ICARUS
INTERNATIONAL COOPERATION FOR SUSTAINABLE AVIATION BIOFUELS

LCA and SDG analysis of SAFs: screening of sustainability indicators

Task 3.1.2: Environmental impacts

WP3: Assessments for cost-effectiveness and sustainability

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EXECUTIVE SUMMARY

This report provides a detailed overview of the sustainability impacts of sustainable aviation fuels (SAFs) by synthesizing the most relevant and up-to-date information from peer-reviewed scientific literature. The results presented map sustainability indicators over the past decade (2014–2024), focusing on data from approximately 50 life cycle assessments (LCAs) published in peer-reviewed studies evaluating the environmental impacts of SAF value chains on a global scale. Data collection for this report is part of Task 3.1 and emphasizes European case studies while also including results from other countries, such as the Mission Innovation Countries (MIC).

Given the strict focus of current policies on decarbonization targets in the aviation sector (e.g., ReFuelEU Aviation and CORSIA), this report places strong emphasis on greenhouse gas (GHG) intensities, the primary metric for comparing SAFs to fossil jet fuel in achieving progressive decarbonization targets. In addition to GHG intensities, the report compiles studies addressing other environmental impacts, such as resource depletion, eutrophication potential, ecotoxicity, and broader effects on human health and ecosystems, which are directly linked to other Sustainable Development Goals (SDGs).

The report begins with an overview of the LCA study profiles, offering a comprehensive analysis of data across multiple variables influencing the environmental performance of SAFs, including feedstock categories, conversion pathways, geographic locations, methodological approaches, and LCA scopes. Recognizing the critical importance of carbon accounting in policymaking and achieving aviation sector decarbonization targets, the report includes a concise review of methodologies for calculating GHG intensities, with a particular focus on the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and the ReFuelEU Aviation Initiative. These methodologies are designed to comply with the Renewable Energy Directive (RED) sustainability criteria.

Given ICARUS's focus on syngas, biocrude oil, and alcohols as SAF precursors, the discussion highlights the environmental impacts of key conversion pathways, including gasification with Fischer-Tropsch synthesis (FT), hydrothermal liquefaction (HTL), and alcohol-to-jet (ATJ). Additionally, the report examines the broader environmental impacts of SAF value chains on other impact categories relevant to the SDGs and reviews studies quantifying the effects of land-use change on SAF GHG intensities.

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Nomenclature

APR	aqueous phase reforming
ATJ	alcohol-to-jet
CCS	carbon capture and storage
CEF	CORSIA eligible fuels
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
EU	European Union
FT	Fischer-Tropsch
GHG	greenhouse gas
HEFA	hydroprocessed esters and fatty acids
HTL	hydrothermal liquefaction
ICAO	International Civil Aviation Organization
ICARUS	International Cooperation for Sustainable Aviation Biofuels
ILUC	indirect land-use change
iBuOH	isobutanol
LCA	life cycle assessment
LCAF	CORSIA low carbon aviation fuels
LHV	lower heating value
LMC	land management changes
LUC	direct land-use change
MIC	Mission Innovation Countries
MJ	megajoule
MSW	municipal solid waste
Mt CO_2	million tons carbon dioxide
RED	Renewable Energy Directive
RFNBO	renewable fuels of non-biological origin
SAF	sustainable aviation fuel
SCS	Sustainability Certification Scheme
SDG	Sustainable Development Goals
SIP	synthesized iso-paraffins
TRL	Technology Readiness Level
WtG	well-to-gate
WtP	well-to-pump
WtT	well-to-tank
WTW	well-to-wake

Introduction

In 2023, global aviation emissions reached 820 Mt CO_2, recovering to approximately 90% of pre-COVID-19 levels and accounting for about 2% of total global GHG emissions[1]. Under a business-as-usual scenario, these emissions are projected to more than double, reaching 1,800 Mt CO_2 by 2050[2]. As part of global efforts to meet the Paris Agreement's goal of carbon neutrality by 2050, aviation has been identified as a priority sector for decarbonization by governments, intergovernmental organizations, and international agencies. The European Union (EU) has set an intermediate target of reducing emissions by 55% by 2030 (compared to 1990 levels) on its path to climate neutrality by 2050, with aviation being a key focus area[3,4]. Similarly, the International Civil Aviation Organization (ICAO) aims to cut aviation emissions by 5% by 2030 and has adopted a long-term objective of achieving net-zero emissions for international aviation by 2050[5].

Among aviation decarbonization strategies — technological advancements, operational efficiencies, and demand-side measures — drop-in Sustainable Aviation Fuels (SAF) is seen as the most impactful near-to mid-term solution. Its compatibility with existing aircraft and fueling infrastructure makes it key to reducing aviation emissions.

To accelerate SAF deployment and ensure emissions reductions, several policy initiatives have been introduced. For international aviation, ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a global market-based mechanism designed to stabilize CO_2 emissions from international flights. It requires airlines to offset emissions through carbon credits while recognizing SAF's lower carbon intensity as a compliance option. In Europe, the Renewable Energy Directive (RED) serves as the EU's overarching policy to promote renewable energy, including SAF, by setting sustainability criteria and GHG reduction requirements[6,7]. Within this framework, the ReFuelEU Aviation initiative specifically targets the aviation sector by mandating a steadily increasing SAF blend, starting at 2% this year, rising to 6% by 2030, 34% by 2040, and at least 70% by 2050. It also includes specific sub-mandates for synthetic fuels, requiring a minimum of 1.2% from 2030, increasing to 35% by 2050.

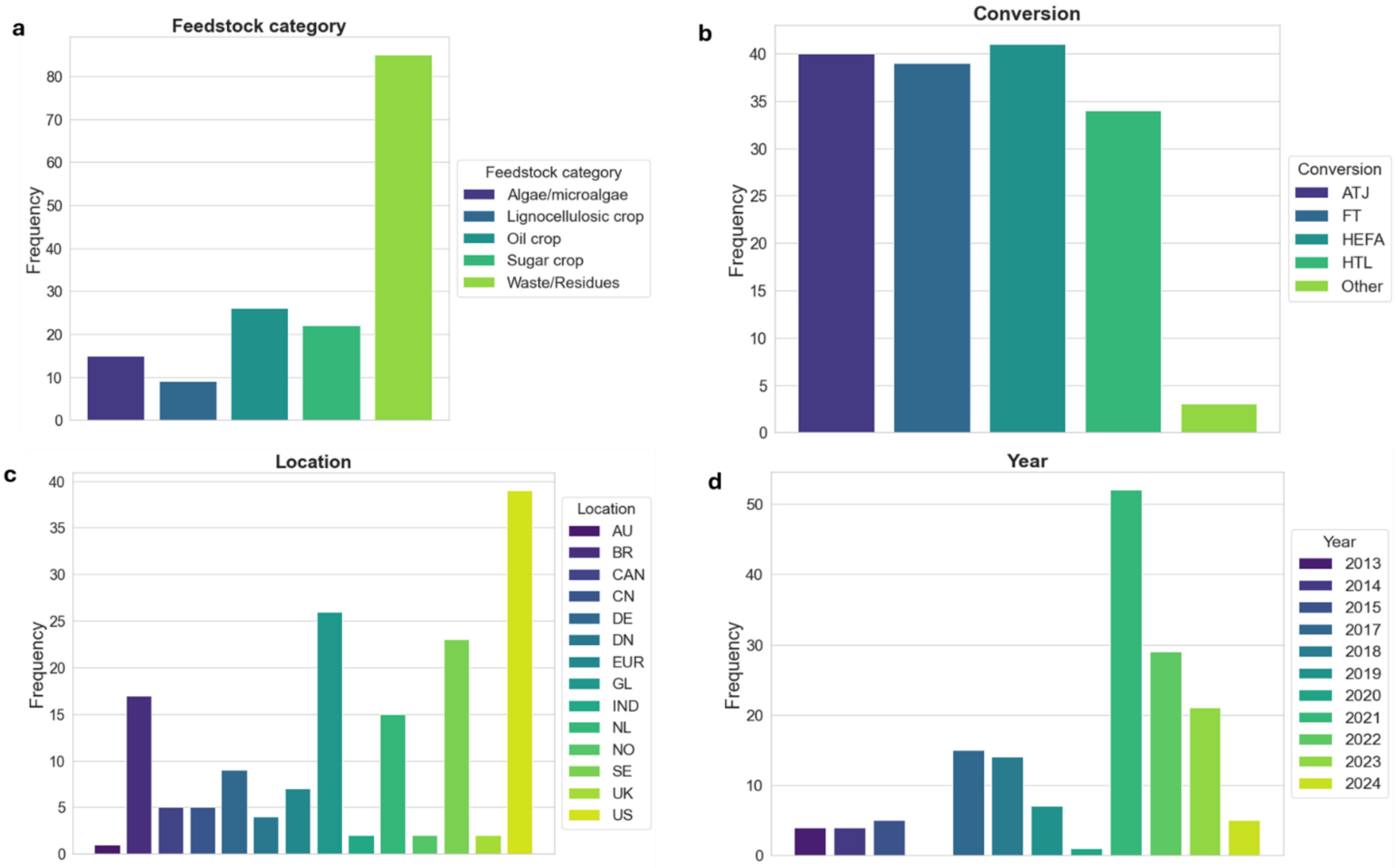
The results presented in this report are based on the collection of sustainability indicators over the last decade (2014-2024), focusing on data from approximately 50 life cycle assessments (LCAs) in peer-reviewed scientific publications dedicated to evaluating the environmental impacts of SAF value chains. Due to the strict emphasis of current policies on decarbonization targets for the aviation sector (such as ReFuelEU Aviation and CORSIA), most of our review reflects a strong focus on greenhouse gas intensities (approximately 150 values), which serve as the common basis for comparing SAF against the fossil jet fuel reference. In addition to GHG intensities, we present a collection of studies addressing the effects of SAF production on other environmental impacts, such as resource depletion, eutrophication potential, ecotoxicity, and other impacts on human health and ecosystems. These factors can directly affect other Sustainable Development Goals (SDGs).

1 Overview of sustainability indicators for SAF value chains

1.1 LCA studies and data profile

The data collection consisted of a thorough screening covering SAF production using different feedstock categories, conversion routes, and locations. As **Figure 1a** shows, most of the GHG intensities are based on the conversion of 'waste and residues' to SAF, representing more than half of all the data collected. This category aggregates a wide range of feedstocks, such as agricultural and forestry residues, municipal solid waste (MSW), used cooking oil, tallow oil, and sludge from wastewater. This finding is consistent with the increasing interest in assessing the climate mitigation potential of SAFs under stricter policies, such as EU RED, where this feedstock category holds primary interest compared to other feedstock sources like oil- and sugar-rich crops.

Figure 1: GHG intensity data profile. Frequency of data reported by feedstock category (a), conversion route (b), location (c), and year of publication (d).



When comparing the main conversion routes in the literature, the collected GHG intensities are relatively equally distributed among the selected conversion pathways. As expected, the hydroprocessed esters and fatty acids (HEFA) route has a slightly higher number of GHG intensity values among the data collected, possibly reflecting the current higher Technology Readiness Level (TRL) of this technology for SAF production (see **Figure 1b**). Although this pathway is not the focus of this report, HEFA represents an important benchmark technology to be compared with other routes. As **Figure 1b** shows, routes further studied in ICARUS can be perceived as highly relevant in life cycle assessments (LCAs), since the frequency of data collected for alcohol-to-jet (ATJ), hydrothermal liquefaction (HTL), and gasification with Fischer-Tropsch (FT) routes are comparable to HEFA.

In terms of location, the data compilation varies according to the scope of the LCAs, which ranged from country-based studies (the vast majority of the data) to more aggregated regions of the world such as Europe[8], including one study referring to GHG intensities of SAFs applicable at a global scope[9]. As **Figure 1c** shows, data for country-based assessments were predominantly found in studies for the United States, Sweden, Brazil, and the Netherlands. Although most of the data relates to European countries, the data collection can be considered representative of the global aviation sector, as it includes other Mission Innovation Countries (MIC) such as Canada, India, China, and Australia. As **Figure 1d** depicts, most of the data are concentrated in the period from 2017 to 2023, with a visible gap in publications in 2020, possibly reflecting the effects of the COVID-19 pandemic on the research community.

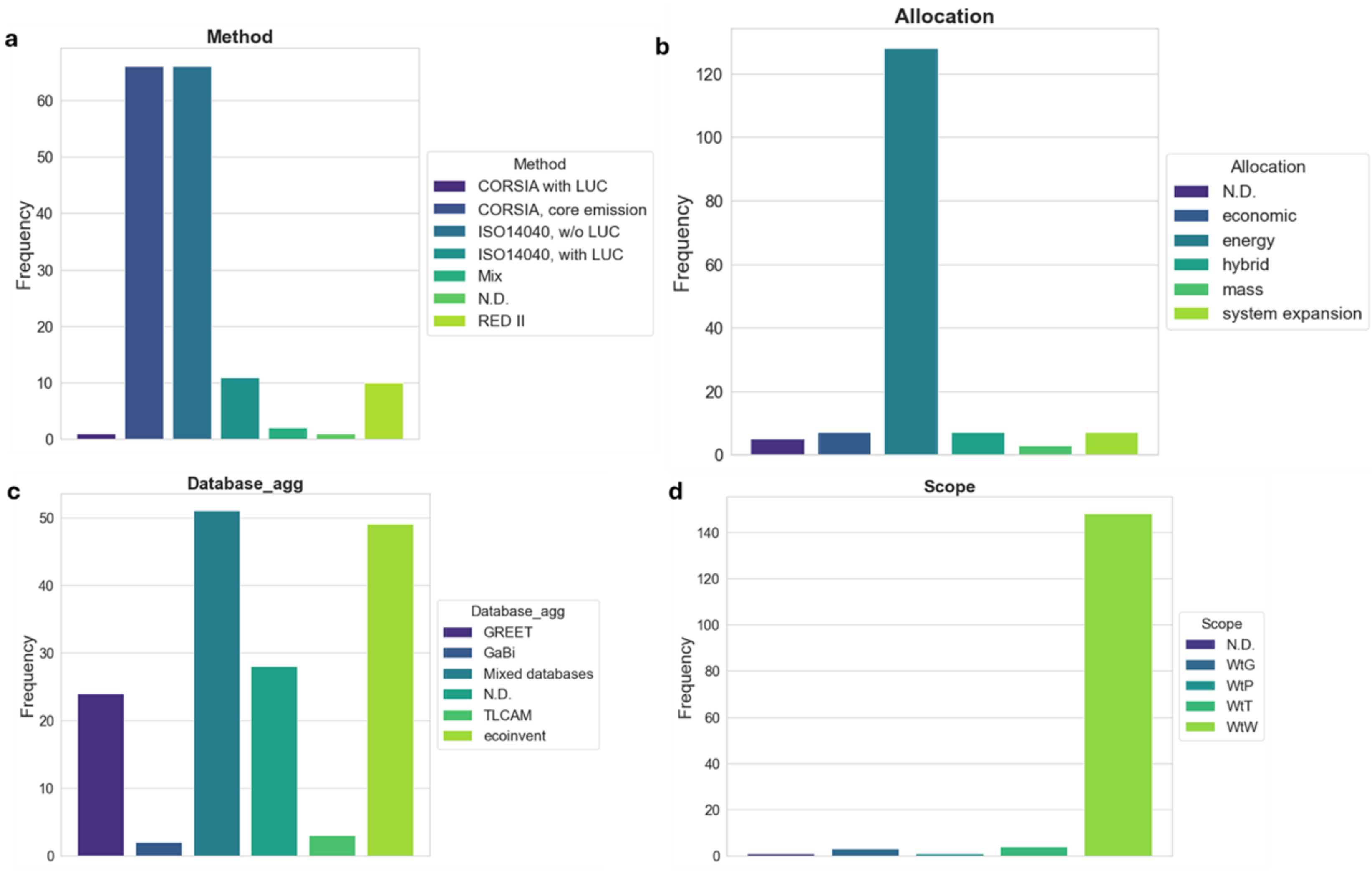
As **Figure 2** indicates, the screening of sustainability impacts differs in terms of scope and assumptions. Carbon accounting standards, allocation methods, choice of background databases, and scope of studies also varied across the different studies. In **Figure 2a**, we observe that most of the collected GHG intensities mention calculations according to 'CORSIA core emissions', i.e., accounting for well-to-wake (WtW) emissions without considering land use changes (either direct or indirect). A similar frequency of data is collected from studies mentioning only the use of LCA, without citing any specific method or standard. Because many publications either omit or exclude the emissions associated with land use change, all such data were aggregated in the 'ISO 14040 w/o land use change' category. Only a few studies[10,11] mention EU RED as the reference for further calculations. **Figure 2b** depicts the approach selected for distributing the LCA impacts among products and co-products, indicating **energy allocation** as the preferred method. This resonates with the CORSIA and EU RED approaches, which focus on the distribution of emissions according to the provision of energy as the main function of the product system. Also, this type of allocation is naturally connected to the unit selected to compare GHG intensity of SAFs, which is grams of CO_2 equivalents per megajoule (g CO_2eq MJ^{-1}).

Another factor influencing the GHG intensities of SAF is the background database, which provides a different pool of datasets to account for the impacts from upstream activities such as power generation, transport, materials, chemicals, and other services used by the biofuel plants. **Figure 2c** shows that the main database used is ecoinvent3, especially in studies assessing the environmental impacts of SAF in the European context. This finding was expected, as this background dataset provides a more detailed compilation of life cycle inventories representing European product systems, particularly those related to energy-intensive sectors. For other regions of the world, other databases used include GREET (in the United States), TLCAM (in China), GaBi, or a mix of the previous ones (using also E3 database in Europe).

In terms of scope (**Figure 2d**), we observe that most studies provide full coverage of SAF life-cycle impacts, i.e., from well-to-wake (WtW). This perspective aligns with most decarbonization policies and certification schemes, where GHG intensity should at least include impacts from biomass cultivation (or residues collection), transportation, conversion to SAF, distribution, and combustion.

Data collected in this report excluded SAF production considering the use of carbon capture and storage (CCS). Although GHG intensities can be negative when using CCS, the higher cost of the technology presents significant challenges for its implementation alongside SAF production in the near term. For this reason, data collection focused on the sustainability analysis of biofuel plants without this technology.

Figure 2: Profile of the data collected. Frequency of data reporting GHG intensities filtered by methodology (a), allocation (b), background database (c), and scope (d). N.D: not defined. WtG: well-to-gate. WtP: well-to-pump. WtT: well-to-tank. WtW: well-to-wake.



1.2 Review on GHG accounting methodologies: CORSIA and RED

CORSIA and the RED are two key frameworks designed to promote the adoption of SAF as a means of decarbonizing the aviation sector. While both aim to reduce GHG emissions from aviation, CORSIA focuses on international emissions, whereas RED applies to the EU. Despite their shared goal, the frameworks differ in their approaches to GHG accounting, sustainability criteria, and regulatory implementation. This section provides a comparative assessment of the methodological differences in GHG accounting between CORSIA and RED.

CORSIA defines SAF as a renewable or waste-derived aviation fuel that meets its sustainability criteria, which cover 14 themes, including carbon reduction, environmental protection, and socioeconomic sustainability. SAF is one of two CORSIA eligible fuels (CEF) that airlines can use to lower offsetting requirements, the other being CORSIA low carbon aviation fuels (LCAF), a fossil-based fuel with lower carbon intensity. For GHG reduction compliance, CORSIA allows operators to report SAF GHG savings using either default values or actual calculations based on the CORSIA methodology, verified by an approved Sustainability Certification Scheme (SCS)[5].

ReFuelEU Aviation, the EU regulation specifically for SAF adoption, defines SAF as synthetic aviation fuels, aviation biofuels, or recycled carbon aviation fuels in accordance with RED[7]. These fuels must comply with RED sustainability criteria for biomass production and GHG reduction, verified through national systems or European Commission-approved voluntary schemes. Synthetic aviation fuels are classified as 'renewable fuels of non-biological origin' (RFNBO), derived from renewable sources other than biomass. Aviation biofuels refer to 'advanced biofuels' produced from feedstocks listed in Part A of Annex IX, while recycled carbon fuels originate from waste streams and exhaust gases of non-renewable origin. RED allows operators to report SAF GHG savings using default values, actual calculations based on RED methodology, or a combination of both[6]. **Table 1** compares the two methodological frameworks for reporting SAF GHG emissions.

Table 1: Comparison of GHG Emission Accounting Methodologies in CORSIA and RED

	CORSIA	RED
Accounting methodology	Life cycle assessment (LCA)	Life cycle assessment (LCA)
System boundary	Well-to-wake	Well-to-wake
Calculation of GHG emissions	**L_{CEF} = core LCA value + ILUC - emission credits** Where, L_{CEF} is the **total emissions** from the CEF; **Core LCA value** is obtained by summing up emissions associated with the life cycle stages of: • **production at source** (e.g., feedstock cultivation); • **conditioning at source** (e.g., feedstock harvesting, collection, and recovery); • **feedstock processing** and extraction; • **feedstock transportation** to processing and fuel production facilities; • feedstock-to-fuel **conversion processes**; • fuel **transportation and distribution** to the blend point;	**$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr}$** Where, E is the **total emissions** from the use of the fuel; e_{ec} is the emissions from the extraction or **cultivation of raw materials**; e_l is the annualized emissions from carbon stock changes caused by **land-use change**; e_p is the emissions from **processing**; e_{td} = emissions from **transport and distribution**; e_u is the emissions from the **fuel in use** (considered zero for biofuels);

	• fuel **transportation** from the blending point to the aircraft uplift location; and • fuel **combustion** in an aircraft engine; **ILUC** (Induced land use change) is set as **default values** provided by ICAO or **zero** (for feedstocks with low land use change risk practices- waste, residues or by-products); and **emission credits** (optional to use), which are avoided landfill or recycling emission credits for CEF derived from municipal solid waste	e_{sca} is the emission savings from **soil carbon accumulation** via improved agricultural management; e_{ccs} is the emission savings from **CO_2 capture and geological storage**; and e_{ccr} is the emission savings from **CO_2 capture and replacement**
GHG accounting	Life-cycle stages until combustion: **Non-biogenic CO_2 = 1 CO_2eq** **CH_4 = 28 CO_2eq** **N_2O = 265 CO_2eq** (CO_2eq 100-year global warming potential values based on IPCC 5th assessment report) Combustion stage: only **non-biogenic CO_2**	**CO_2 = 1 CO_2eq** **CH_4 = 25 CO_2eq** **N_2O = 298 CO_2eq**
Units	grams of CO_2 equivalent per MJ of fuel (in terms of lower heating value), **g CO_2eq MJ^{-1}**	grams of CO_2 equivalent per MJ of fuel (in terms of lower heating value), **g CO_2eq MJ^{-1}**
Feedstocks	Classified as residues (agricultural, aquacultural, fisheries and forestry residues), wastes, by-products, and co-products, listed but not limited to the 'Positive List of Materials'	For advanced biofuels: feedstocks, listed in ANNEX IX Part A. For biofuels: Used cooking oil and Animal fats (ANNEX IX Part B)
Fossil fuel comparator	**89 g CO_2eq MJ^{-1}**	**94 g CO_2eq MJ^{-1}**
GHG emissions savings criteria for SAF	At least **10% reduction** compared to fossil baseline	At least **65% reduction** compared to fossil baseline (at least **70% reduction** for RFNBO)
Allocation of co-products	Emissions allocated based on the **energy content** (lower heating values) of the total energy	Emissions allocated based on the **energy content** (lower heating values) of the total energy

Both CORSIA and RED use a similar approach to calculating total GHG emissions for SAF, accounting for fuel life cycle emissions, land-use change emissions, and emission savings[6,9,12]. However, CORSIA, which focuses specifically on aviation under ICAO, provides more explicit default values for SAF pathways and their feedstocks. In contrast, RED, with a broader scope covering EU renewable energy, offers fewer default values for SAF.

For life cycle emissions, both adopt a well-to-wake LCA approach, covering all key stages—feedstock cultivation, fuel conversion, transportation, distribution, and aircraft use. However, they structure these elements differently: CORSIA groups life cycle emissions under 'core LCA value', while RED distributes them across components like 'e_{ec}', 'e_p', 'e_{td}' and 'e_u'. Additionally, the two methodologies differ in how they characterize GHG emissions, particularly in the CO_2eq values assigned to methane (CH_4) and dinitrogen monoxide (N_2O), which can result in varying GHG scores for the same emissions. CORSIA provides default core LCA values for six SAF pathways: Gasification FT fuel conversion, HEFA conversion, ATJ from isobutanol conversion, ATJ from ethanol conversion, synthesized iso-paraffins (SIP) conversion from hydroprocessed fermented sugars, and co-processing HEFA[13]. In contrast, RED lacks default life cycle emission values for any SAF pathway, requiring operators to apply the methodology to calculate the actual life cycle emissions only.

A key difference also lies in how land-use change emissions for feedstocks are accounted for. In CORSIA methodology, indirect land-use change impacts are captured under the 'ILUC' component, whereas RED uses the 'e_l' component to account for any direct or indirect land-use change impacts. CORSIA allows operators to use ICAO's default ILUC values, which vary based on the conversion pathway and sourcing region[13]. These values are set to zero for feedstocks with low land-use change risk, such as waste, residues, or by-products. In contrast, RED provides estimated default ILUC emission values only for three 'food and feed crops'—cereals and other starch-rich crops, sugars, and oil crops—while considering ILUC emissions as zero for all other feedstocks (as per Annex VIII of the directive)[14]. As a result, certain feedstocks, such as Miscanthus, may have different ILUC values under the two methodologies. For both frameworks, if feedstocks are sourced from land converted after the reference date of January 1, 2008, direct land-use change emissions, based on a similar carbon stock accounting approach, must be used. While the CORSIA methodology applies a 25-year amortization period for calculating DLUC emissions, RED uses a 20-year amortization period for the same purpose[12,14].

In addition to the main components, both frameworks include additional factors for calculating GHG savings from the SAF value chain. CORSIA includes the 'emission credits' component, which provides emission savings linked to avoided landfill or recycling emissions, specifically related to municipal solid waste feedstock. However, the use of emission credits is optional[12]. In contrast, RED includes the components 'e_{sca}', 'e_{ccs}' and 'e_{ccr}' which represent emission savings from soil carbon accumulation, CO_2 capture and geological storage, and CO_2 capture and replacement, respectively. These components in RED are not optional and account for savings from improved agricultural management practices (e.g., reduced or zero-tillage, improved crop rotation), additional savings from CO_2 capture and storage throughout the SAF value chain, and avoided emissions from CO_2 capture during SAF production, which can replace fossil-driven CO_2 in commercial products[6]. CORSIA does not directly mention provisions for reporting these savings.

Although both methodologies address similar feedstocks and their sustainability criteria, CORSIA categorizes them more explicitly into residues, wastes, by-products, and co-products. These are listed in the 'Positive List of Materials' outlined in the ICAO document 'CORSIA Methodology for Calculating Actual Life Cycle Emissions Values'[12]. In contrast, the feedstocks eligible for SAF production under RED are listed in Annex IX of the directive[14]**.** Both methodologies include feedstocks that are either currently in use or under discussion for SAF production, making these lists non-exhaustive. Furthermore, RED's Annex IX is reviewed biennially, allowing for the inclusion of new feedstocks as the SAF production landscape evolves.

While RED places a strong emphasis on waste and residue-based feedstocks, CORSIA takes a broader approach by allowing a wider range of feedstocks, provided they meet its sustainability criteria. RED prioritizes stringent GHG emissions savings thresholds, requiring at least 65% GHG savings (70% for RFNBO) compared to a fossil benchmark of 94 g CO_2eq MJ^{-1}. In contrast, CORSIA permits SAF with as little as 10% GHG savings against an 89 g CO_2eq MJ^{-1} baseline, as long as it complies with its broader sustainability requirements[5,12,14].

1.3 GHG intensities of SAF value chains: Analysis of location and feedstock categories

Figure 3 presents the main results of the data collection for GHG intensities, considering geographical locations and their relationship with different feedstock categories. As **Figure 3a** shows, the lowest values reported in the different locations are always related to waste and residues as the main feedstock, with forestry and agricultural residues being predominant. As previously discussed, most of the data were collected from case studies for SAF production in the United States, Netherlands, Brazil, Sweden, and studies at global and European scales. Data collected for SAF production in the United States cover the widest range of values. The lowest value of 1 g CO_2eq MJ^{-1} refers to SAF produced from wastes and residues[15], and the highest value (111 g CO_2eq MJ^{-1}) is related to SAF produced from microalgae through the fermentation pathway[16]. As mentioned earlier, such higher and lower emissions are not only influenced by the feedstock and the selection of conversion technologies; methodological choices related to the allocation of impacts and regional factors can also influence the results. For instance, the upper bound value is connected to the impacts from heat and power required by the biofuel plant. In the context of the U.S., natural gas is highly used for this purpose, which naturally contributes to an increase in the GHG intensity of SAFs.

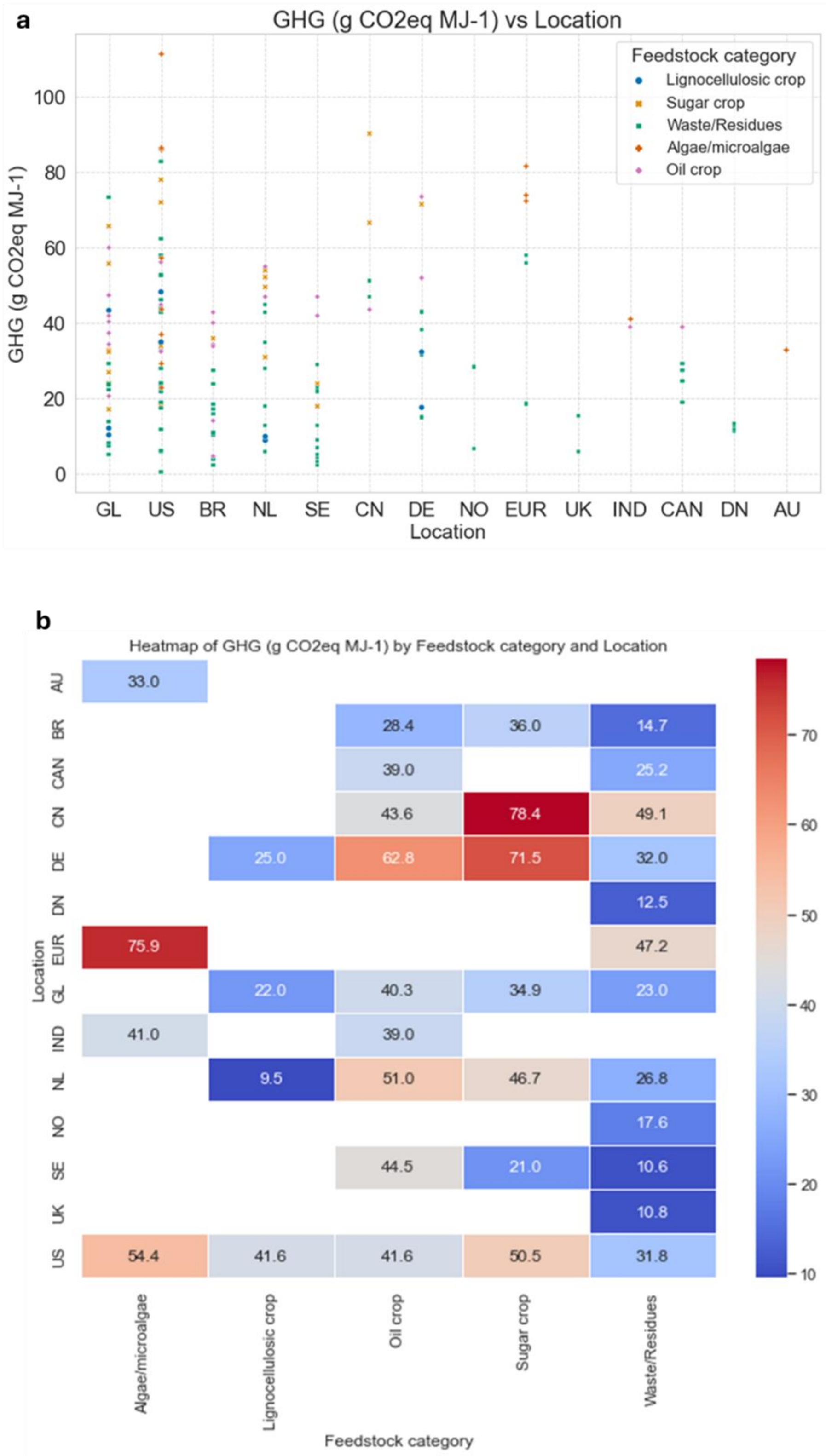
In the Netherlands, Brazil, and Sweden, the spectrum of GHG intensities in the data collected is narrower, ranging from 6-55 g CO_2eq MJ^{-1}, 2-43 g CO_2eq MJ^{-1}, and 3-47 g CO_2eq MJ^{-1}, respectively. In all these countries, the lowest emissions are associated with SAF produced from residues[10,17,18] and the highest emissions are associated with the use of oil crops primarily used to produce SAF through the HEFA process[17–19]. As shown in **Figure 3a**, this range of GHG intensities is below half of the benchmark value for fossil jet fuel (around 90 g CO_2eq MJ^{-1}), reflecting the lower energy consumption in their respective process designs and relatively cleaner energy mixes in those countries.

Figure 3b shows a heat map of GHG intensities when merging location and feedstock categories together. Although the values for carbon intensities were obtained under different methodologies and assumptions, this figure only intends to capture general trends and provide some indications of emissions patterns at the global level. The highest average GHG intensity of 78.4 g CO_2eq MJ^{-1} referred to the production of SAF from sugar crops in China. This result is mainly influenced by data collected from Wang et al. (2023)[20], whose reported GHG intensity of up to 90.2 g CO_{2eq} MJ^{-1} is highly dependent on the use of chemicals and energy inputs in an ethanol-to-jet biofuel plant processing corn. This result might be expected when considering the high carbon intensity of Chinese primary energy sources, which are heavily dependent on the use of fossil coal. Therefore, all energy-intensive sectors (including the production of chemicals) can be indirectly affected by higher greenhouse gas emissions in the upstream value chain.

The lowest aggregated value of SAF production (9.5 g CO_2eq MJ^{-1}) was associated with biofuel produced from lignocellulosic crops in the Netherlands[17]. Although the country's primary energy sources are still heavily dependent on fossil energy, lower emissions were related to the selected conversion pathway (gasification and use of syngas to produce SAF), which is commonly associated with very low emissions and low dependency on external inputs such as heat and electricity. Due to the importance of understanding the influence of conversion pathways on GHG intensities, a deeper analysis is included in this report.

Data aggregated at a global level[9] also shows a wider spectrum of emissions. The lower and upper bounds of GHG intensities were observed for the use of municipal solid waste (MSW) through gasification and the Fischer-Tropsch process. The difference was due to the assumption made for the non-biogenic carbon content in the study: 0% or 40%, producing SAF GHG intensities of 5 and 73 g CO_2eq MJ^{-1}, respectively. As stated earlier, this shows the influence of the assumptions made in the LCA study, which, in this case, included uncertainty regarding the sources of waste. In the case of higher rates of non-biogenic carbon in the MSW, such carbon emissions would be accounted for at the combustion stage of SAFs, thus increasing the footprint.

Figure 3: GHG intensities of SAFs across multiple regions. Data collected according to location and feedstock category (b) Aggregated data in a heat map representing average GHG intensities per location and feedstock category (values in g CO2eq MJ⁻¹).



In Germany, GHG intensities ranged from 15-74 g CO_2eq MJ^{-1}, with the lowest value attributed to the conversion of sewage slurry via HTL[21] and the upper bound to the use of jatropha oil via the HEFA process[22]. Although the use of renewable energy has been increasing constantly in the country since the 2010s, especially with the introduction of solar and wind power, renewable sources are still a minor contributor to the total primary energy consumption in the country. This scenario contributes to elevated emissions in conversion pathways that are more dependent on external heat and power, or the provision of goods and services strongly associated with energy-intensive sectors.

Additional data were collected from other countries such as Australia, Canada, India, Denmark, Norway, and the United Kingdom. Similarly to other regions of the world, the lowest emissions in this group of countries were associated with the use of wastes and residues as feedstock for SAF production. The lowest GHG intensities— around 6 g CO_2eq MJ^{-1}— were reported in studies for the conversion of forestry residues via gasification and FT synthesis in the United Kingdom[23] and Norway[24]. The highest emissions — around 40 g CO_2eq MJ^{-1} — were found in SAF production from canola oil in Canada[25]and jatropha oil in India[26], both produced via the HEFA process.

1.4 GHG intensities of SAF value chains: Analysis of conversion pathways

1.4.1 Gasification with Fischer-Tropsch synthesis (FT)

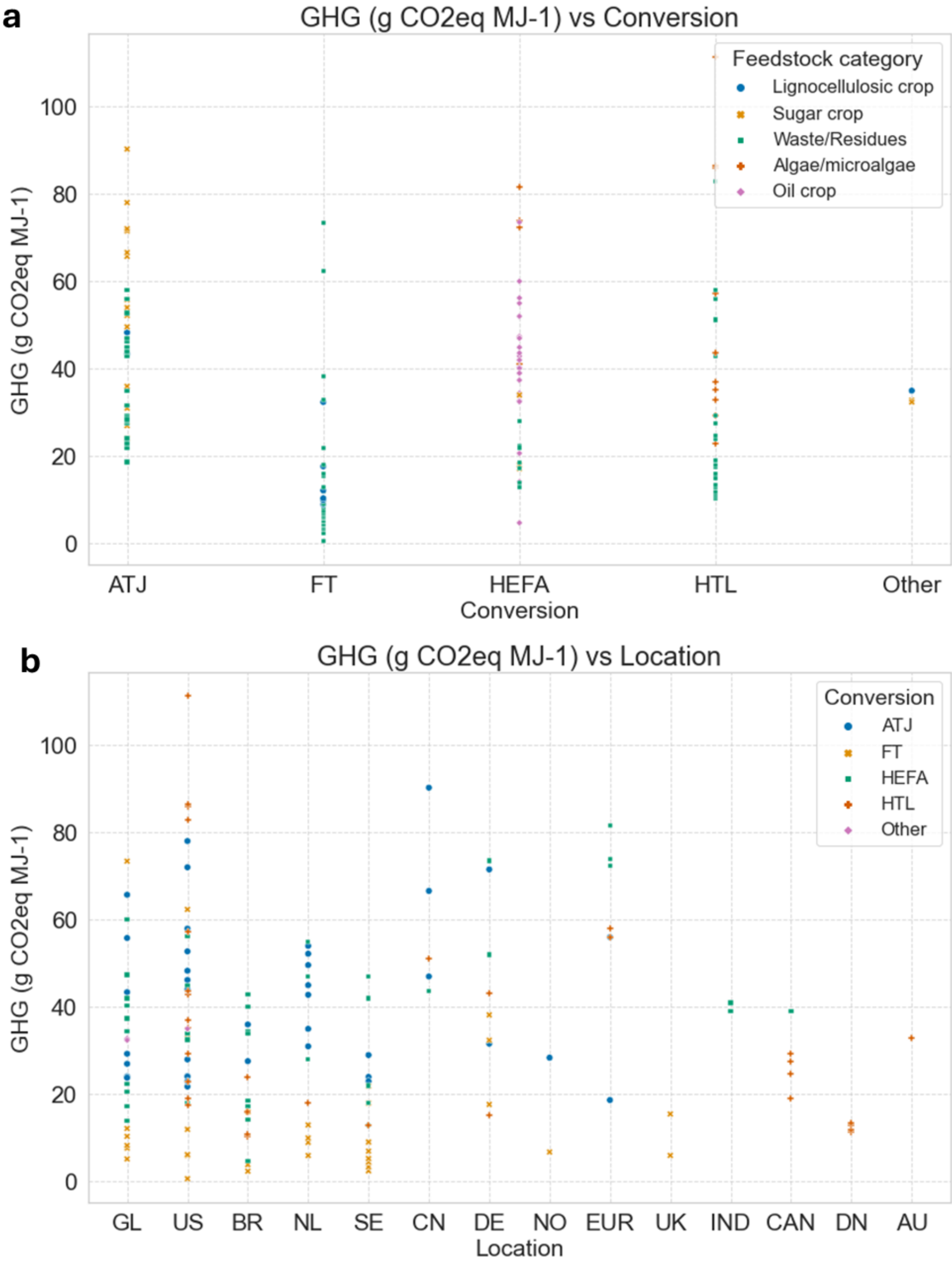
Among the data collected, gasification with Fischer-Tropsch synthesis is frequently the conversion pathway associated with the lowest emission values. As **Figure 4a** shows, most of the GHG intensities are concentrated in the range of 1-20 g CO_2eq MJ^{-1}, mainly associated with studies reporting waste and residues as the main feedstock used in the SAF production process. **Figure 4b** demonstrates that FT conversion is linked to the lowest emissions in almost all locations where such technology is considered in the data sample. For instance, gasification followed by Fischer-Tropsch synthesis in the U.S., Netherlands, Brazil, Sweden, Norway, and the U.K. has the lowest values compared to other conversion routes, except for Germany, where the best value is associated with HTL.

As stated before, the finding that the FT conversion is associated with the lowest GHG intensities was expected due to the high self-sufficiency of gasification plants in terms of energy demand. Unlike other processes, gasification plants can be self-sufficient in terms of heat supply, mostly obtained from the combustion of char and FT off-gases through a steam Rankine cycle or a combined cycle[27]. These effects are captured across the data collection in the literature, which frequently relies on results obtained from process simulations, whose energy and mass balances can represent more optimal situations and larger plant scales. Due to high energy self-sufficiency and lower dependency on chemicals for converting biomass into syngas and then biofuel, GHG intensities from the FT route are mainly influenced by the environmental impacts of biomass production. For instance, in **Figure 4a**, we observe that SAF from lignocellulosic crops – dependent on the impacts of biomass cultivation, harvest, and transport – can lead to slightly higher emissions (around 10 to 30 g CO_2eq MJ^{-1}) compared to agricultural and forestry residues (1-20 g CO_2eq MJ^{-1}), which, in turn, have emissions mostly associated with the collection and transport of biomass to the biofuel plant.

The highest GHG intensities from the FT process are observed for the conversion of MSW to SAF, especially when studies report non-biogenic carbon fractions of up to 40% (i.e., with high presence of plastics, rubber, and other synthetic materials in the municipal waste). In these cases, GHG intensities can be as high as 62 g CO_2eq MJ^{-1} [28] and 73 g CO_2eq MJ^{-1} [9]. This effect is expected since such non-biogenic (i.e., fossil) carbon will be present within fuel molecules, which will be further released during the combustion stage of SAFs.

Although the GHG intensity of FT conversion can be associated with potentially higher climate mitigation potentials across the studies in the literature, values vary considerably. The literature review highlights that the environmental performance of biofuels is always reliant on the biomass-to-fuel efficiency, as emissions and impacts can be offset when more biofuel is produced. Factors affecting biomass-to-fuel efficiency in Fischer-Tropsch are technology-specific and depend on the type of gasifier, syngas and cleaning efficiencies, selectivity of the FT catalyst, type of FT reaction, heat integration and electricity generation, among others[27]. The GHG intensity of SAF via the FT conversion route needs to be carefully assessed, always considering the specific process-design characteristics of the SAF gasification and Fischer-Tropsch synthesis.

Figure 4: GHG intensities of SAFs for multiple pathways: filtering by feedstock categories (a), and different locations (b).



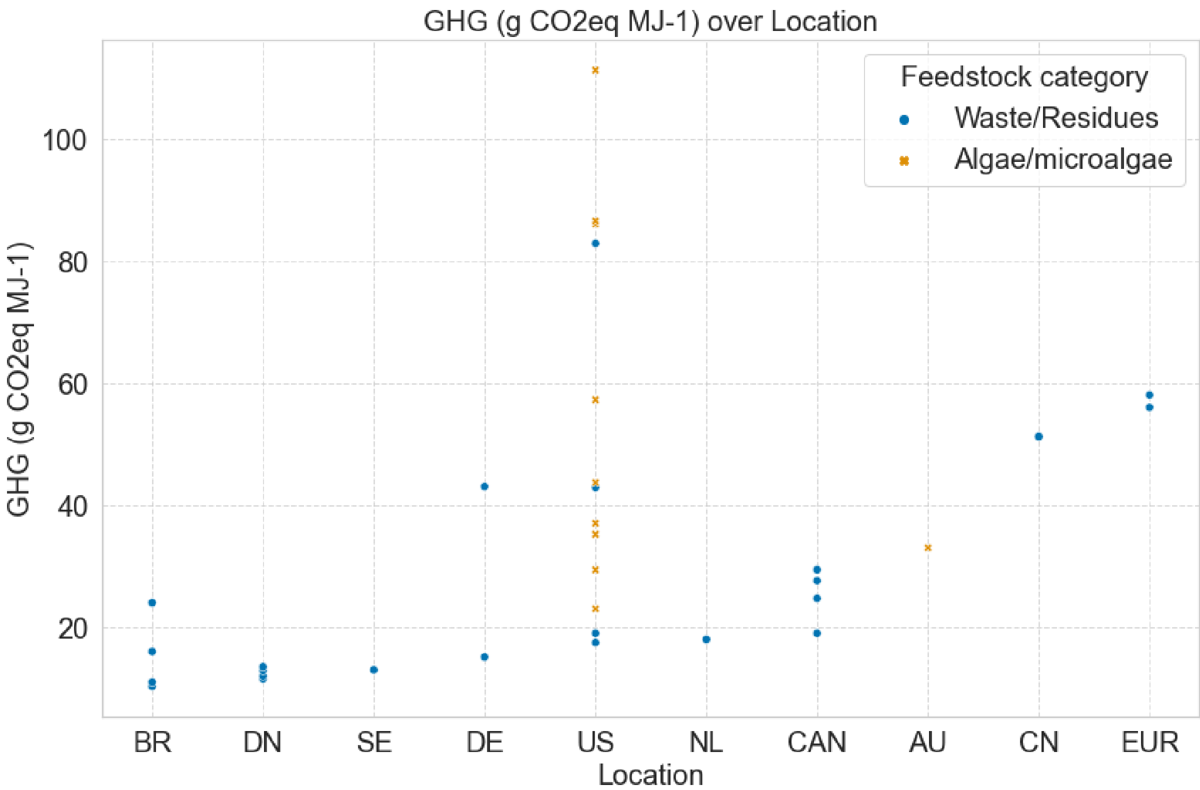
Another important remark from the literature review was the impact of feedstock on the overall GHG intensities. As previously shown, the gasification of materials with higher content of non-biogenic sources (such as municipal solid waste) can lead to SAF emissions very close to fossil jet emissions, whereas studies where FT is based on agricultural and forestry residues as the main feedstock were associated with the lowest emissions among all conversion routes.

In the ICARUS project, more specific analyses will be performed for SAF produced from syngas in Task 3.2. Based on data obtained from computational simulations and with the guidance of experiments carried out in WP2 for specific process-design, we plan to gain a deeper understanding of the main parameters affecting the environmental performances of syngas-to-SAF technologies. This will include identifying the main bottlenecks to decrease the environmental impacts, with a special focus on maximizing climate mitigation benefits. The focus on agricultural and forestry residues for the syngas-to-SAF value chain is also a strategic decision in line with the main findings of the literature review. Considering that the expected emissions from the feedstock are expected to be low, the analysis will increase its resolution by analysing possible improvements in the industrial conversion to test the influence of key steps such as gasification, gas cleaning, and FT catalysis on the final GHG intensity of SAFs, including other environmental impact categories.

1.4.2 Hydrothermal liquefaction (HTL)

Among the data collected for this report, hydrothermal liquefaction is associated with the second-lowest band of GHG intensities when compared to the other three conversion routes. The data collected shows HTL emissions in the range of 10-83 g CO_2eq MJ^{-1}. However, as **Figure 5** indicates, most of the data falls within the interval of 15-35 g CO_2eq MJ^{-1}, with GHG intensities frequently below 20 g CO_2eq MJ^{-1}. As observed for the FT route, HTL also benefits from the use of wastes and residues as the main feedstock, with the lowest value of 10 g CO_2eq MJ^{-1} associated with the use of forestry residues as the main feedstock in Brazil[18]. As shown in **Figure 5**, other countries associated with emissions below 20 g CO_2eq MJ^{-1} include biocrude oil-to-SAF produced from agricultural and forestry residues in Denmark, Sweden, Germany, the United States, the Netherlands, and Canada. It is also clear that most of the studies in the data sample refer to the waste and residues feedstock category, with algae and microalgae GHG intensities predominantly found in publications representing systems in the United States.

Figure 5: GHG intensities of HTL-based SAFs across multiple conversion locations and feedstock categories.



When compared to waste and residues, GHG intensities for the algae and microalgae category ranged from 23 to 111 g CO_2eq MJ^{-1}. The highest emissions were found in a study on biofuel production in the United States[16], where algae were cultivated in algal turf scrubber systems aimed at providing remediation to nutrient-rich surface waters, following the model of Hofmann et al. (2017)[29] for cultivating diatoms, green, and red algae. When analysing the well-to-gate emissions of 111 g CO_{2eq} MJ^{-1}, de Rose et al. (2019)[16] pointed out that more than half of these impacts came from the natural gas required for the plant's boiler and to generate heat for the drying algae step.

The lowest emission for the algae/microalgae category, 23 g CO_2eq MJ^{-1}, is described when modelling the environmental impacts of biofuel production via hydrothermal liquefaction of microalgae in the

U.S.[30]. The main difference from de Rose et al. (2019)[16] can be attributed to the minimization of natural gas usage in the HTL plant. This was achieved by transferring as much energy as possible from the aqueous waste stream to the feed. The biogas produced from the HTL gas phase and biocrude upgrading was fed back into the heating utility, leading to pronounced reductions in natural gas demand entering the HTL system boundary. Therefore, the final GHG intensity for the biofuel was much lower. Most of the emissions in the process were associated with the natural gas and electricity used in the conversion and biocrude upgrading steps.

The environmental performance of HTL is highly dependent on the heat and hydrogen sources for the SAF GHG intensity. Fortier et al. (2014)[31] analyzed the performance of an HTL biofuel plant attached to a wastewater treatment plant in the U.S. and estimated the overall emissions of bio-jet fuel produced from algae as 35 g CO_2eq MJ^{-1}. Their results were particularly sensitive to the extent of heat recycling in the plant, the source of heat for HTL (which could be either fossil or biogenic methane), and the solids content of dewatered algae. In this study, biocrude yield and life cycle emissions from hydrogen production also affected the results, but GHG intensities were less sensitive to these parameters.

Although algae and microalgae were associated with higher emissions when compared to the use of agricultural and forestry residues as feedstocks for HTL-based SAF production, the literature review shows that GHG intensities as low as 20 g CO_2eq MJ^{-1} can be achieved through this pathway. In ICARUS, the biocrude-to-oil value chains using microalgae will be assessed in detail to identify and quantify the bottlenecks of the technology. Therefore, solutions can be proposed to further reduce the environmental impacts of SAF production. As the literature shows, these improvements can be achieved, for instance, by lowering the demand for nutrients and fertilizers in microalgae cultivation. The environmental analysis to be carried out in **Task 3.2** will focus on this direction, including a thorough assessment of microalgae produced from wastewater, where most of the nutrients are already available for biomass growth.

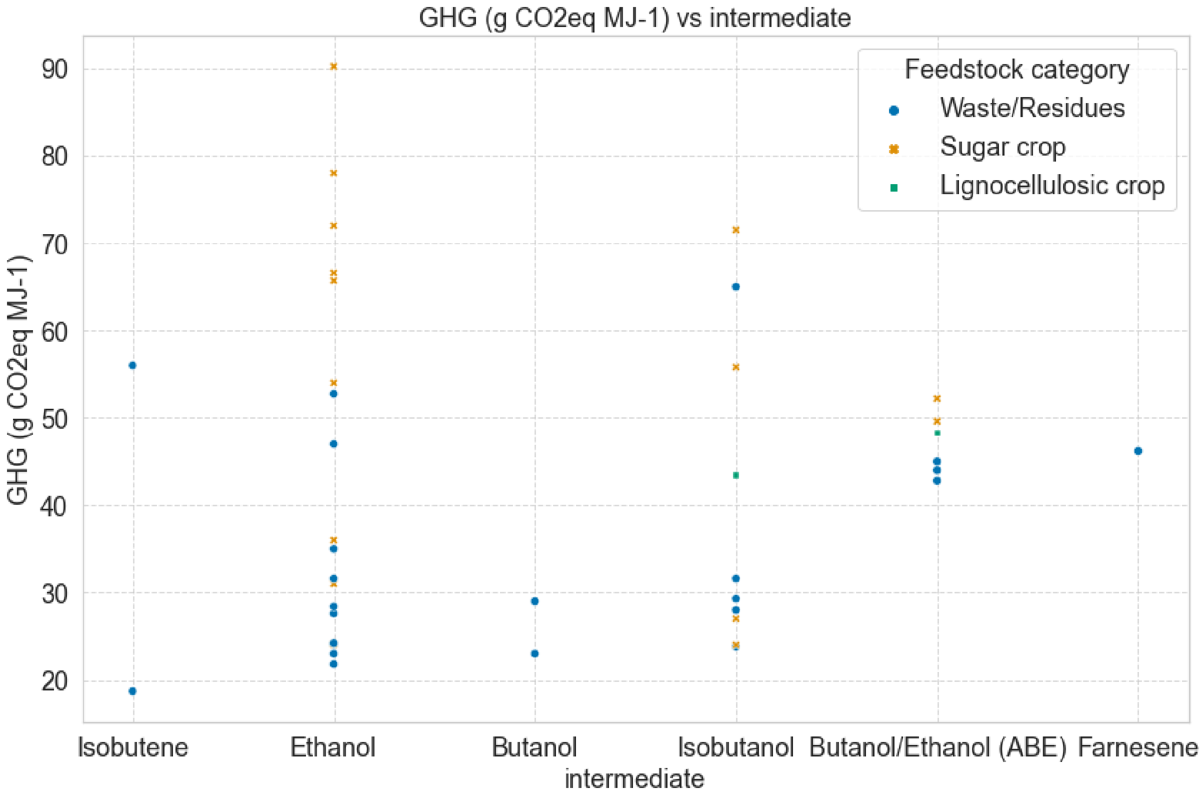
Although biocrude-to-SAF GHG intensities are frequently associated with slightly higher emissions than those obtained from syngas-to-SAF, the mitigation potential for the transport sector can be higher with HTL. This effect is related to the higher biomass-to-fuel conversion rates, i.e., more fuel output can be produced with the same amount of biomass when compared to FT. When scaling up this effect to a country or continent scale, it means that more biofuels can potentially be produced from the biomass, thus abating more emissions per year. This effect was mentioned, for instance, in the production of maritime biofuels from forestry residues in Norway, where multiple fuels are co-produced with a higher biomass-to-fuel conversion rate compared to the syngas-to-fuel pathway[32].

In general, the screening of carbon footprints indicates that the performance of SAF production via HTL is reliant on external inputs, notably the selection of fuel to supply heat in the plant and the hydrogen source for the biocrude upgrading. The possibility of minimizing the dependency on natural gas in the process has been a key point addressed in the publications. The impact of the hydrogen used in the upgrading step was also a relevant parameter contributing to the production of HTL advanced biofuels. Using green hydrogen sources, such as wind and solar, could lead to much lower impacts when compared to grey hydrogen sources, i.e., those produced from steam methane reforming.

1.4.3 Alcohol-to-jet (ATJ)

Figure 6 highlights the data collected for the ATJ conversion pathway. GHG intensities were aggregated into different intermediates (isobutanol, butanol, ethanol, farnesene, isobutene, or a mix of butanol and ethanol). Among the feedstocks used in this route, lignocellulosic crops, sugar crops (such as sugarcane, corn, wheat, cassava, and sugar beet), and waste/residues (primarily agricultural and forestry residues) are identified as the main ones. As observed in other conversion routes, emissions show a broad range, varying from 18 to 90g CO_2eq MJ^{-1}. Most of the SAF GHG intensities associated with wastes and residues fall between 20-45 g CO_2eq MJ^{-1}, with the highest emissions occurring when sugar crops are used as the main feedstock (ranging from 30-90 g CO_2eq MJ^{-1}). Data for lignocellulosic crops (such as switchgrass and herbaceous energy crops) were more limited, resulting in a narrower range of 43-48 g CO_2eq MJ^{-1}.

Figure 6: Results from literature screening of GHG intensities of ATJ-based SAFs across multiple intermediates and feedstock categories.



The lowest GHG intensity for a second-generation SAF process was reported by Puschnigg et al. (2023)[33], which converts softwood residues into fermentable sugars. The pentose fraction (C5 sugars) is fermented into isobutene using genetically engineered *E. coli*. In this biofuel plant configuration, SAF isoparaffins are produced alongside fertilizer and animal feed, which are credited as emissions offsets, reducing the total SAF GHG intensity. The study explored multiple scenarios, with emissions ranging from 18 to 56 g CO_2eq MJ^{-1}. The lower bound (18 g CO_2eq MJ^{-1}) corresponds to a biofuel plant where thermal energy is supplied by a lignin boiler, and electricity comes from renewable sources. In this scenario, approximately 50% of emissions were associated with pretreatment and enzymatic hydrolysis, which are more energy- and material-intensive than other stages. Auxiliary processes, including material transport, pumps, storage, blowers, and heat exchangers, accounted for around 20% of emissions. The higher emission scenario (56 g CO_2eq MJ^{-1}) reflects a plant using natural gas for heat and electricity, with lignin not utilized onsite. The emission breakdown remained consistent, with most GHG emissions attributed to wood-to-sugar conversion.

Wang et al. (2023)[20] reported the highest GHG intensity for the ATJ route (90 g CO_2eq MJ^{-1}), analyzing SAF production strategies using various feedstocks and ethanol as the main intermediate. This peak value was associated with corn grain feedstock in China, where ethanol is derived from starch hydrolysis and fermentation, followed by dehydration, oligomerization, hydrogenation, and distillation to jet fuel. Feedstock farming (35% of emissions) and hydrolysis/fermentation (35%) were significant contributors due to high diesel, fertilizer, and chemical use. The carbon intensity of upstream activities in China, reliant on coal, natural gas, and oil, also contributed. The lowest value (31.6 g CO_2eq MJ^{-1}) was for corn cob gasification-fermentation followed by ethanol-to-jet conversion, which consumed the least energy while generating surplus electricity.

In ICARUS **Task 3.2**, the environmental analysis will focus on SAF value chains based on isobutanol (iBuOH) as an intermediate. As shown in **Figure 6**, the best emission values range from 24–32 g CO_2eq MJ^{-1}. Prussi et al. (2021)[9] identified key factors influencing emissions, including feedstock transportation, co-location of facilities, net heat and enzyme demand for iBuOH fermentation, and final fuel transportation. The lowest value (24 g CO_2eq MJ^{-1}) was for SAF from sugarcane, with cultivation and collection contributing over 50% of emissions, followed by fuel conversion (20%). For corn grain (55.8 g CO_2eq MJ^{-1}) and herbaceous energy crops (43.4 g CO_2eq MJ^{-1}), conversion contributed over 50% of emissions, with cultivation contributing less than 30%. For agricultural and forestry residues (29 and 24 g CO_2eq MJ^{-1}, respectively), conversion accounted for 70% of life-cycle emissions.

Bhatt et al. (2023)[34] modelled ATJ emissions using isobutanol derived from agricultural and forestry residues in the U.S. Corn stover was pretreated to release sugars, followed by enzymatic hydrolysis and fermentation to produce isobutanol. Alcohol was then upgraded to jet fuel via catalytic dehydration and oligomerization. The resulting GHG intensity was 28 g CO_2eq MJ^{-1}, though the study did not provide a detailed emissions breakdown.

Neulin and Kaltschmitt (2018)[22] reported a similar GHG intensity (31 g CO_2eq MJ^{-1}) for iBuOH-to-kerosene conversion using wheat straw in Germany. Their process included steam explosion pretreatment, enzymatic hydrolysis, and fermentation, followed by isobutanol dehydration, oligomerization, and hydrogenation. Most emissions (50%) were attributed to wheat straw transportation, reflecting its low energy density. Optimization of transportation logistics could significantly reduce emissions.

However, some studies reported higher emissions for ATJ pathways using isobutanol. Vela-Garcia et al. (2020)[35] assessed biofuel production from corn stover in the U.S., where isobutanol was oligomerized and hydrogenated into triisobutane. The study estimated 65 g CO_2eq MJ^{-1}, using core emissions data for isobutanol production (58 g CO_2eq MJ^{-1}) from Tao et al. (2014)[36]. In the latter, corn stover emissions were primarily attributed to feedstock production and harvesting (~50%), conversion (~30%), and preprocessing (~15%). Burdens from farming were allocated to corn grain, with additional stover harvesting impacts assigned to the residues.

Neulin and Kaltschmitt (2018)[22] reported the highest ATJ GHG intensity (71 g CO_2eq MJ^{-1}) for kerosene produced from wheat grain. Farming contributed ~85% of emissions (60 g CO_2eq MJ^{-1}), reflecting the burdens of wheat cultivation. Although emissions were significantly higher than for straw-based SAF, the study highlighted a 35% reduction in jet fuel production costs when using wheat grain.

The ATJ pathway using isobutanol shows promise for GHG reductions compared to fossil jet fuel, with potential reductions up to 73% relative to the kerosene benchmark (89 g CO_2eq MJ^{-1})[9]. Agricultural residues are particularly effective for second-generation isobutanol, whereas sugar crops like corn and wheat grains result in higher emissions and are inconsistent with EU RED guidelines. Challenges remain in reducing the environmental burdens of hydrolysis and fermentation, which rely heavily on chemicals. Regional emissions from upstream materials and energy suppliers should align with low-carbon energy systems, such as renewable electricity from wind, solar, hydro, and biomass, to further improve sustainability.

1.5 Effects of direct and indirect land use change

A few studies examining the effects of direct and indirect land use change (LUC and ILUC) on GHG intensities are included in the LCA dataset collected. This focus aligns with the ICARUS project's emphasis on comparing conversion pathways and value chains that utilize waste streams, biomass residues, and intercropping systems to minimize the additional impacts from land use changes associated with SAF production.

Most studies addressing LUC and ILUC impacts focus on crop cultivation for producing oils, sugars, or starches used in biofuel production. For instance, Antony et al. (2024)[25] analysed canola production in Canada for SAF production via the HEFA pathway. Their findings reported life cycle GHG emissions without LUC and land management changes (LMC) ranging from 44–48 g CO_2eq MJ^{-1}. When including LUC and LMC, the values ranged from 16–58 g CO_2eq MJ^{-1}. Notably, LUC and LMC effects induced both increases and reductions in GHG intensities, varying by region due to differences in soil conditions, farming practices, and fertilizer use.

Pamula et al. (2021)[37] evaluated switchgrass conversion via the ATJ pathway using a novel acetone-butanol-ethanol (ABE) fermentation process to enhance n-butanol production. GHG intensities for SAF ranged from 44–61 g CO_2eq MJ^{-1}, depending on direct land use change scenarios, with emissions ranging from -3.9 to 13 g CO_2eq MJ^{-1}. These scenarios assumed switchgrass cultivation on existing farmland, based on Dunn et al. (2013)[38]. ILUC impacts were excluded due to methodological challenges.

Han et al. (2017)[39] assessed corn- and corn-stover-based ATJ pathways in the U.S., incorporating LUC impacts estimated using a consequential analysis with the GREET model[40,41] . The LUC emissions were reported as 8 and -0.7 g CO_2eq MJ^{-1} ethanol for corn and corn stover, respectively, assuming conventional tillage, 30% stover removal, and no organic matter input. Sensitivity analysis revealed ranges of 5 to 17 g CO_2eq MJ^{-1} for corn ethanol and -1.4 to -0.6 g CO_2eq MJ^{-1} for corn stover ethanol, reflecting variations in LUC estimates.

Neulin and Kaltschmitt (2018)[22] analyzed SAFs produced from various feedstocks (e.g., wheat straw, willow wood chips, jatropha, palm oil) and pathways (e.g., ATJ, biogas-to-liquid, HEFA). While LUC effects were not detailed for most pathways, uncertainties were noted for HEFA-based fuels, with LUC estimates around ±37 g CO_2eq MJ^{-1} for palm and jatropha cultivation. However, the study did not specify the methodology used to derive these values or why they were identical for both feedstocks.

Prussi et al. (2021)[9] compiled ILUC emission values under the CORSIA framework for various pathways and feedstocks. ILUC was described as resulting from interactions among commodity markets, agricultural and non-agricultural markets, and international trade. Using economic models (GTAP-BIO and GLOBIOM), default ILUC values for the ATJ pathway showed the highest emissions for U.S. corn (2 g CO_2eq MJ^{-1}) and the lowest for Miscanthus in the EU (-54 g CO_2eq MJ^{-1}). For FT-based SAFs, all feedstocks yielded negative ILUC values, ranging from -4 g CO_2eq MJ^{-1} for U.S. switchgrass to -33 g CO_2eq MJ^{-1} for EU Miscanthus. The HEFA pathway exhibited the highest ILUC emissions, with notable values for palm in Malaysia and Indonesia (39 g CO_2eq MJ^{-1}), soybean in Brazil (27 g CO_2eq MJ^{-1}), and rapeseed in Europe (24 g CO_2eq MJ^{-1}).

As observed, ILUC values span a wide range, from -54 to 39 g CO_2eq MJ^{-1}, influenced by differences in methodologies, models, and assumptions. This variability can significantly affect conclusions regarding SAFs' climate mitigation potential compared to fossil fuels. Given the uncertainties and complexities of modelling global cause-effect relationships, further analysis in **Task 3.2** will treat them as external variables in the life cycle assessment of biocrude-, syngas-, and alcohol-to-jet pathways. Moreover, ICARUS value chains will focus on the use of waste streams, residues and feedstocks with positive impact on the net carbon balance of SAF production systems.

1.6 Effects of SAF production on other impact categories

Table 2 presents the most relevant LCAs analyzing additional environmental impact categories for SAFs as reported in the literature. Cavalett and Cherubini (2018)[24] evaluated the potential implications of deploying forestry residue-based SAFs on multiple SDGs. Their study compared the ATJ and FT conversion pathways to the fossil fuel benchmark. While the GHG intensities of SAFs were significantly lower than those of fossil jet fuel, the authors highlighted that SAFs also outperformed fossil fuels in SDG 7 (Affordable and Clean Energy) and SDG 15 (Life on Land). These advantages were attributed to reduced reliance on non-renewable energy sources (e.g., diesel and coal) and a lower impact on land transformation and terrestrial ecosystems during biofuel production. However, the study also identified quantitative trade-offs associated with other SDGs that would require targeted technological and supply chain improvements to mitigate. For example, impacts related to terrestrial acidification, particulate matter formation, coal use, hazardous waste, and aquatic acidification in the ATJ pathway could be reduced compared to the fossil fuel benchmark if future advancements lead to lower chemical demand during biomass pretreatment and improved overall process efficiency.

Table 2: List of LCA studies reporting other impact categories for SAFs, in chronological order.

Feedstock	Conversion	List of impacts	Location	Authors
Pennycress	HEFA	Global warming potential, fossil energy use.	US	Fan et al., 2013
Algae	HTL	Global warming potential, fossil energy use.	US	Frank et al., 2013
Algae	HTL	Global warming potential, Fossil fuel use, eutrophication.	US	Mu et al., 2017
Corn	ATJ	Water consumption, fossil fuel use.	US	Han et al., 2017
Forestry residues	FT	Global warming potential, terrestrial acidification, terrestrial ecotoxicity, terrestrial eutrophication, human toxicity (cancer), human toxicity (non-cancer), particulate matter formation, freshwater eutrophication, water depletion index, freshwater ecotoxicity, non-renewable energy, fossil depletion, coal use, photochemical oxidant formation, ozone formation (human), bulk waste, ecological footprint, metal depletion, hazardous waste, marine eutrophication, marine aquatic ecotoxicity, aquatic acidification, ecosystems, ecosystems damage potential, land transformation.	NO	Cavalett and Cherubini, 2018
Switchgrass	FT	Global warming potential, water demand, land requirement.	DE	Schmidt et al., 2018
Palm oil	HEFA	Global warming potential, non-renewable energy, aquatic eutrophication, aquatic acidification, terrestrial acidification, ozone layer depletion, respiratory inorganics, human health, ecosystem quality, resources.	BR	Vasquez et al., 2019
Sugarcane	ATJ	Global warming potential, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, freshwater toxicity, marine toxicity, terrestrial toxicity, photochemical oxidant formation, particulate matter formation, and fossil fuel depletion.	BR	Capaz et al., 2021
Microalgae	HTL	Global warming potential, acidification, ecotoxicity, human health (carcinogenic and non-carcinogenic), ozone depletion, photochemical ozone formation, fossil fuel depletion, and respiratory effects.	US	Chen and Quinn, 2021
Forestry residues	FT	Global warming potential, stratospheric ozone depletion, ionizing radiation, ozone formation, human health, fine particulate matter formation, terrestrial ecosystems, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity, water consumption.	UK	Michaga et al., 2022
Corn stover	HTL	Global warming potential, acidification potential, eutrophication potential, fossil depletion potential.	EUR	Zoppi et al., 2023
Sugarcane residues	HTL	Global warming potential, ozone formation (human health), freshwater eutrophication, terrestrial ecotoxicity, land use, mineral resource scarcity, fossil resource scarcity.	BR	Deuber et al. 2023

Han et al. (2017)[39] assessed the ethanol-to-jet pathway using corn grain and corn stover in the U.S., comparing these feedstocks to fossil jet fuel in terms of GHG emissions, fossil fuel use, and water consumption. For water consumption, the impacts of SAF derived from corn stover were more than five times lower than those from corn grain. However, biofuels overall performed worse than fossil fuels in this category. The primary contributors to the higher water consumption impacts were enzymes, catalysts, and other chemicals used in the conversion process, which accounted for over half of the impacts. Conversely, SAFs demonstrated better performance in the global warming and fossil fuel use categories, largely due to their reduced reliance on non-renewable energy sources.

Michaga et al. (2022)[23] conducted a sustainability assessment of SAF production from forestry residues via the FT pathway in the U.K., evaluating impacts on climate, human health, biodiversity, and resource scarcity. SAFs outperformed fossil jet fuel in categories such as climate change, ozone depletion, and ionizing radiation. However, SAFs exhibited poorer environmental performance in categories like marine eutrophication, primarily due to nitrogen fertilizer consumption during forest cultivation. While many LCA studies do not allocate the environmental burdens of forest cultivation to residues, this study used a life cycle inventory from a background database that applied economic allocation to distribute forestry cultivation impacts to wood chips. As a result, the FT pathway showed lower performance in other environmental impact categories compared to the fossil reference.

Deuber et al. (2023)[42] analyzed HTL-based SAF production from sugarcane residues in Brazil, finding significantly lower impacts than fossil jet fuel in global warming, ozone formation, terrestrial ecotoxicity, and fossil resource scarcity categories. These advantages were primarily linked to lower impacts during the combustion stage. However, SAFs performed worse in the freshwater eutrophication category due to phosphorus-rich nutrient emissions reaching freshwater systems, a consequence of partially allocating sugarcane cultivation impacts to sugarcane bagasse. Similarly, Chenn and Quinn (2021)[30] identified trade-offs between global warming potential and other environmental categories for HTL-based fuel derived from microalgae. While the process reduced climate impacts, it increased impacts such as acidification, eutrophication, and ozone depletion. For eutrophication, the authors suggested that improving nutrient recycling to 90% during feedstock cultivation could reverse these trade-offs, making the biofuel more favourable compared to the fossil reference.

Zoppi et al. (2023)[8] evaluated the HTL pathway for converting corn stover and lignin-rich streams from a second-generation bioethanol plant into SAFs. The HTL plant design incorporated onsite hydrogen production via aqueous phase reforming (APR) and water electrolysis. The comparison of the HTL-APR system showed that while the GHG intensities of SAFs derived from corn stover and lignin-rich streams were similar, differences emerged in other impact categories. Fossil depletion potential was 20% higher for corn stover than the lignin-rich streams, primarily due to higher thermal power consumption linked to greater natural gas use. Acidification potential was also higher for corn stover, largely because of the increased replacement of the platinum catalyst in the APR system compared to lignin-rich streams. Eutrophication potential was similar for both feedstocks but slightly higher for lignin-rich streams due to increased impacts from wastewater treatment, which stemmed from higher chemical oxygen demand and total nitrogen in the wastewater.

The analysis of additional environmental impacts indicates that reductions in global warming potential (GHG intensity) and fossil fuel use are often associated with trade-offs in other categories, such as eutrophication and acidification. Since these results are heavily influenced by feedstock selection, conversion pathways, and methodological choices, tailor-made LCAs are essential to uncover the potentials and bottlenecks associated with different SDGs. To harmonize LCA methodologies across SAF value chains, **Task 3.2** will conduct customized analyses of the biocrude-to-SAF, syngas-to-SAF, and alcohol-to-jet pathways. This will allow more consistent approach to identify strengths and limitations specific to each value chain.

2 Final remarks

The screening of sustainability impacts revealed several important insights regarding SAF value chains. For the syngas-to-SAF pathway, FT conversion demonstrates potentially lower GHG intensities across studies in the literature and less dependency on external inputs for energy and heat production in the biofuel plant. Gasification of materials with higher non-biogenic content (e.g., municipal solid waste) can result in SAF emissions approaching those of fossil jet fuel, however, these values are less frequent in the literature. Conversely, studies using agricultural and forestry residues as the primary feedstock for FT conversion reported the lowest emissions among all conversion routes.

The GHG intensities of SAF production via the biocrude oil-to-SAF pathway are heavily influenced by external inputs, both the type of fuel used for plant heating and the hydrogen source for biocrude upgrading. Reducing dependence on natural gas has been a key focus in research. The hydrogen source significantly affects HTL biofuel production, with green hydrogen from renewable sources like wind or solar energy offering much lower environmental impacts compared to grey hydrogen derived from steam methane reforming. While biocrude-to-SAF processes typically exhibit slightly higher GHG emissions than syngas-to-SAF, HTL has the potential of providing greater climate mitigation for the transport sector due to its higher biomass-to-fuel conversion efficiency, on average. This efficiency allows more biofuel to be produced from the same biomass, enabling higher emissions reductions at larger scales, such as country or continent-wide implementations.

The ATJ pathway, particularly using isobutanol, shows considerable potential for reducing GHG intensity compared to fossil jet fuel, with reductions exceeding 70% relative to fossil kerosene. These reductions are especially notable when second-generation feedstocks like agricultural residues are used to produce isobutanol. However, the environmental impacts of hydrolysis and fermentation processes remain a key challenge for second-generation alcohol intermediates due to their reliance on chemical inputs. Addressing these challenges will require integrating upstream material and energy supply chains with low-carbon energy systems, such as renewable electricity from wind, solar, hydro, or biomass.

Our analysis highlights significant uncertainty in LUC and ILUC values due to variations in methodologies, econometric models, and analytical assumptions. Given the substantial uncertainties and the complexity of modelling global cause-effect relationships, our further analyses in ICARUS will focus more on the evaluation core environmental impacts of biocrude-, syngas-, and alcohol-to-jet conversion pathways, instead of exploring parametrization of these relationships.

Analyses of other environmental categories reveal that reductions in SAF GHG intensity often involve trade-offs in other impacts such as eutrophication and acidification. These outcomes are heavily influenced by feedstock selection, conversion pathways, and methodological approaches. To better understand the specific potentials and challenges associated with different SDGs, customized LCAs for SAFs are crucial. **Task 3.2** will perform tailored analyses of the biocrude-to-SAF, syngas-to-SAF, and ATJ pathways to identify the strengths and limitations of each technology in terms of assessing the impacts on other SDGs.

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