produced biofuel (see *Appendix D2*). However, it is important to note that this figure is valid only under the assumption that the hydrogen is produced via electrolysis. For natural gas, 1000 cubic feet constitutes 1093 MJ of energy (EIA, n.d.-b), and every cubic foot of natural gas costs approximately $0.005 according to current industrial prices (EIA, n.d.-c). Combining these values with the aforementioned 7818 MJ per ton of produced biofuel (see *Appendix D3*) gives that natural gas contributes about $32.259 per ton of produced biofuel. Finally, for electricity, the same industrial cost as used in the oil extraction section will be assumed; $0.083 per kWh (EIA, n.d.-a). Thus, multiplying the 61 kWh per ton of produced biofuel by $0.083 per kWh gives a fair cost estimate for electricity used in HEFA conversion for camelina: $5.063 per ton of biofuel.

However, as aforementioned, the by-products produced by HEFA conversion are also highly important to consider in regards to the economic feasibility of the process. For the purposes of this paper, it will be assumed that the by-products are sold for their market values, and offset costs in this way. According to Han et al. (2013), the yields of naphtha and propane mix from 1 ton of produced biofuel are 3359 MJ and 4444 MJ respectively. Given that naphtha has an energy content of 43.2 MJ per kg (Han et al., 2013) and a recent market price of $0.55 per kg (Aburto et al., 2025), it can be calculated that the value of the gas produced per ton of produced HEFA biofuel is about $42.765 in cost offset (see *Appendix D4*). Similarly, given the energy content of the propane mix by-product from HEFA conversion, 44.4 MJ per kg (Han et al., 2013), and a recent market price for propane, $0.8 per kg (Aburto et al., 2025), it can also be calculated that the cost contribution from the propane mix is about $80.072 per ton of biofuel in cost offset (see *Appendix D5*). Summing the approximately $42.765 per ton of biofuel and about $80.072 per ton of biofuel gives a combined final cost offset of about $122.837 per ton of produced biofuel.

Concluding economics, the costs for hydrogen, natural gas, and electricity to produce 1 ton of camelina HEFA SAF were: $197.25, approximately $32.259, and $5.063, respectively. Summing these values gives about $234.572 per ton of produced biofuel. However, the offsetting value of naphtha and propane must also be factored into the analysis, removing about $122.837 from the price, and bringing the total down to about $111.735 per ton of biofuel. Further dividing this figure by 1000 provides that producing 1 kg of HEFA SAF from camelina costs around $0.112. Furthermore, converting this value to be in terms of input oil rather than produced biofuel, using the fact that 1 kg of input camelina provides only 0.75 kg of biofuel via HEFA (Han et al., 2013), gives a final cost of approximately $0.084 per kg input oil (see *Appendix D6*).

Combustion

The final stage of SAF use is the combustion stage. SAF combustion is complex in terms of environmental impact, because it not only leads to the direct release of CO_2, but also emits numerous other environmentally impactful substances, which may alter atmospheric chemistry (Lee et al., 2023). Such emissions include NO_x, H_2O (water vapor), SO_2, particulate matter (PM), CO, and unburned hydrocarbons (UCH). An important note regarding this step is that today, SAF regulations require that they be blended with traditional jet fuels, up to a maximum of 50% (DOE, n.d.-b). Nevertheless, for the purposes of this paper, combustion will be considered as that solely of the SAF derived from HEFA conversion, without blending: This is because SAFs can be used without traditional fuel blending, despite existing regulations. Furthermore, this section will only consider the climate impact of SAF combustion, as without blending, there are no combustion costs to consider.

Various studies have shown that SAF emissions of most gases/substances do not differ greatly in terms of climate emissions from traditional jet fuels. For instance, Song et al. (2024) found that the emissions of CO_2, NO_x, CO, and UHC from various SAFs (including camelina based fuels) were insignificantly different from those of traditional jet A1 fuel. However, certain gases and substances do differ between SAFs and ordinary fuels. In particular, Song et al. (2024) also found that the SO_2 and PM emissions from SAF combustion were significantly lower than those of traditional jet fuels, while Teoh et al. (2022) cited that the water vapor emissions can be up to 10% higher.

In general, SO2 (which forms sulfate particles), PM, and water vapor play a role in the climate through the formation of jet contrails (Lee et al., 2023). Contrails form when water vapor attaches to particulate matter, and they may form cirrus clouds at high altitudes, producing a net positive climate impact (although contrails have both positive and negative climate impacts) (Lee et al., 2023). Furthermore, contrails are one of the most environmentally impactful factors related to aviation (NASA, 2017). According to Teoh et al. (2022), studies estimate that SAFs may increase contrail prevalence by 1-8%, due to their increased water vapor emissions as compared to traditional fuels. However, Lee et al. (2023) explains that the interaction between PM, SO2 (sulfate particles), and water vapor in contrails and cloud formation is highly uncertain. Furthermore, even if Teoh et al. 's (2022) figure is to be considered, it represents only a relatively small change in the magnitude of traditional fuel contrails. Thus, given the similarities in most emissions between SAFs and traditional jet fuels, in addition to high uncertainties regarding, at most, small differences in certain contrail-related emissions, this paper will consider the climate impact of SAF combustion to be relatively equivalent to that of traditional jet fuel.

In terms of combustion emissions, standard petroleum jet fuel produces 74 g of CO_2e per MJ of fuel (Prussi et al., 2021). Converting to kilograms, and factoring in the energy density of SAF, 44 MJ per kg (Norazmi, n.d.), gives that the combustion emissions of SAF lie at 3.256 kg of CO_2e per kg of combusted SAF (see *Appendix E*).

Overall Results

The previous sections of this paper have reviewed each of the individual stages of creating HEFA fuel from camelina, including feedstock growth and extraction, transport and oil extraction, HEFA conversion, and combustion. This section will combine each of these values to generate complete, final figures for the lifecycle emissions and costs of generating HEFA fuels from camelina. Then, these figures will be compared to those of traditional jet fuel.

Beginning with the feedstock production and extraction, the CO_2e emissions to produce 1 kg of camelina were found to be around 0.395 kg of CO_2e per kg of camelina grown, and the cost was found to be around $0.244 per kg of camelina grown. Moving on to transportation, the figures were approximately 0.015 kg of CO_2e per kg of transported oilseed, and about $0.012 per kg of transported oilseed. Summing these transportation values with their respective counterparts for the oil extraction stage; about 0.026 kg of CO_2e per kg of oilseed, and around $0.177 per kg of oilseed in cost offset, gives the combined transportation and emissions values: around 0.041 kg of CO_2e per kg oilseed, and around $0.165 per kg of oilseed in cost offset. Continuing on to HEFA conversion, it was concluded that the process adds approximately 0.678 kg of CO_2e per kg of input oil, and about $0.084 per kg of input oil. Lastly, for combustion, the emissions figure was found to be 3.256 kg of CO_2e per kg of SAF, with no combustion costs added. These values represent the mathematical results of this research paper, however, they still must be combined into two single figures for emissions and costs, to be compared to traditional fuels. Combining the values by assuming a 1 kg input of camelina feedstock and converting to per megajoule of biofuel (see *Appendix F*), gives the absolute final approximate values for the lifecycle emissions and costs of producing camelina biofuel via HEFA: 0.140 kg CO_2e per MJ, and $0.011 per MJ.

In comparison to the emission values for traditional petroleum jet fuel, these numbers produce surprising results. According to Prussi et al. (2021), the combustion emissions of petroleum jet fuel account for 83% of its total lifecycle GHG emissions, or 0.074 kg of CO_2e per MJ. Thus, by multiplying this figure by 1/0.83, the lifecycle GHG emissions of petroleum jet fuel can be found to lie around 0.089 kg of CO_2e per MJ. This value is also supported by Song et al. (2024) who concluded a figure of 0.090 kg (90 g) in their own study. Importantly, this value of 0.089 kg is reasonably less than the 0.140 kg calculated for SAF; specifically amounting to approximately 64% of this value.

In contrast, the above cost value for SAF is less than that of traditional jet fuels.

Comparing in particular to jet A1 fuel, a highly conventional petrol jet fuel (Song et al., 2024), current costs lie at $697.6 per ton according to Jet-A1-Fuel (n.d.). Dividing by the calorific value of kerosene jet fuels, 44.1 GJ per ton (United Nations Statistics Division, 2014), gives approximately $15.819 per GJ, and further converting from per gigajoule to per megajoule (see *Appendix A5*) gives about $0.016 per MJ. This value for traditional fuel is approximately 141% of that calculated above for SAFs.

Conclusion

Discussion

The major focus of this research paper was to evaluate the environmental and economic performance of sustainable aviation fuels derived via the HEFA pathway, from the camelina crop as a feedstock, across their entire lifecycle. The purpose of this analysis was to increase the currently limited understanding of the practical application of SAFs as a whole, in comparison to traditional fuels. The analysis was performed via the combination of values from various research papers in the field, to derive overall values for each state of the HEFA production, and thus total ending values. The initial hypothesis based on academic literature in the field regarding this question was that camelina HEFA SAF would demonstrate a reduction in environmental footprint as compared to traditional jet fuels, while roughly matching the costs of these fuels. However, this hypothesis was incorrect. The research paper found that traditional jet fuels only had about 64% of the greenhouse gas release of the SAF, but approximately 141% of the total cost. The table below summarizes the important values derived throughout the paper, which can be found in the conclusion paragraphs of each stage section.

Figure 3

Summarized Result Values by Stage with Totals

Summarized Values (rounded to 3 decimals)							
Stage of Production *(specific units provided)*	Feedstock Growth *1 kg of camelina oilseed*	Transportation *1 kg of camelina oilseed*	Oil Pressing *1 kg of input camelina oilseed*	HEFA Conversion *1 kg of input camelina oil*	Combustion *1 kg of camelina biofuel*	Total SAF Values *1 MJ of camelina biofuel*	Total Jet Fuel Values *1 MJ of modern jet fuel*
Greenhouse Gas Emission *(kg of CO_2e)*	0.395	0.015	0.026	0.678	3.256	0.140	0.089
Cost *($)*	0.244	0.012	-0.177 (cost offset)	0.084	0	0.011	0.016

It is important to recognize that the results of the study – in going against the hypothesis – also go against the general theme in the academic literature surrounding sustainable aviation fuels. Excluding the possibility of errors (see limitations and future research), this suggests that the assumptions and specific data points used within this paper had a significant impact on the results that it produced. Nevertheless, assumptions were justified and data was carefully screened, providing credibility to the numerical conclusion.

Sensitivity Analysis

Even so, two major assumptions (one for emissions and costs each) were made in the paper that should be stress tested. The first of these assumptions was that HEFA SAF has approximately the same combustion emissions as ordinary jet fuel. By applying the same math in the overall values section (see *Appendix F*), it can be found that the combustion emissions of HEFA SAF would need to be around 1.022 kg of CO_2e per kg of SAF for the lifecycle emissions to match those of ordinary fuels. In relation to the actual calculated SAF combustion emissions figure, 3.256 kg of CO_2e per kg of SAF, the required value represents about 31% of the assumed emissions. Although the combustion emissions relationship was somewhat uncertain, this vast difference suggests the infeasibility of the required figure and the impact of other factors. Continuing, the second major assumption was that by-products of the production process – camelina meal, naphtha, and propane – were all sold for their market values. Once again applying the math in the overall values section (see *Appendix F*), but adjusting the values by removing all contributions from selling by-products, gives a final cost of around $0.034 per MJ. In comparison to the traditional cost of about $0.016 per MJ, this represents around 212.5%, and in comparison to the calculated cost of $0.011, it quantifies about 309%. These differences indicate the large impact that assuming by-products were sold had on the results of the study, and somewhat oppose this assumption by demonstrating alignment with the hypothesis in its absence.

Implications

Taking the assumptions of this paper to be true, results of this research paper pose some potentially important implications for the future of aviation. If SAFs derived from camelina via HEFA do have a greater environmental footprint as compared to traditional fuels, then perhaps the fuel pathway studied in the paper should be avoided in the interest of reducing the environmental footprint of aviation. However, if economic success takes priority over climate stability, then perhaps the fuel pathway should be implemented to reduce the costs associated with aviation. While both interesting possibilities, the results of this study could also potentially reflect the applicability of the aspects of SAF production analyzed. For example, this study could indicate the environmental infeasibility and economic practicality of the HEFA pathway specifically, regardless of the crop used. Similarly, the results could also implicate camelina as a poor and economically viable crop for SAFs. In contrast, the results could even more broadly indicate that SAFs as a whole do not have the capacity to reduce climate footprint as compared to traditional fuels, but do have the capacity to reduce costs, regardless of the production pathway or input source.

Regardless, the only truly anchored connections that can be made with this research are those relating directly to the exact fuel pathway studied: To reiterate, the research presents a conflict, where the use of camelina to produce SAF via the HEFA route increases environmental impact, but reduces costs.

Considerations and Assumptions

Following the sensitivity analysis performed above, it is crucial to reiterate that this paper relied on many key assumptions made: camelina was assumed to be grown as a cover crop under moderate conditions; transportation was modeled by trucking of under 200 km; oil extraction was considered via mechanical pressing energy, without regard for purification and cleaning, and with the assumption of camelina meal being sold; HEFA conversion was analyzed via energy use, with electrolysis derived hydrogen, and with naphtha and propane by-products sold; pure HEFA SAF combustion was assumed, and considered equal in emissions to ordinary fuel, with no combustion costs analyzed.

Even further, it is important to note that many of the sources used for cost throughout the various sections of this paper relate to modern prices, particularly in the United States of America.

Limitations and Future Research

Given the aforementioned assumptions, as well as other factors specific to this paper, there are some limitations of the research presented here that are uniquely important to appraise. First, combining quantitative values from multiple independent studies introduces inherent uncertainty, as source data may reflect different experimental conditions, geographic contexts, or methodological approaches. Second, economic figures, particularly energy and commodity prices, are time-sensitive and may shift significantly, altering the cost analysis. Third, while a broad range of sources was consulted, some relevant literature may not have been captured due to access barriers or search limitations.

However, on the subject of limitations, it should be considered that strong precautions and efforts were taken to mitigate the limitations of this paper, as much as possible, when possible. Numerical figures were analyzed and corroborated for accuracy, computational errors were parsed and removed when found, sources were found with strong attempts to create a wide range of consideration, and economic figures were made as current as possible.

Concluding with the topic of further research, the fact that the results of this study conflict with the general academic theme warrants further investigation into the applicability of SAFs. For one, more research on sustainable aviation fuel pathways and biological input sources could help to corroborate or counter existing works in the field, and thus contribute to a definitive answer. In particular, further analysis into the lifecycle of the HEFA route with camelina as a feedstock would be beneficial to build upon this work and corroborate or refute it. Further investigations on SAFs may benefit from using an even wider range of sources than this paper to provide stronger confirmation of data.

Furthermore, another potential realm requiring more investigation could be the field involving new and developing methods to produce sustainable aviation fuels. These methods, given the results of this paper, could present better alternatives to existing SAF methods, and would thus be of importance to research and explore.

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Appendix A

Unit Conversions

A1:

$$1000 \text{ kg} = 1 \text{ ton}$$

Thus

$$Mass_{kg} / 1000 = Mass_{tons}$$

Or conversely

$$Mass_{tons} \times 1000 = Mass_{kg}$$

A2:

$$2.205 \text{ lb} = 1 \text{ kg}$$

Thus

$$Mass_{lb} / 2.205 = Mass_{kg}$$

Or conversely

$$Mass_{kg} \times 2.205 = Mass_{lb}$$

A3:

$$1.609 \text{ km} = 1 \text{ mi}$$

Thus

$$\text{Distance}_{km} / 1.609 = \text{Distance}_{mi}$$

Or conversely

$$\text{Distance}_{mi} \text{ x } 1.609 = \text{Distance}_{km}$$

A4:

$$1000 \text{ g} = 1 \text{ kg}$$

Thus

$$\text{Mass}_{g} / 1000 = \text{Mass}_{kg}$$

Or conversely

$$Mass_{kg} \times 1000 = Mass_{g}$$

A5:

$$1000 \text{ MJ} = 1 \text{ GJ}$$

Thus

$$Energy_{MJ} / 1000 = Energy_{GJ}$$

Or conversely

$$Energy_{GJ} \times 1000 = Energy_{MJ}$$

Appendix B

Transportation Stage Calculations

Beginning with 0.4 lb of CO_2 per ton-mile (Congressional Budget Office, 2022), converting from pounds of CO_2 to kilograms of CO_2 (see *Appendix A2*):

$$0.4 \text{ lb } CO_2 / (\text{ton x mi}) = 0.181 \text{ kg } CO_2 / \text{ton x mi}$$

Converting from ton-miles to ton-kilometers (see *Appendix A3*):

$$0.181 \text{ kg } CO_2 / \text{ton x mi} = 0.113 \text{ kg } CO_2 / \text{ton x km}$$

Multiplying by the assumed 133 km average distance (Li and Mupondwa, 2016):

$$0.113 \text{ kg } CO_2 / \text{ton x km x } 133 \text{ km} = 14.994 \text{ kg } CO_2 / \text{ton}$$

Converting from tons of camelina to kilograms of camelina (see *Appendix A1*):

$$14.994 \text{ kg } CO_2 / \text{ton} = 0.015 \text{ kg } CO_2 / \text{kg}$$

Final transportation emissions value: 0.015 kg CO_2 / kg

Appendix C

Oil Extraction Stage Calculations

C1:

Starting with 0.043 kg of CO_2e per lb of extracted oil and 27.4% of input oilseed mass extracted as oil (Dangol et al., 2015), multiplying the values to convert from per pound of oil to per pound of input oilseed:

$$0.043 \text{ kg } CO_2e \text{ / lb oil x } 0.274 \text{ lb oil / lb oilseed} = 0.012 \text{ kg } CO_2e \text{ / lb oilseed}$$

Converting from pounds of oilseed to kilograms of oilseed (see *Appendix A2*):

$$0.012 \text{ kg } CO_2e \text{ / lb oilseed} = 0.026 \text{ kg } CO_2e \text{ / kg oilseed}$$

Final oil extraction emissions value: 0.026 kg CO_2e / kg oilseed

C2:

Starting with 72.6% of input mass as meal (Dangol et al., 2015), assume a 1 kg input of camelina mass:

$$1 \text{ kg oilseed x } 0.726 \text{ kg meal / (kg oilseed)} = 0.726 \text{ kg meal}$$

Multiplying by the $0.25 per kg of meal (Bertacchi et al., 2020):

0.726 kg meal x $0.25 / kg meal = $0.182

Recognizing the initial 1 kg input oilseed assumption:

$0.182 = $0.182 / kg oilseed

Subtracting from the earlier $0.004 / kg oilseed figure:

$0.004 / kg oilseed - 0.182 / kg oilseed = -$0.177 / kg oilseed

Final oil extraction cost value: -$0.177 kg oilseed (cost offset)

Appendix D

HEFA Conversion Stage Calculations

D1:

Starting with 0.021 kg CO_2e per MJ of SAF, and 44.1 MJ / kg of SAF (Han et al., 2013), multiplying the values:

0.021 kg CO_2e / MJ SAF x 44.1 MJ / kg SAF = 0.904 kg CO_2e / kg SAF

Multiplying by 0.75 to include the fact that 1 kg of input camelina oil converts via HEFA into only 0.75 kg of biofuel:

0.904 kg CO_2e / kg SAF x 0.75 kg SAF / kg oil = 0.678 kg CO_2e / kg oil

Final HEFA conversion emissions value: 0.678 kg CO_2e / kg oil

D2:

Starting with 4734 MJ of H_2 per ton of biofuel (Han et al., 2013), and 120 MJ per kg of H_2 (DOE, n.d.-a), dividing the values:

4734 MJ H_2 / ton biofuel / 120 MJ / kg H_2 = 39.45 kg H_2 / ton biofuel

Multiplying by 5 for $5 / kg for H_2 (Vickers et al., 2020):

$$39.45 \text{ kg } H_2 \text{ / ton biofuel x \$5 / kg } H_2 = \text{\$197.25 / ton biofuel}$$

Final hydrogen cost contribution to HEFA conversion: $197.25 / ton biofuel

D3:

Starting with $0.005 per cubic foot of natural gas (EIA, n.d.-c) and 1000 cubic feet of natural gas per 1093 MJ (EIA, n.d.-b) multiplying to get cost per megajoule:

$0.005 / cubic foot x 1000 cubic feet / 1093 MJ = $0.004 / MJ

Multiplying by the 7818 MJ / ton of produced biofuel (Han et al., 2013) to account for magnitude of natural gas use:

$0.004 / MJ x 7818 MJ / ton biofuel = $32.259 / ton biofuel

Final natural gas contribution to HEFA conversion: $32.259 / ton produced biofuel

D4:

Starting with 3359 MJ per ton of biofuel and 43.2 MJ per kg naphtha (Han et al., 2013), dividing to find naphtha mass ratio:

3395 MJ / ton biofuel / 43.2 / kg naphtha = 77.755 kg naphtha / ton biofuel

Multiplying by -$0.55 per kg naphtha (Aburto et al., 2025) for current naphtha prices (negative for cost offset):

77.755 kg naphtha / ton biofuel x -$0.55 / kg naphtha = -$42.765 / ton biofuel

Final naphtha cost contribution: -$42.765 / ton biofuel (cost offset)

D5:

Starting with 4444 MJ per ton biofuel and 44.4 MJ per kg propane (Han et al., 2013), dividing to find the propane mass ratio:

4444 MJ / ton biofuel / 44.4 MJ / kg propane = 100.09 kg propane / ton biofuel

Multiplying by -$0.8 per kg propane (Aburto et al., 2025), for current propane prices (negative for cost offset):

100.09 kg propane / ton biofuel x -$0.8 / kg propane = -$80.072 / ton biofuel

Final propane mix cost contribution: -$80.072 / ton biofuel

D6:

Starting with $0.112 per kg of produced biofuel, and 0.75 kg produced biofuel per kg input oil

(Han et al., 2013), multiplying to convert to input oil:

$0.112 / kg biofuel x 0.75 kg biofuel / kg oil = $0.084 / kg oil

Final HEFA conversions cost value: $0.084 / kg oil

Appendix E

Combustion Stage Calculation

Starting with 74 g CO_2e per MJ fuel (Prussi et al., 2021), converting from grams to kilograms (see *Appendix A4*):

$$74 \text{ g } CO_2\text{e / MJ fuel} = 0.074 \text{ kg } CO_2\text{e / MJ fuel}$$

Multiplying by the energy density of SAF, 44 MJ / kg fuel (Norazmi, n.d.):

$$0.074 \text{ kg } CO_2\text{e / MJ fuel x 44 MJ / kg fuel} = 3.256 \text{ kg } CO_2\text{e / kg fuel}$$

Final combustion emissions value: 3.256 kg CO_2e / kg fuel

Appendix F

Results Stage Calculation

Starting with feedstock growth values of 0.395 kg of CO_2e per kg of grown camelina feedstock and $0.244 per kg of grown camelina feedstock, assume a 1 kg input of feedstock:

$$0.395 \text{ kg } CO_2e \text{ / kg oilseed} = 0.395 \text{ kg } CO_2e$$

$$\$0.244 \text{ / kg oilseed} = \$0.244$$

Applying the assumption to the transport and oil extraction figures, 0.041 kg of CO_2e per kg oilseed and -$0.165 per kg of oilseed (negative for cost offset):

$$0.041 \text{ kg } CO_2e \text{ / kg oilseed} = 0.041 \text{ kg } CO_2e$$

$$-\$0.165 \text{ / kg oilseed} = -\$0.165$$

Adding the resulting feedstock growth values to the transportation and oil extraction values:

$$0.395 \text{ kg } CO_2e + 0.041 \text{ kg } CO_2e = 0.410 \text{ kg } CO_2e$$

$$\$0.244 - \$0.165 = \$0.079$$

Recognizing that these values apply for the above 1 kg feedstock input assumption, and that oil extraction only extracts 27.4% of input mass as oil (Dangol et al., 2015):

$$1 \text{ kg oilseed x } 0.274 \text{ kg oil / kg oilseed} = 0.274 \text{ kg oil}$$

Multiplying the HEFA conversion values, 0.678 kg of CO_2e per kg of input oil and $0.084 per kg of input oil, by 0.274 kg of oil to match the assumption:

$$0.678 \text{ kg } CO_2e \text{ / kg oil x } 0.274 \text{ kg oil} = 0.186 \text{ kg } CO_2e$$

$$\$0.084 \text{ / kg oil x } 0.274 \text{ kg oil} = \$0.023$$

Adding these resulting values to the earlier summed feedstock growth, transportation, and oil extraction figures:

$$0.410 \text{ kg } CO_2e + 0.186 \text{ kg } CO_2e = 0.596 \text{ kg } CO_2e$$

$$\$0.079 + \$0.023 = \$0.102$$

Further recognizing that HEFA conversion yields only 0.75 kg of biofuel per kg of input oil (Han et al., 2013), by multiplying by the earlier calculated 0.274 figure:

$$0.274 \text{ kg oil x } 0.75 \text{ kg biofuel / kg oil} = 0.206 \text{ kg biofuel}$$

Multiplying the combustion values, 3.256 kg of CO_2e per kg of biofuel, and $0 per kg biofuel, by 0.206 kg of biofuel to further match the assumption:

$$3.256 \text{ kg } CO_2e \text{ / kg biofuel x } 0.206 \text{ kg biofuel} = 0.669 \text{ kg } CO_2e$$

$0 / kg biofuel x 0.206 kg biofuel = $0

Adding these resulting values to the most recent summed values from the feedstock growth, transportation, oil extraction, and HEFA conversion stages:

0.596 kg CO_2e + 0.669 kg CO_2e = 1.265 kg CO_2e

$0.102 + $0 = $0.102

Again recognizing the assumption of 1 kg of camelina input feedstock, translating to 0.247 kg of oil, and then to, 0.206 kg of biofuel; multiplying 0.206 kg of biofuel by 44.1 MJ per kg of biofuel (Han et al., 2013):

0.206 kg biofuel x 44.1 MJ / kg biofuel = 9.063 MJ

Dividing by 9.063 MJ, acknowledging the fact that the most recent summed emission and cost values above represent those for this amount of biofuel (1 kg of camelina feedstock = 0.274 kg of oil = 0.206 kg biofuel = 9.063 MJ)

1.265 kg CO_2e / 9.063 MJ = 0.140 kg CO_2e / MJ

$0.102 / 9.063 MJ = $0.011 / MJ

Final emission and cost values: 0.140 kg CO_2e / MJ, $0.011 / MJ

Review of Paper: “The Environmental and Economic Performance of Camelina-Derived HEFA Sustainable Aviation Fuels: A Secondary Data Attributional Lifecycle Analysis”

As demand for jet fuel rises significantly, both because of increases in air travel by consumers and for transportation related to commercial distribution of goods and more, both the economic and environmental costs are projected to rise significantly, the latter a particular concern especially since air travel has an outsized role proportionally in terms its transportation sector greenhouse gas emissions, making solutions for environmentally-friendlier fuels and options paramount for policymakers and overall efforts to reduce environmental footprints. While much has been said and researched more recently, according to the author, about Sustainable Aviation Fuels, or SAFs, a comprehensive examination of both net economic costs and environmental costs compared to conventional jet fuel has been lacking, and this review paper, citing extensive literature and performing thorough calculations, attempts to bridge the gaps in the literature. In doing so, the study presents some perhaps unanticipated findings – that SAFs are cheaper operationally but larger in terms of equivalent carbon dioxide emissions per unit of fuel combusted. The latter is a significant concern not only for environmental advocates but more broadly in the realm of seeking to reduce global emissions over time. Assumptions and presented limitations aside, this review paper may have substantial ramifications for various sectors seeking to both shave costs and reduce carbon footprints, and for that reason this study is a compelling one that is worthy of publication.

Overall, I only have a few minor questions and concerns, but these should be very manageable for the author to address, and I also will say that grammatically and logically, the written document reads well, with very few errors detected. That said, it is always a good idea to give the next version one final, careful read prior to the final publication stage. I list a modest number of concerns below but applaud the author for a working draft that is both timely and clear.

One minor note is that usually it is best practice (and often required for submission to journals) to include line numbers for clarity sake – this helps reviewers refer to specific line items in the text and averts any confusion for authors as well. Please include line numbers in future submissions. Relatedly, it is usually best practice for organizational purposes for readers to label sections as *1, 2, 3, …* and subsections as *1.1, 1.2, 2.1, 2.2, … etc.* Furthermore, this helps break down sections and subsections more clearly.

1) Towards the bottom of page 3, the text mentions that electric and hydrogen power are alternative forms of aircraft power that are potentially sustainable. Though not discussed at length in this study, might these types of aircrafts be more environmentally friendly than the employment of SAFs for aviation fuel purposes? Or would this require a completely new study?
2) I appreciate the "Literature Gap" subsection, and often such a section is lacking or insufficient. The last sentence of that subsection in particular is very helpful, e.g. "*As a result, the precise focus … on the environmental and economic performance of the HEFA pathway given a lifecycle analysis …*"
3) In the second paragraph of the "*Transportation and Oil Extraction"* subsection, in looking at the Li and Mupondwa (2016) conference paper, it looks as though that mean distance of 133 km is based on Canadian production. Would the number be much different in the U.S. or other parts of the world with regards to Camelina oilseed? Might the production costs, and therefore the transportation emissions, be worse in some areas that are more spread out geographically?
4) As a follow-up to point 3 above, the author does state that the figure is an estimate given the "variability of trucking emissions", and I appreciate this, but also wonder whether or not some additional uncertainty estimates might be possible in some of the calculations, e.g. would it be possible to calculate the 95th confidence intervals for any of the intermediate or final numbers obtained? I understand that a mean value was often chosen for purposes of simplicity, but it may be helpful for both comparison purposes and for others, especially when referring to the topline results, to have a likely window of values.
5) Toward the bottom of page 23 in the "Sensitivity Analysis" subsection, it is stated that "HEFA SAF has approximately the same combustion emissions as ordinary jet fuel." Where does this assumption come from, and are you able to provide a reference?
6) Note: from a presentation perspective, usually the figure caption appears below the panel. A title is permissible as well, but a figure should generally be self-explanatory. I would suggest adding captions for Figures 1 and 2. Similarly, I would recommend adding a more appropriate title for your table at the top of page 22.
7) Broader question: Do the implications of your research suggest that SAFs should not be used if solely environmental footprint reductions are sought? This seems somewhat discouraging from the perspective of possible risk reduction. I also wonder, if the suggestion that SAFs tend to slightly increase contrails, if the radiative forcing ramifications versus traditional jet fuel on climate are even worse? I know that you mentioned and cite literature that suggests that the differences in contrail production between SAFs and traditional jet fuel may be small, but even a modest

increase could exacerbate the already somewhat counterintuitive findings of your study.

Review Title: The Environmental and Economic Performance of Camelina-Derived HEFA Sustainable Aviation Fuels: A Secondary Data Attributional Lifecycle Analysis

Overall Decision: Accept with major revisions or Review and resubmit

General Review

Overall, this is a relevant paper with a methodology that is suitable for publication. Using the available literature to integrate and analyze the environmental and economic aspects of aviation fuel decarbonization pathways is a time-intensive and rigorous project that demonstrates critical thinking. The manuscript demonstrates a significant amount of effort, and several sections are already strong, particularly the feedstock growth, transportation, oil extraction, and HEFA conversion sections. The way the author uses citations here is excellent.

However, there are two major conceptual issues that need to be addressed before publication.

First, the main environmental conclusion of the manuscript is highly sensitive to the lifecycle accounting assumptions used for combustion emissions within the HEFA pathway analysis. While the calculations themselves appear internally consistent from an arithmetic perspective, the conclusion that camelina-derived HEFA SAF produces higher lifecycle emissions than conventional fossil jet fuel appears to be strongly influenced by how combustion emissions are incorporated into the analysis. In the current framework, combustion emissions assigned to SAF appear to use values comparable to those of conventional fossil jet fuel. However, in many lifecycle assessment frameworks for biofuels, combustion emissions are treated differently from fossil jet fuel emissions because the carbon released during biomass combustion originated from atmospheric carbon previously absorbed during feedstock growth rather than from geological fossil carbon stocks. Because of this, lifecycle analyses for SAF pathways often account for combustion emissions within a biogenic carbon cycle rather than treating them identically to fossil fuel combustion emissions.

As a result, the manuscript would benefit from more explicitly explaining:

- how biogenic carbon uptake during feedstock growth is incorporated into the lifecycle framework,
- how combustion emissions from SAF are being treated relative to conventional jet fuel,

and whether the current accounting approach may unintentionally overestimate lifecycle emissions by treating SAF combustion emissions equivalently to fossil jet fuel emissions without fully accounting for the biogenic carbon cycle.

This issue becomes particularly important when comparing your results to recent integrated TEA-LCA and meta-analysis literature on SAF pathways. Recent studies evaluating camelina HEFA pathways under more conventional SAF lifecycle accounting frameworks generally report lifecycle emissions substantially below fossil jet fuel baselines while still accounting for high fertilizer and diesel inputs associated with camelina cultivation. In contrast, the current manuscript reports lifecycle emissions substantially higher than fossil jet fuel, suggesting that the treatment of combustion emissions and biogenic carbon cycling may be driving the discrepancy.

One possible approach would be to treat combustion CO_2 from SAF as biogenic within the lifecycle boundary while still accounting for all fossil energy inputs associated with production and processing. Another approach would be to explicitly justify why combustion emissions were treated equivalently to fossil jet fuel emissions and clearly discuss the limitations and implications of using this accounting framework.

If the manuscript chooses to maintain the current accounting approach, I strongly recommend:

- explicitly explaining how biogenic carbon is incorporated into the lifecycle framework,
- clarifying how the selected accounting methodology differs from more conventional SAF lifecycle accounting approaches,
- and rewording the environmental conclusions so they are specific to the assumptions and accounting framework used within this study.

In other words, under the current framework the manuscript may conclude that camelina-derived HEFA SAF performs worse environmentally than conventional jet fuel under the selected accounting assumptions. However, the author should avoid presenting this conclusion as a generalized statement about SAF pathways overall because under many conventional SAF lifecycle accounting frameworks this conclusion may not apply.

Second, the manuscript currently overstates the absence of integrated environmental and economic analysis for camelina-based SAF pathways. While inebriated TEA-LCA studies remain less common than single focus analysis, there is already an existing body of literature combining lifecycle environmental assessments and economic analysis for camelina derived aviation fuels. Thus, the novelty of the paper should be reframed more carefully. The contribution of the manuscript is still valuable, particularly in terms of using the literature to derive your calculations. However, you should not understate the state of literature since its underrepresentation of the available body of literature.

Section specific Comments

Abstract:

Please do not forget to properly define acronyms when introducing them in your manuscript. For example: Sustainable Aviation Fuel (SAF) or Hydroprocessed Esters and Fatty Acids (HEFA)

Your abstract is very clear up to the sentence:

“This paper thus concentrates on fuels produced from camelina via HEFA and attempts to determine the environmental and economic performance of such fuels, across production and use.”

After this line, it becomes somewhat unclear what the difference is between the initial analysis and the second part of the analysis. Specifically, it becomes difficult to understand how the manuscript is addressing the “lack of literature on the lifecycle environmental and economic performance of HEFA” while primarily relying on a literature review and synthesis approach.

You are presenting an interesting contribution; however, the wording of the abstract should be revised so that it more accurately reflects the outputs of a literature review and harmonization study rather than reading as though the paper generated an entirely new empirical lifecycle dataset.

Background

Great job in the first two paragraphs of your background section. The use of citations is strong and helps establish context effectively.

In the final section of your second paragraph, discussing some of the current technological, infrastructure, storage, and efficiency limitations associated with Hydrogen technologies would make your argument for SAF as a more immediately feasible alternative even stronger.

Literature Gap / Literature Review

You have identified a very interesting literature gap. However, the way you are currently writing this section could be much clearer.

Right now, the initial paragraphs read as though integrated environmental and economic analyses of SAF pathways have never been conducted before. However, later sections of the manuscript acknowledge that some integrated studies do exist. This creates inconsistency in how the literature gap is framed. The paragraphs in this section could be simplified significantly because right now they are difficult to follow. The same idea is repeated several times using slightly different wording.

A clearer frame would be something like:

Most previous work have focused either on the environmental performance or the economic performance of SAF pathways individually, while comparatively fewer studies have integrated both lifecycle environmental assessment and techno-economic analysis within the same framework, particularly for camelina-derived HEFA pathways.

The manuscript currently overstates the absence of integrated environmental and economic analyses for camelina-based SAF pathways. While integrated studies remain less common than single-focus analyses, there is already an existing body of literature combining lifecycle environmental assessment and techno-economic analysis for camelina-derived aviation fuels.

In other words, your approach to synthesizing and harmonizing existing environmental and economic literature is still valuable and relevant. However, the manuscript currently understates the amount of existing research already performing integrated TEA-LCA analyses. This should be addressed more carefully in the manuscript.

Rather than implying that this type of work has largely never been done before, I recommend positioning your novelty more specifically. For example, you could explain that your contribution focuses on synthesizing literature that individually explored environmental or economic dimensions in greater depth and harmonizing those values under a common framework,

Additionally, your literature review currently does not sufficiently explain why camelina via the HEFA pathway was specifically selected and why it is particularly suitable for addressing your research question compared to other feedstocks or pathways.

Methodology

Right now, your project is very interesting; however, portions of the methodology section are difficult to follow because the writing becomes overly dense and abstract.

For example, the second paragraph of your methodology could be communicated more clearly as follows:

The study collected emissions and cost data for each stage of the HEFA lifecycle from existing literature and combined these values to estimate overall environmental and economic performance. Because different studies reported results using different units and assumptions, unit conversions and mathematical standardization were performed to ensure comparability across sources. This approach was necessary because previous research has typically focused on either environmental or economic performance separately rather than integrating both forms of analysis. Additionally, the study analyzed each lifecycle stage individually instead of relying solely on final lifecycle estimates from previous papers, since the existing HEFA literature remains limited and lacks consistent conclusions.

Good job defining the search terms and databases used.

Figures and Tables

Figure 1 currently needs additional explanation. When you source a figure from another paper, you need to:

- properly cite the original paper in the figure caption,
- explain why the figure is being included,
- and explain its relevance to your analysis.

Right now, Figure 1 appears in the paper but is never fully integrated into the narrative. Every figure included in the manuscript should serve a purpose and should be referenced within the text at least once.

Great job on your Feedstock Growth section. That section is very clear and understandable, and the citation of the papers is excellent.

It also seems like there may be significant economic and efficiency benefits associated with solvent extraction pathways. Because of this, it is important to mention within your limitations section that alternative pathways for feedstock oil extraction were not considered within the analysis. It might be good to add justification for it from an the economic perspective.

I. Appropriateness of the Topic				
Inappropriate ______	Doubtful ______	Marginal ______	Suitable ______	Highly Appropriate __x___

II. Conceptual Adequacy				
Inadequate ______	Weak ______	Marginal ______	Good ___x__	Outstanding ______

III. Mastery of Relevant Literature				
Inadequate	Weak	Marginal x	Good	Outstanding

IV. Technical Adequacy

Completely Inadequate	Major Problems	Minor Problems	Good	Outstanding
______	___x__	______	______	__x___

V. Clarity of Presentation				
Unclear, requires extensive rewriting	Major Problems	Minor Problems	Good	Outstanding
______	__x___	______	______	______

VI. Significance of Contribution to the Field				
None	Trivial	Modest	Good	Outstanding
______	______	______	__x___	______

VII. Reviewer Recommendation				
REJECT Almost no chance that problems can be resolved.	REJECT, DESPITE MERIT Although parts of the manuscript have merit, it is unlikely that the problems can be resolved.	INVITE REVISION Possibly publishable if problems noted in my review are resolved.	CONDITIONAL ACCEPTANCE Publishable if the minor problems noted in my review are resolved.	ACCEPT Subject only to normal copy editing, if any.
____	______	__x___	______	______

The Environmental and Economic Performance of Camelina-Derived HEFA Sustainable Aviation Fuels: A Secondary Data Attributional Lifecycle Analysis

Abstract

The annual global demand for jet fuel is projected to exceed 230 billion gallons by the year 2050, more than doubling the 106 billion gallon demand from 2020. However, aviation accounts for approximately 11% of all transportation greenhouse gas emissions, presenting the challenge of decoupling the growing aviation industry from its associated environmental footprint. Recently, research has focused on the potential of sustainable aviation fuels (SAFs) for this purpose. Of the numerous existing methods for SAF production, the hydroprocessed esters and fatty acids (HEFA) route is the most mature for real-world application. Furthermore, within HEFA, the camelina crop poses immense potential as a feedstock. This paper thus concentrates on fuels produced from camelina via HEFA, and attempts to determine the environmental and economic performance of such fuels, across production and use. The latter part of this focus relates to the limited literature evaluating the lifecycle environmental and economic performance of HEFA, which this paper aims to address. The secondary data analysis presented here extracted numerical figures for each step of the HEFA process from nearly 50 credible sources, and mathematically synthesized them to produce the lifecycle analysis. Surprisingly, this review found that under certain conditions, camelina HEFA SAFs had a greater environmental impact as compared to traditional fuels, while still costing less to manufacture. This unique finding may speak to the conditions considered, the viability of the fuel pathway studied, or the greater feasibility of SAF implementation.

Keywords: sustainable aviation fuels, HEFA, camelina, lifecycle analysis

The Environmental and Economic Performance of Camelina-Derived HEFA Sustainable Aviation Fuels: A Secondary Data Attributional Lifecycle Analysis

1.1. Background

The already large aviation industry is poised for incredible growth in coming years. The jet fuel market alone is expected to more than double its value from 2020, as outlined by the Department of Energy, or DOE (n.d.-b). However, this growth will bring with it a surge in the aviation industry's environmental footprint. Currently, around 11% of all transportation greenhouse gas (GHG) emissions originate from aviation (D'Ascenzo et al., 2024). This constitutes around 2-3% of all human carbon emissions, in addition to emissions from other GHGs such as water vapor and methane. Even apart from these gases, aviation releases other environmentally detrimental substances into the atmosphere, such as soot and sulfur (Chireshe et al., 2025).

The severe environmental impacts of aviation pose a serious issue, especially when considered in conjunction with the coming growth of the aviation industry. Recently, research has focused on the use of sustainable aviation fuels, or SAFs, to resolve this issue. Sustainable aviation fuels are defined as jet fuels that can be produced from renewable sources of energy, such as biomass or hydrogen. SAFs are crucial to aviation because they pose the potential to reduce the environmental footprint of the industry – both in manufacturing and emissions – without the need for significant structural changes to existing aircraft and infrastructure. Additionally, while other methods for aircraft environmental sustainability do exist, such as electric or hydrogen power, there are numerous technical barriers faced by these nascent methods (Song et al., 2024), further contributing to the importance of SAFs. For example, using hydrogen power in aviation would require overcoming hydrogen's low volumetric energy density, requirements for cryogenic storage, uncertain climate impacts, and more.

1.2. Purpose

Environmental performance is inevitably a major point of concern for sustainable aviation fuels; however, economic performance is also of paramount importance. Today, fuel represents around 20-30% of the operating costs of an airline (DOE, n.d.-b). As such, for sustainable aviation fuels to be practical in real world application, they must be capable not only of decreasing the environmental footprint of aviation, but also of being produced at feasible costs relative to existing fuels.

At the moment, there are numerous developed SAF production pathways, including: Hydroprocessed esters and fatty acids, alcohol-to-jet, hydroprocessing of fermented sugars, Fischer-Tropsch, pyrolysis, aqueous phase reforming, and power-to-liquid. Of these existing routes, the hydroprocessed esters and fatty acids route, or HEFA, is currently the most mature (Bauen et al., 2020). HEFA makes use of renewable feedstocks to obtain oils and fats, which are then hydroprocessed to create fuel. Being the most mature existing SAF pathway, HEFA poses the greatest potential for sustainable aviation fuel implementation. Despite its overall significance, however, an immensely important consideration for the HEFA process is the feedstock implemented. In this regard, the camelina crop is a feedstock with incredible potential, because it requires little energy to grow, contains high amounts of non-food oil, and can be grown without interfering with other agriculture as a cover crop (Wang et al., 2020). These characteristics are important because they indicate that camelina can be grown with minimal environmental impact, while also producing a high magnitude of oil to be converted to fuel. The goal of this paper is to analyze existing literature to obtain secondary data values, then present a full environmental and economic lifecycle analysis of the HEFA production route given camelina as a feedstock. In this way, this paper will provide a robust analysis of SAF performance under mature and promising conditions, to help evaluate the realistic feasibility of SAF implementation in the modern world.

1.3. Literature Gap

There is currently limited SAF-focused literature on the lifecycle environmental and economic performance of the HEFA route. This is because many works have analyzed either the lifecycle environmental or the lifecycle economic performance of SAFs, but comparatively fewer have analyzed both, and even fewer have done so for the HEFA route.

Many recent works in the field have focused exclusively on the lifecycle environmental performance of sustainable aviation fuels. For example, Kurzawska-Pietrowicz (2023) reviewed the lifecycle emissions of various sustainable aviation fuels, Abayo et al. (2024) compared the environmental impact of various SAF pathways, and Zemanek et al. (2020) analyzed the emissions from using oilseeds in the HEFA route. However, works exclusively analyzing environmental impacts have naturally not examined the lifecycle economic impacts of SAFs, although in some instances such works may be directed specifically at HEFA. In contrast, much other literature has focused exclusively on the lifecycle economic performance of sustainable aviation fuels. For instance, Pearlson et al. (2013) created estimates for the economics of the HEFA route. However, literature in this category similarly does not present the lifecycle environmental performance of SAFs, although it may also focus solely on HEFA. A highly important note is that even when synthesized together, these types of SAF evaluations focusing exclusively on lifecycle environmental or economic performance cannot produce the same impact as combined lifecycle analyses can. Thus, these exclusive analyses cannot fill the gap produced by the currently limited combined literature. As discussed previously, there are various

SAF pathways and assumptions that can be made in the process of analysis. While the combination of exclusively environmental and economic works can produce more broad conclusions on the environmental and economic performance of SAFs, it can struggle to produce conclusions for specific pathways and assumptions, which is where the differentiation from combined analyses occurs. This is because no two separate works utilize the exact same framework to evaluate SAFs; as a result, an exclusively environmental analysis often lacks an economic counterpart with the same pathway and assumptions to produce comprehensive environmental and economic conclusions for its framework. The lack of combined conclusions for specific frameworks from exclusive analysis poses an important limitation because while generalizable conclusions are helpful, SAF practicality varies greatly across pathways and assumptions, making framework-specific conclusions important for differentiation and understanding. It also poses a limitation because, as discussed earlier, both environmental impact and cost are essential factors to consider in relation to the practicality of SAF application, and neither can be ignored.

Resolving this limitation with works focusing exclusively on either the lifecycle environmental or economic performance of SAFs, some literature has also focused on both of these factors; however, this literature is less common compared to the exclusive analyses, which establishes the beginnings of the research gap of this paper. Grim et al. (2022), for instance, reviewed the lifecycle environmental and economic aspects of the power-to-liquids SAF production pathway. Similarly, Gonzales-Garay et al. (2022) reviewed the lifecycle environmental and economic feasibility of the Fischer-Trophsch and methanol-to-fuels given different energy sources. Additionally, Braun et al. (2024) analyzed various SAF production methods, including HEFA, to determine lifecycle environmental impact and pricing. Yet, the majority of papers in this domain do not focus exclusively and comprehensively on the HEFA pathway to SAF production, although sometimes, as in the case of Braun et al. (2024), the method may be analyzed alongside others. In other words, while papers analyzing the lifecycle environmental or economic performance of SAFs sometimes focus specifically on HEFA, papers that present both the lifecycle environmental and economic performance of SAFs are rarely directed towards thoroughly analyzing HEFA.

However, there are some papers that resolve this, and provide an environmental and economic analysis focusing specifically on the HEFA pathway. Seber et al. (2014), for instance, looked at the lifetime environmental and economic impacts of HEFA fuel production given waste oils and tallows as feedstocks. Nevertheless, literature in this specific domain is minimal, and, as in the case of the paper from Seber et al. (2014), not always recent, as is particularly important in the realm of economics. As a result, the precise focus of this paper on the environmental and economic performance of the HEFA pathway given a lifecycle analysis is beneficial by contributing to the currently limited research surrounding this specific domain.

1.4. Research Question and Hypothesis

To summarize the aforementioned explanations, the question that this paper seeks to answer is: What is the economic and environmental performance of sustainable aviation fuels produced from camelina via the HEFA pathway, when considering full lifecycle analysis? The initial hypothesis regarding this question is that HEFA SAFs produced from camelina have an environmental footprint approximately 20% less than traditional fuels, while still roughly matching the costs of these fuels.

2. Methodology

To prove this hypothesis, the body of this secondary analysis was chronologically structured around the various stages of the HEFA route: Feedstock production, transport and oil extraction, HEFA conversion, and combustion. In each stage, the paper tracked two measures of SAF performance: CO_2 equivalent emissions for environmental performance, and cost in dollars for economic performance. Also for each step, the magnitude of these two measures was placed in relation to the "input" quantity for that stage. For example, for the oil extraction step, emissions and costs were given per kilogram of feedstock, as feedstock was the input quantity for oil extraction. One important note should be included in regards to the feedstock production and combustion stages. Many recent works in the field of sustainable aviation fuels evaluate these stages in parallel, and thus consider the emissions from SAF combustion to be environmentally neutral. This is because the carbon released into the environment during SAF combustion originates from the carbon absorbed from the environment during the feedstock growth. However, this paper instead considered the feedstock growth and combustion stages independently. Biogenic carbon uptake was incorporated into the feedstock section, and the combustion emissions were separately included in the combustion section. This choice was made because it was theorized to allow for a more thorough and transparent approach to evaluating each step of HEFA SAF production. This choice was also made because combustion emissions from SAFs are known to produce meaningful non-CO_2 emissions that would not be offset by feedstock growth, and because it was unknown how the intermediate stages between the feedstock growth and combustion would impact the presence of absorbed carbon in the emissions themselves.

The paper followed the two measures of performance in each stage by drawing any discovered quantitative values for emissions and cost, and combining them mathematically to produce overall values for that stage. This secondary method of analysis was beneficial because it allowed for the use of raw data from the previous literature on the lifecycle environmental or economic performance of HEFA (see Literature Gap) to fill the lack of research on both factors in one framework. Additionally, a stage by stage analysis was performed as opposed to a synthesis of final lifecycle values from existing works given the difficulties and inaccuracies in combining calculated environmental and economic figures from different papers (see Literature Gap).

Once values for each step of the process were derived, they were combined through further unit conversion to produce final values for emissions and cost. These values were then compared to those of traditional fuels, as obtained from credible and corroborated sources, to establish improvement or deterioration in both categories. This form of analysis produced the secondary analytical nature of this paper, and the conditions and assumptions established produced its attributional quality.

In terms of information sourcing, sources analyzed within this research paper were found using the following search terms: Sustainable, aviation, lifecycle, environmental, fuel, economic, and HEFA, as well as other search terms tangential to the field of sustainable aviation fuels. These search terms were used in research databases, such as JSTOR and Google Scholar, as well as in ordinary search engines such as Google. Furthermore, only sources from 2000 and onward were considered. Under these conditions, the research paper considered a total of 70 sources, of which 47 sources were used within the body of the paper. The sources used were chosen for the scope of relevant information they covered, and the credibility and expertise they offered. Specifically, sources considered for the analysis of the paper were excluded if they did not provide quantitative data regarding the HEFA pathway. Similarly, sources considered for the introduction were rejected if they did not present expertise in their subject field. Of the sources used in the body of the paper, 39 were academic research papers, 7 were government or otherwise credible reports, and 1 was a credible website.

A highly important note should also be made in regard to the way that calculations were performed throughout the entirety of the paper. Throughout the paper, data from sources was taken in exact specificity as originally found when used in calculations. In the same way, calculated numbers from original source values were stored to exact specificity for further computation. However, when original figures or calculated values were presented, they were rounded to three decimal places (and identified as approximates unless in the appendixes), or left with their original number of decimals if not present in this specificity. Furthermore, even if original figures were identified as approximated in the sources from which they came, they were not identified as such in the paper, and used according to the rules above. These choices were made to improve the understanding and ease of the reader.

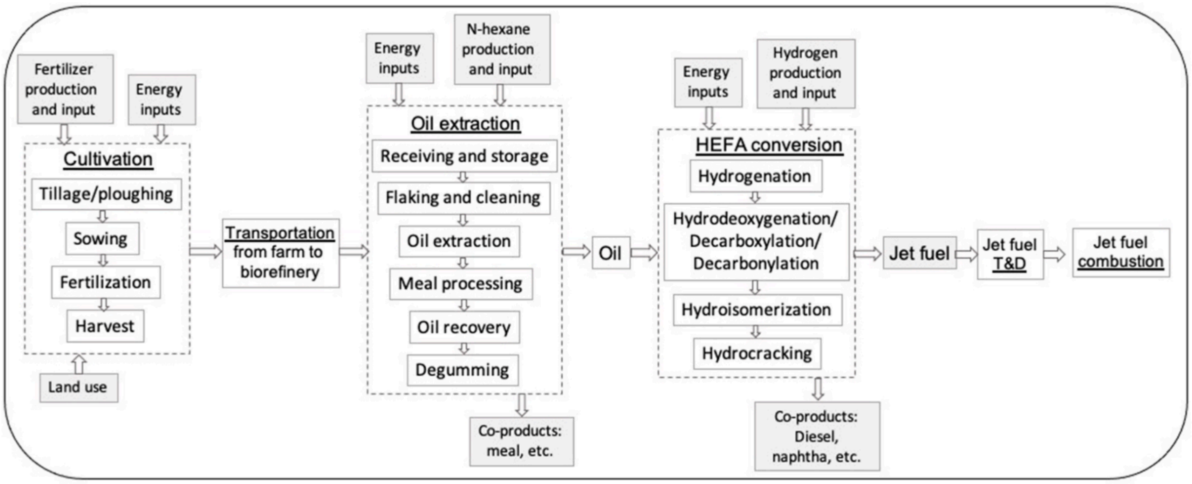
2.1. Key Abbreviation Definitions

- metric kilogram = kg
- metric kilometer = km
- CO2 equivalent = CO_2e
- metric megajoule = MJ
- metric gigajoule = GJ
- metric kilowatt-hour = kWh
- metric ton = ton
- imperial pound = lb
- imperial mile = mi
- metric gram = g

3. Analysis

Figure 1

Lifecycle HEFA Fuel Production Pathway



Note. Figure from Seber et al. (2022). Depicts the different stages of the HEFA lifecycle analyzed in this paper. Also illustrates the substeps within the broader stages, as well as input requirements and outputs.

3.1. Feedstock Growth

The first stage of the HEFA process is the growth of a feedstock (Figure 1); for the purposes of this paper, camelina. Feedstock growth is an exceedingly important consideration in the HEFA lifecycle, because it can sequester significant volumes of atmospheric carbon dioxide. However, feedstock growth is also an incredibly complex factor, because feedstocks themselves require energy to grow, and may have impacts on other agriculture. Camelina as a feedstock is grown for its oilseeds, from which oil can be extracted to create SAFs (Li & Mupondwa, 2016). The goal of this section is to analyze camelina growth within the HEFA process, to determine its environmental and economic impacts.

As explained previously, the environmental impacts of camelina growth must be considered by analyzing both the resources needed to grow the crop, and the resulting greenhouse gas sequestration. This paper will consider typical to marginally conservative growing conditions for camelina, to obtain the most accurate and broadly applicable results. One value for camelina's environmental impact can be found in a study from Krzyzaniak and Stolarski (2019), which calculated that under reduced tilling conditions, growing one hectare of camelina produced a net release of between 1732 and 1772 kg of CO_2e (in regards to climate impact) gas. However, this study ignored carbon sequestration within the soil in which the camelina was grown. Krzyzaniak and Stolarski (2025) later incorporated this factor into a separate study in which they used the SimaPro 9.6 software to simulate plant growth, allowing them to refine their figure down to 762 kg of CO_2e per hectare, with a 0.95 confidence interval ranging from approximately 140-1700. This figure is supported by other previously performed studies such as that of Krohn and Matthias (2012), which found between 650 and 950 kg of net CO_2 emissions given low input growth conditions. An important point to note regarding these studies is that each analyzed camelina as the only crop growing on a plot of land, but did not consider the potential environmental benefits or drawbacks of other crops that might otherwise be grown on that land. As such, the figures in each of these studies should be taken at value only if camelina is considered as being grown in its most common form; as a cover crop, during a time when most others cannot feasibly be grown. Using the above figures with this in mind, it can be concluded that net carbon emissions from camelina growth, when considering input resources and carbon sequestration, lies approximately around 750 kg of CO_2e per hectare grown. Finally, dividing this value by the the average camelina yield of around 1900 kg of oilseed per hectare (Li and Mupondwa, 2016; Zhang et al., 2021) gives that the carbon emissions from camelina growth lie around 0.395 kg of CO_2e per kg of oilseed. However, the question of the associated costs of this growth still remains.

In regard to answering this question, this paper will focus on various factors that affect the cost of camelina growth for HEFA, such as machinery costs, farming resources, and land use. In a paper by Li and Mupondwa (2016), the average cost for camelina growth was cited as $463 per hectare, given the average yield of 1900 kg of camelina oilseed per hectare found by the authors, and corroborated by Zhang et al. (2021). This figure took into account numerous production variables, including fertilizer cost, machinery, repair, depreciation, land investment, labour, and more. Additionally, Li and Mupondwa (2016) also found that the cost to grow camelina varied depending on the yield per hectare, with low yields of around 700 kg per hectare costing $0.66 per kg of oilseed, and high yields of 3300 kg per hectare costing only $0.14 per kg of oilseed. Nevertheless, the authors' cost-value for an average yield of camelina oilseed is more broadly applicable to various circumstances, and is thus a significantly more accurate figure for the purposes of this paper. As such, dividing $463 per hectare by the average camelina yield of 1900 kg per hectare gives an accurate cost of approximately $0.244 per kg of oilseed. An important point to note regarding camelina oilseeds is the economic impact of camelina meal, which is derived from the oilseeds after the oil has been extracted, and can be sold for a profit (Li & Mupondwa, 2016). However, this impact will be analyzed in a later section, as it falls under the oil production stage of HEFA rather than under feedstock growth. Overall, it can be concluded that the cost to grow camelina for the HEFA route is approximately $0.244 per kg of oilseed.

3.2. Transportation And Oil Extraction

The second step of the HEFA process involves two stages: The transport of a feedstock to a biorefinery, and the subsequent extraction of oil from that feedstock (Seber et al., 2022). In terms of environmental and economic impacts, both of these stages are incredibly important to consider. Freight transport releases greenhouse gases that damage the environment (Congressional Budget Office, 2022), and also adds costs to the lifecycle of HEFA. Similarly, oil extraction requires energy that generates both GHGs and furthers the costs of the process.

Firstly, the transportation of feedstocks to biorefineries for oil extraction is an important player in the emissions associated with HEFA. According to statistics from the Congressional Budget Office (2022), trucking - the primary method of freight transportation - produces 0.4 lb of CO2 per ton-mi (transporting one ton a distance of one mile). This figure is incomplete without a transport distance, but a study by Li and Mupondwa (2016) found that feedstock transportation to processing plants within a 200 km radius took an average distance of 133 km. This paper will assume transport distances under 200 km, and accordingly apply the 133 km average. However, it should be noted that this figure is geographically constrained, and may differ by region. Combining this value with the trucking emissions figure (see *Appendix B*), it can be reasonably concluded that transportation emissions amount to around 0.015 kg of CO_2 per kg of camelina. It is important to note that this figure is an estimate, not an exact calculation by any means, especially given the variability of trucking emissions highlighted by the Congressional Budget Office (2022). Nevertheless, it is a reasonable estimate given the information, and thus merits a continuation to consider costs.

For the aforementioned 200 km radius, Li and Mupondwa (2016) also found that feedstock transportation had an average impact of $12.29 per ton of oilseed transported. Converting this figure from per ton of oilseed to per kilogram of oilseed (see *Appendix A1*), it can be concluded that transportation costs add around $0.012 per kg of camelina. Moving on, the next relevant consideration in this stage is the impact of oil extraction itself.

There are currently two major recognized methods of feedstock oil extraction: Mechanical pressing, and solvent extraction, although enzymatic extraction may also be considered in this regard (Pikula et al., 2020). Of these two methods, mechanical pressing is less expensive (Pikula et al., 2020), more time efficient (Ofori-Boateng et al., 2012), and is the only method used in small scale facilities (Veljkovic et al., 2022). In addition, solvent extraction may result in negative environmental impacts (Pikula et al., 2020). For these environmental and economic reasons, this paper will consider only the mechanical pressing method of oil extraction. However, there are nevertheless important concerns with mechanical pressing, including the need for oil filtration and purification (Popa et al., 2017), and a reduced oil extraction efficiency as compared to solvent extraction (Ofori-Boateng et al., 2012). The method itself consists of cleaning oilseeds, pressing them to extract oil, and purifying the oil to prepare it for HEFA conversion (Seber et al., 2022).

For the mechanical pressing method, the environmental impacts of camelina oil extraction mainly come from the electricity needed to execute oilseed crushing, as this is the stage that naturally requires the most energy. A thorough empirical study from Dangol et al. (2015) reported that such emissions amounted to 0.043 kg of CO_2e per lb of refined oil produced by mechanical pressing. Given that this study also reported extracting 27.4% of camelina input mass as oil, calculations (see *Appendix C1*) show that the emissions from oil extraction are approximately 0.026 kg of CO_2e per kg of input oilseed. To reiterate, this value assumes negligible contributions from the cleaning and purification processes, given the low energy input and lack of environmentally damaging substances involved with these stages. However, while the environmental impacts of camelina oil pressing can be considered in this way, the costs of the process involve numerous other factors.

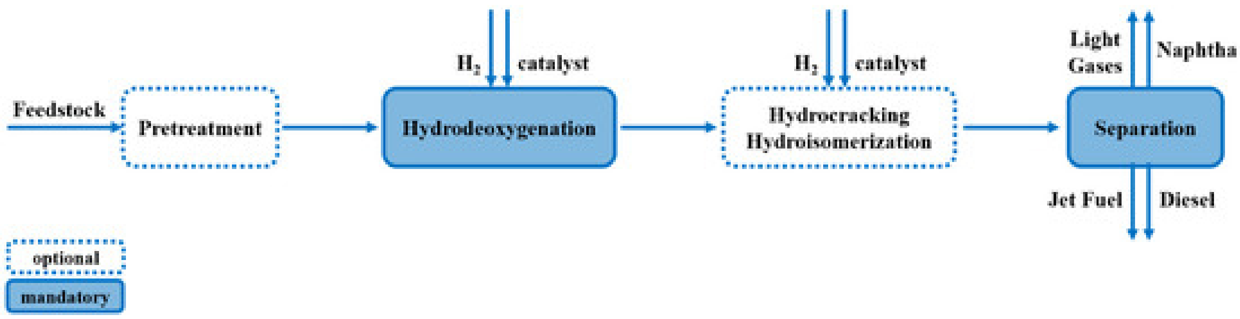
For the purposes of this paper, the costs of camelina mechanical oil extraction will be considered using two factors: The energy required for oil pressing, and the by-product (meal) produced by the extraction. The energy for oil extraction is naturally an important factor for cost, and relevant mainly to the actual oil pressing stage itself. The by-products, however, are also important to consider, because they can be sold to offset other costs (Veljkovic et al., 2022). First looking at oil pressing, the energy required to press oilseed typically falls at 0.05 kWh per kg (Singh & Bargale, 2000). Furthermore, the U.S. Energy Information Administration, or EIA (n.d.-a), cites current average industrial prices for electrical energy as $0.083 per kWh. Multiplying these figures gives a relatively minute value of about $0.004 per kg of oilseed. However, this cost can be offset by selling the camelina meal left behind by the oil extraction. As aforementioned, Dangol et al. (2015) found that mechanical pressing can extract 27.4% of inputted camelina oilseed mass as actual oil. The remaining 72.6% of input camelina mass is therefore left behind as meal. Combining this value with the price of camelina meal, $0.25 per kg (Bertacchi et al., 2020), and further accounting for the approximately $0.004 per kg for electrical energy (see *Appendix C2*) demonstrates that the final oil extraction cost value is around $0.177 per kg of oilseed in cost offset (revenue).

3.3. HEFA Conversion

The third and perhaps most complex stage of the HEFA process is the actual conversion of feedstock oils into HEFA fuel (Seber et al., 2022). Ignoring the pretreatment stage that this paper covered in the previous section, HEFA conversion begins with reacting feedstock oil and H_2 at a high temperature and pressure to remove oxygen; a process known as hydrotreating (DOE, n.d.-b). Once this step is completed, the resulting substance becomes functional fuel (Monteiro et al., 2022). However, to meet the various requirements of jet fuel, it is hydrocracked and hydroisomerized again using H_2 as a catalyst (DOE, n.d.-b). Finally, after these steps, the upgraded fuel is separated from the other products of the reaction, resulting in usable biofuel. This section will analyze both the emissions and cost of this HEFA conversion step, with camelina as a feedstock in mind.

Figure 2

Simplified and Complete Visual of the HEFA Process



Note. Figure from Monteiro et al. (2022). Shows how feedstocks are turned into HEFA fuel, which stages are mandatory, and what the inputs and outputs of the process are.

The environmental impacts of HEFA conversion are a large consideration for the process as a whole. This is due to the large amounts of energy, H_2, and natural gases needed for this stage. According to Han et al. (2013), the net HEFA conversion related emissions for camelina are approximately 0.021 kg (20.5 g) of CO_2e per MJ of SAF produced. Han et al. (2013) considered various factors in this figure, such as hydrogen input and energy requirements. Given the calorific value of camelina HEFA biofuel; 44.1 MJ per kg of SAF, and the fact that 1 kg of input camelina oil converts via HEFA into only 0.75 kg of biofuel (Han et al., 2013), it can be concluded that HEFA conversion releases about 0.678 kg of CO_2e per kg of input camelina oil (see *Appendix D1*).

Regarding costs, HEFA conversion is relevant due to the energy associated with hydroprocessing, but also because of the by-products that are produced through conversion, namely naphtha and a propane mix (Figure 2); which can also be sold to offset energy costs. An important note is that diesel can also be a by-product (Seber et al., 2014), but will be ignored for the purposes of this paper, as the studies used for economic analyses - such as that from Han et al. (2013) - also do not consider it. First regarding energy, there are three major concerns: H_2, natural gas, and electricity. According to Han et al. (2013), hydrogen use for camelina HEFA processing lies at 4734 MJ of H_2 per ton of produced biofuel. Similarly, natural gas use is 7818 MJ per ton of biofuel, and electricity use makes up 61 kWh per ton of biofuel. For H_2 use, implementing hydrogen's energy density of 120 MJ per kg (DOE, n.d.-a), and a reasonable cost assumption for electrolysis produced hydrogen, $5 per kg (Vickers et al., 2020), shows that hydrogen use in HEFA conversion constitutes $197.25 per ton of produced biofuel (see *Appendix D2*). However, it is important to note that this figure is valid only under the assumption that the hydrogen is produced via electrolysis. For natural gas, 1000 cubic feet constitutes 1093 MJ of energy (EIA, n.d.-b), and every cubic foot of natural gas costs approximately $0.005 according to current industrial prices (EIA, n.d.-c). Combining these values with the aforementioned 7818 MJ per ton of produced biofuel (see *Appendix D3*) gives that natural gas contributes about $32.259 per ton of produced biofuel. Finally, for electricity, the same industrial cost as used in the oil extraction section will be assumed; $0.083 per kWh (EIA, n.d.-a). Thus, multiplying the 61 kWh per ton of produced biofuel by $0.083 per kWh gives a fair cost estimate for electricity used in HEFA conversion for camelina: $5.063 per ton of biofuel.

However, as aforementioned, the by-products produced by HEFA conversion are also highly important to consider in regards to the economic feasibility of the process. For the purposes of this paper, it will be assumed that the by-products are sold for their market values, and offset costs in this way. According to Han et al. (2013), the yields of naphtha and propane mix from 1 ton of produced biofuel are 3359 MJ and 4444 MJ respectively. Given that naphtha has an energy content of 43.2 MJ per kg (Han et al., 2013) and a recent market price of $0.55 per kg (Aburto et al., 2025), it can be calculated that the value of the gas produced per ton of produced HEFA biofuel is about $42.765 in cost offset (see *Appendix D4*). Similarly, given the energy content of the propane mix by-product from HEFA conversion, 44.4 MJ per kg (Han et al., 2013), and a recent market price for propane, $0.8 per kg (Aburto et al., 2025), it can also be calculated that the cost contribution from the propane mix is about $80.072 per ton of biofuel in cost offset (see *Appendix D5*). Summing the approximately $42.765 per ton of biofuel and about $80.072 per ton of biofuel gives a combined final cost offset of about $122.837 per ton of produced biofuel.

Concluding economics, the costs for hydrogen, natural gas, and electricity to produce 1 ton of camelina HEFA SAF were: $197.25, approximately $32.259, and $5.063, respectively. Summing these values gives about $234.572 per ton of produced biofuel. However, the offsetting value of naphtha and propane must also be factored into the analysis, removing about $122.837 from the price, and bringing the total down to about $111.735 per ton of biofuel. Further dividing this figure by 1000 provides that producing 1 kg of HEFA SAF from camelina costs around $0.112. Furthermore, converting this value to be in terms of input oil rather than produced biofuel, using the fact that 1 kg of input camelina provides only 0.75 kg of biofuel via HEFA (Han et al., 2013), gives a final cost of approximately $0.084 per kg input oil (see *Appendix D6*).

3.4. Combustion

The final stage of SAF use is the combustion stage. SAF combustion is complex in terms of environmental impact, because it not only leads to the direct release of CO_2, but also emits numerous other environmentally impactful substances, which may alter atmospheric chemistry

(Lee et al., 2023). Such emissions include NO_x, H_2O (water vapor), SO_2, particulate matter (PM), CO, and unburned hydrocarbons (UCH). An important note regarding this step is that today, SAF regulations require that they be blended with traditional jet fuels, up to a maximum of 50% (DOE, n.d.-b). Nevertheless, for the purposes of this paper, combustion will be considered as that solely of the SAF derived from HEFA conversion, without blending: This is because SAFs can be used without traditional fuel blending, despite existing regulations. Furthermore, this section will only consider the climate impact of SAF combustion, as without blending, there are no combustion costs to consider. To reiterate, a full emissions analysis is presented below, as this paper did not consider emissions to be offset by biogenic carbon uptake during feedstock growth.

Various studies have shown that SAF emissions of most gases/substances do not differ greatly in terms of climate emissions from traditional jet fuels. For instance, Song et al. (2024) found that the emissions of CO_2, NO_x, CO, and UHC from various SAFs (including camelina based fuels) were insignificantly different from those of traditional jet A1 fuel. However, certain gases and substances do differ between SAFs and ordinary fuels. In particular, Song et al. (2024) also found that the SO_2 and PM emissions from SAF combustion were significantly lower than those of traditional jet fuels, while Teoh et al. (2022) cited that the water vapor emissions can be up to 10% higher.

In general, SO_2 (which forms sulfate particles), PM, and water vapor play a role in the climate through the formation of jet contrails (Lee et al., 2023). Contrails form when water vapor attaches to particulate matter, and they may form cirrus clouds at high altitudes. These cirrus clouds produce a net negative climate impact, although they have both positive and negative climate impacts (Lee et al., 2023). Contrails are one of the most environmentally impactful factors related to aviation (NASA, 2017). According to Teoh et al. (2022), studies estimate that

SAFs may increase contrail prevalence by 1-8%, due to their increased water vapor emissions as compared to traditional fuels. However, Lee et al. (2023) explains that the interaction between PM, SO_2, and water vapor in contrails and the resulting cloud formation is highly uncertain. This means that it remains unclear how SAF use influences the magnitude of contrail formation, and the resulting cloud formation. Furthermore, even if Teoh et al. 's (2022) figure is to be considered, it represents only a relatively small change in the magnitude of traditional fuel contrails. It is important to note on this point that the magnitude of contrail formation is not the only factor that influences the magnitude of cloud formation, and thereby the magnitude of climate impact. Contrails from SAFs and traditional fuels may be internally different, which can influence how they produce clouds, and thus their impact on the climate. However, the high level of uncertainty on how the emission differences between SAFs and traditional fuels impacts cloud formation from contrails means that differences in climate impact caused by internal contrail differences are difficult to quantify. Thus, given the similarities in most emissions between SAFs and traditional jet fuels, in addition to high uncertainties regarding contrail impacts, this paper will consider the climate impact of SAF combustion to be relatively equivalent to that of traditional jet fuel.

In terms of combustion emissions, standard petroleum jet fuel produces 74 g of CO_2e per MJ of fuel (Prussi et al., 2021). Converting to kilograms, and factoring in the energy density of SAF, 44 MJ per kg (Norazmi, n.d.), gives that the combustion emissions of SAF lie at 3.256 kg of CO_2e per kg of combusted SAF (see *Appendix E*).

3.5. Overall Results

The previous sections of this paper have reviewed each of the individual stages of creating HEFA fuel from camelina, including feedstock growth and extraction, transport and oil extraction, HEFA conversion, and combustion. This section will combine each of these values to generate complete, final figures for the lifecycle emissions and costs of generating HEFA fuels from camelina. Then, these figures will be compared to those of traditional jet fuel.

Beginning with the feedstock production and extraction, the CO_2e emissions to produce 1 kg of camelina were found to be around 0.395 kg of CO_2e per kg of camelina grown, and the cost was found to be around $0.244 per kg of camelina grown. Moving on to transportation, the figures were approximately 0.015 kg of CO_2e per kg of transported oilseed, and about $0.012 per kg of transported oilseed. Summing these transportation values with their respective counterparts for the oil extraction stage; about 0.026 kg of CO_2e per kg of oilseed, and around $0.177 per kg of oilseed in cost offset, gives the combined transportation and emissions values: around 0.041 kg of CO_2e per kg oilseed, and around $0.165 per kg of oilseed in cost offset. Continuing on to HEFA conversion, it was concluded that the process adds approximately 0.678 kg of CO_2e per kg of input oil, and about $0.084 per kg of input oil. Lastly, for combustion, the emissions figure was found to be 3.256 kg of CO_2e per kg of SAF, with no combustion costs added. These values represent the mathematical results of this research paper, however, they still must be combined into two single figures for emissions and costs, to be compared to traditional fuels. Combining the values by assuming a 1 kg input of camelina feedstock and converting to per megajoule of biofuel (see *Appendix F*), gives the absolute final approximate values for the lifecycle emissions and costs of producing camelina biofuel via HEFA: 0.140 kg CO_2e per MJ, and $0.011 per MJ.

In comparison to the emission values for traditional petroleum jet fuel, these numbers produce surprising results. According to Prussi et al. (2021), the combustion emissions of petroleum jet fuel account for 83% of its total lifecycle GHG emissions, or 0.074 kg of CO_2e per MJ. Thus, by multiplying this figure by 1/0.83, the lifecycle GHG emissions of petroleum jet fuel can be found to lie around 0.089 kg of CO_2e per MJ. This value is also supported by Song et al. (2024) who concluded a figure of 0.090 kg (90 g) in their own study. Importantly, this value of 0.089 kg is reasonably less than the 0.140 kg calculated for SAF; specifically amounting to approximately 64% of this value.

In contrast, the above cost value for SAF is less than that of traditional jet fuels. Comparing in particular to jet A1 fuel, a highly conventional petrol jet fuel (Song et al., 2024), current costs lie at $697.6 per ton according to Jet-A1-Fuel (n.d.). Dividing by the calorific value of kerosene jet fuels, 44.1 GJ per ton (United Nations Statistics Division, 2014), gives approximately $15.819 per GJ, and further converting from per gigajoule to per megajoule (see *Appendix A5*) gives about $0.016 per MJ. This value for traditional fuel is approximately 141% of that calculated above for SAFs.

4. Conclusion

4.1 Discussion

The major focus of this research paper was to evaluate the environmental and economic performance of sustainable aviation fuels derived via the HEFA pathway, from the camelina crop as a feedstock, across their entire lifecycle. The purpose of this analysis was to increase the currently limited understanding of the practical application of SAFs as a whole, in comparison to traditional fuels. The analysis was performed via the combination of values from various research papers in the field, to derive overall values for each state of the HEFA production, and thus total ending values. The initial hypothesis based on academic literature in the field regarding this question was that camelina HEFA SAF would demonstrate a reduction in environmental footprint as compared to traditional jet fuels, while roughly matching the costs of these fuels. However, this hypothesis was incorrect. The research paper found that traditional jet fuels only had about 64% of the greenhouse gas release of the SAF, but approximately 141% of the total cost. Table 1 below summarizes the important values derived throughout the paper, which can be found in the conclusion paragraphs of each stage section.

Table 1

Emissions and Costs Broken Down by Stage of Production

Stage of Production *(specific units provided)*	Feedstock Growth *1 kg of camelina oilseed*	Transportation *1 kg of camelina oilseed*	Oil Pressing *1 kg of input camelina oilseed*	HEFA Conversion *1 kg of input camelina oil*	Combustion *1 kg of camelina biofuel*	Total SAF Values *1 MJ of camelina biofuel*	Total Jet Fuel Values *1 MJ of modern jet fuel*
Greenhouse Gas Emission *(kg of CO_2e)*	0.395	0.015	0.026	0.678	3.256	0.140	0.089
Cost *($)*	0.244	0.012	-0.177 (cost offset)	0.084	0	0.011	0.016

Note. All figures rounded to three decimal places.

It is important to recognize that the results of the study – in going against the hypothesis – also go against the general theme in the academic literature surrounding sustainable aviation fuels. Excluding the possibility of errors (see Limitations and Future Research), this suggests that the assumptions used within this paper had a significant impact on the results that it produced (see Considerations and Assumptions). Nevertheless, assumptions were justified and errors were carefully screened, providing credibility to the numerical conclusion.

4.2. Implications

Based on this credibility, the results of this research paper pose some potentially important implications for the future of aviation. If the fuel pathway studied in this paper, taking the assumptions to be true, produces a larger environmental footprint as compared to traditional fuels, then perhaps it should be avoided in the interest of reducing the environmental footprint of aviation as a whole. However, if economic success takes priority over climate stability, then perhaps the fuel pathway should be implemented to reduce costs. These both serve as interesting direct extensions of the numerical conclusions above. However, the results of this study could also be indirectly extended to reflect the aspects of SAF production analyzed, rather than the holistic pathway studied. For example, this study could indicate the environmental infeasibility and economic practicality of the HEFA pathway specifically, regardless of the crop used. Similarly, the results could also implicate camelina as a poor and economically viable crop for HEFA, or SAFs as a whole. In contrast, the results could even more broadly indicate that SAFs as a whole do not have the capacity to reduce climate footprint as compared to traditional fuels, but do have the capacity to reduce costs, regardless of the production pathway or input source.

Regardless, the only truly anchored connections that can be made with this research are those relating directly to the exact fuel pathway studied, under the exact assumptions considered. The results may speak to HEFA, camelina, and SAFs as a whole, but they must not be taken as generalized conclusions about them, because the inclusion of these factors and the assumptions makes the impact of each unclear. To reiterate, the research presents a conflict, where the use of camelina to produce SAF via the HEFA route increases environmental impact, but reduces costs.

4.3. Considerations and Assumptions

On the subject of conditions, it is crucial to reiterate that this paper relied on many key assumptions made: biogenic carbon intake and combustion were considered in separate stages rather than as environmentally neutral in parallel; camelina was assumed to be grown as a cover crop under moderate conditions; transportation was modeled by trucking of under 200 km; oil extraction was considered via mechanical pressing energy, without regard for purification and cleaning, and with the assumption of camelina meal being sold; HEFA conversion was analyzed via energy use, with electrolysis derived hydrogen, and with naphtha and propane by-products sold; pure HEFA SAF combustion was assumed, and considered equal in emissions to ordinary fuel, with no combustion costs analyzed.

As aforementioned, these assumptions likely played a role in differentiating the results of this paper from the broader body of literature. As a result, they are essential to understand in the context of the research implications. However, it remains unclear which assumptions, if any, may have significantly impacted the results and shifted them away from the hypothesis. Even so, the main conceptual difference between this paper and the larger body of literature was the independent consideration of biogenic carbon uptake and combustion emissions. This assumption may have caused this paper to unintentionally overestimate the emissions from the HEFA lifecycle. This is particularly true because the independent feedstock-combustion assumption relies on some “hidden” conditions that the typical framework (see Methodology) does not. For example, the framework applied in this paper does not account for the potential emissions released by the use of the camelina meal by-product, whereas the typical framework does. Nevertheless, this assumption is difficult to test because it is so deeply ingrained in the framework of the paper.

4.4. Sensitivity Analysis

Although the main conceptual difference in this paper is difficult to test, there are two important mathematical assumptions that can and should be stress tested to determine how they impacted the results. The first of these assumptions was that HEFA SAF has approximately the same combustion emissions as ordinary jet fuel (see Combustion). This was a major assumption given the uncertainty regarding SAF emissions. By applying the same math in the overall values section (see *Appendix F*), it can be found that the combustion emissions of HEFA SAF would need to be around 1.022 kg of CO_2e per kg of SAF for the lifecycle emissions to match those of ordinary fuels. In relation to the actual calculated SAF combustion emissions figure, 3.256 kg of CO_2e per kg of SAF, the required value represents about 31% of the assumed emissions. Although the combustion emissions relationship was somewhat uncertain, this vast difference suggests the infeasibility of the required figure and the impact of other factors. Continuing, the second major assumption was that by-products of the production process – camelina meal, naphtha, and propane – were all sold for their market values. Once again applying the math in the overall values section (see *Appendix F*), but adjusting the values by removing all contributions from selling by-products, gives a final cost of around $0.034 per MJ. In comparison to the traditional cost of about $0.016 per MJ, this represents around 212.5%, and in comparison to the calculated cost of $0.011, it quantifies about 309%. These differences indicate the large impact that assuming by-products were sold had on the results of the study, and somewhat oppose the choice to include this assumption by demonstrating alignment with the hypothesis in its absence. Overall, the sensitivity analysis demonstrates that the combustion assumption was likely not the sole cause for the difference in results from the body of literature, whereas the selling of by-products likely did play a major role.

4.5. Limitations and Future Research

There are some limitations of the research presented here that are uniquely important to appraise. Firstly, the assumptions made in this paper place limitations on its applicability, as discussed earlier. Second, combining quantitative values from multiple independent studies introduces inherent uncertainty, as source data may reflect different experimental conditions, geographic contexts, or methodological approaches. This is part of the inherent uncertainty of the secondary analysis methodology. Third, economic figures, particularly energy and commodity prices, are time-sensitive and may shift significantly, altering the cost analysis. On this subject, it should be noted that some of the economic and environmental figures of this study were relevant to specific geographic locations, such as the United States, because more broad figures could not be found. These figures also pose a limitation because they were not considered assumptions, but do introduce certain unaccounted-for geographic assumptions about the fuel production. Fourth, while a broad range of sources was consulted, some relevant literature may not have been captured due to access barriers or search limitations.

However, on the subject of limitations, it should be considered that strong precautions and efforts were taken to mitigate the limitations of this paper, as much as possible, when possible. Numerical figures were analyzed and corroborated for accuracy, computational errors were parsed and removed when found, sources were found with strong attempts to create a wide range of consideration, and economic figures were made as current as possible.

Concluding with the topic of further research, the fact that the results of this study conflict with the general academic theme warrants further investigation into the applicability of SAFs. For one, more research on sustainable aviation fuel pathways and biological input sources could help to corroborate or counter existing works in the field, and thus contribute to a definitive answer. In particular, further analysis into the lifecycle of the HEFA route with camelina as a feedstock would be beneficial to build upon this work and corroborate or refute it. Further investigations on SAFs may benefit from using an even wider range of sources than this paper to provide stronger confirmation of data.

Furthermore, another potential realm requiring more investigation could be the field involving new and developing methods to produce sustainable aviation fuels. These methods, given the results of this paper, could present better alternatives to existing SAF methods, and would thus be of importance to research and explore.

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Appendix A

Unit Conversions

A1:

$$1000\ \text{kg} = 1\ \text{ton}$$

Thus

$$Mass_{kg} / 1000 = Mass_{tons}$$

Or conversely

$$Mass_{tons} \times 1000 = Mass_{kg}$$

A2:

$$2.205\ \text{lb} = 1\ \text{kg}$$

Thus

$$Mass_{lb} / 2.205 = Mass_{kg}$$

Or conversely

$$Mass_{kg} \times 2.205 = Mass_{lb}$$

A3:

$$1.609 \text{ km} = 1 \text{ mi}$$

Thus

$$\text{Distance}_{km} / 1.609 = \text{Distance}_{mi}$$

Or conversely

$$\text{Distance}_{mi} \text{ x } 1.609 = \text{Distance}_{km}$$

A4:

$$1000 \text{ g} = 1 \text{ kg}$$

Thus

$$\text{Mass}_{g} / 1000 = \text{Mass}_{kg}$$

Or conversely

$$Mass_{kg} \times 1000 = Mass_{g}$$

A5:

$$1000 \text{ MJ} = 1 \text{ GJ}$$

Thus

$$Energy_{MJ} / 1000 = Energy_{GJ}$$

Or conversely

$$Energy_{GJ} \times 1000 = Energy_{MJ}$$

Appendix B

Transportation Stage Calculations

Beginning with 0.4 lb of CO_2 per ton-mile (Congressional Budget Office, 2022), converting from pounds of CO_2 to kilograms of CO_2 (see *Appendix A2*):

$$0.4 \text{ lb } CO_2 / (\text{ton x mi}) = 0.181 \text{ kg } CO_2 / \text{ton x mi}$$

Converting from ton-miles to ton-kilometers (see *Appendix A3*):

$$0.181 \text{ kg } CO_2 / \text{ton x mi} = 0.113 \text{ kg } CO_2 / \text{ton x km}$$

Multiplying by the assumed 133 km average distance (Li and Mupondwa, 2016):

$$0.113 \text{ kg } CO_2 / \text{ton x km x } 133 \text{ km} = 14.994 \text{ kg } CO_2 / \text{ton}$$

Converting from tons of camelina to kilograms of camelina (see *Appendix A1*):

$$14.994 \text{ kg } CO_2 / \text{ton} = 0.015 \text{ kg } CO_2 / \text{kg}$$

Final transportation emissions value: 0.015 kg CO_2 / kg

Appendix C

Oil Extraction Stage Calculations

C1:

Starting with 0.043 kg of CO_2e per lb of extracted oil and 27.4% of input oilseed mass extracted as oil (Dangol et al., 2015), multiplying the values to convert from per pound of oil to per pound of input oilseed:

$$0.043 \text{ kg } CO_2e \text{ / lb oil x } 0.274 \text{ lb oil / lb oilseed} = 0.012 \text{ kg } CO_2e \text{ / lb oilseed}$$

Converting from pounds of oilseed to kilograms of oilseed (see *Appendix A2*):

$$0.012 \text{ kg } CO_2e \text{ / lb oilseed} = 0.026 \text{ kg } CO_2e \text{ / kg oilseed}$$

Final oil extraction emissions value: 0.026 kg CO_2e / kg oilseed

C2:

Starting with 72.6% of input mass as meal (Dangol et al., 2015), assume a 1 kg input of camelina mass:

$$1 \text{ kg oilseed x } 0.726 \text{ kg meal / (kg oilseed)} = 0.726 \text{ kg meal}$$

Multiplying by the \$0.25 per kg of meal (Bertacchi et al., 2020):

0.726 kg meal x $0.25 / kg meal = $0.182

Recognizing the initial 1 kg input oilseed assumption:

$0.182 = $0.182 / kg oilseed

Subtracting from the earlier $0.004 / kg oilseed figure:

$0.004 / kg oilseed - 0.182 / kg oilseed = -$0.177 / kg oilseed

Final oil extraction cost value: -$0.177 kg oilseed (cost offset)

Appendix D

HEFA Conversion Stage Calculations

D1:

Starting with 0.021 kg CO_2e per MJ of SAF, and 44.1 MJ / kg of SAF (Han et al., 2013), multiplying the values:

$$0.021 \text{ kg } CO_2e \text{ / MJ SAF x 44.1 MJ / kg SAF} = 0.904 \text{ kg } CO_2e \text{ / kg SAF}$$

Multiplying by 0.75 to include the fact that 1 kg of input camelina oil converts via HEFA into only 0.75 kg of biofuel:

$$0.904 \text{ kg } CO_2e \text{ / kg SAF x 0.75 kg SAF / kg oil} = 0.678 \text{ kg } CO_2e \text{ / kg oil}$$

Final HEFA conversion emissions value: 0.678 kg CO_2e / kg oil

D2:

Starting with 4734 MJ of H_2 per ton of biofuel (Han et al., 2013), and 120 MJ per kg of H_2 (DOE, n.d.-a), dividing the values:

$$4734 \text{ MJ } H_2 \text{ / ton biofuel / 120 MJ / kg } H_2 = 39.45 \text{ kg } H_2 \text{ / ton biofuel}$$

Multiplying by 5 for $5 / kg for H_2 (Vickers et al., 2020):

39.45 kg H_2 / ton biofuel x \$5 / kg H_2 = \$197.25 / ton biofuel

Final hydrogen cost contribution to HEFA conversion: \$197.25 / ton biofuel

D3:

Starting with \$0.005 per cubic foot of natural gas (EIA, n.d.-c) and 1000 cubic feet of natural gas per 1093 MJ (EIA, n.d.-b) multiplying to get cost per megajoule:

\$0.005 / cubic foot x 1000 cubic feet / 1093 MJ = \$0.004 / MJ

Multiplying by the 7818 MJ / ton of produced biofuel (Han et al., 2013) to account for magnitude of natural gas use:

\$0.004 / MJ x 7818 MJ / ton biofuel = \$32.259 / ton biofuel

Final natural gas contribution to HEFA conversion: \$32.259 / ton produced biofuel

D4:

Starting with 3359 MJ per ton of biofuel and 43.2 MJ per kg naphtha (Han et al., 2013), dividing to find naphtha mass ratio:

3395 MJ / ton biofuel / 43.2 / kg naphtha = 77.755 kg naphtha / ton biofuel

Multiplying by -$0.55 per kg naphtha (Aburto et al., 2025) for current naphtha prices (negative for cost offset):

77.755 kg naphtha / ton biofuel x -$0.55 / kg naphtha = -$42.765 / ton biofuel

Final naphtha cost contribution: -$42.765 / ton biofuel (cost offset)

D5:

Starting with 4444 MJ per ton biofuel and 44.4 MJ per kg propane (Han et al., 2013), dividing to find the propane mass ratio:

4444 MJ / ton biofuel / 44.4 MJ / kg propane = 100.09 kg propane / ton biofuel

Multiplying by -$0.8 per kg propane (Aburto et al., 2025), for current propane prices (negative for cost offset):

100.09 kg propane / ton biofuel x -$0.8 / kg propane = -$80.072 / ton biofuel

Final propane mix cost contribution: -$80.072 / ton biofuel

D6:

Starting with $0.112 per kg of produced biofuel, and 0.75 kg produced biofuel per kg input oil

(Han et al., 2013), multiplying to convert to input oil:

$0.112 / kg biofuel x 0.75 kg biofuel / kg oil = $0.084 / kg oil

Final HEFA conversions cost value: $0.084 / kg oil

Appendix E

Combustion Stage Calculation

Starting with 74 g CO_2e per MJ fuel (Prussi et al., 2021), converting from grams to kilograms (see *Appendix A4*):

$$74 \text{ g } CO_2e \text{ / MJ fuel} = 0.074 \text{ kg } CO_2e \text{ / MJ fuel}$$

Multiplying by the energy density of SAF, 44 MJ / kg fuel (Norazmi, n.d.):

$$0.074 \text{ kg } CO_2e \text{ / MJ fuel x 44 MJ / kg fuel} = 3.256 \text{ kg } CO_2e \text{ / kg fuel}$$

Final combustion emissions value: 3.256 kg CO_2e / kg fuel

Appendix F

Results Stage Calculation

Starting with feedstock growth values of 0.395 kg of CO_2e per kg of grown camelina feedstock and \$0.244 per kg of grown camelina feedstock, assume a 1 kg input of feedstock:

$$0.395 \text{ kg } CO_2e \text{ / kg oilseed} = 0.395 \text{ kg } CO_2e$$

$$\$0.244 \text{ / kg oilseed} = \$0.244$$

Applying the assumption to the transport and oil extraction figures, 0.041 kg of CO_2e per kg oilseed and -\$0.165 per kg of oilseed (negative for cost offset):

$$0.041 \text{ kg } CO_2e \text{ / kg oilseed} = 0.041 \text{ kg } CO_2e$$

$$-\$0.165 \text{ / kg oilseed} = -\$0.165$$

Adding the resulting feedstock growth values to the transportation and oil extraction values:

$$0.395 \text{ kg } CO_2e + 0.041 \text{ kg } CO_2e = 0.410 \text{ kg } CO_2e$$

$$\$0.244 - \$0.165 = \$0.079$$

Recognizing that these values apply for the above 1 kg feedstock input assumption, and that oil extraction only extracts 27.4% of input mass as oil (Dangol et al., 2015):

$$1 \text{ kg oilseed x } 0.274 \text{ kg oil / kg oilseed} = 0.274 \text{ kg oil}$$

Multiplying the HEFA conversion values, 0.678 kg of CO_2e per kg of input oil and \$0.084 per kg of input oil, by 0.274 kg of oil to match the assumption:

$$0.678 \text{ kg } CO_2e \text{ / kg oil x } 0.274 \text{ kg oil} = 0.186 \text{ kg } CO_2e$$

$$\$0.084 \text{ / kg oil x } 0.274 \text{ kg oil} = \$0.023$$

Adding these resulting values to the earlier summed feedstock growth, transportation, and oil extraction figures:

$$0.410 \text{ kg } CO_2e + 0.186 \text{ kg } CO_2e = 0.596 \text{ kg } CO_2e$$

$$\$0.079 + \$0.023 = \$0.102$$

Further recognizing that HEFA conversion yields only 0.75 kg of biofuel per kg of input oil (Han et al., 2013), by multiplying by the earlier calculated 0.274 figure:

$$0.274 \text{ kg oil x } 0.75 \text{ kg biofuel / kg oil} = 0.206 \text{ kg biofuel}$$

Multiplying the combustion values, 3.256 kg of CO_2e per kg of biofuel, and \$0 per kg biofuel, by 0.206 kg of biofuel to further match the assumption:

$$3.256 \text{ kg } CO_2e \text{ / kg biofuel x } 0.206 \text{ kg biofuel} = 0.669 \text{ kg } CO_2e$$

$$\$0 \text{ / kg biofuel x } 0.206 \text{ kg biofuel} = \$0$$

Adding these resulting values to the most recent summed values from the feedstock growth, transportation, oil extraction, and HEFA conversion stages:

$$0.596 \text{ kg } CO_2e + 0.669 \text{ kg } CO_2e = 1.265 \text{ kg } CO_2e$$

$$\$0.102 + \$0 = \$0.102$$

Again recognizing the assumption of 1 kg of camelina input feedstock, translating to 0.247 kg of oil, and then to, 0.206 kg of biofuel; multiplying 0.206 kg of biofuel by 44.1 MJ per kg of biofuel (Han et al., 2013):

$$0.206 \text{ kg biofuel x } 44.1 \text{ MJ / kg biofuel} = 9.063 \text{ MJ}$$

Dividing by 9.063 MJ, acknowledging the fact that the most recent summed emission and cost values above represent those for this amount of biofuel (1 kg of camelina feedstock = 0.274 kg of oil = 0.206 kg biofuel = 9.063 MJ)

$$1.265 \text{ kg } CO_2e \text{ / } 9.063 \text{ MJ} = 0.140 \text{ kg } CO_2e \text{ / MJ}$$

$$\$0.102 \text{ / } 9.063 \text{ MJ} = \$0.011 \text{ / MJ}$$

Final emission and cost values: 0.140 kg CO_2e / MJ, $0.011 / MJ

The Environmental and Economic Performance of Camelina-Derived HEFA Sustainable Aviation Fuels: A Secondary Data Attributional Lifecycle Analysis

Abstract

The annual global demand for jet fuel is projected to exceed 230 billion gallons by the year 2050, more than doubling the 106 billion gallon demand from 2020. However, aviation accounts for approximately 11% of all transportation greenhouse gas emissions, presenting the challenge of decoupling the growing aviation industry from its associated environmental footprint. Recently, research has focused on the potential of sustainable aviation fuels~~, or~~ (SAFs)~~,~~ for this purpose. Of the numerous existing methods for SAF production, the hydroprocessed esters and fatty acids~~, or~~ (HEFA) route~~,~~ is the most mature for real-world application. Furthermore, within HEFA, the camelina crop poses immense potential as a feedstock. This paper thus concentrates on fuels produced from camelina via HEFA, and attempts to determine the environmental and economic performance of such fuels, across production and use. The latter part of this focus relates to the limited ~~lack of~~ literature on the lifecycle environmental and economic performance of HEFA, which this paper aims to address. The secondary data analysis presented here extracted numerical figures for each step of the HEFA process from nearly 50 credible sources, and mathematically synthesized them to produce the lifecycle analysis. ~~The secondary data analysis presented here analyzes nearly 50 academic and otherwise credible sources for this purpose.~~ Surprisingly, this review found that under certain conditions, camelina HEFA SAFs had a greater environmental impact as compared to traditional fuels, while still costing less to manufacture. This unique finding may speak to the conditions considered, the viability of the fuel pathway studied, or the greater feasibility of SAF implementation.

Keywords: sustainable aviation fuels, HEFA, camelina, lifecycle analysis

The Environmental and Economic Performance of Camelina-Derived HEFA Sustainable Aviation Fuels: A Secondary Data Attributional Lifecycle Analysis

1.1. Background

The already large aviation industry is poised for incredible growth in coming years. The jet fuel market alone is expected to more than double its value from 2020, as outlined by the Department of Energy, or DOE (n.d.-b). However, this growth will bring with it a surge in the aviation industry's environmental footprint. Currently, around 11% of all transportation greenhouse gas (GHG) emissions originate from aviation (D'Ascenzo et al., 2024). This constitutes around 2-3% of all human carbon emissions, in addition to emissions from other GHGs such as water vapor and methane. Even apart from these gases, aviation releases other environmentally detrimental substances into the atmosphere, such as soot and sulfur (Chireshe et al., 2025).

The severe environmental impacts of aviation pose a serious issue, especially when considered in conjunction with the coming growth of the aviation industry. Recently, research has focused on the use of sustainable aviation fuels, or (SAFs), to resolve this issue. Sustainable aviation fuels are defined as jet fuels that can be produced from renewable sources of energy, such as biomass or hydrogen. SAFs are crucial to aviation because they pose the potential to reduce the environmental footprint of the industry – both in manufacturing and emissions – without the need for significant structural changes to existing aircraft and infrastructure. Additionally, while other methods for aircraft environmental sustainability do exist, such as electric or hydrogen power, there are numerous technical barriers faced by these nascent methods (Song et al., 2024), further contributing to the importance of SAFs. For example, using hydrogen power in aviation would require overcoming hydrogen's low volumetric energy density, requirements for cryogenic storage, uncertain climate impacts, and more.

1.2. Purpose

Environmental performance is inevitably a major point of concern for sustainable aviation fuels; however, economic performance is also of paramount importance. Today, fuel represents around 20-30% of the operating costs of an airline (DOE, n.d.-b). As such, for sustainable aviation fuels to be practical in real world application, they must be capable not only of decreasing the environmental footprint of aviation, but also of being produced at feasible costs relative to existing fuels.

At the moment, there are numerous developed SAF production pathways, including: Hydroprocessed esters and fatty acids, alcohol-to-jet, hydroprocessing of fermented sugars, Fischer-Tropsch, pyrolysis, aqueous phase reforming, and power-to-liquid. Of these existing routes, the hydroprocessed esters and fatty acids (HEFA) route~~, or HEFA~~, is currently the most mature (Bauen et al., 2020). HEFA makes use of renewable feedstocks to obtain oils and fats, which are then hydroprocessed to create fuel. Being the most mature existing SAF pathway, HEFA poses the greatest potential for sustainable aviation fuel implementation. Despite its overall significance, however, an immensely important consideration for the HEFA process is the feedstock implemented. In this regard, the camelina crop is a feedstock with incredible potential, because it requires little energy to grow, contains high amounts of non-food oil, and can be grown without interfering with other agriculture as a cover crop (Wang et al., 2020). These characteristics are important because they indicate that camelina can be grown with minimal environmental impact, while also producing a high magnitude of oil to be converted to fuel. The goal of this paper is to analyze existing literature to obtain secondary data values, then present a full environmental and economic lifecycle analysis of the HEFA production route given camelina as a feedstock. In this way, this paper will provide a robust analysis of SAF performance under mature and promising conditions, to help evaluate the realistic feasibility of SAF implementation in the modern world.

1.3. Literature Gap

There is currently limited SAF-focused literature ~~a gap in the literature surrounding SAFs in research focused~~ on the lifecycle environmental and economic performance of the HEFA route. This is because many works have analyzed either the lifecycle environmental or the lifecycle economic performance of SAFs, but comparatively fewer have analyzed both, and even fewer have done so for the HEFA route.

Many ~~Various~~ recent works in the field have focused exclusively on the lifecycle environmental performance of sustainable aviation fuels. For example, Kurzawska-Pietrowicz (2023) reviewed the lifecycle emissions of various sustainable aviation fuels, Abayo et al. (2024) compared the environmental impact of various SAF pathways, and Zemanek et al. (2020) analyzed the emissions from using oilseeds in the HEFA route. However, ~~such~~ works exclusively analyzing environmental impacts have naturally not examined the lifecycle economic impacts of SAFs, although in some instances such works may be directed specifically at HEFA. ~~have not examined the lifecycle economic impacts of SAFs in parallel, although in some instances they may be directed specifically at the HEFA.~~ In contrast, much other literature has focused exclusively on the lifecycle economic performance of sustainable aviation fuels.~~;~~ F~~f~~or instance, Pearlson et al. (2013) created estimates for the economics of the HEFA route. However, ~~such~~ literature in this category similarly does not~~fails to~~ present the lifecycle environmental performance of SAFs, although it may also focus solely on HEFA. A highly important note is that even when synthesized together, these types of SAF evaluations focusing exclusively on lifecycle environmental or economic performance cannot produce the same impact as combined lifecycle analyses can. Thus, these exclusive analyses cannot fill the gap produced by the currently limited combined literature. As discussed previously, there are various SAF pathways and assumptions that can be made in the process of analysis. While the combination of exclusively environmental and economic works can produce more broad conclusions on the environmental and economic performance of SAFs, it can struggle to produce conclusions for specific pathways and assumptions, which is where the differentiation from combined analyses occurs. This is because no two separate works utilize the exact same framework to evaluate SAFs; as a result, an exclusively environmental analysis often lacks an economic counterpart with the same pathway and assumptions to produce comprehensive environmental and economic conclusions for its framework. The lack of combined conclusions for specific frameworks from exclusive analysis poses an important limitation because while generalizable conclusions are helpful, SAF practicality varies greatly across pathways and assumptions, making framework-specific conclusions important for differentiation and understanding. It also poses a limitation because, as discussed earlier, both environmental impact and cost are essential factors to consider in relation to the practicality of SAF application, and neither can be ignored.

Resolving this limitation ~~issue~~ with works focusing exclusively on either the lifecycle environmental or economic performance of SAFs, some literature has also focused on both of these factors; however, this literature is less common compared to the exclusive analyses, which establishes the beginnings of the research gap of this paper. Grim et al. (2022), for instance, reviewed the lifecycle environmental and economic aspects of the power-to-liquids SAF production pathway. Similarly, Gonzales-Garay et al. (2022) reviewed the lifecycle environmental and economic feasibility of the Fischer-Trophsch and methanol-to-fuels given different energy sources. Additionally, Braun et al. (2024) analyzed various SAF production methods, including HEFA, to determine lifecycle environmental impact and pricing. Yet, the ~~vast~~ majority of papers in this domain do not focus exclusively and comprehensively on the HEFA pathway to SAF production, although sometimes ~~very rarely~~, as in the case of Braun et al. (2024), the method may be analyzed alongside others. In other words, while papers analyzing the lifecycle environmental or economic performance of SAFs sometimes focus specifically on HEFA, papers that present both the lifecycle environmental and economic performance of SAFs are rarely directed towards thoroughly analyzing HEFA.

However ~~Finally~~, there are some papers that resolve this ~~even this literature gap~~, and provide an environmental and economic analysis focusing specifically on the HEFA pathway. Seber et al. (2014), for instance, looked at the lifetime environmental and economic impacts of HEFA fuel production given waste oils and tallows as feedstocks. Nevertheless, literature in this ~~highly~~ specific domain is minimal, and, as in the case of the paper from Seber et al. (2014), not always recent, as particularly important in the realm of economics ~~is important particularly in the realm of economics~~. As a result, the precise focus of this paper on the environmental and economic performance of the HEFA pathway given a lifecycle analysis is beneficial by contributing to the currently limited research ~~research gap~~ surrounding this specific domain.

1.4. Research Question and Hypothesis

To summarize the aforementioned explanations, the question that this paper seeks to answer is: What is the economic and environmental performance of sustainable aviation fuels produced from camelina via the HEFA pathway, when considering full lifecycle analysis? The initial hypothesis regarding this question is that HEFA SAFs produced from camelina have an environmental footprint approximately 20% less than traditional fuels, while still roughly matching the costs of these fuels.

2. Methodology

To prove this hypothesis, the body of this secondary analysis was chronologically structured around the various stages of the HEFA route: Feedstock production, transport and oil extraction, HEFA conversion, and combustion. In each stage, the paper tracked two measures of SAF performance: CO_2 equivalent emissions for environmental performance, and cost in dollars for economic performance. Also for each step, the magnitude of these two measures was placed in relation to the "input" quantity for that stage. For example, for the oil extraction step, emissions and costs were given per kilogram of feedstock, as feedstock was the input quantity for oil extraction. One important note should be included in regards to the feedstock production and combustion stages. Many recent works in the field of sustainable aviation fuels evaluate these stages in parallel, and thus consider the emissions from SAF combustion to be environmentally neutral. This is because the carbon released into the environment during SAF combustion originates from the carbon absorbed from the environment during the feedstock growth. However, this paper instead considered the feedstock growth and combustion stages independently. Biogenic carbon uptake was incorporated into the feedstock section, and the combustion emissions were separately included in the combustion section. This choice was made because it was theorized to allow for a more thorough and transparent approach to evaluating each step of HEFA SAF production. This choice was also made because combustion emissions from SAFs are known to produce meaningful non-CO2 emissions that would not be offset by feedstock growth, and because it was unknown how the intermediate stages between the feedstock growth and combustion would impact the presence of absorbed carbon in the emissions themselves.

The paper followed the two measures of performance in each stage by drawing any discovered quantitative values for emissions and cost, and combining them mathematically to produce overall values for that stage. This secondary method of analysis was beneficial because it allowed for the use of raw data from the previous literature on the lifecycle environmental or economic performance of HEFA (see Literature Gap) to fill the lack of research on both factors in one framework. Additionally, a stage by stage analysis was performed as opposed to a synthesis of final lifecycle values from existing works given the difficulties and inaccuracies in combining calculated environmental and economic figures from different papers (see Literature Gap). ~~The paper followed the two measures of performance by drawing any discovered quantitative values for emissions and cost in each stage, and synthesizing them to produce overall values for that stage. Such synthesis was performed as values were used to corroborate others, or as mathematical arithmetic and unit conversions were done to combine values and align them with the input unit for each step. This secondary method of analysis was particularly beneficial given the presence of some research on either the lifecycle environmental or lifecycle economic HEFA performance, by allowing the synthesis of existing literature to fill the gap in research on both forms of analysis. Additionally, a stage by stage analysis was performed as opposed to a synthesis of final lifecycle values from papers given the lack of extensive literature even on either environmental or economic HEFA analysis, and an absence of definitive conclusions for either aspect.~~

Once values for each step of the process were derived ~~applying the analysis~~, they were combined through further unit conversion to produce final values for emissions and cost. These values were then compared to those of traditional fuels, as obtained from credible and corroborated sources, to establish improvement or deterioration in both categories. This form of analysis produced the secondary analytical nature of this paper, and the conditions and assumptions established produced its attributional quality.

In terms of information sourcing, sources analyzed within this research paper were found using the following search terms: Sustainable, aviation, lifecycle, environmental, fuel, economic, and HEFA, as well as other search terms tangential to the field of sustainable aviation fuels. These search terms were used in research databases, such as JSTOR and Google Scholar, as well as in ordinary search engines such as Google. Furthermore, only sources from 2000 and onward were considered. Under these conditions, the research paper considered a total of 70 sources, of which 47 sources were used within the body of the paper. The sources used were chosen for the scope of relevant information they covered, and the credibility and expertise they offered. Specifically, sources considered for the analysis of the paper were excluded if they did not provide quantitative data regarding the HEFA pathway. Similarly, sources considered for the introduction were rejected if they did not present expertise in their subject field. Of the sources used in the body of the paper, 39 were academic research papers, 7 were government or otherwise credible reports, and 1 was a credible website.

A highly important note should also be made in regard to the way that calculations were performed throughout the entirety of the paper. Throughout the paper, data from sources was taken in exact specificity as originally found when used in calculations. In the same way, calculated numbers from original source values were stored to exact specificity for further computation. However, when original figures or calculated values were presented, they were rounded to three decimal places (and identified as approximates unless in the appendixes), or left with their original number of decimals if not present in this specificity. Furthermore, even if original figures were identified as approximated in the sources from which they came, they were not identified as such in the paper, and used according to the rules above. These choices were made to improve the understanding and ease of the reader.

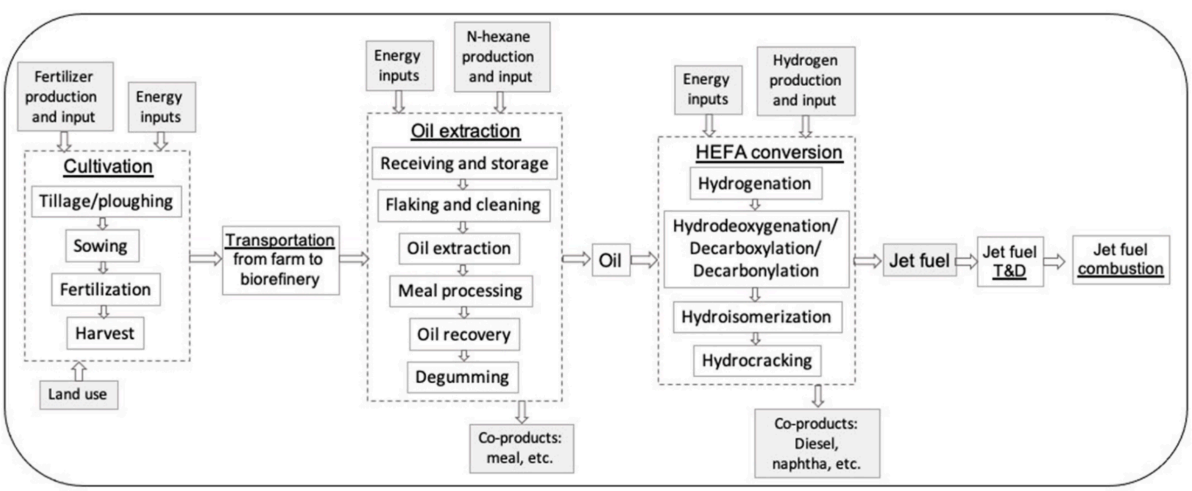
2.1. Key Abbreviation Definitions

- metric kilogram = kg
- metric kilometer = km
- CO2 equivalent = CO_2e
- metric megajoule = MJ
- metric gigajoule = GJ
- metric kilowatt-hour = kWh
- metric ton = ton
- imperial pound = lb
- imperial mile = mi
- metric gram = g

3. Analysis

Figure 1

Lifecycle HEFA Fuel Production Pathway



Note. Figure from Seber et al. (2022). Depicts the different stages of the HEFA lifecycle analyzed in this paper. Also illustrates the substeps within the broader stages, as well as input requirements and outputs. ~~Shows substages within broader steps of HEFA production, as well as requirements and outputs.~~

3.1. Feedstock Growth

The first stage of the HEFA process is the growth of a feedstock (Figure 1~~Seber et al., 2022~~); for the purposes of this paper, camelina. Feedstock growth is an exceedingly important consideration in the HEFA lifecycle, because it can sequester significant volumes of atmospheric carbon dioxide. However, feedstock growth is also an incredibly complex factor, because feedstocks themselves require energy to grow, and may have impacts on other agriculture. Camelina as a feedstock is grown for its oilseeds, from which oil can be extracted to create SAFs (Li & Mupondwa, 2016). The goal of this section is to analyze camelina growth within the HEFA process, to determine its environmental and economic impacts.

As explained previously, the environmental impacts of camelina growth must be considered by analyzing both the resources needed to grow the crop, and the resulting greenhouse gas sequestration. This paper will consider typical to marginally conservative growing conditions for camelina, to obtain the most accurate and broadly applicable results. One value for camelina's environmental impact can be found in a study from Krzyzaniak and Stolarski (2019), which calculated that under reduced tilling conditions, growing one hectare of camelina produced a net release of between 1732 and 1772 kg of CO_2e (in regards to climate impact) gas. However, this study ignored carbon sequestration within the soil in which the camelina was grown. Krzyzaniak and Stolarski (2025) later incorporated this factor into a separate study in which they used the SimaPro 9.6 software to simulate plant growth, allowing them to refine their figure down to 762 kg of CO_2e per hectare, with a 0.95 confidence interval ranging from approximately 140-1700. This figure is supported by other previously performed studies such as that of Krohn and Matthias (2012), which found between 650 and 950 kg of net CO_2 emissions given low input growth conditions. An important point to note regarding these studies is that each analyzed camelina as the only crop growing on a plot of land, but did not consider the potential environmental benefits or drawbacks of other crops that might otherwise be grown on that land. As such, the figures in each of these studies should be taken at value only if camelina is considered as being grown in its most common form; as a cover crop, during a time when most others cannot feasibly be grown. Using the above figures with this in mind, it can be concluded that net carbon emissions from camelina growth, when considering input resources and carbon sequestration, lies approximately around 750 kg of CO_2e per hectare grown. Finally, dividing this value by the the average camelina yield of around 1900 kg of oilseed per hectare (Li and Mupondwa, 2016; Zhang et al., 2021) gives that the carbon emissions from camelina growth lie around 0.395 kg of CO_2e per kg of oilseed. However, the question of the associated costs of this growth still remains.

In regard to answering this question, this paper will focus on various factors that affect the cost of camelina growth for HEFA, such as machinery costs, farming resources, and land use. In a paper by Li and Mupondwa (2016), the average cost for camelina growth was cited as $463 per hectare, given the average yield of 1900 kg of camelina oilseed per hectare found by the authors, and corroborated by Zhang et al. (2021). This figure took into account numerous production variables, including fertilizer cost, machinery, repair, depreciation, land investment, labour, and more. Additionally, Li and Mupondwa (2016) also found that the cost to grow camelina varied depending on the yield per hectare, with low yields of around 700 kg per hectare costing \$0.66 per kg of oilseed, and high yields of 3300 kg per hectare costing only \$0.14 per kg of oilseed. Nevertheless, the authors' cost-value for an average yield of camelina oilseed is more broadly applicable to various circumstances, and is thus a significantly more accurate figure for the purposes of this paper. As such, dividing \$463 per hectare by the average camelina yield of 1900 kg per hectare gives an accurate cost of approximately \$0.244 per kg of oilseed. An important point to note regarding camelina oilseeds is the economic impact of camelina meal, which is derived from the oilseeds after the oil has been extracted, and can be sold for a profit (Li & Mupondwa, 2016). However, this impact will be analyzed in a later section, as it falls under the oil production stage of HEFA rather than under feedstock growth. Overall, it can be concluded that the cost to grow camelina for the HEFA route is approximately \$0.244 per kg of oilseed.

3.2. Transportation And Oil Extraction

The second step of the HEFA process involves two stages: The transport of a feedstock to a biorefinery, and the subsequent extraction of oil from that feedstock (Seber et al., 2022). In terms of environmental and economic impacts, both of these stages are incredibly important to consider. Freight transport releases greenhouse gases that damage the environment (Congressional Budget Office, 2022), and also adds costs to the lifecycle of HEFA. Similarly, oil extraction requires energy that generates both GHGs and furthers the costs of the process.

Firstly, the transportation of feedstocks to biorefineries for oil extraction is an important player in the emissions associated with HEFA. According to statistics from the Congressional Budget Office (2022), trucking - the primary method of freight transportation - produces 0.4 lb of CO2 per ton-mi (transporting one ton a distance of one mile). This figure is incomplete without a transport distance, but a study by Li and Mupondwa (2016) found that feedstock transportation to processing plants within a 200 km radius took an average distance of 133 km. This paper will assume transport distances under 200 km, and accordingly apply the 133 km average. However, it should be noted that this figure is geographically constrained, and may differ by region. Combining this value with the trucking emissions figure (see *Appendix B*), it can be reasonably concluded that transportation emissions amount to around 0.015 kg of CO_2 per kg of camelina. It is important to note that this figure is an estimate, not an exact calculation by any means, especially given the variability of trucking emissions highlighted by the Congressional Budget Office (2022). Nevertheless, it is a reasonable estimate given the information, and thus merits a continuation to consider costs.

For the aforementioned 200 km radius, Li and Mupondwa (2016) also found that feedstock transportation had an average impact of $12.29 per ton of oilseed transported. Converting this figure from per ton of oilseed to per kilogram of oilseed (see *Appendix A1*), it can be concluded that transportation costs add around $0.012 per kg of camelina. Moving on, the next relevant consideration in this stage is the impact of oil extraction itself.

There are currently two major recognized methods of feedstock oil extraction: Mechanical pressing, and solvent extraction, although enzymatic extraction may also be considered in this regard (Pikula et al., 2020). Of these two methods, mechanical pressing is less expensive (Pikula et al., 2020), more time efficient (Ofori-Boateng et al., 2012), and is the only method used in small scale facilities (Veljkovic et al., 2022). In addition, solvent extraction may result in negative environmental impacts (Pikula et al., 2020). For these environmental and economic reasons, this paper will consider only the mechanical pressing method of oil extraction. However, there are nevertheless important concerns with mechanical pressing, including the need for oil filtration and purification (Popa et al., 2017), and a reduced oil extraction efficiency as compared to solvent extraction (Ofori-Boateng et al., 2012). The method itself consists of cleaning oilseeds, pressing them to extract oil, and purifying the oil to prepare it for HEFA conversion (Seber et al., 2022).

For the mechanical pressing method, the environmental impacts of camelina oil extraction mainly come from the electricity needed to execute oilseed crushing, as this is the stage that naturally requires the most energy. A thorough empirical study from Dangol et al. (2015) reported that such emissions amounted to 0.043 kg of CO_2e per lb of refined oil produced by mechanical pressing. Given that this study also reported extracting 27.4% of camelina input mass as oil, calculations (see *Appendix C1*) show that the emissions from oil extraction are approximately 0.026 kg of CO_2e per kg of input oilseed. To reiterate, this value assumes negligible contributions from the cleaning and purification processes, given the low energy input and lack of environmentally damaging substances involved with these stages. However, while the environmental impacts of camelina oil pressing can be considered in this way, the costs of the process involve numerous other factors.

For the purposes of this paper, the costs of camelina mechanical oil extraction will be considered using two factors: The energy required for oil pressing, and the by-product (meal) produced by the extraction. The energy for oil extraction is naturally an important factor for cost, and relevant mainly to the actual oil pressing stage itself. The by-products, however, are also important to consider, because they can be sold to offset other costs (Veljkovic et al., 2022). First looking at oil pressing, the energy required to press oilseed typically falls at 0.05 kWh per kg (Singh & Bargale, 2000). Furthermore, the U.S. Energy Information Administration, or EIA (n.d.-a), cites current average industrial prices for electrical energy as \$0.083 per kWh. Multiplying these figures gives a relatively minute value of about \$0.004 per kg of oilseed.

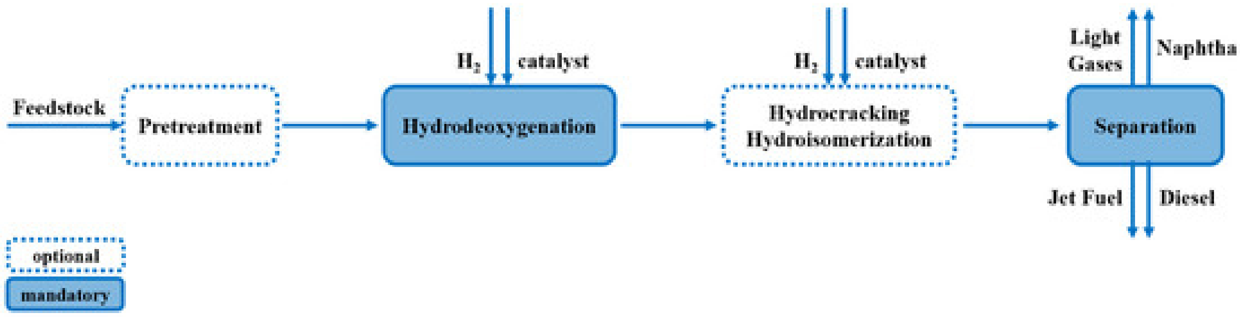
However, this cost can be offset by selling the camelina meal left behind by the oil extraction. As aforementioned, Dangol et al. (2015) found that mechanical pressing can extract 27.4% of inputted camelina oilseed mass as actual oil. The remaining 72.6% of input camelina mass is therefore left behind as meal. Combining this value with the price of camelina meal, \$0.25 per kg (Bertacchi et al., 2020), and further accounting for the approximately \$0.004 per kg for electrical energy (see *Appendix C2*) demonstrates that the final oil extraction cost value is around \$0.177 per kg of oilseed in cost offset (revenue).

3.3. HEFA Conversion

The third and perhaps most complex stage of the HEFA process is the actual conversion of feedstock oils into HEFA fuel (Seber et al., 2022). Ignoring the pretreatment stage that this paper covered in the previous section, HEFA conversion begins with reacting feedstock oil and H_2 at a high temperature and pressure to remove oxygen; a process known as hydrotreating (DOE, n.d.-b). Once this step is completed, the resulting substance becomes functional fuel (Monteiro et al., 2022). However, to meet the various requirements of jet fuel, it is hydrocracked and hydroisomerized again using H_2 as a catalyst (DOE, n.d.-b). Finally, after these steps, the upgraded fuel is separated from the other products of the reaction, resulting in usable biofuel. This section will analyze both the emissions and cost of this HEFA conversion step, with camelina as a feedstock in mind.

Figure 2

Simplified and Complete Visual of the HEFA Process



Note. Figure from Monteiro et al. (2022). Shows how feedstocks are turned into HEFA fuel, which stages are mandatory, and what the inputs and outputs of the process are.

The environmental impacts of HEFA conversion are a large consideration for the process as a whole. This is due to the large amounts of energy, H_2, and natural gases needed for this stage. According to Han et al. (2013), the net HEFA conversion related emissions for camelina are approximately 0.021 kg (20.5 g) of CO_2e per MJ of SAF produced. Han et al. (2013) considered various factors in this figure, such as hydrogen input and energy requirements. Given the calorific value of camelina HEFA biofuel; 44.1 MJ per kg of SAF, and the fact that 1 kg of input camelina oil converts via HEFA into only 0.75 kg of biofuel (Han et al., 2013), it can be concluded that HEFA conversion releases about 0.678 kg of CO_2e per kg of input camelina oil (see *Appendix D1*).

Regarding costs, HEFA conversion is relevant due to the energy associated with hydroprocessing, but also because of the by-products that are produced through conversion, namely naphtha and a propane mix (Figure 2~~Monteiro et al., 2022~~); which can also be sold to offset energy costs. An important note is that diesel can also be a by-product (Seber et al., 2014), but will be ignored for the purposes of this paper, as the studies used for economic analyses - such as that from Han et al. (2013) - also do not consider it. First regarding energy, there are three major concerns: H_2, natural gas, and electricity. According to Han et al. (2013), hydrogen use for camelina HEFA processing lies at 4734 MJ of H_2 per ton of produced biofuel. Similarly, natural gas use is 7818 MJ per ton of biofuel, and electricity use makes up 61 kWh per ton of biofuel. For H_2 use, implementing hydrogen's energy density of 120 MJ per kg (DOE, n.d.-a), and a reasonable cost assumption for electrolysis produced hydrogen, $5 per kg (Vickers et al., 2020), shows that hydrogen use in HEFA conversion constitutes $197.25 per ton of produced biofuel (see *Appendix D2*). However, it is important to note that this figure is valid only under the assumption that the hydrogen is produced via electrolysis. For natural gas, 1000 cubic feet constitutes 1093 MJ of energy (EIA, n.d.-b), and every cubic foot of natural gas costs approximately $0.005 according to current industrial prices (EIA, n.d.-c). Combining these values with the aforementioned 7818 MJ per ton of produced biofuel (see *Appendix D3*) gives that natural gas contributes about $32.259 per ton of produced biofuel. Finally, for electricity, the same industrial cost as used in the oil extraction section will be assumed; $0.083 per kWh (EIA, n.d.-a). Thus, multiplying the 61 kWh per ton of produced biofuel by $0.083 per kWh gives a fair cost estimate for electricity used in HEFA conversion for camelina: $5.063 per ton of biofuel.

However, as aforementioned, the by-products produced by HEFA conversion are also highly important to consider in regards to the economic feasibility of the process. For the purposes of this paper, it will be assumed that the by-products are sold for their market values, and offset costs in this way. According to Han et al. (2013), the yields of naphtha and propane mix from 1 ton of produced biofuel are 3359 MJ and 4444 MJ respectively. Given that naphtha has an energy content of 43.2 MJ per kg (Han et al., 2013) and a recent market price of $0.55 per kg (Aburto et al., 2025), it can be calculated that the value of the gas produced per ton of produced HEFA biofuel is about $42.765 in cost offset (see *Appendix D4*). Similarly, given the energy content of the propane mix by-product from HEFA conversion, 44.4 MJ per kg (Han et al., 2013), and a recent market price for propane, $0.8 per kg (Aburto et al., 2025), it can also be calculated that the cost contribution from the propane mix is about $80.072 per ton of biofuel in cost offset (see *Appendix D5*). Summing the approximately $42.765 per ton of biofuel and about $80.072 per ton of biofuel gives a combined final cost offset of about $122.837 per ton of produced biofuel.

Concluding economics, the costs for hydrogen, natural gas, and electricity to produce 1 ton of camelina HEFA SAF were: $197.25, approximately $32.259, and $5.063, respectively. Summing these values gives about $234.572 per ton of produced biofuel. However, the offsetting value of naphtha and propane must also be factored into the analysis, removing about $122.837 from the price, and bringing the total down to about $111.735 per ton of biofuel. Further dividing this figure by 1000 provides that producing 1 kg of HEFA SAF from camelina costs around $0.112. Furthermore, converting this value to be in terms of input oil rather than produced biofuel, using the fact that 1 kg of input camelina provides only 0.75 kg of biofuel via HEFA (Han et al., 2013), gives a final cost of approximately $0.084 per kg input oil (see *Appendix D6*).

3.4. Combustion

The final stage of SAF use is the combustion stage. SAF combustion is complex in terms of environmental impact, because it not only leads to the direct release of CO_2, but also emits numerous other environmentally impactful substances, which may alter atmospheric chemistry (Lee et al., 2023). Such emissions include NO_x, H_2O (water vapor), SO_2, particulate matter (PM), CO, and unburned hydrocarbons (UCH). An important note regarding this step is that today, SAF regulations require that they be blended with traditional jet fuels, up to a maximum of 50%

(DOE, n.d.-b). Nevertheless, for the purposes of this paper, combustion will be considered as that solely of the SAF derived from HEFA conversion, without blending: This is because SAFs can be used without traditional fuel blending, despite existing regulations. Furthermore, this section will only consider the climate impact of SAF combustion, as without blending, there are no combustion costs to consider. To reiterate, a full emissions analysis is presented below, as this paper did not consider emissions to be offset by biogenic carbon uptake during feedstock growth.

Various studies have shown that SAF emissions of most gases/substances do not differ greatly in terms of climate emissions from traditional jet fuels. For instance, Song et al. (2024) found that the emissions of CO_2, NO_x, CO, and UHC from various SAFs (including camelina based fuels) were insignificantly different from those of traditional jet A1 fuel. However, certain gases and substances do differ between SAFs and ordinary fuels. In particular, Song et al. (2024) also found that the SO_2 and PM emissions from SAF combustion were significantly lower than those of traditional jet fuels, while Teoh et al. (2022) cited that the water vapor emissions can be up to 10% higher.

In general, SO_2~~2~~ (which forms sulfate particles), PM, and water vapor play a role in the climate through the formation of jet contrails (Lee et al., 2023). Contrails form when water vapor attaches to particulate matter, and they may form cirrus clouds at high altitudes. These cirrus clouds~~,~~ produce~~ing~~ a net negative ~~positive~~ climate impact, ~~(~~although they ~~contrails~~ have both positive and negative climate impacts~~)~~ (Lee et al., 2023). ~~Furthermore, Cc~~Contrails are one of the most environmentally impactful factors related to aviation (NASA, 2017). According to Teoh et al. (2022), studies estimate that SAFs may increase contrail prevalence by 1-8%, due to their increased water vapor emissions as compared to traditional fuels. However, Lee et al. (2023) explains that the interaction between PM, SO_2~~2 (sulfate particles)~~, and water vapor in contrails and the resulting cloud formation is highly uncertain. This means that it remains unclear how SAF use influences the magnitude of contrail formation, and the resulting cloud formation. Furthermore, even if Teoh et al. 's (2022) figure is to be considered, it represents only a relatively small change in the magnitude of traditional fuel contrails. It is important to note on this point that the magnitude of contrail formation is not the only factor that influences the magnitude of cloud formation, and thereby the magnitude of climate impact. Contrails from SAFs and traditional fuels may be internally different, which can influence how they produce clouds, and thus their impact on the climate. However, the high level of uncertainty on how the emission differences between SAFs and traditional fuels impacts cloud formation from contrails means that differences in climate impact caused by internal contrail differences are difficult to quantify. Thus, given the similarities in most emissions between SAFs and traditional jet fuels, in addition to high uncertainties regarding contrail impacts~~, at most, small differences in certain contrail-related emissions~~, this paper will consider the climate impact of SAF combustion to be relatively equivalent to that of traditional jet fuel.

In terms of combustion emissions, standard petroleum jet fuel produces 74 g of CO_2e per MJ of fuel (Prussi et al., 2021). Converting to kilograms, and factoring in the energy density of SAF, 44 MJ per kg (Norazmi, n.d.), gives that the combustion emissions of SAF lie at 3.256 kg of CO_2e per kg of combusted SAF (see *Appendix E*).

3.5. Overall Results

The previous sections of this paper have reviewed each of the individual stages of creating HEFA fuel from camelina, including feedstock growth and extraction, transport and oil extraction, HEFA conversion, and combustion. This section will combine each of these values to generate complete, final figures for the lifecycle emissions and costs of generating HEFA fuels from camelina. Then, these figures will be compared to those of traditional jet fuel.

Beginning with the feedstock production and extraction, the CO_2e emissions to produce 1 kg of camelina were found to be around 0.395 kg of CO_2e per kg of camelina grown, and the cost was found to be around $0.244 per kg of camelina grown. Moving on to transportation, the figures were approximately 0.015 kg of CO_2e per kg of transported oilseed, and about $0.012 per kg of transported oilseed. Summing these transportation values with their respective counterparts for the oil extraction stage; about 0.026 kg of CO_2e per kg of oilseed, and around $0.177 per kg of oilseed in cost offset, gives the combined transportation and emissions values: around 0.041 kg of CO_2e per kg oilseed, and around $0.165 per kg of oilseed in cost offset. Continuing on to HEFA conversion, it was concluded that the process adds approximately 0.678 kg of CO_2e per kg of input oil, and about $0.084 per kg of input oil. Lastly, for combustion, the emissions figure was found to be 3.256 kg of CO_2e per kg of SAF, with no combustion costs added. These values represent the mathematical results of this research paper, however, they still must be combined into two single figures for emissions and costs, to be compared to traditional fuels. Combining the values by assuming a 1 kg input of camelina feedstock and converting to per megajoule of biofuel (see *Appendix F*), gives the absolute final approximate values for the lifecycle emissions and costs of producing camelina biofuel via HEFA: 0.140 kg CO_2e per MJ, and $0.011 per MJ.

In comparison to the emission values for traditional petroleum jet fuel, these numbers produce surprising results. According to Prussi et al. (2021), the combustion emissions of petroleum jet fuel account for 83% of its total lifecycle GHG emissions, or 0.074 kg of CO_2e per MJ. Thus, by multiplying this figure by 1/0.83, the lifecycle GHG emissions of petroleum jet fuel can be found to lie around 0.089 kg of CO_2e per MJ. This value is also supported by Song et al. (2024) who concluded a figure of 0.090 kg (90 g) in their own study. Importantly, this value of 0.089 kg is reasonably less than the 0.140 kg calculated for SAF; specifically amounting to approximately 64% of this value.

In contrast, the above cost value for SAF is less than that of traditional jet fuels. Comparing in particular to jet A1 fuel, a highly conventional petrol jet fuel (Song et al., 2024), current costs lie at $697.6 per ton according to Jet-A1-Fuel (n.d.). Dividing by the calorific value of kerosene jet fuels, 44.1 GJ per ton (United Nations Statistics Division, 2014), gives approximately $15.819 per GJ, and further converting from per gigajoule to per megajoule (see *Appendix A5*) gives about $0.016 per MJ. This value for traditional fuel is approximately 141% of that calculated above for SAFs.

4. Conclusion

4.1. Discussion

The major focus of this research paper was to evaluate the environmental and economic performance of sustainable aviation fuels derived via the HEFA pathway, from the camelina crop as a feedstock, across their entire lifecycle. The purpose of this analysis was to increase the currently limited understanding of the practical application of SAFs as a whole, in comparison to traditional fuels. The analysis was performed via the combination of values from various research papers in the field, to derive overall values for each state of the HEFA production, and thus total ending values. The initial hypothesis based on academic literature in the field regarding this question was that camelina HEFA SAF would demonstrate a reduction in environmental footprint as compared to traditional jet fuels, while roughly matching the costs of these fuels. However, this hypothesis was incorrect. The research paper found that traditional jet fuels only had about 64% of the greenhouse gas release of the SAF, but approximately 141% of the total cost. The table below summarizes the important values derived throughout the paper, which can be found in the conclusion paragraphs of each stage section.

Table 1

Emissions and Costs Broken Down by Stage of Production

~~Summarized Values (rounded to 3 decimals)~~¶							
Stage of Production *(specific units provided)*	Feedstock Growth *1 kg of camelina oilseed*	Transportation *1 kg of camelina oilseed*	Oil Pressing *1 kg of input camelina oilseed*	HEFA Conversion *1 kg of input camelina oil*	Combustion *1 kg of camelina biofuel*	Total SAF Values *1 MJ of camelina biofuel*	Total Jet Fuel Values *1 MJ of modern jet fuel*
Greenhouse Gas Emission *(kg of CO_2e)*	0.395	0.015	0.026	0.678	3.256	0.140	0.089
Cost *($)*	0.244	0.012	-0.177 (cost offset)	0.084	0	0.011	0.016

Note. All figures rounded to three decimal places.

It is important to recognize that the results of the study – in going against the hypothesis – also go against the general theme in the academic literature surrounding sustainable aviation fuels. Excluding the possibility of errors (see L~~l~~imitations and F~~f~~uture R~~r~~esearch), this suggests that the assumptions ~~and specific data points~~ used within this paper had a significant impact on the results that it produced (see Considerations and Assumptions). Nevertheless, assumptions were justified and data was carefully screened, providing credibility to the numerical conclusion.

~~***Sensitivity Analysis***~~¶

~~Even so, two major assumptions (one for emissions and costs each) were made in the paper that should be stress tested, to determine how they impacted the results. The first of these~~

assumptions was that HEFA SAF has approximately the same combustion emissions as ordinary jet fuel. This was a major assumption given the uncertainty regarding SAF emissions. By applying the same math in the overall values section (see *Appendix F*), it can be found that the combustion emissions of HEFA SAF would need to be around 1.022 kg of CO_2e per kg of SAF for the lifecycle emissions to match those of ordinary fuels. In relation to the actual calculated SAF combustion emissions figure, 3.256 kg of CO_2e per kg of SAF, the required value represents about 31% of the assumed emissions. Although the combustion emissions relationship was somewhat uncertain, this vast difference suggests the infeasibility of the required figure and the impact of other factors. Continuing, the second major assumption was that by-products of the production process – camelina meal, naphtha, and propane – were all sold for their market values. Once again applying the math in the overall values section (see *Appendix F*), but adjusting the values by removing all contributions from selling by-products, gives a final cost of around $0.034 per MJ. In comparison to the traditional cost of about $0.016 per MJ, this represents around 212.5%, and in comparison to the calculated cost of $0.011, it quantifies about 309%. These differences indicate the large impact that assuming by-products were sold had on the results of the study, and somewhat oppose the choice to include this this assumption by demonstrating alignment with the hypothesis in its absence.

4.2. Implications

Based on this credibility, theTaking the assumptions of this paper to be true, results of this research paper pose some potentially important implications for the future of aviation. If the fuel pathway studied in this paper, taking the assumptions to be true, produces a larger environmental footprint as compared to traditional fuels, then perhaps it should be avoided in the interest of reducing the environmental footprint of aviation as a whole. However, if economic success takes priority over climate stability, then perhaps the fuel pathway should be implemented to reduce costs. These both serve as interesting direct extensions of the numerical conclusions above. However, the results of this study could also be indirectly extended to reflect the aspects of SAF production analyzed, rather than the holistic pathway studied. For example, this study could indicate the environmental infeasibility and economic practicality of the HEFA pathway specifically, regardless of the crop used. Similarly, the results could also implicate camelina as a poor and economically viable crop for HEFA, or SAFs as a whole. ~~If SAFs derived from camelina via HEFA do have a greater environmental footprint as compared to traditional fuels, then perhaps the fuel pathway studied in the paper should be avoided in the interest of reducing the environmental footprint of aviation. However, if economic success takes priority over climate stability, then perhaps the fuel pathway should be implemented to reduce the costs associated with aviation. While both interesting possibilities, the results of this study could also potentially reflect the applicability of the aspects of SAF production analyzed. For example, this study could indicate the environmental infeasibility and economic practicality of the HEFA pathway specifically, regardless of the crop used. Similarly, the results could also implicate camelina as a poor and economically viable crop for SAFs.~~ In contrast, the results could even more broadly indicate that SAFs as a whole do not have the capacity to reduce climate footprint as compared to traditional fuels, but do have the capacity to reduce costs, regardless of the production pathway or input source.

Regardless, the only truly anchored connections that can be made with this research are those relating directly to the exact fuel pathway studied, under the exact assumptions considered. The results may speak to HEFA, camelina, and SAFs as a whole, but they must not be taken as generalized conclusions about them, because the inclusion of these factors and the assumptions makes the impact of each unclear. To reiterate, the research presents a conflict, where the use of camelina to produce SAF via the HEFA route increases environmental impact, but reduces costs.

4.3. Considerations and Assumptions

On the subject of conditions,~~Following the sensitivity analysis performed above~~, it is crucial to reiterate that this paper relied on many key assumptions made: biogenic carbon intake and combustion were considered in separate stages rather than as environmentally neutral in parallel; camelina was assumed to be grown as a cover crop under moderate conditions; transportation was modeled by trucking of under 200 km; oil extraction was considered via mechanical pressing energy, without regard for purification and cleaning, and with the assumption of camelina meal being sold; HEFA conversion was analyzed via energy use, with electrolysis derived hydrogen, and with naphtha and propane by-products sold; pure HEFA SAF combustion was assumed, and considered equal in emissions to ordinary fuel, with no combustion costs analyzed.

As aforementioned, these assumptions likely played a role in differentiating the results of this paper from the broader body of literature. As a result, they are essential to understand in the context of the research implications. However, it remains unclear which assumptions, if any, may have significantly impacted the results and shifted them away from the hypothesis. Even so, the main conceptual difference between this paper and the larger body of literature was the independent consideration of biogenic carbon uptake and combustion emissions. This assumption may have caused this paper to unintentionally overestimate the emissions from the HEFA lifecycle. This is particularly true because the independent feedstock-combustion assumption relies on some “hidden” conditions that the typical framework (see Methodology) does not. For example, the framework applied in this paper does not account for the potential emissions released by the use of the camelina meal by-product, whereas the typical framework does. Nevertheless, this assumption is difficult to test because it is so deeply ingrained in the framework of the paper.

~~Even further, it is important to note that many of the sources used for cost throughout the various sections of this paper relate to modern prices, particularly in the United States of America.~~

4.4. Sensitivity Analysis

Although the main conceptual difference in this paper is difficult to test, there are two important mathematical assumptions that can and should be stress tested to determine how they impacted the results. The first of these assumptions was that HEFA SAF has approximately the same combustion emissions as ordinary jet fuel (see Combustion). This was a major assumption given the uncertainty regarding SAF emissions. By applying the same math in the overall values section (see *Appendix F*), it can be found that the combustion emissions of HEFA SAF would need to be around 1.022 kg of CO_2e per kg of SAF for the lifecycle emissions to match those of ordinary fuels. In relation to the actual calculated SAF combustion emissions figure, 3.256 kg of CO_2e per kg of SAF, the required value represents about 31% of the assumed emissions. Although the combustion emissions relationship was somewhat uncertain, this vast difference suggests the infeasibility of the required figure and the impact of other factors. Continuing, the second major assumption was that by-products of the production process – camelina meal, naphtha, and propane – were all sold for their market values. Once again applying the math in the overall values section (see *Appendix F*), but adjusting the values by removing all contributions from selling by-products, gives a final cost of around \$0.034 per MJ. In comparison to the traditional cost of about $0.016 per MJ, this represents around 212.5%, and in comparison to the calculated cost of $0.011, it quantifies about 309%. These differences indicate the large impact that assuming by-products were sold had on the results of the study, and somewhat oppose the choice to include this assumption by demonstrating alignment with the hypothesis in its absence. Overall, the sensitivity analysis demonstrates that the combustion assumption was likely not the sole cause for the difference in results from the body of literature, whereas the selling of by-products likely did play a major role.

4.5. Limitations and Future Research

T~~Given the aforementioned assumptions, as well as other factors specific to this paper, t~~here are some limitations of the research presented here that are uniquely important to appraise. Firstly, the assumptions made in this paper place limitations on its applicability, as discussed earlier. Second~~First~~, combining quantitative values from multiple independent studies introduces inherent uncertainty, as source data may reflect different experimental conditions, geographic contexts, or methodological approaches. This is part of the inherent uncertainty of the secondary analysis methodology. Third~~Second~~, economic figures, particularly energy and commodity prices, are time-sensitive and may shift significantly, altering the cost analysis. On this subject, it should be noted that some of the economic and environmental figures of this study were relevant to specific geographic locations, such as the United States, because more broad figures could not be found. These figures also pose a limitation because they were not considered assumptions, but do introduce certain unaccounted-for geographic assumptions about the fuel production. Fourth~~Third~~, while a broad range of sources was consulted, some relevant literature may not have been captured due to access barriers or search limitations.

However, on the subject of limitations, it should be considered that strong precautions and efforts were taken to mitigate the limitations of this paper, as much as possible, when possible. Numerical figures were analyzed and corroborated for accuracy, computational errors were parsed and removed when found, sources were found with strong attempts to create a wide range of consideration, and economic figures were made as current as possible.

Concluding with the topic of further research, the fact that the results of this study conflict with the general academic theme warrants further investigation into the applicability of SAFs. For one, more research on sustainable aviation fuel pathways and biological input sources could help to corroborate or counter existing works in the field, and thus contribute to a definitive answer. In particular, further analysis into the lifecycle of the HEFA route with camelina as a feedstock would be beneficial to build upon this work and corroborate or refute it. Further investigations on SAFs may benefit from using an even wider range of sources than this paper to provide stronger confirmation of data.

Furthermore, another potential realm requiring more investigation could be the field involving new and developing methods to produce sustainable aviation fuels. These methods, given the results of this paper, could present better alternatives to existing SAF methods, and would thus be of importance to research and explore.

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Appendix A

Unit Conversions

A1:

$$1000 \text{ kg} = 1 \text{ ton}$$

Thus

$$Mass_{kg} / 1000 = Mass_{tons}$$

Or conversely

$$Mass_{tons} \times 1000 = Mass_{kg}$$

A2:

$$2.205 \text{ lb} = 1 \text{ kg}$$

Thus

$$Mass_{lb} / 2.205 = Mass_{kg}$$

Or conversely

$$Mass_{kg} \times 2.205 = Mass_{lb}$$

A3:

$$1.609 \text{ km} = 1 \text{ mi}$$

Thus

$$\text{Distance}_{km} / 1.609 = \text{Distance}_{mi}$$

Or conversely

$$\text{Distance}_{mi} \text{ x } 1.609 = \text{Distance}_{km}$$

A4:

$$1000 \text{ g} = 1 \text{ kg}$$

Thus

$$\text{Mass}_{g} / 1000 = \text{Mass}_{kg}$$

Or conversely

$$Mass_{kg} \text{ x } 1000 = Mass_{g}$$

A5:

$$1000 \text{ MJ} = 1 \text{ GJ}$$

Thus

$$Energy_{MJ} / 1000 = Energy_{GJ}$$

Or conversely

$$Energy_{GJ} \text{ x } 1000 = Energy_{MJ}$$

Appendix B

Transportation Stage Calculations

Beginning with 0.4 lb of CO_2 per ton-mile (Congressional Budget Office, 2022), converting from pounds of CO_2 to kilograms of CO_2 (see *Appendix A2*):

$$0.4 \text{ lb } CO_2 / (\text{ton x mi}) = 0.181 \text{ kg } CO_2 / \text{ton x mi}$$

Converting from ton-miles to ton-kilometers (see *Appendix A3*):

$$0.181 \text{ kg } CO_2 / \text{ton x mi} = 0.113 \text{ kg } CO_2 / \text{ton x km}$$

Multiplying by the assumed 133 km average distance (Li and Mupondwa, 2016):

$$0.113 \text{ kg } CO_2 / \text{ton x km x } 133 \text{ km} = 14.994 \text{ kg } CO_2 / \text{ton}$$

Converting from tons of camelina to kilograms of camelina (see *Appendix A1*):

$$14.994 \text{ kg } CO_2 / \text{ton} = 0.015 \text{ kg } CO_2 / \text{kg}$$

$$\text{Final transportation emissions value: } 0.015 \text{ kg } CO_2 / \text{kg}$$

Appendix C

Oil Extraction Stage Calculations

C1:

Starting with 0.043 kg of CO_2e per lb of extracted oil and 27.4% of input oilseed mass extracted as oil (Dangol et al., 2015), multiplying the values to convert from per pound of oil to per pound of input oilseed:

$$0.043 \text{ kg } CO_2e \text{ / lb oil x } 0.274 \text{ lb oil / lb oilseed} = 0.012 \text{ kg } CO_2e \text{ / lb oilseed}$$

Converting from pounds of oilseed to kilograms of oilseed (see *Appendix A2*):

$$0.012 \text{ kg } CO_2e \text{ / lb oilseed} = 0.026 \text{ kg } CO_2e \text{ / kg oilseed}$$

Final oil extraction emissions value: 0.026 kg CO_2e / kg oilseed

C2:

Starting with 72.6% of input mass as meal (Dangol et al., 2015), assume a 1 kg input of camelina mass:

$$1 \text{ kg oilseed x } 0.726 \text{ kg meal / (kg oilseed)} = 0.726 \text{ kg meal}$$

Multiplying by the \$0.25 per kg of meal (Bertacchi et al., 2020):

0.726 kg meal x $0.25 / kg meal = $0.182

Recognizing the initial 1 kg input oilseed assumption:

$0.182 = $0.182 / kg oilseed

Subtracting from the earlier $0.004 / kg oilseed figure:

$0.004 / kg oilseed - 0.182 / kg oilseed = -$0.177 / kg oilseed

Final oil extraction cost value: -$0.177 kg oilseed (cost offset)

Appendix D

HEFA Conversion Stage Calculations

D1:

Starting with 0.021 kg CO_2e per MJ of SAF, and 44.1 MJ / kg of SAF (Han et al., 2013), multiplying the values:

$$0.021 \text{ kg } CO_2e \text{ / MJ SAF x } 44.1 \text{ MJ / kg SAF} = 0.904 \text{ kg } CO_2e \text{ / kg SAF}$$

Multiplying by 0.75 to include the fact that 1 kg of input camelina oil converts via HEFA into only 0.75 kg of biofuel:

$$0.904 \text{ kg } CO_2e \text{ / kg SAF x } 0.75 \text{ kg SAF / kg oil} = 0.678 \text{ kg } CO_2e \text{ / kg oil}$$

Final HEFA conversion emissions value: 0.678 kg CO_2e / kg oil

D2:

Starting with 4734 MJ of H_2 per ton of biofuel (Han et al., 2013), and 120 MJ per kg of H_2 (DOE, n.d.-a), dividing the values:

$$4734 \text{ MJ } H_2 \text{ / ton biofuel / } 120 \text{ MJ / kg } H_2 = 39.45 \text{ kg } H_2 \text{ / ton biofuel}$$

Multiplying by 5 for \$5 / kg for H_2 (Vickers et al., 2020):

$$39.45 \text{ kg } H_2 \text{ / ton biofuel x \$5 / kg } H_2 = \text{\$197.25 / ton biofuel}$$

Final hydrogen cost contribution to HEFA conversion: $197.25 / ton biofuel

D3:

Starting with $0.005 per cubic foot of natural gas (EIA, n.d.-c) and 1000 cubic feet of natural gas per 1093 MJ (EIA, n.d.-b) multiplying to get cost per megajoule:

$0.005 / cubic foot x 1000 cubic feet / 1093 MJ = $0.004 / MJ

Multiplying by the 7818 MJ / ton of produced biofuel (Han et al., 2013) to account for magnitude of natural gas use:

$0.004 / MJ x 7818 MJ / ton biofuel = $32.259 / ton biofuel

Final natural gas contribution to HEFA conversion: $32.259 / ton produced biofuel

D4:

Starting with 3359 MJ per ton of biofuel and 43.2 MJ per kg naphtha (Han et al., 2013), dividing to find naphtha mass ratio:

3395 MJ / ton biofuel / 43.2 / kg naphtha = 77.755 kg naphtha / ton biofuel

Multiplying by -$0.55 per kg naphtha (Aburto et al., 2025) for current naphtha prices (negative for cost offset):

77.755 kg naphtha / ton biofuel x -$0.55 / kg naphtha = -$42.765 / ton biofuel

Final naphtha cost contribution: -$42.765 / ton biofuel (cost offset)

D5:

Starting with 4444 MJ per ton biofuel and 44.4 MJ per kg propane (Han et al., 2013), dividing to find the propane mass ratio:

4444 MJ / ton biofuel / 44.4 MJ / kg propane = 100.09 kg propane / ton biofuel

Multiplying by -$0.8 per kg propane (Aburto et al., 2025), for current propane prices (negative for cost offset):

100.09 kg propane / ton biofuel x -$0.8 / kg propane = -$80.072 / ton biofuel

Final propane mix cost contribution: -$80.072 / ton biofuel

D6:

Starting with $0.112 per kg of produced biofuel, and 0.75 kg produced biofuel per kg input oil

(Han et al., 2013), multiplying to convert to input oil:

$0.112 / kg biofuel x 0.75 kg biofuel / kg oil = $0.084 / kg oil

Final HEFA conversions cost value: $0.084 / kg oil

Appendix E

Combustion Stage Calculation

Starting with 74 g CO_2e per MJ fuel (Prussi et al., 2021), converting from grams to kilograms (see *Appendix A4*):

$$74 \text{ g } CO_2\text{e / MJ fuel} = 0.074 \text{ kg } CO_2\text{e / MJ fuel}$$

Multiplying by the energy density of SAF, 44 MJ / kg fuel (Norazmi, n.d.):

$$0.074 \text{ kg } CO_2\text{e / MJ fuel x 44 MJ / kg fuel} = 3.256 \text{ kg } CO_2\text{e / kg fuel}$$

Final combustion emissions value: 3.256 kg CO_2e / kg fuel

Appendix F

Results Stage Calculation

Starting with feedstock growth values of 0.395 kg of CO_2e per kg of grown camelina feedstock and \$0.244 per kg of grown camelina feedstock, assume a 1 kg input of feedstock:

$$0.395 \text{ kg } CO_2e \text{ / kg oilseed} = 0.395 \text{ kg } CO_2e$$

$$\$0.244 \text{ / kg oilseed} = \$0.244$$

Applying the assumption to the transport and oil extraction figures, 0.041 kg of CO_2e per kg oilseed and -\$0.165 per kg of oilseed (negative for cost offset):

$$0.041 \text{ kg } CO_2e \text{ / kg oilseed} = 0.041 \text{ kg } CO_2e$$

$$-\$0.165 \text{ / kg oilseed} = -\$0.165$$

Adding the resulting feedstock growth values to the transportation and oil extraction values:

$$0.395 \text{ kg } CO_2e + 0.041 \text{ kg } CO_2e = 0.410 \text{ kg } CO_2e$$

$$\$0.244 - \$0.165 = \$0.079$$

Recognizing that these values apply for the above 1 kg feedstock input assumption, and that oil extraction only extracts 27.4% of input mass as oil (Dangol et al., 2015):

$$1 \text{ kg oilseed x } 0.274 \text{ kg oil / kg oilseed} = 0.274 \text{ kg oil}$$

Multiplying the HEFA conversion values, 0.678 kg of CO_2e per kg of input oil and $0.084 per kg of input oil, by 0.274 kg of oil to match the assumption:

$$0.678 \text{ kg } CO_2e \text{ / kg oil x } 0.274 \text{ kg oil} = 0.186 \text{ kg } CO_2e$$

$$\$0.084 \text{ / kg oil x } 0.274 \text{ kg oil} = \$0.023$$

Adding these resulting values to the earlier summed feedstock growth, transportation, and oil extraction figures:

$$0.410 \text{ kg } CO_2e + 0.186 \text{ kg } CO_2e = 0.596 \text{ kg } CO_2e$$

$$\$0.079 + \$0.023 = \$0.102$$

Further recognizing that HEFA conversion yields only 0.75 kg of biofuel per kg of input oil (Han et al., 2013), by multiplying by the earlier calculated 0.274 figure:

$$0.274 \text{ kg oil x } 0.75 \text{ kg biofuel / kg oil} = 0.206 \text{ kg biofuel}$$

Multiplying the combustion values, 3.256 kg of CO_2e per kg of biofuel, and $0 per kg biofuel, by 0.206 kg of biofuel to further match the assumption:

$$3.256 \text{ kg } CO_2e \text{ / kg biofuel x } 0.206 \text{ kg biofuel} = 0.669 \text{ kg } CO_2e$$

$$\$0 \text{ / kg biofuel x } 0.206 \text{ kg biofuel} = \$0$$

Adding these resulting values to the most recent summed values from the feedstock growth, transportation, oil extraction, and HEFA conversion stages:

$$0.596 \text{ kg } CO_2e + 0.669 \text{ kg } CO_2e = 1.265 \text{ kg } CO_2e$$

$$\$0.102 + \$0 = \$0.102$$

Again recognizing the assumption of 1 kg of camelina input feedstock, translating to 0.247 kg of oil, and then to, 0.206 kg of biofuel; multiplying 0.206 kg of biofuel by 44.1 MJ per kg of biofuel (Han et al., 2013):

$$0.206 \text{ kg biofuel x } 44.1 \text{ MJ / kg biofuel} = 9.063 \text{ MJ}$$

Dividing by 9.063 MJ, acknowledging the fact that the most recent summed emission and cost values above represent those for this amount of biofuel (1 kg of camelina feedstock = 0.274 kg of oil = 0.206 kg biofuel = 9.063 MJ)

$$1.265 \text{ kg } CO_2e \text{ / } 9.063 \text{ MJ} = 0.140 \text{ kg } CO_2e \text{ / MJ}$$

$$\$0.102 \text{ / } 9.063 \text{ MJ} = \$0.011 \text{ / MJ}$$

Final emission and cost values: 0.140 kg CO_2e / MJ, \$0.011 / MJ

Peer Review 1 Revision Replies

Thank you for your feedback and critical analysis! I really appreciate your help in improving my paper for submission. I've tried to address each point of concern in the revised manuscript, and the below paragraphs summarize my responses and changes. The numbers to the right of the paragraphs indicate which paragraphs from the peer review they correspond to.

1-3: Thank you! I fully agree with the overview and summary of the manuscript.

4: My version of the paper seems to show up with line numbers, but there's a chance that they did not go through with the submission. I'll be more careful next time with checking for line numbers. I've also labeled each section and subsection with a numerical identifier in front of the actual subtitle.

5-6: Yes! It's entirely possible that these more developing forms of aircraft power could be more environmentally friendly than SAFs. To my understanding, research is currently being produced on this topic, but this paper would likely be unable to address it given its focus on SAFs. Even so, I've expanded on the discussion of hydrogen aviation in the purpose section, and better explained that its current technical limitations were the reason it was not focused on in the study.

7: Yes, these are both possibilities that represent a limitation of the paper. Many of the identified figures in the paper are applicable to broad geographic regions, but not globally, as many factors vary from location to location. It is thus possible that the figure from Li and Mupondwa (2016) is different in other parts of the world, and possibly represents a worse situation in more geographically spread out regions. However, this kind of uncertainty is part of the paper's framework, because the paper relies on secondary figures that are not always globally applicable. The solution to this is to mention the uncertainty as a limitation. I've altered the discussion of the limitations section to make the geographic uncertainties of some of the paper's figures more clear, and also directly mentioned the geographic uncertainty of the Li and Mupondwa figure.

8: It would technically be possible to create some uncertainty estimates for the intermediate and final values, but it would likely be infeasible. The majority of the data points obtained from the limited literature in the field were individual numbers as opposed to ranges, and only the feedstock section came with a confidence interval. Without ranges or confidence intervals for the majority of the data, it would be highly difficult and likely inaccurate to run and present a statistical test like a Monte Carlo test. Running such a test would also require numerous assumptions that could introduce more uncertainty than they would resolve. Thus, it may be infeasible to present confidence intervals or ranges for the intermediate or final values, although such ranges would be incredibly beneficial.

9: Yes, this assumption comes from the combustion subsection in the analysis section of the text. The following paragraph and the explanatory text that comes after it establish the paper's stated assumption that SAF emissions approximately match those of traditional fuels:

"Various studies have shown that SAF emissions of most gases/substances do not differ greatly in terms of climate emissions from traditional jet fuels. For instance, Song et al. (2024) found that the emissions of CO2, NOx, CO, and UHC from various SAFs (including camelina based fuels) were insignificantly different from those of traditional jet A1 fuel."

I've added a reference to the combustion section to reiterate this idea in the sensitivity analysis.

10: I believe Figures 1 and 2 have titles and captions at the moment, but the captions consist only of citations for those figures. I've added to those captions to add some description of the figures. I've also adjusted the title of the table to be more appropriate, and outside of the table itself and underneath the table number (Table 1), to adhere to the APA format.

11: In a way the results of the research do implicate this, but there is some nuance to this idea. The results of the research paper are only truly applicable under the specific circumstances that were considered, although they may speak to other similar situations. Thus, the paper indicates that under the specific pathway and assumptions considered, SAFs may be less environmentally friendly as compared to traditional fuels. However, the paper does not directly speak to other pathways and circumstances, which leaves the broader possibility for SAF implementation very open. It could also be true that the radiative effects of SAFs could be worse than those of traditional jet fuels if SAFs slightly increase contrails, because contrails are known to produce cirrus clouds that have a net warming impact. However, the reason that emissions were considered equal in the study is because it remains somewhat uncertain how SAFs affect cloud formation through contrails. Specifically, it is known that SAFs decrease particulate matter release and increase water vapor release, but it remains highly unclear how these changes affect the magnitude and internal characteristics of contrails, which determine cloud formation and climate impact. This is something on reflection I feel could be expressed more clearly in the paper, and I have attempted to address this in the combustion subsection with a discussion of contrails.

Peer Review 2 Revision Replies

Thank you for your feedback and critical analysis! I really appreciate your help in improving my paper for submission. I've tried to address each point of concern in the revised manuscript, and the below paragraphs summarize my responses and changes. The numbers to the right of the paragraphs indicate which paragraphs from the peer review they correspond to, and the bolded subtitles similarly indicate the section of the peer review being discussed.

General Review:

1-14: Thank you! This is something I also noted as a difference within the manuscript, and I fully agree that my approach differs from the traditional framework. I've made some changes to attempt to better explain how biogenic carbon is incorporated, how combustion emissions are being treated compared to traditional fuels, how the paper's approach differs from the traditional one, how the environmental conclusions are specific to the assumptions made, and how the chosen approach for this paper may overestimate the emissions. First, I've included a discussion in the methodology section explaining how the approach of this paper differs from the traditional one. This discussion includes a description of the approach of this paper, which outlines the treatment of biogenic carbon, and combustion emissions. Second, I have also added a reminder of this discussion in the combustion section. Third, I have altered the implications section of the conclusion to make it more clear that the results of the research paper are only directly applicable to situations that match the assumptions made in the paper. Finally, I have added a discussion in the assumptions and considerations section that outlines how the unique approach to considering lifecycle emissions may unintentionally overestimate the emissions.

15: I understand how the literature review may overstate the absence of similar literature. I have added a new paragraph and changed some of the wording to better reflect that the manuscript is not addressing a complete gap in literature, but rather a somewhat understudied field. The new paragraph is also intended to help improve the logic of the foundation of the review, which helps make it clearer that the similar literature discussed in the later paragraphs is not non-existent.

Section Specific Comments:

Abstract:

1-5: I've altered the abstract and manuscript to define the acronyms as they are present. Also, I've altered the wording of the abstract to try and make it clearer that the paper is addressing its literature gap by relying on other literature. Specifically, I've tried to show that the paper uses literature on the individual steps of the HEFA process to build a combined lifecycle analysis, and does not directly use such combined lifecycle analysis for which the literature is limited. This change was also intended to help the abstract show that the paper is fundamentally a literature review, and not producing empirical results.

Background:

1-2: Thank you for the feedback! I've added the discussion about hydrogen technologies. I also believe that it will be beneficial.

Literature Gap / Literature Review:

1-7: I agree. I feel that the confusion in the literature review comes from some of the early wording that makes it seem as if integrated environmental and economic analyses have not been performed before. I also agree that the repetition in the paragraphs makes the reasoning less easy to follow. I've adjusted the review to try and address these issues. There is a new paragraph at the start of the review, and new wording and framing throughout to accomplish this. The new paragraph is specifically intended to strengthen the logical foundation of the early paragraphs, and to make it more clear in the later paragraphs that the literature gap of the paper is not completely void of works, but rather limited. The new wording and framing is also intended to show that the gap of the paper is not void, but also helps to reduce repetition and improve clarity.

8: I agree that this analysis is not present in the literature review, but I believe that it is located in the previous “Purpose” section. Here, the following paragraph is included:

“At the moment, there are numerous developed SAF production pathways, including: Hydroprocessed esters and fatty acids, alcohol-to-jet, hydroprocessing of fermented sugars, Fischer-Tropsch, pyrolysis, aqueous phase reforming, and power-to-liquid. Of these existing routes, the hydroprocessed esters and fatty acids route, or HEFA, is currently the most mature (Bauen et al., 2020). HEFA makes use of renewable feedstocks to obtain oils and fats, which are then hydroprocessed to create fuel. Being the most mature existing SAF pathway, HEFA poses the greatest potential for sustainable aviation fuel implementation. Despite its overall significance, however, an immensely important consideration for the HEFA process is the feedstock implemented. In this regard, the camelina crop is a feedstock with incredible potential, because it requires little energy to grow, contains high amounts of non-food oil, and can be grown without interfering with other agriculture as a cover crop (Wang et al., 2020). The goal of this paper is to analyze existing literature to obtain secondary data values, then present a full environmental and economic lifecycle analysis of the HEFA production route given camelina as a feedstock, and thus provide a robust analysis of the HEFA pathway.”

I feel that this paragraph does a solid job of explaining the focus on camelina, and thus I left this section unaltered.

Methodology:

1-4: I fully agree. I’ve tried to reduce the density of the methodology by improving upon the transitions, and including more simple sentences and vocabulary. In particular, I’ve made major changes to the second paragraph.

Figures and Tables:

1-6: I’ve added a reference for Figure 1 in the text, and explained its relevance in the note directly under the figure. I feel that this will help incorporate the figure into the narrative and make its purpose more explicit. However, I believe that there was a citation for Figure 1 in the figure caption. The caption for the figure was the following:

"*Note*. Figure from Seber et al. (2022)."

I've kept this citation in addition to the above changes.

7: I agree. I've added an explanation of how the consideration of only one extraction method is something that limits the results of the paper in the assumptions section. More specifically, I've cited the extraction choice as an assumption, and included a discussion of how the assumptions of the paper limit its applicability in the limitations section. I've also added an economic justification for the consideration of the oil pressing extraction method with a small paragraph.