

Energy–environmental nexus in green hydrogen-assisted conversion of second-crop canola to sustainable aviation fuel: Toward low-carbon bioenergy systems

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ABSTRACT

Aviation fuel remains the main cost and environmental burden in air transport. This study presents a well-to-wake life cycle assessment (LCA) of canola-based Sustainable Aviation Fuel (SAF) under tropical conditions, based on primary data from Brazilian producers. The analysis encompasses agricultural, pre-processing, and conversion stages via the hydroprocessed esters and fatty acids (HEFA) pathway, revealing the potential of second-crop canola for low-carbon aviation. The study integrates process modeling, renewable hydrogen, and land-use efficiency to capture drivers across stages. The ReCiPe method was applied to 1 MJ of biokerosene as the functional unit. Agriculture dominates GHG emissions (34.2 g CO₂ eq. MJ⁻¹), driven primarily by fertilizer production and soil N₂O emissions, while the HEFA phase contributes 12.8 g CO₂ eq. MJ⁻¹. Substituting fossil hydrogen with photovoltaic- and wind-based hydrogen for in HEFA upgrading reduces emissions by 92 to 96.6%, resulting in up to 19.6% lower total life-cycle emissions. Compared to Jet-A1, SAF decreases fossil depletion by 59% and achieves climate benefits; however, it entails higher burdens in selected non-climate impact categories. Freshwater and marine eutrophication reach approximately 0.01 g P eq. MJ⁻¹ and 0.7 g N eq. MJ⁻¹, respectively, while human toxicity is above 1 g 1,4-DB eq. MJ⁻¹, with the agricultural stage accounting for over 90% of these impacts, particularly fertilizer production and use. Land occupation (0.074 m² yr MJ⁻¹) is optimized through canola soybean rotation, mitigating deforestation risks. The findings demonstrate canola's strategic role in Brazil's decarbonization policies, highlighting the need for improved fertilizer management and renewable hydrogen integration to advance SAF.

Index summary

| Nomenclature | | LUC | Land use change |
|--------------|--|-----|-----------------|
| AP | Acidification Potential | N | Nitrogen |
| ASTM | American Society for Testing and Materials | NOx | Nitrogen Oxides |

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| | | | |
|-----|----------------------------|-------------------------------|----------------------|
| BOD | Biological Oxygen Demand | NO ₂ | Nitrous oxide |
| BR | Brazil | OtJ | Oil-to-Jet |
| CCS | Carbon Capture and Storage | P | Phosphorus |
| CED | Cumulative Energy Demand | P ₂ O ₄ | Phosphorus tetroxide |

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|------------------|---|-----------------|---|
| CH ₄ | Methane | PM2.5 | Particulate Matter <2.5 μm |
| CO ₂ | Carbon Dioxide | RoW | Rest of World |
| COD | Chemical Oxygen Demand | SAF | Sustainable Aviation Fuel |
| CONAB | Companhia Nacional de Abastecimento | SDG | Sustainable Development Goal |
| CORSIA | Carbon Offsetting and Reduction Scheme for International Aviation | SICV | Sistema de Inventário do Ciclo de Vida |
| Cu | Copper | SM | Supplementary Material |
| DOC | Dissolved Organic Carbon | SMR | Steam Methane Reforming |
| EP | Eutrophication Potential | SOx | Sulfur Oxides |
| FED | Fossil Energy Demand | SO ₂ | Sulfur Dioxide |
| GHG | Greenhouse Gas | SPK | Synthetic Paraffinic Kerosene |
| GLO | Global | TOC | Total Organic Carbon |
| GWP | Global Warming Potential | VOC | Volatile Organic Compounds |
| H ₂ | Hydrogen | WTT | Well-to-Tank |
| HEFA | Hydroprocessed Esters and Fatty Acids | WTW | Well-to-Wheels |
| HRJ | Hydroprocessed Renewable Jet | Symbols | |
| IATA | International Air Transport Association | ρ | Density |
| ICAO | International Civil Aviation Organization | E | Energy |
| K ₂ O | Potassium oxide | LHV | Lower Heating Value |
| LCA | Life Cycle Assessment | V | Volume |
| LPG | Liquefied petroleum gas | | |

1. Introduction

The aviation sector has expanded rapidly in recent decades, driving global trade and economic growth [1,2]. Despite improvements in aircraft efficiency, it remains a major source of greenhouse gas (GHG) emissions [1], with aviation fuel representing the sector's largest operational cost and environmental burden [3]. In response, international bodies such as the International Air Transport Association (IATA) and the International Civil Aviation Organization (ICAO) have set targets for a 1.5% annual fuel efficiency gain, emissions stabilization from 2020, and a 50% reduction in net emissions by 2050 relative to 2005 levels [4–6]. Supporting these goals, ICAO implemented the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which regulates CO₂ emissions and certifies eligible alternative fuels [7–10]. Within this context, sustainable aviation fuels (SAFs) have emerged as a key strategy to meet regulatory and climate targets, while supporting broader global agendas such as the Sustainable Development Goals (SDGs) [11].

Among current SAF production routes, oil-to-jet (OtJ) pathways, particularly hydroprocessed esters and fatty acids (HEFA), are the most mature [9,12]. HEFA converts lipid-rich feedstocks into hydroprocessed renewable jet (HRJ) fuel, a type of synthetic paraffinic kerosene (SPK), which must be blended with conventional jet fuel (10 to 50%) per ASTM D7566 [4,9,13–16]. Despite technical feasibility, high production costs and environmental impacts comparable to fossil-based fuels limit large-scale adoption. Recent studies have shown that SAF optimization must balance cost, emissions, and supply risks, highlighting the need for integrated environmental and economic approaches [17].

A promising innovation involves integrating green hydrogen into the HEFA pathway to enhance environmental performance. Hydrogen is essential for the hydrodeoxygenation process, but conventional sources, mainly steam methane reforming, emit significant GHGs [18,19]. Green hydrogen, produced via electrolysis using wind or solar power, could substantially reduce emissions [20]. Brazil's abundant renewable energy resources make it a promising hub for green hydrogen, reducing emissions within the national SAF supply chain [21].

HEFA-compatible feedstocks include soybean, palm, jatropha,

camelina, pennycress, canola, and animal fats, offering flexibility across different agricultural contexts [9,12,22,23]. Canola (*Brassica napus*) is the third most-produced vegetable oil globally, accounting for around 16% of global output [24,25]. In Brazil, cultivation is concentrated in the South, with a projected yield of 1459 kg ha⁻¹ for 2025 and a reported area of 131,100 ha [26]. Field data from Brazil's southern region during the 2022–2023 harvests indicate yields up to 2115 kg ha⁻¹, highlighting the canola crop's potential. Although canola is traditionally a temperate-climate crop grown as a second-season option, recent trials in the Midwest suggest potential for tropical adaptation [27,28]. Reported yields vary widely across regions and species, ranging from 238 to 483 kg ha⁻¹ for *Brassica juncea* in northern Paraná [29], up to 3001 kg ha⁻¹ for *Brassica napus* under irrigation in Brazil's Midwest region [30], and reaching similar levels in the South under favorable conditions [31]. These findings highlight the sensitivity of off-season canola to temperature and water availability and reinforce the limitations of using average national data for international comparisons.

Assessing the environmental performance of SAF production in Brazil requires a comprehensive Life Cycle Assessment (LCA), which captures environmental impacts across the entire production chain, from raw material extraction to fuel utilization [32,33]. While bio-kerosene production from canola holds considerable potential, research in Brazil remains scarce, particularly regarding environmental impacts. Existing studies on oilseed-based SAFs typically emphasize feedstock selection [3,34] and refining technologies [35], with limited attention to canola. Although SAF is increasingly recognized as a key strategy for decreasing aviation, most LCA focus on conventional crops like soybean and palm oil [16,36]. In contrast, canola despite its global relevance and increasing interest as a rotational or second-crop feedstock, has received comparatively little attention in the Brazilian context. Table 1 summarizes LCA studies for SAF derived from oil-based feedstocks, revealing that canola has received limited attention, with few studies evaluating greenhouse gas emissions, land use, and the integration of low-carbon hydrogen within the HEFA pathway.

Beyond the limited number of studies, Table 1 highlights substantial heterogeneity across SAF LCAs in terms of feedstock selection, system boundaries, software platforms, methodological approaches, and reported impact metrics, which limits cross study comparability and leaves important gaps for canola based SAF in Brazil. Notably, no previous study provides a fully documented well-to-wake assessment of second crop canola SAF under Brazilian tropical conditions integrating primary agricultural data and conversion stage decarbonization strategies within a consistent methodological framework. To address this gap, this study evaluates canola (*Brassica napus*) as a second crop feedstock through a well-to-wake life cycle assessment conducted in Sphera LCA for Experts, applying the ReCiPe midpoint (H) method across multiple impact categories. The assessment is based on primary data for agricultural production and pre-processing and explicitly documents system boundaries and inventory assumptions along the HEFA pathway. In addition, renewable hydrogen is evaluated within HEFA upgrading, and results are interpreted in a policy relevant context aligned with *RenovaBio* [38–40] the Brazilian Fuel of Future Law (Law n° 14.993/2024), and CORSIA.

2. Life cycle assessment

2.1. Goal and scope

This study performed an attributional Life Cycle Assessment (A-LCA) to evaluate the environmental performance of SAF produced from canola via the HEFA pathway in Brazil. The assessment considered two regional contexts (current production in the South and prospective expansion in the Midwest, Fig. 1(a)) and compared the resulting SAF to fossil-based Jet-A1 across three blending scenarios (100% Jet-A1, 50% SAF blend, and 100% SAF). The analysis also considered different hydrogen sources for HEFA conversion, including fossil-based (gray)

Table 1

Summary of life cycle assessment studies on sustainable aviation fuel production using the Hydroprocessed Esters and Fatty Acids process.

| Feedstock | Software, methodology and impact categories | Reported impact results for SAF | Contributions | Ref. |
|--|--|--|--|------|
| Canola (<i>Brassica napus</i>) | Software: SimaPro Method: IPCC 2013 System Boundaries: Farm-to-fly (cultivation, oil extraction, HEFA conversion, distribution, fuel use) Impact Categories: GHG, CED and FED | GHG: -10 to 55 g CO ₂ eq./MJ CED: 1.4–1.6 MJ/MJ ^d FED: 0.38–0.43 MJ/MJ ^d | Investigates life cycle GHG emissions, energy demands, and impacts of canola-derived jet fuel; Highlights soil carbon sequestration benefits and GHG reductions from replacing fallow with canola; Suggests HEFA coproducts for hydrogen production. | [37] |
| Palm, macauba, soybean oils | Software: SimaPro Method: ReCiPe Midpoint System Boundaries: Cradle-to-gate assessment covering oil crop production, oil extraction, and conversion to renewable jet fuel Impact Categories: Climate change, Fossil depletion, Human toxicity, Terrestrial acidification, Agricultural land occupation | Climate change: 16.9–22.3 g CO ₂ eq./MJ Other impact categories: NR (reported only comparatively) | Compares HEFA, FT, and ATJ routes for RJF production in Brazilian sugarcane biorefineries; HEFA routes have the highest RJF production potential; FT routes have the best economic indices; LCA and techno-economic analysis, providing valuable insights for policy and decision-making in RJF. | [16] |
| Palm, macauba, soybean oils | Software: SimaPro (used for life-cycle inventory aggregation) Method: Water footprint (green, blue, gray); no LCIA midpoint method applied System Boundaries: Cradle-to-grave (cultivation, oil extraction, HEFA conversion, transportation, fuel use); rainfed cultivation (no irrigation); energy-based allocation Impact Categories: Water footprint (green, blue, gray) | Total WF ^c : 131–143 m ³ /GJ Green WF ^f : 89.5–94.3 m ³ /GJ Blue WF ^g : 4–6 m ³ /GJ Gray WF ^h : 37–44 m ³ /GJ | Cradle-to-grave life cycle of rapeseed-derived HEFA jet fuel; Environmental benefits of rapeseed in crop rotation with wheat to enhance soil quality and reduce nitrate leaching; Comprehensive water footprint analysis (water usage) and crop rotation benefits. | [36] |
| Pennycress (<i>Thlaspi arvense</i>) | Software: Open LCA Method: TRACI | GWP: 35–49 kg CO ₂ eq./GJ AP: 0.45–0.65 | Higher energy efficiency for pennycress-based | [22] |

Table 1 (continued)

| Feedstock | Software, methodology and impact categories | Reported impact results for SAF | Contributions | Ref. |
|-----------|---|---|--|------|
| | System Boundaries: Well-to-biorefinery gate (cultivation, oil extraction, HEFA-HRJ conversion); energy-based allocation Impact Categories: GWP ⁱ , AP ^j , EP ^k , OD ^l , POF ^m | kg SO ₂ eq./GJ EP: 0.7–1.0 kg N eq./GJ OD: 1.7–2.3 × 10 ⁻⁶ kg CFC-11 eq./GJ POF: 1.5–2.2 kg O ₃ eq./GJ | HRJ compared to other oilseeds; Lower GWP and AP compared to conventional jet fuel and other oilseed-based HRJ; Fertilization is the main contributor to the impact; Efficient nutrient management for impact reduction. | |

a Greenhouse Gas Emissions.

b Cumulative energy demand.

c Fossil Energy Demand.

^d MJ/MJ: Amount of cumulative or fossil energy required to produce 1 MJ of SAF.

e Water Footprint.

f Green WF: rainwater evapotranspired during cultivation.

g Blue WF: surface and groundwater consumed across the life cycle.

h Gray WF: freshwater required to assimilate N and P emissions.

i Global Warming Potential.

j Acidification Potential.

k Eutrophication Potential.

l Ozone Depletion.

m Photochemical Ozone Formation.

NR was used when absolute values were not reported in the original studies.

and renewable (green) H₂ derived from solar and wind electricity, according to each scenario (Fig. 1(b)).

2.1.1. Functional unit and system boundaries

The functional unit adopted in this study is 1 MJ of fuel used to power an aircraft, enabling consistent comparison across the three fuel scenarios (Section 2.5). This unit is used in fuel-related LCAs and enables normalization across fuels with different densities and heating values [18,41].

The system boundary follows a well-to-wake (WTW) configuration, consistent with CORSIA guidelines [23], and includes all stages from raw material extraction to fuel combustion in aircraft engines. The analysis covers five phases: (i) canola cultivation, (ii) oil extraction and refining, (iii) biokerosene conversion via HEFA (including different H₂ sources), (iv) inter-stage transportation, and (v) fuel use. Emissions from both direct and indirect land use change (dLUC and iLUC) were not considered; however, land use occupation is captured as an impact category through the applied life cycle impact assessment method (ReCiPe). This structure depicts the full flow of materials and energy, supporting comprehensive environmental accounting. The system configuration is shown in Fig. 1(c).

2.2. Life cycle impact assessment (LCIA)

The LCIA followed ISO14040 and 14044 [42] and was modeled using Sphera's LCA for Experts (v.10.9.1.17) with Ecoinvent v3.11. The ReCiPe (H) midpoint method was applied due to its broad adoption [18, 43,44], compatibility with LCA tools, and inclusion of land use occupation as an area time demand indicator [43,45]. The impact categories assessed in this study included climate change (g CO₂ eq.), fossil depletion (g oil eq.), metal depletion (g Cu eq.), freshwater consumption (L), freshwater eutrophication (g P eq.), marine eutrophication (g N eq.), fine particulate matter formation (g PM_{2.5} eq.), photochemical ozone formation (ecosystems and human health) (g NO_x eq.), terrestrial

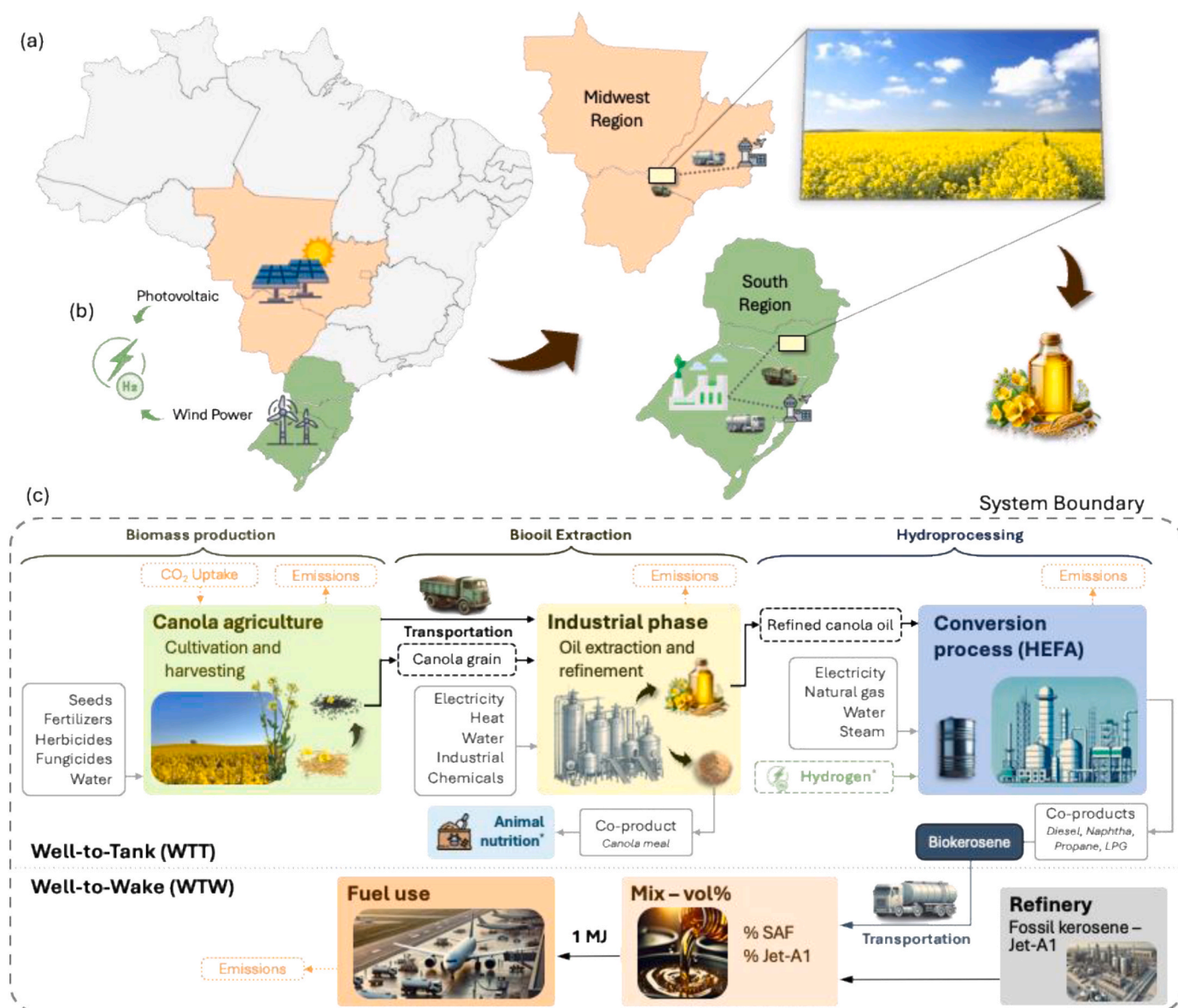


Fig. 1. (a) Map of Brazil highlighting current canola production areas in the Southern region, along with potential expansion zones in other regions, particularly the Midwest. (b) The potential use of wind power and photovoltaic energy sources for hydrogen production. (c) Well-to-wake (WTW) life cycle system boundaries for the functional unit of 1 MJ of produced fuel.

acidification (g SO₂ eq.), stratospheric ozone depletion (g CFC-11 eq.), freshwater ecotoxicity (g 1.4-DB eq.), human toxicity (cancer and non-cancer) (g 1.4-DB eq.), marine ecotoxicity (g 1.4-DB eq.), terrestrial ecotoxicity (g 1.4-DB eq.), ionizing radiation (Bq Co-60 eq.), and land use (annual crop (m² eq. y⁻¹)) based on the ReCiPe methodology [18].

2.3. Life cycle inventory - LCI

Data sources included primary data and secondary data from literature and reports, supplemented by Ecoinvent v3.11 and Sphera databases. Primary data for the agricultural and oil extraction phases were obtained directly from producers and a canola oil processing company (Celena Alimentos), in collaboration with the Brazilian Agricultural Research Corporation (Embrapa Agroenergia).

To ensure consistency and completeness in the LCA, flow selection was based on Ecoinvent market activities to represent average supply mixes and associated transportation between supply chain processes, using country-specific or regionalized datasets for Brazil when available. This choice provides a pragmatic approximation of current background

supply chains within a well-to-wake attributional LCA. It does not represent a site-specific configuration, nor does it involve facility location or supply chain optimization [46].

Fig. 1(c) presents the overall study framework and system boundary, whereas Fig. 2 provides a more detailed representation of the foreground production chain and associated inventory flows up to HEFA conversion. A basket symbol indicates market flows. Processes sourced from the Sphera and Ecoinvent databases are marked with corresponding icons. Table S1–S20 provide detailed inventory data and supporting information for each phase, normalized to relevant inputs or outputs.

2.3.1. Agricultural phase

The LCI for the agricultural phase (Fig. 2(a)) is presented in Table S1 of the SM, with considerations and assumptions provided in Table S2. This includes the references used to estimate direct field emissions, such as GHGs and heavy metals, based on literature.

The LCI was developed using a productivity value of 2115 kg ha⁻¹, representing average yields reported by producers in Rio Grande do Sul

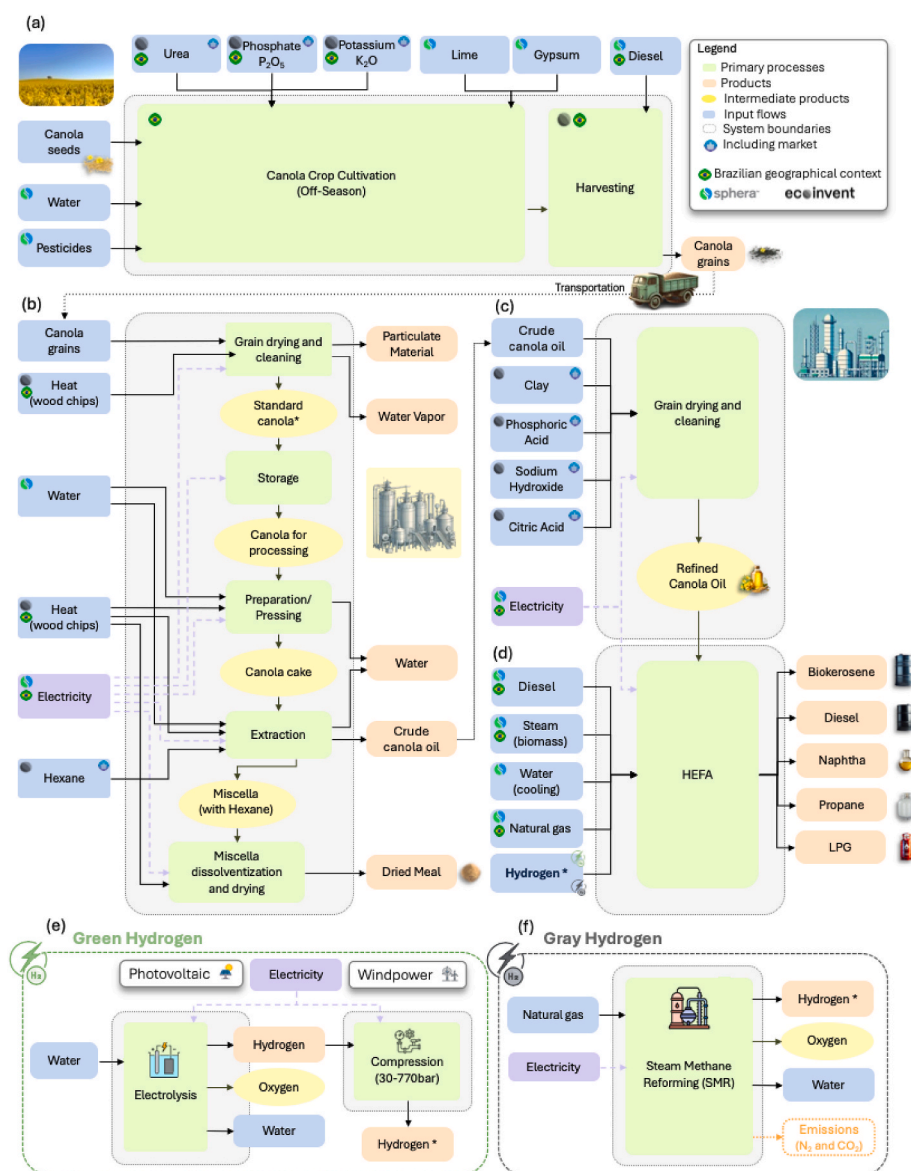


Fig. 2. The technological model of (a) canola production during the off-season, with transport to (b) the industrial phase of canola oil extraction, (c) the refining of oil, and (d) sustainable aviation fuel production via the HEFA pathway, representing the production chain up to fuel conversion. (e) Green hydrogen production via electrolysis powered by renewable electricity (photovoltaic and wind), adapted from Vásquez et al. [19]. (f) Gray hydrogen production through Steam Methane Reforming (SMR) using natural gas, based on Capaz et al. [18]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and Paraná during the 2022–2023 seasons.

The oil content adopted in this study corresponds to 0.34 kg of crude oil per kg of canola seed processed, reflecting industrial extraction efficiencies consistent with reported oil contents for canola seeds [47].

Tables S1–S3 document the agricultural inventory up to the farm gate, including field inputs and operations (Table S1–S2) and the harvesting step (Table S3). Table S4–S8 report background inventories for auxiliary materials used in downstream stages, particularly oil extraction and refining. Table S9 reports the background market inventory for urea production, while its field application is accounted for within the agricultural inventory. The agricultural inventory is defined up to the farm gate, providing the foreground basis for subsequent industrial and refining stages.

2.3.2. Oil extraction and refining

Table S10–11 present the LCI for the canola oil extraction (Fig. 2(b)) and refinement of crude canola oil (Fig. 2(c)), normalized for the

processing of 1 kg of canola grain and 1 MJ of fuel under the different SAF blending scenarios. Data were primarily literature-based [19], supplemented by the Ecoinvent and Sphera databases. The mass yield from crude to refined oil was assumed to be 0.977 kg of refined oil per kg of crude oil, corresponding to 1000 kg of refined oil per 1024.1 kg of crude oil processed, which implies approximately 2.3% mass losses during refining due to removal of impurities and minor components. Table S12–13 provide data for the cogeneration (heat and power) and Jet-A1 fuel, adapted from global and regional databases. Whenever possible, processes were selected to reflect the Brazilian context, as indicated by the Brazilian flag in Fig. 2.

2.3.3. HEFA conversion and H₂ supply

The HEFA pathway was modeled based on the conversion of refined canola oil into multiple fuel products, including SAF, green diesel, naphtha, propane, and liquefied petroleum gas (LPG). The process is illustrated in Fig. 2(d), while Table S14 of the Supplementary Material

(SM) reports the life cycle inventory data associated with the HEFA conversion stage. Based on the reference inventory adopted from Vásquez et al. [19], the production of 1 ton of biokerosene requires 2024.29 kg of refined canola oil and 80.97 kg of hydrogen for hydrodeoxygenation and hydrocracking reactions. Expressed in normalized terms, this corresponds to a biokerosene yield of 0.494 kg SAF per kg of refined oil and a hydrogen demand of 0.040 kg H₂ per kg of processed refined oil (equivalent to 0.081 kg H₂ per kg of SAF produced). Based on the adopted HEFA life cycle inventory, producing 1 kg of SAF requires 2.02 kg of refined oil and 0.081 kg of H₂, and yields 0.472 kg of green diesel, 0.142 kg of naphtha, 0.085 kg of propane, and 0.0551 kg of LPG as co-products. Combining extraction, refining, and HEFA conversion yields results in an overall SAF yield of approximately 0.164 kg per kg of canola seed processed.

Although several studies have assessed HEFA jet fuel production from canola or rapeseed oils [48], publicly available literature providing process-level life cycle inventories with sufficient detail for transparent and reproducible LCA modeling remains limited [49]. For this reason, the LCI for canola oil refining and the HEFA conversion stage were constructed using soybean data due to technological similarities, a practice also adopted in previous studies [21].

However, this assumption introduces uncertainty, as differences in the fatty acid profile between canola and soybean oils, particularly in terms of saturation level and average oxygen removal requirement, may influence hydrogen consumption during hydrodeoxygenation and hydrocracking. These inventories were further complemented with data from Ecoinvent and Sphera databases. Therefore, the results related to hydrogen demand in the HEFA step should be interpreted considering this limitation, and the development of canola-specific HEFA inventories is identified as a key priority for future research.

Hydrogen is the key input in the HEFA pathway, essential for hydrodeoxygenation and hydrocracking. Two supply routes were considered due to their distinct environmental profiles: gray hydrogen (Fig. 2(e)), produced via steam methane reforming of natural gas [18], and green hydrogen (Fig. 2(f)), generated through electrolysis [19] powered by wind or solar energy [20,50]. For gray hydrogen, compression and distribution requirements are implicitly included in the adopted SMR life cycle inventory, which represents centralized industrial hydrogen supply and does not model compression as a separate unit operation [18]. For green hydrogen, compression was modeled explicitly following the structure of the reference dataset [19], representing a conservative upper-bound assumption for electricity demand. Hydrogen supply was modeled using background life cycle inventories and was treated as an external input to the HEFA process in all scenarios; no on-site hydrogen generation was assumed. For the Brazilian context, the fossil-based hydrogen inventory was adapted from Capaz et al. [18], and additional scenarios modeled green hydrogen via electrolysis based on Vásquez et al. [19]. Renewable electricity sources included photovoltaic and wind power, with inventories detailed in Table S15–S17.

2.3.4. Transportation and distribution

Transportation within life cycle stages was included in the LCI. 200 km was assumed from agricultural sites to industrial facilities, where oil extraction, refining, and HEFA conversion are co-located. From the conversion plant to airport refueling, 250 km was adopted, being the average proximity to major international terminals. Transport relied on diesel fueled Euro 6 trucks (28–32 t gross weight, 22 t payload), considering the effectiveness of this standard in reducing regulated emissions and aligning with stringent international policies on vehicular pollution control [51].

For fuel use, a 65 t payload aircraft was chosen based on international SAF policies, with a default 2500 km operational distance (Sphera LCA model), adjusted for potential emission factors of aircraft engines operating on SAF (Table S18) using data from the literature [18,52,53]. Mass losses during transport and blending operations were not considered. Table S19 details the LCI for a cargo plane operating over a 2500

km payload, considering fuel blending scenarios.

2.4. Allocation and Co-product handling

To clarify the allocation procedure, the industrial phase includes both oil extraction and refining (Fig. 1(c)), which yields two coproducts: crude canola oil and canola meal. As oil extraction is the main driver of upstream activities, impacts from agriculture and extraction were initially partitioned between the two outputs based on energy content, with crude oil receiving 53.98% of the allocation.

Energy-based allocation was adopted at the oil extraction stage to ensure methodological consistency with the functional unit defined in energy terms (1 MJ of aviation fuel) and with the overall fuel-oriented system boundaries of the study. This approach aligns with regulatory life cycle assessment frameworks such as RenovaBio, which allocates impacts among coproducts based on lower heating values (LHVs) under a well-to-wheel attributional perspective [54]. While mass-based allocation is commonly applied in oilseed crushing when coproducts are primarily treated as food or feed commodities [55], the present study models the system from an energy carrier perspective, where energy content better reflects the functional role of outputs within the biofuel value chain. In accordance with ISO 14044, the allocation procedure was selected based on the goal and scope definition of the study, and the same energy-based principle was consistently maintained at the HEFA conversion stage for hydrocarbon coproducts to avoid internal methodological inconsistencies [56].

The refined oil then enters the HEFA conversion stage, which yields several fuel components, including biokerosene (SAF), green diesel, naphtha, propane, and LPG. Among these, biokerosene accounts for 56.83% of the total energy content and was used as the basis for allocating the impacts of all upstream processes, including agriculture, processing, and conversion. Although the term “biorefinery” is often used to describe the full biomass-to-fuel chain, this study refers to the HEFA conversion as a distinct process. This segmentation is consistent with conventional practices in the petroleum industry, where extraction, refining, and fuel production are treated as distinct stages. Additional information on allocation procedures is provided in Table S20 in the SM.

2.5. System scenario modeling

System scenarios were modeled covering the agricultural, industrial, and refining phases of SAF production from canola via the HEFA pathway. Three configurations were assessed based on a functional unit of 1 MJ of fuel: (i) the benchmark scenario used 100% fossil Jet-A1, including market activity and combustion emissions under the Brazilian context; (ii) the blend scenario consisted of a 50:50 volumetric mix of SAF and Jet-A1, in line with CORSIA guidelines, which allow up to 50% SAF in international flights due to its compatibility with conventional aircraft engines [7,23]; and (iii) the 100% SAF scenario, although not yet ASTM-certified [13], was included to assess maximum substitution potential and reflects successful test flights, with those conducted by Embraer in Brazil [57]. All scenarios incorporated regional conditions and hydrogen sourcing. Due to differing densities and heating values, a 50:50 volume-based mixture was calculated (Eq. (1)) to deliver 1 MJ of energy for the blend scenario.

$$V = \frac{E_{blend}}{\frac{1}{LHV_{SAF} \times \rho_{SAF}} + \frac{1}{LHV_{Jet} \times \rho_{Jet}}} \quad (1)$$

Here, LHV_{SAF} and LHV_{Jet} are the lower heating values of SAF-HEFA (44.21 MJ kg⁻¹ [58]) and Jet-A1 (44.10 MJ kg⁻¹); $\rho_{SAF} = 757.5$ kg m⁻³ and $\rho_{Jet} = 800$ kg m⁻³ are their densities; and E_{blend} is the target energy of the blend, in this case, 1 MJ. This resulted in equal volumes of 1.45×10^{-5} m³ for SAF and Jet-A1, contributing 0.487 MJ and 0.513 MJ, totaling 1 MJ of blended fuel.

3. Results and discussion

The LCA findings are presented in four parts: product and coproduct distribution under mass and energy partitioning bases (Section 3.1), environmental impacts (Section 3.2), emissions by life cycle stage (Section 3.3), and a policy context discussion (Section 3.4).

3.1. Product and coproduct distribution in canola-derived SAF production

This section presents the distribution of the main product and

coproduct streams along the canola derived SAF (biokerosene) production chain via the HEFA pathway, highlighting key inventory flows of water, electricity, and biomass that support the subsequent allocation of environmental burdens. Fig. 3 shows the Sankey diagram to visualize coproduct distribution and the partitioning basis. Distinct outcomes are observed depending on the partitioning basis: mass-based partitioning (kg) assigns a larger share to coproducts such as canola meal, whereas energy-based partitioning (MJ) assigns greater importance to energy dense streams such as canola oil and SAF.

Fig. 3(a) illustrates the mass-based partitioning across the canola-

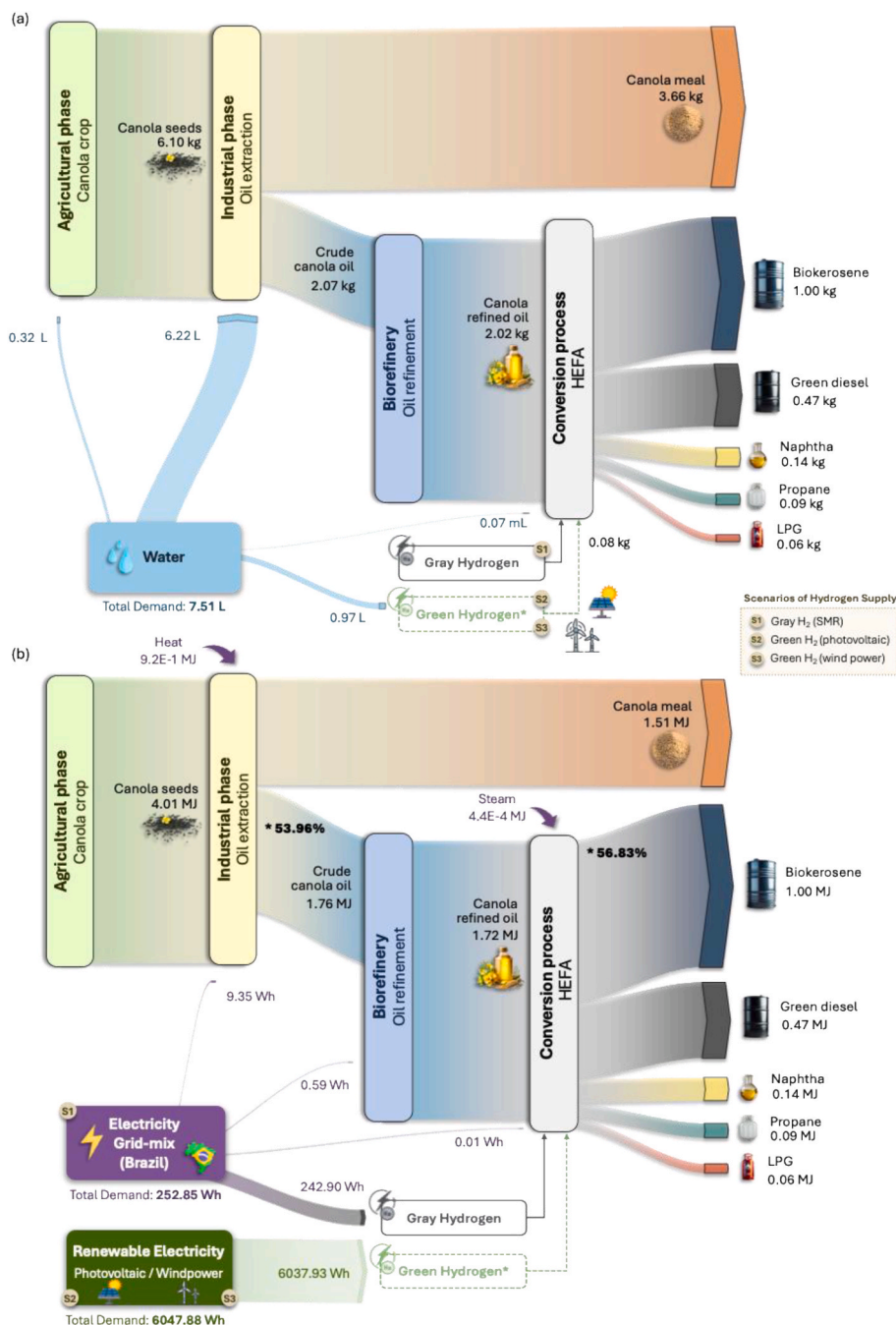


Fig. 3. Sankey diagram illustrating the mass and energy balance for the distribution of coproducts in the HEFA-biokerosene production process and the distribution of coproducts across the main process stages: agriculture, oil extraction and refining, and HEFA conversion. (a) Mass-based allocation to produce 1 kg of biokerosene, including water demand (L), hydrogen consumption, and the associated electricity requirements for green hydrogen production via electrolysis, highlighting their role in the hydroprocessing stage. (b) Energy-based allocation to produce 1 MJ of biokerosene (SAF), emphasizing the contribution of electricity supplied by the Brazilian grid mix and renewable electricity sources considered in the hydrogen supply scenarios. See Table S2–S19 for detailed LCI flows. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

derived SAF production chain. Mass based partitioning is presented here solely to illustrate material flows in the Sankey diagram, whereas the allocation applied to impact results throughout the LCA is energy based, as defined in Section 2.4. To produce 1 kg of SAF, 6.10 kg of canola seeds are required. During oil extraction, 2.07 kg of crude canola oil and 3.66 kg of canola meal are generated, highlighting the importance of coproduct handling. After refining, 2.02 kg of oil enters the HEFA process, which yields multiple outputs, including SAF, green diesel, naphtha, propane, and LPG. This flow demonstrates the system's complexity and underlines the need for partitioning strategies based on mass or energy content.

Freshwater demand, as reported in Fig. 3(a), varies significantly by production stage and is presented as an inventory input distributed across subprocesses. In the agricultural phase, water use is minimal, estimated at 0.32 L per kg of SAF (relative to 5.22×10^{-2} L MJ⁻¹), and primarily associated with pesticide dilution, typically 200 L ha⁻¹ per application, repeated up to four times per season. Notably, canola in Brazil is cultivated as a second-season crop, relying on residual rainfall and grown without irrigation, especially in expansion regions like the Cerrado. This reinforces the context-specific nature of water inputs in the LCI.

As shown in Fig. 3(a), the total freshwater demand is 7.51 L per kg of SAF. This demand is largely attributed to the oil extraction stage, which requires 6.22 L per kg of SAF (1.41×10^{-1} L MJ⁻¹) for cooling and steam preconditioning and thus represents the major share of the system's total water requirement [59]. Electrolysis for green H₂ supply contributes 0.97 L per kg of SAF (2.20×10^{-2} L MJ⁻¹), while water use during oil refining and HEFA conversion is comparatively minor (0.18 L kg⁻¹). Although the industrial phase is water-intensive, these processes do not generate contaminated effluents, and opportunities for water reuse have been identified, supporting further environmental improvements. These values are reported as inventory inputs in Fig. 3(a), rather than as a closed water balance with explicit outflows.

Fig. 3(b) illustrates the energy flows, highlighting electricity, heat, and steam demands across stages. As with water use in Fig. 3(a), energy consumption is concentrated in oil extraction, which requires 9.3×10^{-3} kWh per MJ of SAF, accounting for 94% of the system's grid electricity use. This high energy requirement for crude oil extraction stems from mechanical pressing, solvent recovery, and thermal conditioning, which are necessary to optimize oil yield. Refining consumes 5.9×10^{-2} kWh per MJ of SAF (5.9%), and the HEFA process uses 9.0×10^{-6} kWh MJ⁻¹ (0.1%).

Another energy demand outside the Brazilian electricity grid mix is the heat provided during the crude oil extraction phase (0.92 MJ), supplied by heat and power co-generation using wood chips. Additionally, process steam generated from biomass is used to supply heat during the HEFA conversion phase (4.36×10^{-4} MJ). The reliance on dedicated woodchip biomass has been increasingly replaced by the utilization of agro-industrial and forestry residues, an approach that has shown promise in reducing the environmental impacts associated with this stage of the process and may serve as a viable solution for improving the sustainability of future implementations [60–63].

Electrolysis energy demand is not included in the Brazilian grid mix, as green H₂ production in the country primarily relies on surplus renewable energy, contributing to environmental sustainability and system decarbonization [64]. The electrolysis process requires 1.37E01 kWh per MJ of SAF, with electricity sourced directly from photovoltaic or wind power.

Overall, Fig. 3 provides a compact view of the distribution of the main product and coproduct streams and selected inventory inputs under the adopted partitioning bases. Auxiliary process flows and emission exchanges are reported in full in the SM and are discussed in Sections 3.2 and 3.3, where environmental impacts and stage-wise emissions are analyzed.

3.2. Environmental impacts

Fig. 4 illustrates the potential environmental impacts associated with HEFA-biokerosene fuel production, as characterized by the ReCiPe method, revealing significant contributions across categories such as ecosystem quality (Section 3.2.1), air pollution (Section 3.2.2), toxicity and radiation (Section 3.2.3), and land use (Section 3.2.4). Notably, specific phases of the production chain emerged as dominant contributors to certain impact categories (detailed in Section 3.3), underscoring critical hotspots in system. A comprehensive breakdown of these contributions is presented in Table S21 and S22, enabling a deep interpretation of sustainability trade-offs.

3.2.1. Ecosystem quality

Fig. 4(a) shows the impact category of Ecosystem Quality, including Climate Change, Marine Eutrophication, Freshwater Eutrophication, Freshwater Consumption, Metal and Fossil Depletion. Regarding Climate Change, it is possible to observe that using a 50% SAF blend, the maximum allowed by ASTM, results in a 20.2% reduction in GHG emissions (70.14 g CO₂ eq.) compared to 100% Jet A-1 (87.90 g CO₂ eq.).

To contextualize these climate change results, the Brazilian second-crop canola HEFA pathway was compared with the CORSIA default value for HEFA from oilseed crops. The CORSIA default carbon intensity for canola-derived HEFA produced in North America is reported as 15.40 g CO₂ eq. for the feedstock production stage [7], with total default pathway values reflecting standardized assumptions. The results obtained in the present study demonstrate that the integration of renewable hydrogen and region-specific agricultural data allows the Brazilian system to achieve competitive or lower life-cycle emissions relative to international benchmark assumptions, highlighting the potential sustainability advantage of localized production conditions.

In the hypothetical scenario using 100% SAF, emissions would further decrease to 51.51 g CO₂ eq., corresponding to a 41.4% reduction. These values exceed the minimum 10% reduction threshold established by CORSIA for eligible SAF.

While SAF delivers substantial climate benefits, it increases several midpoint impact categories associated with agricultural inputs compared to Jet A-1. Freshwater Eutrophication rises from 6.83×10^{-5} to 1.15×10^{-2} g P eq. MJ⁻¹, and Marine Eutrophication from 1.18×10^{-3} to 7.24×10^{-1} g N eq. MJ⁻¹ when shifting from Jet A-1 to 100% SAF, representing increases of approximately two orders of magnitude. These increases are primarily driven by fertilizer production and field emissions during the canola cultivation stage, which dominates the overall contribution to these categories. A similar trend is observed for Human Toxicity (cancer effects), which increases from 2.95×10^{-2} to 1.12 g 1,4-DB eq. MJ⁻¹, approximately 38 times higher for 100% SAF. As with eutrophication, upstream agricultural processes account for the majority of this impact.

Therefore, the trade-off highlighted in Fig. 4 is structurally linked to crop-based feedstock production rather than the HEFA conversion stage. Despite these increases, canola remains a comparatively water-efficient oilseed crop, requiring less water than several alternative feedstocks, which partially mitigates the agricultural burden [65].

The agricultural phase is also the dominant contributor to Stratospheric Ozone Depletion and Human Toxicity (cancer and non-cancer), accounting for 99.10% (5.09×10^{-3} g CFC-11 eq.), 93.51% (1.04 g 1,4-DB eq.), and 92.65% (54.46 g 1,4-DB eq.), respectively. Water-related impacts, such as Freshwater Consumption, Freshwater Eutrophication, and Marine Eutrophication, similarly range from 98.95% to 99.94% (25.60 L, 0.01 g P eq., 0.72 g N eq.). In contrast, categories like Terrestrial Acidification (91.10%, 1.62 g SO₂ eq.) and Ecotoxicity (59.72%, 40.80 g 1,4-DB eq.) are less dominated by the agricultural phase. Importantly, most of these impacts stem not from direct on-field emissions, but from upstream processes in the supply chain, particularly the production of fertilizers (P₂O₅, K₂O, urea) and soil amendments

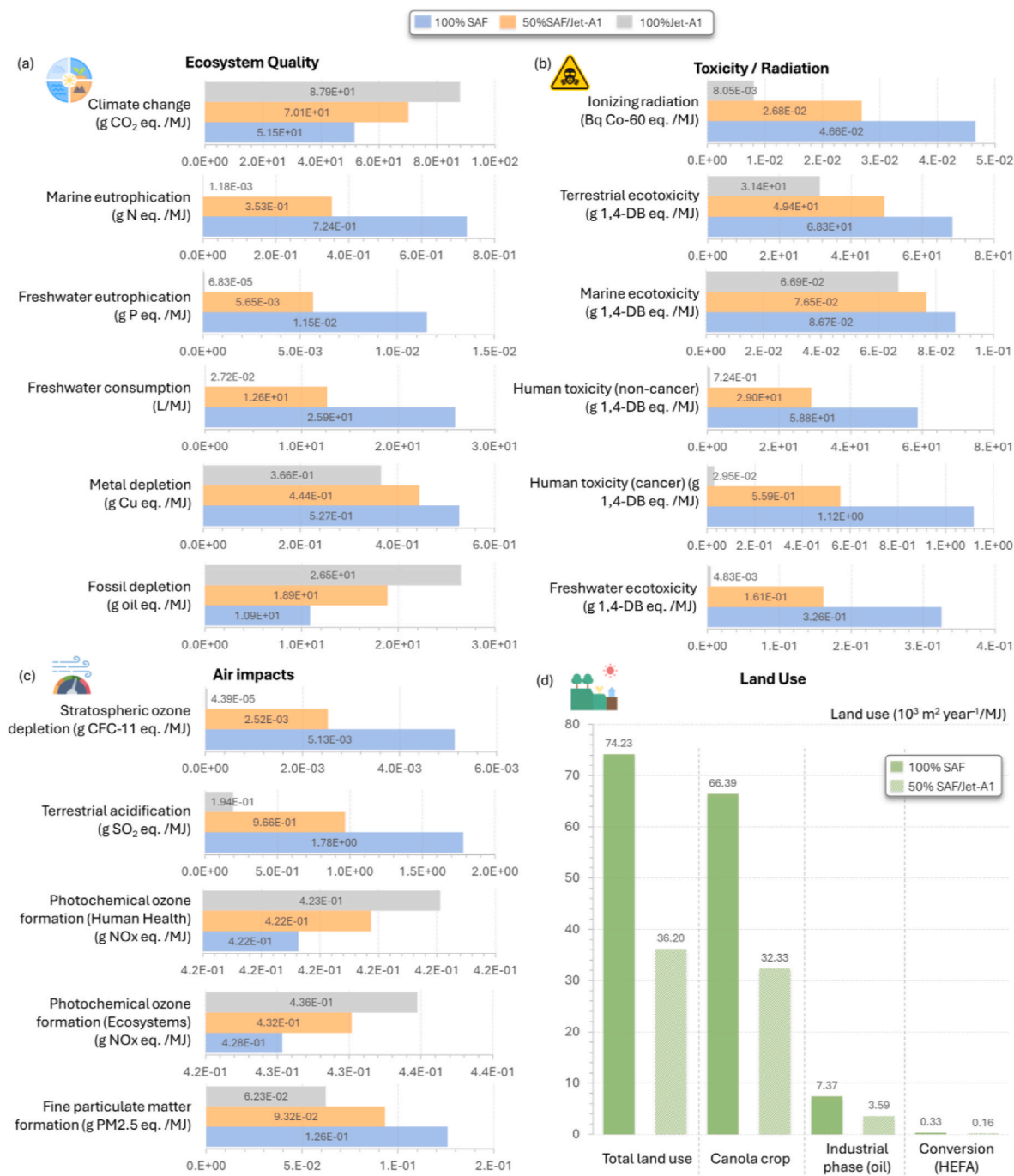


Fig. 4. Impact categories for HEFA-biokerosene in different scenarios (100% SAF, 50% SAF/ Jet-A1, and 100% Jet-A1) using the ReCiPe methodology, classified into three main groups: (a) Ecosystem Quality, (b) Toxicity and Radiation, and (c) Air Impacts. (d) Land Use is given special attention, measured as annual crop land occupation (m² eq. year⁻¹).

(limestone, clay).

Although the fossil kerosene scenario (100% Jet-A1) presents the highest Fossil Depletion potential impact, as expected, the 100% SAF still considerably contributes to this category. This is due to the presence of market activities associated with the production and transport of fertilizers (P₂O₅, K₂O, Urea) and industrial inputs (hexane, clay, citric acid, phosphoric acid, sodium hydroxide). Overall, the Fossil Depletion represents 10.86 g oil eq. in 100% SAF, representing 41.0% of the impact of 100% Jet-A1 scenario (26.46 g oil eq.). The market activities include inland waterway transport (barges, diesel), road transport (diesel lorries), maritime transport (container ships using heavy fuel oil), and rail transport (train fleets, average fuel consumption) in Brazil

and the Rest of the World, as detailed in Table S4–S9.

Overall, these findings reinforce the critical role of the agricultural phase in shaping environmental impacts. Khanali et al. [33] similarly highlights chemical fertilizers and diesel fuel as major contributors to global warming, acidification, and eutrophication, emphasizing the need for improved fertilizer management to mitigate environmental burdens [66].

3.2.2. Toxicity and radiation

Fig. 4(b) demonstrates that all impact categories related to Toxicity and Ionizing Radiation reflect higher values for the 100% SAF scenario when compared to 100% Jet A-1. These include Ionizing Radiation,

Terrestrial Ecotoxicity, Marine Ecotoxicity, Human Toxicity, and Freshwater Ecotoxicity. These higher potential impacts are largely attributed to upstream agricultural and industrial processes, particularly the production and transport of fertilizers, pesticides, and chemical inputs used in SAF manufacturing. The extraction and processing of these materials contribute to releasing toxic substances into the environment [67].

This result underscores an important trade-off: while SAF offers meaningful reductions in climate impacts, it may impose greater environmental burdens in toxicity and ecosystem health categories. As such, a holistic sustainability assessment is needed, one that accounts not only for decarbonization potential but also for the broader environmental footprint of SAF production. Strategies such as cleaner fertilizer manufacturing, integrated pest management, and low-toxicity industrial inputs should be prioritized to reduce these adverse effects and enhance the overall sustainability of SAF pathways.

3.2.3. Air pollution

Fig. 4(c) presents the Air Pollution impact category, including Stratospheric Ozone Depletion, Terrestrial Acidification, Photochemical Ozone Formation, and Fine Particulate Matter Formation. Terrestrial Acidification is primarily driven by NH_3 , NO_x , and SO_x emissions, with agriculture accounting (91.10%) for the 100% SAF scenario. This is largely associated with the use of inorganic potassium fertilizer (K_2O). In contrast, Terrestrial Ecotoxicity is largely associated with heavy metal emissions to air, occurring in the agricultural phase (59.72%), but also in the industrial phase (40.21%) for the 100% SAF scenario. The industrial contribution is almost entirely attributed to heat generation from wood chips. For both impact categories, nitrogen inputs from chemical fertilizers and crop residues are the predominant sources of emissions.

Regarding the Photochemical Ozone Formation (Human Health and Ecosystems) category, which is closely linked to nitrogen oxide emissions, the overall impact of the 100% SAF scenario (0.42 g NO_x eq. MJ^{-1} (Human Health) and 0.43 g NO_x eq. MJ^{-1} (Ecosystems)) is very similar to that of the 100% Jet-A1 scenario (0.42 g NO_x eq. MJ^{-1} (Human Health) and 0.44 g NO_x eq. MJ^{-1} (Ecosystems)). Although SAF combustion results in 11.73% lower NO_x eq. compared to fossil kerosene, this advantage is offset by upstream contributions. These contributions are mainly related to emissions from the agricultural and industrial phases, along with those from fuel combustion itself. In contrast, the impact of 100% Jet-A1 is concentrated almost entirely in the use phase (86.04%), with upstream emissions limited solely to those associated with kerosene.

3.2.4. Land use

Fig. 4(d) shows the total land use for 100%-SAF reaching $7.42 \times 10^{-2} \text{ m}^2 \text{ year}^{-1} \text{ MJ}^{-1}$, compared to $3.62 \times 10^{-2} \text{ m}^2 \text{ year}^{-1} \text{ MJ}^{-1}$ for the 50% SAF/Jet-A1 blend. This difference is anticipated due to the agricultural phase, particularly the canola production, which accounts for $6.64 \times 10^{-2} \text{ m}^2 \text{ year}^{-1} \text{ MJ}^{-1}$ in the 100%-SAF pathway. The land required for canola production is nearly double in the 100%-SAF scenario compared to the blend ($3.23 \times 10^{-2} \text{ m}^2 \text{ year}^{-1} \text{ MJ}^{-1}$), as expected.

The industrial phase (related to oil extraction and processing) contributes $7.37 \times 10^{-3} \text{ m}^2 \text{ year}^{-1} \text{ MJ}^{-1}$, while the conversion step via HEFA adds only $3.35 \times 10^{-4} \text{ m}^2 \text{ year}^{-1} \text{ MJ}^{-1}$, representing 9.93% and 0.45% of total land use in the 100% SAF scenario, respectively. Although their contributions are considerably smaller than those of the agricultural phase, they are not negligible. The industrial phase's land occupation is primarily associated with heat production from wood chips, a common energy source in Brazil's South and Midwest regions, where canola production is concentrated. Similarly, the HEFA conversion process relies on steam produced from biomass, which reflects Brazil's renewable energy matrix. The feedstock production remains the dominant driver of land occupation in SAF systems. It is important to note that the land use results reported here refer to land use occupation as an

area time demand indicator. Emissions from land use change are not included in this impact category and are discussed separately below. This concentration of land use potential impacts in the agricultural stage raises important concerns related to land competition, biodiversity loss, and the potential for land use change (LUC), especially in scenarios of large-scale SAF deployment.

However, as shown in Table 1, few studies have addressed this impact category in depth. For instance, although Obnamia et al. [41] assessed LUC for canola crops, their study focused on Canada, where canola is a primary crop. In contrast, canola is typically grown as a second crop in Brazil, which significantly differs in the land-use dynamics and environmental implications.

It is also important to note that LUC emissions were not assessed in the present study, as robust, spatially explicit LUC and indirect land use change (iLUC) factors for second crop canola under Brazilian conditions were not available within the scope of this attributional LCA. Notwithstanding, it is worth highlighting that canola is produced as a second crop in Brazil, typically following soybean in the same agricultural year. This sequential use of land avoids the need for direct land expansion, which would otherwise be required to produce additional biomass, representing a key advantage in terms of land-use efficiency. Nevertheless, while this characteristic supports the exclusion of direct LUC, iLUC effects cannot be fully excluded. If considered, iLUC would introduce additional upstream CO_2 equivalent burdens associated with market mediated land displacement and crop system adjustments and, therefore, could increase the overall carbon intensity of canola derived SAF, particularly under large scale deployment scenarios. Potential mechanisms include crop displacement effects and shifts in primary crop cycles, while longer-term soil carbon responses may also play a role depending on local management and temporal assumptions. Accordingly, the climate benefits reported here should be interpreted as conditional on the exclusion of iLUC, which remains a relevant source of uncertainty in policy relevant frameworks such as CORSIA.

If LUC emissions were considered, particularly under a soy-canola rotation, allocation between both crops would be required, according to the latest BRLUC modeling approach [68]. This methodology distributes emissions across multiple crops, treating second crops as partial CO_2 emitters while reducing the share attributed to primary crops. In such a system, LUC-related emissions would be divided, directly affecting the overall carbon footprint of SAF derived from canola. This underscores the need for spatially explicit and crop-rotation-aware assessments to more accurately reflect the sustainability performance of biofuel production systems [68]. Accordingly, iLUC should be regarded as a qualitative limitation and source of uncertainty for CORSIA aligned carbon intensity reporting in the present assessment. Integrating this methodology would improve carbon accounting in future assessments. Additionally, incorporating risk-integrated LCA approaches, as already applied in frameworks for Brazilian bioenergy systems [69], can further enhance the robustness and relevance of such evaluations.

In summary, considering the total environmental impact (Fig. 4), the categories of Marine Eutrophication, Freshwater Eutrophication and Water Consumption (Fig. 4(a)), Stratospheric Ozone Depletion (Fig. 4(b)), Human Toxicity (cancer and non-cancer), and Freshwater Ecotoxicity (Fig. 4(c)) exhibited nearly negligible values for fossil fuels. Still, the values were significantly higher in scenarios involving SAF production. This is directly linked to the use of agrochemicals, including fertilizers and pesticides, in the early stages of production [18]. These findings emphasize the need to expand LCA analyses beyond climate change to avoid "carbon tunnel vision," ensuring a holistic evaluation of potential environmental impacts, enhancing decision-making and providing a clearer understanding of biofuel's overall sustainability [70].

Additionally, as highlighted by Capaz et al. [18], the allocation of pesticide emissions to air, water, and soil is often simplified or omitted in LCAs, relying on assumptions rather than detailed modeling. Nonetheless, this aspect is critical for capturing toxicity-related impact

categories. In the present study, however, these emissions were meticulously calculated and described (Table S1–S2), ensuring greater accuracy in the potential impact assessment.

3.3. Environmental impacts across the Canola-SAF production chain

The following section returns the focus to Climate Change, specifically addressing the distribution of GHGs emissions across the main

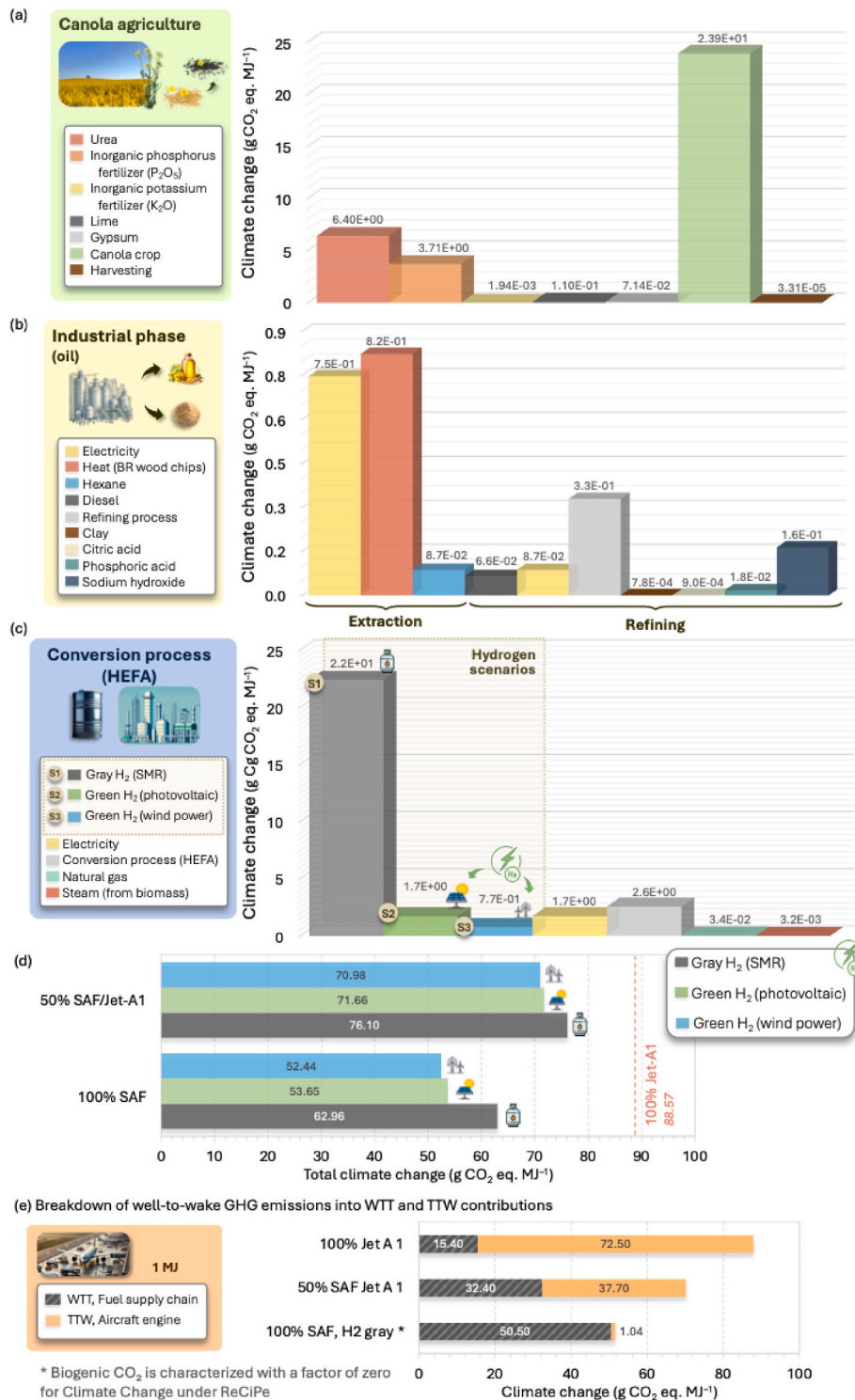


Fig. 5. Emission contributions from different life cycle stages. (a) Canola production emissions from farming activities. (b) Industrial phase. (c) Emissions from the HEFA process using H₂ from gray (SMR) and green sources (photovoltaic and wind power). (d) Potential emission reduction achieved by replacing gray with green H₂. (e) Well to wake Climate Change per 1 MJ, disaggregated into well-to-tank and tank-to-wake contributions. The WTT stage includes feedstock production, processing, and fuel upgrading. The TTW stage represents aircraft combustion emissions, including fossil CO₂, biogenic CO₂, and non-CO₂ emissions as represented in the adopted aircraft inventory. Under the applied LCIA method (ReCiPe 2016 Midpoint H), biogenic CO₂ is characterized with a factor of zero for Climate Change and therefore does not contribute to the reported impact values. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

production stages of canola-derived SAF and use. Fig. 5 presents a detailed breakdown of emissions for each life cycle stage, from agricultural activities and industrial processing to fuel conversion and final combustion, highlighting the primary sources contributing to the carbon footprint along the entire pathway.

3.3.1. Agricultural phase

In the agricultural phase (Fig. 5(a)) (34.20 g CO₂ eq.), the primary contribution to GHG emissions stems from the canola crop itself (23.91 g CO₂ eq.). This contribution largely reflects upstream processes associated with crop production, including fertilizer manufacture and soil-related emissions, particularly nitrous oxide (N₂O). The second-largest contributor is urea application (6.40 g CO₂ eq. – 18.70% of the agricultural phase), with emissions arising mainly from the transforming activity (6.22 g CO₂ eq.) and, to a lesser extent, from its global market supply (0.18 g CO₂ eq.). Inorganic phosphorus fertilizers (P₂O₅) also contribute significantly to emissions (3.71 g CO₂ eq.), representing 10.86% of the total agricultural emissions.

Although fertilizers are identified as secondary contributors within the agricultural phase, all emissions associated with field operations, including land preparation, sowing, and harvesting, were fully accounted for in the inventory, as documented in Tables S1–S3. Their comparatively smaller contribution reflects the characteristics of the Brazilian second-crop canola system, as represented in the inventory, and benefits from the regional fuel and electricity mix.

Urea plays a significant role in the emissions attributed to canola production, due to the release of CO₂, N₂O, and NO_x during its application [71]. This impact could be mitigated by substituting urea (currently the most convenient fertilizer for Brazilian producers [72]) with biofertilizers, which could lead to a lower environmental footprint in both production and application [73,74]. Biofertilizers developed through more sustainable methods could further reduce post-application environmental impacts [73,75]. In particular, microalgae-derived biofertilizers have shown potential to reduce GHGs emissions, particularly methane (CH₄) and nitrous oxide (N₂O), which exhibit higher GWP than carbon dioxide (CO₂) [73]. Similarly, anaerobic digestate-derived biofertilizers can mitigate marine and freshwater ecotoxicity by reducing heavy metal contamination and eutrophication effects [74]. Thermochemical valorization routes, such as biochar-based fertilizers, also present promising alternatives, enhancing nitrogen availability and microbial activity, effectively lowering soil N₂O emissions and providing a sustainable alternative to conventional urea-based fertilization [61, 76].

It is worth noting that alternative fertilizer pathways based on green hydrogen, such as green ammonia or urea produced via renewable hydrogen, could substantially reduce upstream fertilizer-related emissions. However, such options were not considered in the present assessment, as the integration of green hydrogen was deliberately restricted to the HEFA upgrading stage to isolate its influence on the HEFA pathway. The incorporation of low-carbon fertilizer production therefore represents an important opportunity for future work.

Comparisons between Brazilian canola production and international inventories must be interpreted with caution, as canola in Brazil is grown exclusively as a second-season crop (“safrinha”), under agronomic and climatic conditions distinct from those of temperate regions. Unlike first-season cultivation in temperate countries, Brazilian off-season canola is often limited by residual soil moisture, higher temperatures, and increased pest pressure, affecting yield potential and input efficiency.

Despite these differences, comparisons with inventories reported by Khanali et al. [33], Obnamia et al. [41], and CORSIA [7] reveal relevant contrasts. While overall input levels in Brazil are significantly higher than those reported for the United States, Brazilian canola exhibits a notable reduced pesticide use compared to Iranian systems [33], with pesticide corresponding to 86.35% of Iranian values. Nitrogen fertilizer use corresponds to 61.44%, P₂O₅ to 57.90%, and K₂O shows only a

0.54% difference. The comparatively higher fertilization rates observed in Brazilian second-crop canola reflect the management practices reported in the primary data sources and may be influenced by cultivation after soybean within the same agricultural year. In this context, higher P₂O₅ and K₂O inputs can be required to sustain yield targets depending on site-specific soil fertility and nutrient removal across the rotation. In addition, under tropical off-season conditions, nutrient availability and uptake efficiency may be more variable, and losses can be higher depending on local weather and management, which may lead producers to adopt more conservative fertilization practices to mitigate yield risks. In contrast, CORSIA's inventory values are considerably lower, with fertilizer application in U.S. canola production approximately 5.8 times lower than in Brazil, likely reflecting differences in data sources, productivity levels, assumptions, or methodological choices.

Similarly, Obnamia et al. [41] provide a detailed inventory covering eight canola-producing regions, with average productivity of 2123 kg ha⁻¹ and pesticide use between 0.3 and 4.9 kg ton⁻¹ of canola grains, consistent with the 0.79 kg ton⁻¹ of grains of Brazil. Moreover, fertilizer application in Ref. [41] is higher than in the CORSIA inventory, underscoring the importance of accounting for regional variation and harmonizing data across sources. As previously noted and reinforced by Silva et al. [31] and Zorzenoni et al. [29], the off-season conditions of canola production in Brazil influence productivity and input use, affecting inventory comparability across countries.

3.3.2. Industrial phase – oil extraction and refining

During the industrial phase (Fig. 5(b)), oil extraction accounts for most CO₂ eq. emissions, contributing 70.26% of this stage. Of these emissions, 52.42% are associated with heat generated from wood chips, followed by electricity demand (47.58%) and, to a lesser extent, the use of hexane (5.54%). In the LCA, most emissions originate directly from the refining process itself, primarily in the form of carbon dioxide. Among the industrial inputs, sodium hydroxide has the highest environmental impact, accounting for 89.28% of the emissions associated with processing inputs, including clay, citric acid, phosphoric acid, and sodium hydroxide.

3.3.3. HEFA conversion process

Fig. 5(c) shows that the HEFA conversion is highly sensitive to the source of H₂, which influences the climate impact of SAF production. Gray H₂, produced via steam methane reforming, results in the highest emissions, reaching 22.0 g CO₂ eq. MJ⁻¹, making it the most carbon-intensive input in this phase. Replacing it with green H₂, produced via electrolysis using photovoltaic or wind power, reduces emissions to 1.75 and 0.79 g CO₂ eq. MJ⁻¹, respectively. These values correspond to emission reductions of 86 to 94%, reinforcing the pivotal role of H₂ sourcing in achieving deep decarbonization. Although auxiliary inputs such as electricity, natural gas, and steam contribute less to the total impact, they are not negligible. For example, electricity accounts for 1.7E-01 g CO₂ eq. MJ⁻¹, while natural gas and steam from biomass contribute 3.6E-01 and 6.6E-02 g CO₂ eq. MJ⁻¹, respectively. Therefore, while H₂ dominates the emissions profile, the integration of low-carbon energy sources across all process stages is essential to further minimizing environmental impacts.

This impact is reflected in the total climate change performance of SAF (Fig. 5(d)). When gray H₂ is used, emissions reach 51.51 g CO₂ eq. MJ⁻¹ for 100% SAF and 70.14 g CO₂ eq. MJ⁻¹ for a 50% SAF/Jet-A1 blend. Replacing it with photovoltaic-based H₂ reduces emissions to 40.32 and 64.78 g CO₂ eq. MJ⁻¹, while wind-powered H₂ lowers them further to 39.19 and 64.14 g CO₂ eq. MJ⁻¹, representing up to 55% reduction compared to fossil Jet-A1 (87.90 g CO₂ eq. MJ⁻¹).

Although green H₂ adoption is increasing, global supply remains dominated by fossil-based routes [77]. In Brazil, this transition is supported by favorable conditions for renewables, particularly wind in the South and solar in the Midwest. Aligning SAF biorefineries with these high-potential regions could reduce logistical burdens, optimize land

use, and enhance both environmental and economic performance. This spatial integration is promising in agricultural frontiers such as the Cerrado [31], where second-crop canola coincides with peak solar availability.

3.3.4. Tank-to-wake emissions

Fig. 5(e) reports well-to-wake Climate Change per 1 MJ, explicitly separating well-to-tank (WTT) and tank-to-wake (TTW) contributions. The WTT component aggregates upstream emissions from feedstock production, processing, and fuel upgrading, whereas the TTW component represents aircraft engine emissions at combustion as implemented in the adopted aircraft inventory (Tables S18–S21).

Relative to conventional fuel combustion (100% Jet A1), the Aircraft engine contribution decreases from 72.5 g CO₂ eq. MJ⁻¹ (Jet A1) to 37.7 g CO₂ eq. MJ⁻¹ for the 50% SAF blend (48.0% reduction) and to 1.04 g CO₂ eq. MJ⁻¹ for 100% SAF (98.6% reduction), as reported in the inventory. Under ReCiPe 2016 Midpoint H, biogenic CO₂ from SAF combustion is characterized with a factor of zero and therefore does not contribute to the Climate Change indicator. Consequently, the TTW value reported for 100% SAF should be interpreted as the residual contribution of non-CO₂ combustion species represented in the aircraft dataset, rather than CO₂ from fuel oxidation (Tables S18–S21). This interpretation is consistent with Capaz et al. [18], who also report a residual TTW Climate Change contribution after excluding biogenic CO₂, attributable to non-CO₂ combustion species. Differences in magnitude across studies are expected due to differences in the aircraft operation inventory and the set of non-CO₂ species considered.

3.4. Regulatory context and LCA approaches for HEFA-SPK

3.4.1. Policy frameworks for SAF assessment

Policy frameworks play a crucial role in determining how the environmental impacts of SAF are evaluated. LCA often relies on key methodological assumptions, such as treatment of biogenic CO₂ and GHG accounting boundaries, and other indicators, which significantly influence the resulting metrics and, consequently, policy decisions. This influence is particularly evident in regulatory tools like RenovaCalc and CORSIA [7,78], IPCC guidelines for GHG accounting.

CORSIA and RenovaBio are two major regulatory initiatives promoting the reduction of GHG emissions through the adoption of SAF and biofuels. CORSIA, developed under the International Civil Aviation Organization, seeks to stabilize aviation emissions from 2020 onwards by establishing default and certified life cycle values for SAF [8,79]. Beyond minimum GHG reduction thresholds, CORSIA eligibility is contingent on compliance with feedstock-specific methodological guidance, data quality requirements, and verification procedures under approved sustainability certification schemes. RenovaBio is a Brazilian policy framework that encourages decarbonization through carbon intensity certification and tradable decarbonization credits (CBIOs) [38–40].

To facilitate SAF integration into RenovaBio, RenovaCalc was created as an LCA-based tool that calculates the carbon intensity of biofuels (g CO₂ eq. MJ⁻¹) and estimates CBIO generation per unit of fuel [78]. However, current RenovaCalc configurations for HEFA are limited to soybean, palm oil, and maize, preventing direct comparison with results from this study. The life-cycle GHG intensities calculated here are reported on a well-to-wake basis and in the same units used in CORSIA documentation, enabling a technical comparison with CORSIA carbon intensity metrics. However, this study does not determine formal CORSIA eligibility, since such determination depends on compliance with ICAO requirements beyond the LCA results, including pathway-specific acceptance within the applicable CORSIA framework and independent verification under an approved sustainability certification scheme (e.g., sustainability criteria and chain-of-custody requirements). These certification and auditing steps were beyond the scope of this work. Although canola is not currently represented in RenovaCalc [78], the RenovaBio

policy has been advancing efforts to incorporate new HEFA feedstocks into the calculator, aiming to better reflect the diversity of Brazil's agricultural systems. In parallel, new SAF modules are under development as part of the national Fuels of the Future strategy, supporting the integration of emerging feedstocks and technologies into Brazil's low-carbon fuel framework [35].

3.4.2. Feedstock and regional contexts

In general, feedstock production emerges as the dominant contributor to emissions for most raw materials, except for palm oil, where the processing phase shows the highest impacts. According to CORSIA [7], this feedstock only presents relatively low emissions when methane from palm oil mill effluent (POME) is captured. Without methane capture, emissions from oil extraction significantly increase, making palm oil a high-impact option if proper mitigation measures are not in place [80]. This difference highlights how feedstock performance depends not only on crop type but also on management practices and infrastructure. This pattern is further detailed in Fig. 6, which compares climate change emissions across life cycle stages for HEFA fuels from multiple feedstocks, modeled under different regional and methodological contexts.

Rather than establishing a simple feedstock ranking, the results highlight structural and agronomic contrasts. Perennial crops such as palm and jatropha benefit from high yields, long-term planting cycles, and integrated waste valorization [19,81]. In contrast, annual oilseeds, including soybean [18,19], camelina [81], and canola [41], require seasonal replanting, soil preparation, and typically involve higher input demand per unit of oil produced. Specifically in Brazil, canola is often grown as a second-season crop, taking advantage of residual soil moisture without the need for irrigation. This practice improves land-use efficiency and sets it apart from temperate-climate cultivation systems.

The CORSIA default value for canola production as a primary crop in the USA and Canada is 15.40 g CO₂ eq. MJ⁻¹, which represents a standardized estimate for primary-crop systems under the CORSIA methodological framework [7]. This default is 43.16% lower than the region-specific reported by Obnamia et al. [41] (27.09 g CO₂ eq. MJ⁻¹), based on a detailed assessment in Canada, and it is also lower than the feedstock production stage reported in the present study (34.2 g CO₂ eq. MJ⁻¹), which reflects a region-specific second-crop configuration under tropical Brazilian conditions. These differences can be attributed to crop system configuration (primary versus second crop) and to methodological choices that affect agricultural inventories, including input data granularity and inventory depth, allocation procedures, background datasets, and modeling assumptions.

Concerning the industrial phase, including oil extraction and refining, showed significant variation across different feedstocks, ranging from a minimum of 0.43 g CO₂ eq. MJ⁻¹ for palm oil [19] to a maximum of 3.91 g CO₂ eq. MJ⁻¹ for canola in the USA [41]. Similarly, although canola-derived HEFA values remained close, the HEFA conversion phase also exhibited variation, differing slightly between 13.61 g CO₂ eq. MJ⁻¹ for the USA/Canada [12,41] 0.75 g CO₂ eq. MJ⁻¹ for Brazilian canola HEFA from this study. These differences arise from extraction and conversion methods, energy use, and feedstock composition. Oils with higher free fatty acid content require more intensive refining, while energy sources and process efficiency further influence emissions [19].

3.4.3. Strategic pathways for SAF deployment

From a strategic perspective, promoting crop integration and seasonal diversification is essential to ensure a stable, resilient, and regionally adapted supply of vegetable oils for SAF production. Rather than relying on a single feedstock, policy and industry efforts should focus on diversifying raw materials, optimizing production systems regionally, and enhancing agricultural productivity to strengthen the supply chain and improve sustainability outcomes.

Concerning the conversion phase, beyond direct hydrogen use, Carbon Capture and Storage (CCS) is increasingly being explored as a

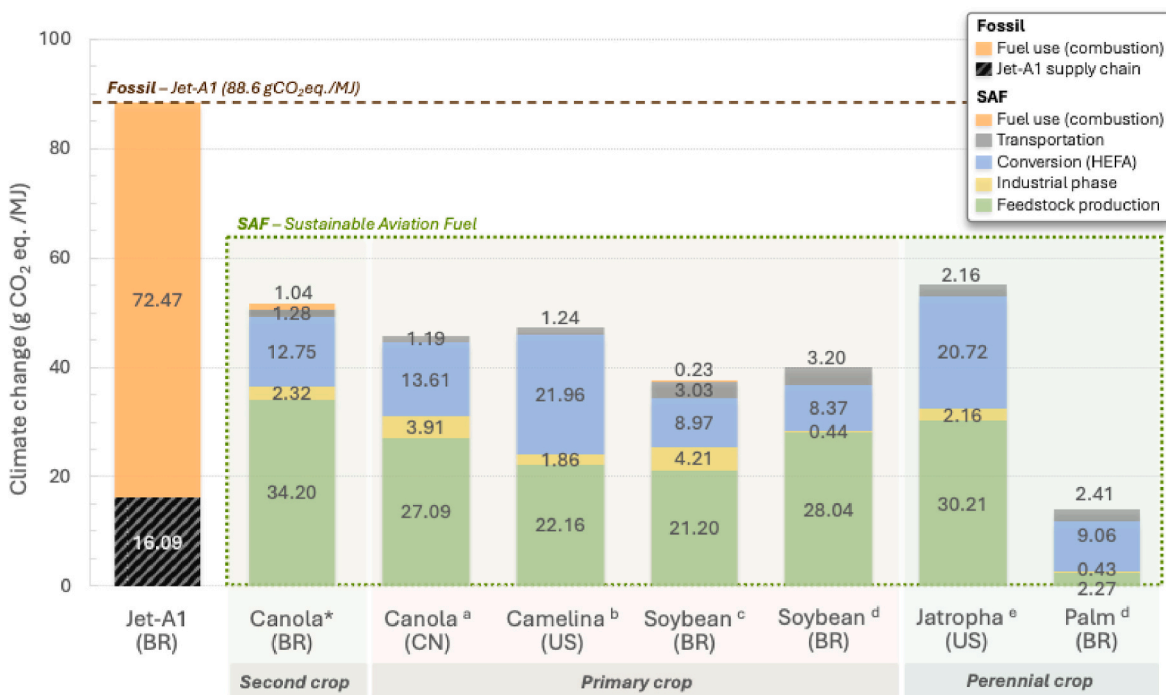


Fig. 6. Climate change emissions ($\text{g CO}_2 \text{ eq. MJ}^{-1}$) for conventional kerosene (Jet-A1) and HEFA-biokerosene produced from different feedstocks. Values reflect different modeling approaches and regional contexts: canola based on feedstock production data from southern Brazil (BR) as a second crop (this study); ^a canola produced in the Canada (CN) [41]; ^b camelina produced in the United States (US) [81]; ^c soybean produced in Brazil (BR) [18]; ^d soybean and palm produced in Brazil (BR) [19]; and ^e jatropa produced in the United States (US) [81]. Feedstocks are explicitly grouped and labeled on the chart according to crop type, distinguishing second crop, annual primary crops, and perennial crops, highlighting differences in land-use efficiency.

complementary strategy in SAF pathways. CCS not only reduces industrial emissions but also enables the synthesis of e-fuels like e-kerosene by combining green hydrogen with captured CO_2 [82,83]. These synthetic fuels offer advantages in storage, distribution, and compatibility with current aviation infrastructure [84]. Given the challenges of direct electrification in aviation, e-fuels remain a promising mid-term decarbonization solution [84,85]. As indicated by Lamas et al. [86], continued integration of sustainable hydrogen, CCS, and biomass-based routes will be key to enabling low-emission aviation and accelerating the energy transition.

In addition, the integration of energy, exergy, economic, and environmental analysis is essential to thoroughly assess the sustainability of SAF production, identifying critical gaps in the joint application of exergoeconomic and exergoenvironmental assessments across conversion routes [87].

4. Limitations and prospects

This study is subject to some limitations that should be considered when interpreting the results. Although the main environmental hotspots along the life cycle were clearly identified, a formal sensitivity or uncertainty analysis was not conducted. Several influential parameters (such as fertilizer emission factors, hydrogen demand in the HEFA process, electricity carbon intensity for green hydrogen production, and allocation choices) are known to vary substantially across regions and studies. Variations in these parameters may affect both the magnitude of the estimated GHG reductions and the trade-offs observed across other environmental impact categories.

Low-carbon fertilizer supply chains (for example green ammonia or green urea produced using renewable hydrogen) were not modeled, as renewable hydrogen was restricted to HEFA upgrading. Agricultural phase results should therefore be interpreted as conditional on the assumed fertilizer supply chain. Future assessments integrating green hydrogen into fertilizer production could further refine the

environmental profile of canola-based SAF.

Direct and indirect land use change (dLUC and iLUC) were not quantified in this assessment. Although the second crop configuration of canola in the assessed Brazilian regional context reduces the likelihood of direct land expansion, iLUC associated with potential crop displacement and multi season soil carbon dynamics cannot be fully excluded. Therefore, the reported carbon intensity results should be interpreted as conditional on the exclusion of LUC effects, which remain a relevant source of uncertainty for CORSIA aligned carbon accounting. The integration of spatially explicit and crop rotation aware LUC modeling represents an important avenue for future SAF evaluations.

In addition, due to data availability constraints, soybean-based life cycle inventory data were used as a proxy for modeling the HEFA conversion of canola oil. Differences in fatty acid composition between canola and soybean oils may influence hydrogen consumption during hydrodeoxygenation and hydrocracking, introducing additional uncertainty at this stage. Consequently, the hydrogen demand associated with the HEFA pathway should be interpreted with caution. The development of feedstock specific conversion inventories would further enhance methodological robustness and policy relevance.

5. Conclusions

This study provides a comprehensive assessment of canola-derived SAF production through the HEFA pathway, highlighting key environmental and technological trade-offs while exploring potential pathways for sustainability improvements. The results highlight a complex interplay between technological efficiency, feedstock characteristics, and broader sustainability metrics.

Although energy allocation favors biokerosene and crude oil, co-products make a meaningful contribution to the system's overall viability. Key environmental trade-offs emerge, with advantages in fossil resource depletion counterbalanced by higher impacts in categories such as eutrophication, toxicity, and acidification, primarily influenced

by agrochemicals use for feedstock production. These findings underscore the need to move beyond carbon-centric evaluations and emphasize the importance of enhancing agricultural inputs, particularly through improved nitrogen management and the adoption of biofertilizers.

Hydrogen sourcing also plays a decisive role in total emissions. Replacing gray hydrogen by green hydrogen, especially with wind or solar energy sources, can drastically lower potential climate impacts, revealing synergies between renewable energy integration and biofuel deployment in Brazil's diverse regions.

Ultimately, future sustainability assessments must evolve beyond static inventories, incorporating updated productivity data and evaluating land-use change associated with second-crop canola production. This spatially explicit perspective is essential for accurately modeling indirect effects and guiding responsible expansion. In this context, further work should also prioritize feedstock-specific HEFA conversion data and targeted sensitivity analyses to address key sources of uncertainty identified in this study. While the absolute results reported here are specific to the Brazilian second-crop canola system and regional electricity mixes, the identified environmental hotspots and the relative trade-offs between feedstock production, hydrogen sourcing, and allocation choices are expected to be qualitatively transferable across HEFA-based SAF systems in other contexts. A truly sustainable SAF strategy will depend on technological innovation, regional integration, and strong policy frameworks that align climate targets with resource efficiency, supply security, and environmental integrity within Brazil's emerging bioeconomy.

CRediT authorship contribution statement

Giulia Cruz Lamas: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alexandre Nunes Cardoso:** Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Priscila Seixas Sabaini:** Writing – review & editing, Writing – original draft, Validation, Formal analysis. **Sandra M. Luz:** Writing – review & editing. **Maria dos Reis Santos Borges:** Writing – review & editing. **Tainara da S. Costa:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Thiago da Silva Gonzales:** Writing – review & editing. **Marília Ieda da Silveira Folegatti Matsuura:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Bruno Galveas Laviola:** Writing – review & editing, Project administration, Funding acquisition. **Thiago O. Rodrigues:** Writing – review & editing, Writing – original draft, Validation, Formal analysis. **Patrick Rousset:** Writing – review & editing. **Edgar A. Silveira:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of generative AI and AI-assisted technologies

During the preparation of this work, the authors used generative artificial intelligence tools to assist with language editing and clarity. The authors carefully reviewed and edited the content and take full responsibility for the integrity, accuracy, and originality of the work.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biombioe.2026.109149>.

Data availability

Data will be made available on request.

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