Comparison of life cycle emissions of alcohol-to-jet sustainable aviation fuels from selected energy plants

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ABSTRACT

The aviation industry has been developing dynamically in recent years; however, it also faces the challenge of reducing CO_2 emissions and striving to achieve climate neutrality by 2050. One solution is the development of sustainable aviation fuels (SAF), which are biofuels that significantly reduce greenhouse gas emissions. This work aims to determine the carbon footprint in the life cycle of SAF produced by the alcohol-to-jet (ATJ) conversion method in two variants: well-to-wake and well-to-tank for selected energy plants – energy willow (*Salix viminalis*), giant miscanthus (*Miscanthus × giganteus*), and hybrid poplar (*Populus* sp.). In the case of well-to-tank emissions, the overall emissions equaled 1049.82 $kgCO_2eq/Mg$, 987.78 $kgCO_2eq/Mg$, and 990.25 $kgCO_2eq/Mg$ for energy willow, giant miscanthus, and hybrid poplar, respectively. The well-to-wake emissions are more than twice as high as wake-to-tank emissions. However, comparing well-to-wake emissions with conventional aviation fuels, Jet A-1 shows a decrease of 46.4%, 45.7%, and 44.1% for hybrid poplar, giant miscanthus, and energy willow, respectively. The results indicate that ATJ-SAF produced from domestic energy crops can substantially surpass regulatory emission reduction targets, underscoring their strong potential to contribute to aviation decarbonization.

Keywords: alcohol-to-jet conversion method, carbon footprint, sustainable aviation fuels.

INTRODUCTION

European aviation is quickly recovering after the COVID pandemic in 2020. According to the European Aviation Safety Agency (EASA), in 2023, flights from Europe have recovered to 91% of the pre-COVID levels. The number of European flights in 2023 reached 8.35 million. European Commission states that the number of passengers transported by air in the EU in 2023 increased by 19.3% compared to 2022 (Eurostat, 2024). According to the Polish Civil Aviation Office (2023), in 2022, Polish airports served almost 41 million passengers, and in 2023, over 52 million passengers (Polish Civil Aviation Office, 2024). The rapid increase in air transport's popularity contributes to its growth, which is followed by the expansion of terminals and commercial fleets worldwide. This phenomenon has drawbacks the increased frequency of flights also increases aviation's environmental impact. In 2022, all flights departing from Europe accounted for 4% of the EU27 total greenhouse gas (GHG) emissions (EASA, 2025). The aviation sector's answer to the growing challenges of environmental protection is decarbonization efforts. Airlines have implemented multiple changes in their procurement practices and flight operations, ranging from operational optimization and improvements in aircraft engines to sustainable aviation fuels (SAF) (Kumar et al., 2025).

SAF is the backbone of the decarbonization efforts of the aviation sector; moreover, its usage in air transport is required by European Union law (Regulation EU 2023/2405). The EU has put forward a series of programs that regulate and enforce the use of SAF either directly or indirectly, which fall under the legislative package known as Fit for 55. The most important ones concerning SAF from the package are ReFuelEU Aviation (Regulation EU 2023/2405) and the European Union Emissions Trade System (EU ETS). The

ReFuelEU Aviation obligates the suppliers of aviation fuel to provide SAF in European airports. According to ReFuelEU, as of 2025, SAF must compromise at least 2% of the total aviation fuel supplied to the airports, and as of 2050, at least 70% (Regulation EU 2023/2405). The EU ETS imposes an obligation on airlines to purchase GHG emission units after exceeding a given, free limit (European Commission, 2015). Multiple international organizations associated with aviation started introducing numerous programs that can help aviation companies reduce their GHG emissions. The most notable of those programs is the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (IATA, 2024). CORSIA was introduced in 2016 by the International Civil Aviation Organization (ICAO), and it is a program that puts forward the need for compensating the aviation sector's CO_2 emissions. CORSIA consists of three phases: the completed piloting phase (in the years 2021–2023), the first phase (in the years 2024–2026), which assumes voluntary participation from member airlines, and the second phase (in the years 2027–2035), which assumes mandatory participation from member airlines. CORSIA assumes that each member airline whose annual CO_2 emissions exceed 10.000 Mg will be obliged to report its emissions starting from 1 January 2019. Moreover, CORSIA imposes upon member airlines the obligation to compensate for their CO_2 emissions that exceed those of the base year, which is 2019 (IATA, 2025). SAF is a biofuel of high enough grade to be used in aircraft. The main goal of SAF is to reduce life-cycle GHG emissions in comparison to conventional Jet A-1 fuel and reduce the usage of non–renewable materials (IATA, 2024). There are multiple methods by which SAF can be produced, although only some of them are approved by the American Society for Testing and Materials (ASTM). Each SAF production pathway has strictly specified feedstocks, chemical reactions, and a maximal share of SAF in the fuel blend. The most frequently used SAF production methods include Fischer–Tropsch synthetic paraffinic kerosene, hydrotreated esters and fatty acids (HEFA), and alcohol-to-jet (ATJ) synthetic paraffinic kerosene (Almena et al., 2024; Kourkoumpas et al., 2024). According to ASTM, the maximum share of the fuel blend of the aforementioned SAF is 50%, although some experimental flights were conducted with 100% of SAF in the blend (IATA, 2024).

The ATJ conversion is a process that converts alcohols to paraffinic kerosene, which allows the production of high–grade biofuels from feedstocks such as energetic plants, forestry, and agricultural waste. After the biomass is converted into alcohol, it then undergoes dehydration into olefins, oligomerization, and hydrogenation processes (Geleynse et al., 2018). The most frequently used alcohols for the production of SAF are bioethanol and isobutanol, and the ATJ method is approved by ASTM (IATA, 2024). The most significant benefits of ATJ are the use of renewable resources, which do not need to be imported from foreign countries, making them independent from foreign economies, and price fluctuations. Furthermore, fuels produced by the ATJ method emit less sulfur oxides and PM than conventional fuel Jet A-1 (Brooks et al., 2016). According to research conducted by EASA, ATJ will be one of the primary methods of SAF production for the foreseeable future (EASA, 2022).

Over the past few decades, interest in bioethanol derived from non-food lignocellulosic biomass has increased due to its abundance, renewability, and low cost (Broda et al., 2022; Stolarski et al., 2015). Given the depletion of fossil fuel resources, rising global energy demands, increasing greenhouse gas emissions, and ongoing climate change, there is an urgent need for sustainable, renewable, and economically viable energy alternatives (Kaletnik et al., 2025). Bioethanol production from short-rotation plants (SRPs), such as giant miscanthus (*Miscanthus giganteus*), energy willow (*Salix* spp.), poplar (*Populus* spp.), sugar sorghum (*Sorghum bicolor*), sugarcane, or cereal straw, aligns with circular economy and zero-waste strategies. SRPs also offer the potential to reduce dependence on the petrochemical industry while enhancing energy security and environmental sustainability (Broda et al., 2022; Kaletnik et al., 2025).

The growing pressure from international organizations and societies created a demand for analyzing the product's life cycle in terms of GHG emissions and the usage of non-renewable resources and energy. The life cycle analysis (LCA) is used to assess a product's environment impact. In the case of jet fuels, there are two main ways of conducting a LCA: well-to-tank (WTT), which takes into account the fuel's environmental impact from the production of feedstock to fueling the aircraft, and well-to-wake (WTW) which takes into account the fuel's environmental impact from the production of feedstock to

combustion in an aircraft's engine (Shönsteiner et al., 2016). This work aims to determine the carbon footprint of sustainable aviation fuels produced by the ATJ conversion method in two variants: WTW and WTT for selected energy plants: energy willow (*Salix viminalis*), giant miscanthus (*Miscanthus × giganteus*), and hybrid poplar (*Populus* sp.). Additionally, the variants obtained emissions in the worst-case scenario without the CO_2 sequestration process.

METHODS

Life cycle emissions of SAF were calculated in two variants: WTT and WTW (Shönsteiner et al., 2016). The primary difference between this approach is illustrated in Figure 1. Both calculations were obtained for 1 Mg of three energy plants: energy willow (*Salix viminalis*), giant miscanthus (*Miscanthus × giganteus*), and hybrid poplar (*Populus* sp.), which are the most popular energy plants in the transitional temperate climate zone (Kaletnik et al., 2025). No allocation procedure (e.g., system expansion, mass or energy allocation) was applied in this study. This approach ensures transparency, avoids uncertainty enables consistent comparison between different production pathways.

Calculation of the carbon footprint from energy crop cultivation

The carbon footprint from 1 ha of energy crop cultivation was taken based on literature data (Table 1). Crop cultivation emissions (C_t) include the emissions of CO_2, N_2O, NH_3, NO_x, and net C. The emissions were calculated from the following cultivation stages: cultivation, planting, growth, harvest, and biomass transport (Krzyżaniak et al., 2020). The emission of CO_2 equivalent of dry mass (E_t) of the analyzed plants does not account for the carbon sequestration process, as we aim to illustrate the emission of the crop cultivation process without considering the role of plants in absorbing CO_2. When the carbon sequestration process is taken into account, the crop production process typically results in a negative CO_2 equivalent emission (Kourkoumpas et al., 2024). In contrast to other similar articles, we have decided to use a methodology that describes a worst-case scenario. This was done to demonstrate that, even without considering the CO_2 sequestration process, SAF can still be a viable solution for decarbonizing aviation. Additionally, a key objective of this study was to compare the WTT and WTW approaches for calculating life cycle emissions of SAF.

Calculating the carbon footprint of SAF production

The carbon footprint of SAF production was calculated based on literature data. According to Kourkoumpas et al. (2024), the SAF production consists of the bioethanol production process and the ATJ process; thus, the emissions of both processes were calculated (Figure 2) based on data from Table 1.
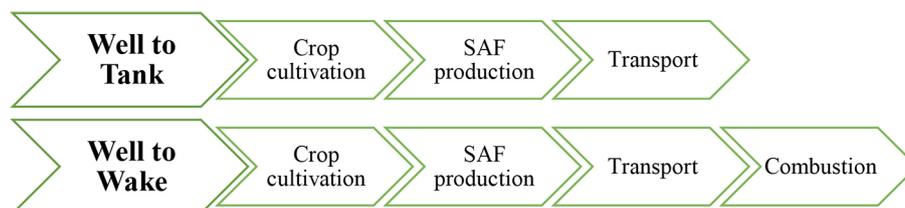

Figure 1. The flowchart of the difference between WTT and WTW life cycle carbon footprint calculations

Table 1. Data for the selected energy plants

Specification	Energy willow	Giant miscanthus	Hybrid poplar
Crop cultivation emission of CO_2 equivalent of dry mass (E_{total}) [kgCO$_2$eq /Mg d.m.]	35.97[1]	33.83[2]	25.17[2]
Mass of bioethanol obtained from dry mass (B_e) [Mg/Mg d.m.]	0.300[4]	0.184[5]	0.257[6]
Energy value of bioethanol (CF_e) [MJ/kg d.m.]	19.2[3]	19.3[3]	18.7[3]

Note: [1](Krzyżaniak et al., 2016); [2](Krzyżaniak et al., 2020); [3](Kurtyka et al., 2019); [4](González-García et al., 2012); [5](Turner et al., 2021); [6](Guo et al., 2014); d.m. – dry mass.
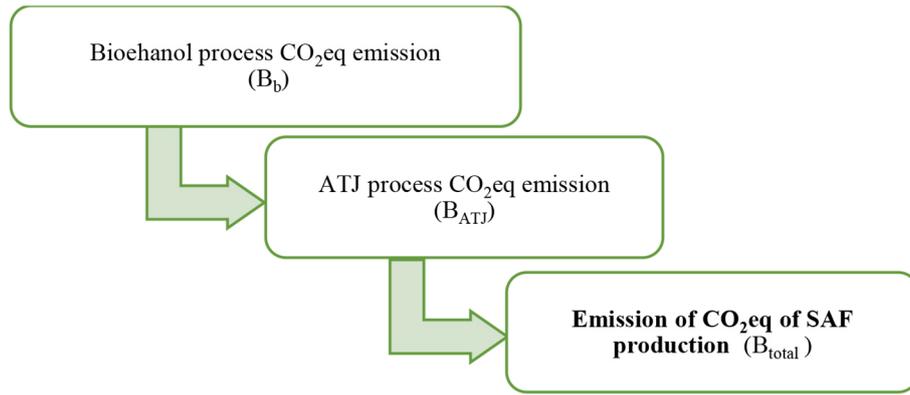
Figure 2. Emissions calculation scheme of the carbon footprint of SAF production

The emission equivalent of bioethanol production (B_b) [gCO$_2$eq/MJ] was calculated based on literature data from Table 1:

$$B_b = B_e \cdot B_p \quad (1)$$

where: B_e – amount of bioethanol obtained from dry mass [Mg/Mg d.m.] (Table 1); B_p – amount of CO$_2$ equivalent of bioethanol production. According to Cooper (2022), it is 28 [gCO$_2$eq/MJ].

The ATJ emission equivalent process (B_{ATJ}) [g CO$_2$eq/MJ] components and corresponding emissions, as summarized in Table 2, are according to Kourkoumpas et al. (2024). The total emission of CO$_2$ equivalent [kgCO$_2$eq/Mg] from the production of 1 Mg of SAF (B_{total}) [kgCO$_2$eq/Mg]:

$$B_{total} = (B_b + B_{ATJ}) \cdot CF_e \quad (2)$$

where: CF_e – energy value of bioethanol [MJ/kg] (Table 1); B_b – The emission equivalent of bioethanol production [gCO$_2$eq/MJ]; B_{ATJ} – the emission equivalent of the ATJ process. According to Kourkoumpas et al. (2024), it is 44.11 gCO$_2$eq/MJ.

Calculating the carbon footprint of transport

The distance from the fields to the refinery was assumed to be 100 km. Using the average emissions from heavy goods transport by trucks of 0.0566 kgCO$_2$eq/Mg·km (Broekaert, Fontaras, 2022), the CO$_2$ equivalent emissions from transporting 1 Mg of material over a distance of 100 km (T_{100}) were calculated [kgCO$_2$eq/ Mg]:

$$T_{100} = T_e \cdot 100 \quad (3)$$

where: T_e – average emissions from heavy goods transport [kgCO$_2$eq/Mg·km].

Table 2. ATJ production process emissions according to Kourkoumpas et al. (2024)

Processes	GHG emissions [gCO$_2$eq/MJ]
Enzymatic hydrolysis	0.06
Yeast fermentation	0.01
Natural gas boiler	12.54
Natural gas cogeneration system	21.13
Electricity to the ethanol plant	1.30
Electricity to the ATJ plant	9.01
Wood waste-fired boiler	0.06
The sum of the CO$_2$ equivalent of the ATJ process (B_{ATJ})	44.11

Calculating the carbon footprint from exhaust emissions during aircraft engine fuel combustion

Looking at the components of GHG emissions of SAF obtained by different methods, according to (Müller-Langer et al., 2020) and (Oehmichen et al., 2022), the combustion emission ranges from 51 to 66 gCO$_2$eq/MJ (on average 56.2 gCO$_2$eq/ MJ). Thus, the carbon footprint [kgCO$_2$eq/Mg] from exhaust emissions during aircraft engine fuel combustion (C_{total}) was calculated:

$$C_{total} = 56.2 \cdot CF_e \quad (4)$$

where: CF_e – energy value of bioethanol [MJ/kg] (Table 1).

RESULTS

The comparison of WTT and WTW emissions for energy willow (*Salix viminalis*), giant miscanthus (*Miscanthus × giganteus*), *and* hybrid poplar (*Populus* sp.) is presented in Figures 3 and 4, respectively.

In the case of WTT emissions (Figure 3), the overall emissions equaled 1049.82 kgCO$_2$eq/Mg, 987.78 kgCO$_2$eq/Mg, and 990.25 kgCO$_2$eq/Mg for energy willow, giant miscanthus, and hybrid poplar, respectively. The primary factor contributing to the aforementioned emissions is the SAF production. The emissions from feedstock cultivation and transport contribute relatively little to the overall carbon footprint. As Figure 3 shows, the choice of feedstock has a significant impact on the life cycle emissions of the analyzed SAF. The feedstock with the highest overall emissions is the energy willow. The WTW emissions of giant miscanthus and hybrid poplar are similar, being apart by a mere 2.47 kgCO$_2$eq/Mg in favor of the miscanthus.

The WTW emissions of analyzed SAF (Figure 4) equal 2128.86 kgCO$_2$eq/Mg for the energy willow, 2069.63 kgCO$_2$eq/Mg for the giant miscanthus, and 2041.19 kgCO$_2$eq/Mg for the hybrid poplar. In this variant, the emissions from SAF production, although still considerable, are overshadowed by the emissions from fuel combustion. SAF from energy willow remains the one with the highest emissions, while hybrid poplar has the lowest emissions of the analyzed fuels in the WTW variant. The best results of hybrid poplars are connected with crop cultivation emissions. However, a highly advantageous resource due to its rapid growth, versatility, environmental benefits, genetic adaptability, economic viability, and strong research backing (Monson et al., 2020). These attributes make them an excellent choice for various industrial and environmental applications. As previously mentioned, SAF can
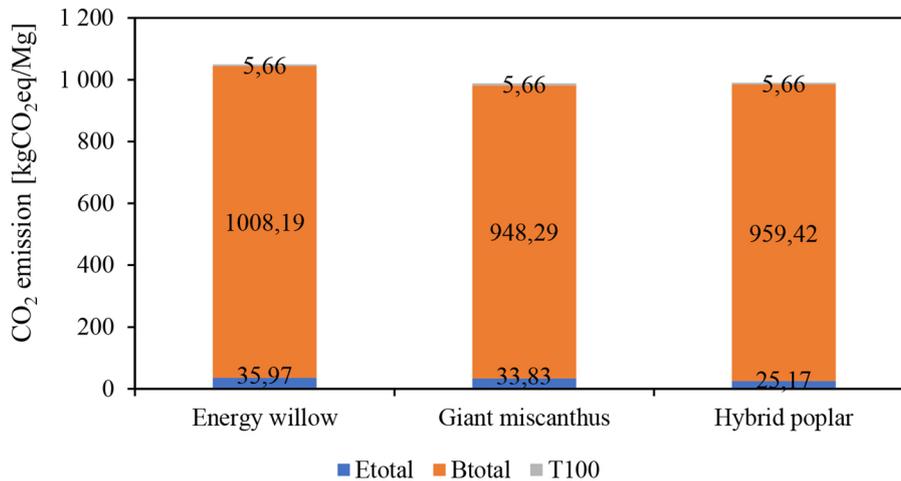

Figure 3. Well-to-tank life cycle emissions of analyzed SAF. Where: E$_{total}$ – crop cultivation emission; B$_{total}$ – SAF production emission; T$_{100}$ – transport of 100 km emission
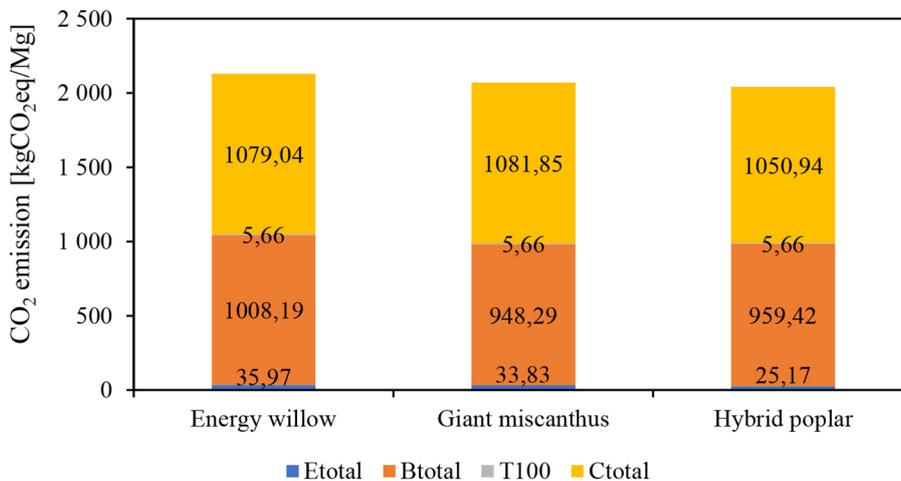

Figure 4. Well-to-wake life cycle emissions of analyzed SAF. Where: E$_{total}$ – crop cultivation emission; B$_{total}$ – SAF production emission; T$_{100}$ – transport of 100 km emission; C$_{total}$ – combustion emission

exhibit lower SO_x and PM emissions during combustion. Kurzawska and Jasiński (2021) indicate that blending 50% ATJ SAF with conventional Jet A-1 can substantially decrease PM emissions – by up to 18% in particle number and 53% in particle mass – compared to using pure Jet A-1 (Kurzawska and Jasiński, 2021). The reduced PM emissions of SAF can also be connected with its composition and production methods. Moreover, SAFs are renewable hydrocarbons that are characterized by low or a lack of SO_2 content (Raji et al., 2025). Even while we consider the positive effect of SAF on SO_2 and PM emissions from fuel combustion (Song et al., 2024), the final amount still remains the most considerable of all the individual processes in the fuel's life cycle. Many authors, when comparing emissions from engine combustion, assume that they are equal to CO_2 sequestration during crop cultivation, without taking into account any differences between individual crops or cultivation methods (Prussi et al., 2021, Uddin et al., 2025). This approach simplifies the analysis and can lead to underestimations. In our case, combustion emissions are 30–42 times higher, depending on the crop being analyzed.

As Figure 5 shows, the SAF production and fuel combustion account for 98–98.5% of the WTW carbon footprint of the analyzed SAF. From this data, we can infer that the efforts to further reduce the life cycle GHG emissions of ATJ SAF should focus on making the bioethanol production more sustainable, for example, by employing renewable energy sources or collaborating with

researchers to develop new conversion technologies (Joyia et al., 2024). Although the share of fuel combustion in the life cycle is even more significant than bioethanol production, the only way to significantly reduce CO_2 emissions (which are the main component of combustion emissions) is use of non-carbon-based fuels such as liquid hydrogen or electric motors (Yelugoti and Wang, 2023). Such a component as SAF transport equaled only 0.3% of the overall emissions. In our case, the distances used in the calculation were 100 km, which also occurs in different studies (Bosona et al., 2019) or extended to 130 km (Ballesteros et al., 2025). Changing the transport emissions increases linearly with transport distance (Bosona et al., 2019) because of multiplying the specific emission (T_e) by the distance. However, the impact on transport is marginal in total emissions.

As shown in Figure 6, even without taking into account the carbon sequestration, the overall WTW carbon footprint of each analyzed SAF remains lower than the WTW carbon footprint of Jet A-1 fuel, which is equal to 3809 $kgCO_2eq/Mg$ or 89 gCO_2eq/MJ (ICAO, 2025). The highest decrease in life cycle emissions is seen in the SAF produced from hybrid poplar (46.4%) compared to conventional Jet A-1 fuel. SAF produced from giant miscanthus and energy willow reduces the aforementioned emissions by 45.7% and 44.1% compared to Jet A-1. This reduction is way more than the 10% required for SAF to be considered CORSIA-eligible fuels (ICAO, 2025). The analysis demonstrates that ATJ SAF
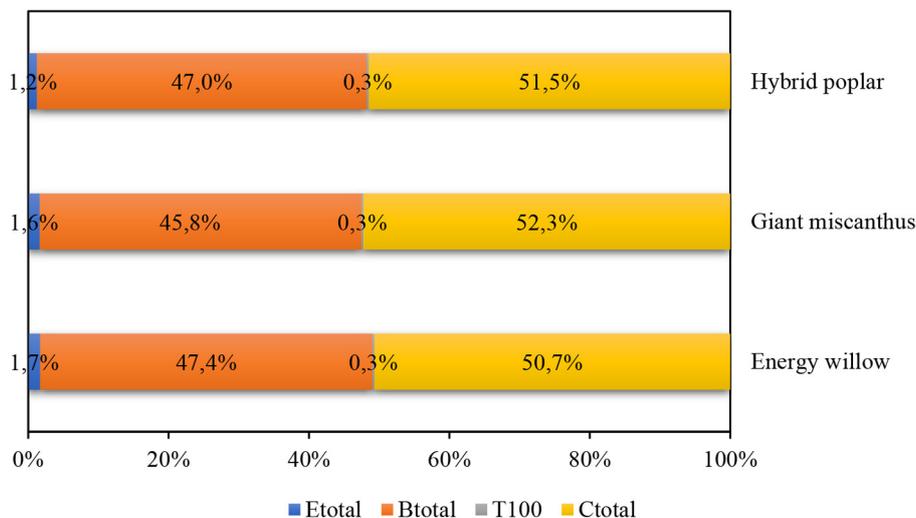

Figure 5. Share of individual processes in the well-to-wake life cycle emissions of the analyzed SAF. Where: E_{total} – crop cultivation emission; B_{total} – SAF production emission; T_{100} – transport of 100 km emission; C_{total} – combustion emission
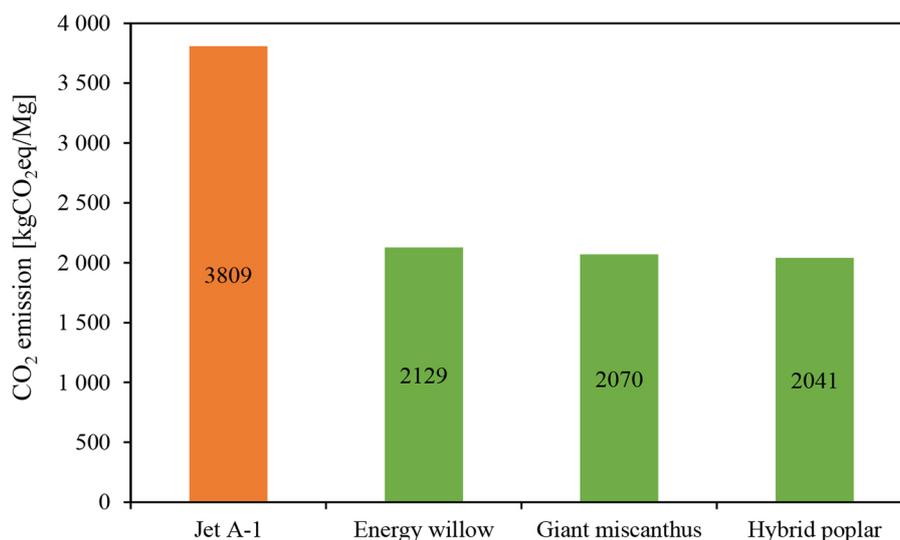
Figure 6. Well to wake carbon footprint comparison of analyzed SAF with Jet A-1

can reduce life cycle emissions of aviation fuels by a large margin while also being derived from renewable feedstocks. Moreover, the production of feedstock for ATJ SAF can allow local farmers to diversify their income sources. A key point to note is that the existing bioethanol production infrastructure makes the ATJ SAF more cost-effective and quicker to introduce. This comparison between the analyzed ATJ SAF and conventional aviation fuel indicates that SAF is the key to decarbonizing aviation for the foreseeable future. In comparison with other studies on the life cycle emissions of SAF, there are a lot of components that impact the final emissions, result in a large number of different findings. Meanwhile, the discrepancies in comparison can be attributed to differences in the methodologies used to calculate emissions (Raji et al., 2025). For this reason, the compared results should come from a single analysis. Only in this way the results are able to compared of the ATJ method with, for example, HEFA, which processes oils and fats, mainly vegetable and waste, into SAF, and the differences are seen. According to Prussi et al. (2021), calculation, comparing the emissions of different SAFs with Jet-A1, presents a reduction of 37–73% and 33–84% for ATJ and HEFA, respectively. On the other hand, Al-jabiri et al. (2024) reported that the addition of 40% sunflower oil to diesel may reduce CO emissions by 32.42% but increase NOx emissions by 19.35%. Also, the operating parameters of individual devices can be adjusted accordingly to achieve the intended results, e.g. regarding emissions (Al-Rbaihat et al.2023).

CONCLUSIONS

Providing the carbon footprint of ATJ SAF derived from bioethanol offers new insights into the environmental performance and process optimization potential of this emerging technology. The results show that SAF made of hybrid poplar can achieve competitive GHG emissions compared to fossil Jet A-1, reducing WTW life cycle emissions by 46.4% compared to conventional fuel Jet A-1. In the case of giant miscanthus and energy willow, the SAF decreases the aforementioned emissions by 45.7% and 44.1%, respectively. This study also helped identify the most significant production stages in the overall carbon footprint of the analyzed SAF and show its share in total emissions. The stages together account for between 98% and 98.5% of the overall emissions. In further research, it should focus on integrating energy, economic, and environmental aspects as a fragile assessment to reduce further impacts. Additionally, greening the bioethanol supply chain is key to achieving truly sustainable ATJ-SAF, providing actionable insights for both technology developers and policymakers to achieve the aviation sector's decarbonization goals by 2050.

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