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Camelina oil for sustainable aviation fuel production: A scenario assessment for recovering European degraded soils

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ABSTRACT

The European aviation sector is currently under pressure to rapidly integrate renewable energy sources, with a particular emphasis on sustainable aviation fuels (SAF), which are essential for achieving short-term decarbonization targets. This study proposes an innovative supply chain producing SAF according to the REFuelEU Aviation's progressive targets for 2050, the international ICAO-CORSIA mandates and the European Union's Renewable Energy Directive for greening the transport sector.

The study focuses on camelina (*Camelina sativa L. Crantz*) grown in Southern European regions on marginal land affected by severe soil degradation. In this case, according to the most recent policy requirements, "severely degraded lands" suitable for advanced biofuels production are currently defined as those under erosion with poor soil organic matter content or with high salinity. Unlike other common oilseeds, camelina can successfully grow in degraded and eroded soils making it particularly well-suited to produce low indirect land-use change (iLUC) risk feedstocks for SAF. The challenges of achieving profitable yields under marginal conditions are examined and discussed.

The results show a potential of 116 thousand km^2 of available lands that can produce 3.2 Mtoe per year of SAF, corresponding to 175 % of bio-SAF mandates in 2030. The calculated carbon intensity of SAF ranges between 10.5 and −30.8 gCO$_2$eq MJ^{-1} depending on the carbon accumulation performances achieved in the cultivated soil and green energy used in the supply chain. By combining economics and greenhouse gas emission savings, the study explores the current gaps between conventional and innovative SAF production.

1. Introduction

The EU is facing the dual challenge of enhancing agricultural productivity for food/feed and relying on sustainable bioenergy from non-food/feed crops, bio-residues and biowastes. At the same time, it is also advancing environmental and climate objectives by increasing emission reduction targets through the EU Climate Law (European Parliament and the Council of the European Union, 2021), recently proposed to be amended with a 90 % greenhouse gas (GHG) reduction target by 2040 (The European Commission (EC), 2025). Biofuels are still considered as a fundamental energy source to decarbonize the transport sector, while maintaining increasingly stringent sustainability and traceability requirements. The Directive (EU) 2023/2413 (European Parliament and the Council of the European Union, 2023a) (referred to as RED III) updating the Renewable Energy Directive (EU) 2018/2001 (European Parliament and the Council of the European Union, 2018) (RED II) set ambitious targets of GHG emissions reduction and renewable energy share within the transport sector, maintaining a specific sub-target for advanced biofuels, i.e. those biofuels generated from non-food feedstocks listed in the Annex IX Part A (e.g. lignocellulosic material, biowastes, etc.). To produce advanced biofuels, the origin of feedstock shall not be in competition with food and feed production in accordance with Annex IX part A of the RED and subsequent amendments (Delegated

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List of acronyms

CAM-BAR	Camelina in rotation with Barley
CHP	Combined Heat and Power
CLC	CORINE Land Cover Classification
CO2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DLUC	Direct Land Use Change
EC	European Commission
EASA	European Union Aviation Safety Agency
FFC	Fossil Fuel Comparator
GHG	Greenhouse Gas
HEFA	Hydrotreated Esters and Fatty Acids
HVO	Hydrotreated Vegetable Oil
HRJ	Hydrotreated Renewable Jet Fuel
ICAO	International Civil Aviation Organization
iLUC	Indirect Land Use Change
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LHV	Low Heating Value
LPG	Liquefied Petroleum Gas
MED	Mediterranean
NUTS2:	Nomenclature of Territorial Units for Statistics, Level 2
RED	Renewable Energy Directive
SAF	Sustainable Aviation Fuels
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
UCO	Used Cooking Oil

Regulation 2024/1405 (The European Commission (EC), 2024a)). The updated list has been consolidated as permanent legislation after the release of a study on the impact of new feedstocks for the production of advanced biofuels (European Commission, 2022). Today, EU policy encourages the production of sustainable advanced biofuels for the hard-to-abate transport sectors, such as aviation and maritime, assuming a progressively increasing electrification of the road sector. This is also reflected in the CO_2 standard for passenger cars (European Parliament and the Council of the European Union, 2023b). Aviation and maritime have specific obligations in terms of alternative fuel share and GHG emissions reduction as set in the REFuelEU Aviation (European Parliament and the Council of the European Union, 2023c) and FuelEU Maritime (European Parliament and the Council of the European Union, 2023d) respectively. While for the maritime sector there is a broad range of alternative fuel options, the aviation sector needs SAF (Sustainable Aviation Fuels), which are drop-in, renewable jet fuels.

Besides the existing EU ETS (The European Commission (EC), 2024b) and the REFuelEU/RED mandates, the sector has also obligations at international level for the ICAO-CORSIA (Prussi et al., 2021a), with sustainable biofuels and synthetic fuels as main actors to deliver defossilisation and GHG emissions reduction.

With the last updated version of the RED Annex IX, the possibility to use non-food/feed crops deriving either from severely degraded lands or intermediate crops for the purpose to produce SAF only, has been added. However for this option, stakeholders called for further clarification since the EU legislation does not provide neither a clear definition of severely degraded lands, nor criteria to determine additional biomass generated by intermediate crops. The current guidelines that provide some definitions on high and low indirect land use change (iLUC) risk biomass within the EU legislation are captured in the Delegated Regulation 2019/807 (European Commission (EC), 2019) and in the Implementing Regulation 2022/996 (European Commission (EC), 2022) respectively. In particular, the difficulty in obtaining low iLUC-risk certification lies in demonstrating that a specific crop yield is truly 'additional' to food and feed production—meaning it exceeds what would have been produced without specific interventions.

For updated criteria to define severely degraded lands, the EC has first conducted a preliminary study (Guidehouse Netherlands, 2022) to set minimum requirements either at <1 % of Soil Organic Matter (SOM, which is made of about 50 % Soil Organic Carbon, SOC) and severe signs of erosion on 25 % of the land surface, or >8 dS m^{-1} electrical conductivity for significantly salinized land. In 2024, Guidehouse re-evaluated the thresholds in a new study for the EC (Guidehouse Netherlands, 2024) to investigate ten representative case studies (at world-wide level) targeting low iLUC-risk crops and proposed updated figures. After the on-field campaigns, a higher threshold has been proposed at <3.4 % SOM and >1.5 t ha^{-1} y^{-1} soil loss for erosion (using maps or photographic evidence to show signs of erosion), or >4.0 dS m^{-1} electrical conductivity for salinated soil. The need for clear guidelines and soil parameters achievable to reach minimum cultivation conditions, has a fundamental importance to develop new projects that may undergo through the biofuels' certification process (i.e. implemented by various EC-recognized voluntary schemes (European Commission website, 2024a)), which should be applicable to any type of feedstock, in any region, and at any scale.

The use of agricultural land to provide biofuels is still controversial, but many opportunities instead appear when sustainable agricultural practices are used to deliver multiple co-benefits with the common goal to sustain soil carbon accumulation, preserve soil health, and deliver sustainable biomass and/or food and feed: the (2023–2027) Common Agricultural Policy (The European Commission (EC)) fosters crop rotations for soil health to support the transition towards more sustainable food and farming systems; the EU Biodiversity strategy for 2030 (European Commission, 2021), together with the EU Soil Strategy (European Commission (EC), 2021), aim to preserve soil status and/or restore soil quality to counter the effect of climate change; the EU Bioeconomy Strategy aims to develop a sustainable and circular bioeconomy around biomass supply chains delivering bio-based products. Considering this intricate policy framework, the challenge between a reliable agriculture system and the supply of sustainable biomass remains an uncharted issue.

Particularly, for the rapid decarbonization of the aviation sector, the oilseed crops are of great interest due to the possibility to supply sustainable lipids for HVO (Hydrotreated Vegetable Oil)/HEFA (Hydrotreated Esters and Fatty Acids) technology (Shahriar and Khanal, 2022; del et al., 2022) or co-processing (i.e. a similar process but using the same infrastructure of crude oil processing), which are fully mature, commercial technologies (Van Dyk and Saddler, 2024; Panoutsou et al., 2021). Currently, the main feedstocks to produce SAF are mainly used cooking oil and other waste lipids or industrial residual oils (Motola et al., 2024), which are limited. This makes the possibility to use non-food oil-crops cultivated in severely degraded lands or as intermediate crop an attractive opportunity. However, this type of agricultural systems involves uncertainty in selecting the most suitable non-food competing crops to be used in generally marginal areas. Additionally, biomass yield would be low and the implementation of business models becomes even more challenging, requiring long term support. The EC funded several projects in the last decades targeting the development of specific case studies investigating the use of sustainable, alternative cropping systems for aviation biofuels production (Prussi et al., 2019). Thanks to these contributions, today there are numerous studies that have generated scientific evidence on how to cultivate sustainable low-ILUC risk oil-crops (Buffi and Motola, 2023; Zanetti et al., 2024a; Sumfleth et al., 2020; Panoutsou et al., 2022; Fermeglia and Perišić, 2023), which also perform carbon farming and potentially restore degraded lands (in particular for the Mediterranean (MED) area) that are undergoing desertification due to climate change (Halbac-Cotoara-zamfir et al., 2020; Ferreira et al., 2022).

This work investigates the scenario for *Camelina sativa* cultivation in EU to produce SAF, considering the most recent EU regulatory limitations to consider this crop eligible for advanced biofuels production for aviation purposes. Camelina is increasingly recognized for its potential to be cultivated in degraded lands, poor soil conditions and various pedoclimatic conditions (Obour et al., 2015; Zanetti et al., 2021, 2024b; Matteo et al., 2020). It has been also largely tested as rotational crop with cereals and/or legumes in several climate zones where a multi-cropping system is possible for climatic conditions (Blanc et al., 2024; Franke et al., 2018; Panagea et al., 2025). Specific criteria to model camelina growth in selected Southern EU territories are set for this purpose since it does not directly fall under any of the definitions in the new Annex IX part A because: (1) it is a feed crop; (2) it doesn't meet the minimum requirements to be considered an "intermediate crop" since it would not have the conditions to grow if placed after cereals or legumes in non-irrigated land. In such arid areas, there would be some chances to adapt the crop rotation scheme, but in this case camelina would no longer be a true intermediate crop and should be treated as a main crop. Therefore, to cultivate camelina in sustainable conditions, this paper proposes a hybrid scheme between the two definitions cultivating the crop in "severely degraded" lands with a biennial rotation scheme with a cereal (that can be also replaced by a legume) because it's the only way to ensure it can be successfully cultivated. Since the implementing rules of the proposed new definition of the RED Annex IX' update have not been set yet, one purpose of this paper is to propose scientific evidence to demonstrate that allowing for additional practices would make sustainable options possible, particularly in the EU Southern territories.

Within the framework of the Horizon 2020 Bio4A project (Advanced Sustainable Biofuels for Aviation) (Bio4A | Advanced Sustainable Biofuels), a refined concept of land marginality has been developed to guide the sustainable expansion of camelina cultivation for biofuel feedstock. The novelty of this study advances the model proposed by Schillaci et al., 2023 within BIO4A, which features a multi-cropping system investigating barley and camelina rotations, integrating the most recent land and soil degradation requirements set by the EU legislation to produce low-iLUC risk biofuels (European Commission (EC), 2022; Guidehouse Netherlands, 2024). Specific target areas in the EU MED are selected to investigate the application of a 20-year rotation of camelina and barley with low soil inputs. Given that such agricultural rotation may be agronomically unsustainable in the long term scenario (particularly within the context of Mediterranean agroecosystems), alternative crops to camelina may be considered for a real scenario. Specifically, the proposed cereal component of the system (i.e. barley) can be effectively alternated with other cereal species (e.g. oat or wheat) or, more beneficially, with a leguminous crop on an alternating-year basis (Guarnaccia et al., 2024; Stagnari et al., 2017; Zegada-Lizarazu and Monti, 2011).

The scope of this work is to evaluate the camelina oilseeds potential for vegetable oil production towards Hydrotreated Renewable Jet fuel (HRJ), the most consolidated pathway to produce SAF. First, the camelina SAF production potential is evaluated at country level, and a market price is estimated. Secondly, a comprehensive GHG emissions assessment based on the EU-compliant methodology (RED) to produce feedstock for sustainable biofuels is proposed, together with guidelines also for ICAO-CORSIA purposes. Even though other studies already investigated the use of camelina as feedstock for SAF and its GHG emissions assessment (Resurreccion et al., 2021; Shonnard et al., 2010; Wang et al., 2020; Karlsson Potter et al., 2023; Miller and Kumar, 2013; Li and Mupondwa, 2014), they mainly focus on carbon intensity and energy balance evaluation under specific geographical or process assumptions. While they provided valuable insights into the environmental performance of camelina-based fuels, they did not include a comprehensive evaluation of policy frameworks or sustainability criteria, nor did they estimate realistic SAF production volumes and GHG savings compliant with current EU and international legislation. Differently, the current study proposes an innovative cross-sectoral integration of agronomic modelling, soil degradation and carbon-farming assessment, policy-compliant GHG accounting, techno-economic analysis, and policy evaluation. By merging these domains, the study provides for the first time a unified scenario connecting Camelina cultivation on degraded lands with the certification and sustainability requirements of RED and ICAO-CORSIA. Finally, this study proposes a strategy to enhance environmental benefits through agronomic best practices and renewable energy penetration within the value chains, while quantifying the additional GHG savings and the economic gap between SAF produced from camelina cultivated on severely degraded lands and conventional SAF, by applying a dedicated methodology to estimate the current offset and GHG reduction cost across different production pathways.

2. Supply chain assessment

2.1. Agricultural model

This study is developed on the cultivation of camelina in rotation with Barley (CAM-BAR), which is modelled in the study of Schillaci et al., 2023. The model integrates a process-based crop and soil model named ARMOSA (Perego et al., 2013) with a set of topographical and soil conditions to estimate the productivity of oilseeds from c and grains from barley across various soil types and climatic conditions, with a particular focus on southern MED regions. The rationale for concentrating on MED zones was attributed to their susceptibility to desertification and soil erosion (Ferreira et al., 2022; Panagos et al., 2021), making the cultivation of stress-tolerant and nutrient-efficient crops like camelina a viable strategy for soil carbon preservation and biomass production (Zanetti et al., 2021). To set the CAM-BAR modelling framework for identifying lands suitable for low-iLUC risk biofuel production in the EU, this work integrates additional classification layers aligned with the EU sustainability criteria. Specifically, three filters to the CAM-BAR results have been applied, to identify the potentially eligible land for camelina-based biofuel production.

- First, following the CORINE land cover classification (CLC) (Kosztra et al., 2019), specific agricultural areas have been selected to identify key-spots which may be considered suitable for biofuels production at low-iLUC risk. These include non-irrigated areas, lands under abandonment for harsh climate conditions, remote areas where agriculture is not performed for logistical problems and in some cases, lands with a high risk of marginality. Specifically, this study considers "2.1.1 Non-irrigated arable land" and the group "2.4.1, 2.4.2, 2.4.3 Heterogeneous agricultural areas in southern EU area".
- Second, lands with a Soil Organic Carbon (SOC) threshold (top 20 cm soil) up to 1.7 %, are considered. SOC is estimated considering an average soil bulk density of about 1.2–1.3 kg dm^{-1} considering the first 20 cm topsoil (Panagos et al., 2024), as depicted by the EU guidelines.
- Third, lands with camelina oilseed yield greater than 1.4 t ha^{-1} y^{-1} are individuated for economic profitability as proposed in literature (Panoutsou and Alexopoulou, 2020). In such areas, soil is subject to minimal fertilization and conventional tillage, diverging from other recent studies that investigated similar value chains (Ceriani et al., 2024a).

Aggregating those layers, a new map is generated showing land in which camelina can be cultivated. Data are calculated per region at NUTS2 level and aggregated per country. Looking at the resulting map, a large share of the areas are subjected to erosion (i.e. over 1.5 t ha^{-1} y^{-1} soil loss as requirement for the RED) being either coastal or sloped terrains with high-intensity rainfall patterns followed by extended dry periods, or internal areas under desertification with poor vegetation. This statement is supported by numerous studies available from literature (Ferreira et al., 2022; Panagos et al., 2015; Csikós and Tóth, 2023). Barley productivity has not been considered for this study.

2.2. Description of the supply chain and data gathering

The supply chain of camelina oil to SAF production is thoroughly investigated in each processing step to collect data necessary for a comprehensive techno-economic and environmental assessment. This enables an in-depth analysis of the entire conversion process. Modern biorefineries supplied by sustainable lipids process up to 1 megaton per year of triglycerides (Van Dyk and Saddler, 2024; Prussi et al., 2019; BEST and IEA Bioenergy Task 39, 2022; Hurtig et al., 2023), which for the EU mostly mean Used Cooking Oil (UCO) and waste lipids. So, for camelina oil, a similar size is assumed. The whole value chain for SAF production is evaluated as follows.

- Camelina has been cultivated according to the cropping system proposed in Schillaci et al., 2023, with minimal tillage and N-based fertilizers input corresponding to 50 kg of nitrogen per ha^{-1}. This strategy is also proposed in other studies (Keshavarz-Afshar et al., 2015; Malhi et al., 2014) and allows to assume a yearly average oilseeds production of 1.4 t ha^{-1} (threshold set in this study for minimum oilseeds yield per ha^{-1}), maintaining all other conditions as described for the Bio4A value chains (Medina Martos and Chiaramonti, 2023).
- On field operations as fertilizers distribution, tillage, sowing and oilseeds harvesting consider best practices developed within recent EU-funded projects (4CE-*MED* (CE-MED project) and *CARINA* (Carina project)). The proposed harvesting scenario considers two different strategies: swathing when camelina has already reached maximum yield and oil content plus combining at full seed maturity (innovative practice) and direct combining at full seed maturity (standard practice). The main advantage using the innovative technique is based on a reduction of 5 % crop cycle timing (Pari et al., 2024) compared to the standard practices (Stefanoni et al., 2021) maintaining similar energy inputs for machinery. Calculations of diesel consumption are based on the findings proposed by Brandess (Brandess, 2012) and calculated according to the formula (as shown in eq. (1)) used by ASABE standards (ASABE, 2006a; ASABE, 2006b) and described in Grisso et al. (Grisso et al., 2010).

$$Q_f = (0.0434 \times X + 0.019) \times P_{PTO} \tag{eq.1}$$

Where:

$\mathrm{Q_f}$ = diesel fuel consumption at partial load and full throttle (l h^{-1}).

X = fraction of equivalent PTO power available (decimal) - PTO is defined as “the power take-off - calculated from the torque and the speed at that power.

$$\mathrm{X = P/P_{RATED}}$$

All other operations are maintained as described in the Bio4A project documentation (Medina Martos and Chiaramonti, 2023).

- Oilseed storage, vegetable oil extraction and meal separation, vegetable oil cleaning and transport to HVO plants are considered the same as for the traditional vegetable oils producing biofuels (Prussi et al., 2020a; Edwards et al., 2019). Specific details on how to process camelina to edible oil for biofuels production are described in literature (Ceriani et al., 2024b; Veljković et al., 2022). HVO plant is modelled to maximize jet fuel (HEFA) production, i.e. considering a hydrotreating process prioritizing renewable jet (HRJ) production. While the conventional HVO process maximizes the diesel fraction (De Paz Carmona et al., 2019; Schlehöfer et al., 2024) targeting to deoxygenation reactions of the carboxylic groups, increasing HRJ (HEFA) yields requires instead further cracking of the resulting paraffins or olefins, increasing temperature, catalysts selectivity and hydrogen demand (needed to promote isomerization) (Verma et al., 2023; Vásquez et al., 2017). Reported jet yields in the literature therefore vary with process design and feedstock, up to 60 % maximum (Główka et al., 2024), but also show lower effective jet yields when the process is operated to maximize isomerization/cracking that is needed to meet cold-flow specification (Bellussi et al., 2016). For this model, the conversion process is modelled according to Mannion et al., 2024 and is parameterized using data from Chu et al. (2017) (Chu et al., 2017). Hydrogen is produced either from electrolyzers powered by renewable electricity, or steam methane reforming of fossil natural gas. The conversion efficiency is 53.5 kg of jet fuel per 100 kg of camelina oil processed.
- Jet fuel logistics, including transport and distribution to airports, have been considered as described for Bio4A case studies within the MED area (Medina Martos and Chiaramonti, 2023).

2.3. Biofuels production scenario and soil carbon offset

By combining agro-modelling results on oilseeds production and the conversion efficiencies proposed in the supply chain described above, the vegetable oil production is estimated according to eq. (2).

(eq. (2)) Camelina Oil Production = (Oilseeds Production × Lipids extraction efficiency [%]) × Overall Area.

Where:

- Oilseeds Production is the amount of dry camelina seeds produced per hectare (calculated from the model).
- Lipids extraction efficiency: the percentage of lipids extracted from camelina seeds was set at 38 %.
- Overall area according to the labels proposed in section 2.1: oilseed yield ≥1.4 t ha^{-1}; SOC ≤1.7 %; CLC classifications.

Then, SAF production as energy output is estimated according to eq. (3).

(eq. (3)) SAF Production = Camelina Oil Production × SAF conversion efficiency [%] × LHV

- SAF conversion efficiency is 53.5 % in mass (as described in 2.2).
- LHV is the low heating value of HRJ, corresponding to 43.74 MJ kg^{-1} (Mannion et al., 2024). This value is consistent with other measured values for SAF as studied by Boehm et al. (2022), which investigated the LHV of several bio- and fossil-derived jet fuels and found that paraffinic HRJ fuels with high iso-paraffin content exhibited LHVs in the range of 43.6–44.1 MJ kg^{-1}. This assumed value therefore lies within the reported confidence interval for iso-paraffin-dominated HRJ fuels and accurately reflects the expected composition of the fuel modelled in this study.

To evaluate the contribution of SAF within the EU commercial jet fuel share, detailed statistical data on final energy consumption for transports for each EU Member States are sourced from Eurostat (European Commission; Eurostat).

Finally, GHG emissions savings for soil carbon accumulation are evaluated on the average yearly SOC change [t ha^{-1}] considering 20 years of rotation, which is calculated as shown in eq. (4).

$$Average\ yearly\ SOC\ change = \frac{\sum_{i=0}^{10} \Delta\ SOC_{CAM} + \sum_{j=0}^{10} \Delta\ SOC_{BAR}}{i+j} \tag{eq.4}$$

Where ΔSOC is the yearly variation of SOC per crop, with i and j representing the years in the rotation cycle for even and odd years, respectively.

2.4. Economic estimates

The cost analysis for producing SAF from camelina oil is based on existing literature data and open-source databases. For camelina seeds production in 2025, this study considers a cost of 409 € t^{-1}. This is sourced from Stolarski et al. (2018), which provides an estimate for 2017, assuming a yield of 1.4 t ha^{-1} of oilseeds. Although they assume higher nitrogen fertilizer inputs than our current study, similar costs for other agricultural operations, such as sowing and diesel consumption, are observed. Since the price of urea has nearly doubled from 2017 to 2023 (Statista), there is no need for additional compensation for fertilizer expenses.

The cost to produce other commercial oilseeds is considered to be 308 € t^{-1} in 2025, based on Panoutsou and Alexopoulou (2020) and assuming a stable cost since 2020. The average selling price of EU vegetable oils in 2017 was 750 € t^{-1} (Rapeseed Oil vs Soybean Oil). Applying the same ratio between production costs and selling prices, camelina selling price should be approximately 998 € t^{-1} in 2017, maintaining similar income levels for farmers. (Rapeseed Oil vs Soybean Oil) Given a 33 % increase in the selling price of vegetable oils up to 2025 (Directorate General for Agricolture and Rural Development, 2025), this would translate to a camelina oil selling price of 1326 € t^{-1} in 2025. Differently, used cooking oil (UCO), which is the main feedstock of commercial SAF to date, has a market selling price of approximately 950 € t^{-1} (converted from Fastmarkets (2025) assuming CIF Rotterdam, 0.9 €/USD). The cost of producing SAF from camelina oil through hydroprocessing is based on techno-economic assessments from the literature. Monte et al. (2022) reported that the cost of feedstock (camelina oil) constitutes about 80 % of the total operational expenditures, highlighting the dominance of feedstock price in determining SAF production costs. Several other studies (de Jong et al., 2015; Pavlenko et al., 2019; Pearlson et al., 2013; Brandt et al., 2021) indicate feedstock costs shares between 50 and 70 % of overall SAF production costs at commercial scale. To integrate these data and address uncertainty, a refined cost evaluation was conducted (details are reported in Annex A). Operating expenditures were first calibrated according to the shares reported before. A Monte Carlo uncertainty analysis (50,000 iterations) was then performed, capturing realistic variability in feedstock prices, conversion costs, O&M expenditures and capital recovery. Feedstock prices for camelina oil and UCO were modelled using lognormal distributions with coefficients of variation of 20–25 %, while conversion, O&M and CAPEX parameters were described using probability distributions inferred from the ±20–50 % variability reported in existing TEA studies (de Jong et al., 2015; Davis and Bartling, 2022). The simulation generated probability distributions for SAF production cost and quantified the sensitivity of the results to the underlying variables.

The results show that the mean SAF cost from camelina oil is approximately 2220 € t^{-1}, while SAF derived from UCO exhibits a mean cost of 1797 € t^{-1} (as shown in Fig. 1), aligning with those estimated in recent studies (Hamelinck et al., 2021 and European Union Aviation Safety Agency, 2024).

The final stage of results aims to assess the economic gap for producing SAF from camelina cultivated on severely degraded lands compared to conventional, commercial SAF derived from UCO, in function of their carbon intensities. In the EU there are opportunities based on rewarding GHG emission savings through the recent mandates for transport sector as extended by RED III. Therefore, this study proposes a methodology to calculate the current offset of SAF produced from different pathways, moving beyond mandates that obligate operators to purchase SAF[1], which aim to promote further GHG emissions reduction.

3. GHG emissions accounting

3.1. Methodology

The GHG emissions accounting methodology used for this study follows an attributional approach and is described in the Annex V of the Renewable Energy Directive (EU) 2018/2001. This methodology has been developed to calculate the carbon intensity of all biofuels, therefore the pre-calculated emission factors for road biofuels (also called "default values"; details of the calculations are described in Edwards et al. (2019) (Edwards et al.)) cannot be used for aviation purposes. Compared to the traditional Life Cycle Assessment (LCA), RED methodology can be described as a simplified analysis studying GHG emissions accounting. Within this calculation model, emissions related to the infrastructure construction, maintenance and decommissioning of fuel and electricity producing facilities, including materials cycles, are not considered. According to the RED guidelines, emissions are allocated between the main product (fuel) and co-products (e.g. oil cake) depending on their energy content (i.e. Low Heating Value - LHV). The functional unit is the lower heating value of fuel produced and combusted.

The proposed calculations also align with the methodology used for the International Civil Aviation Organization (ICAO), established the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), to calculate aviation GHG emissions for the production and use of SAF (International Civil Aviation Organization, 2024a). Here, SAF's carbon intensity consists of two main components: the main "Core LCA" carbon intensity and the "Indirect Land Use Change (iLUC)" contribution (details are described in Prussi et al. (2021b). Since RED does not consider iLUC emissions, Core LCA emissions of RED and CORSIA use the same methodology to account for the SAF carbon intensity, with the only need to adapt the global warming potential from the IPCC's assessment reports. Both RED and CORSIA permit to use either "actual" LCA values, meaning values calculated according to the methodologies proposed, or a combination of both disaggregated default and actual values.

The goal of the GHG emissions assessment presented in this study is to calculate the life-cycle emissions to produce SAF from camelina, including GHG savings from carbon farming and degraded lands recovery. The system boundaries include the supply chain described in section 2.2, plus the utilization (combustion) of the fuel, which is set to zero as all produced CO_2 is biogenic (according to both CORSIA and RED rules). Carbon intensities of SAF pathways are evaluated for both waste lipids (i.e. UCO and tallow) and camelina, which is investigated in a standard (business-as-usual) and a best (considering decarbonized inputs) scenario.

3.2. GHG emissions reduction and crediting mechanisms

Requirements to determine biofuels sustainability differ between RED and CORSIA. Within the RED framework, the GHG emissions savings are calculated by comparing the carbon intensity of the biofuel to a reference fossil fuel comparator (FFC) set at 94 $gCO_2eq\ MJ^{-1}$ (as shown in eq. (5)).

$$\%\ \text{GHG savings} = \frac{FFC - E}{FFC} \tag{eq.5}$$

Where E are the total emissions from the biofuel. A minimum of 65 %

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[1] In the EU, biofuel production is primarily driven by market regulations and mandates rather than direct financial incentives, a contrast to models seen in regions like the US.

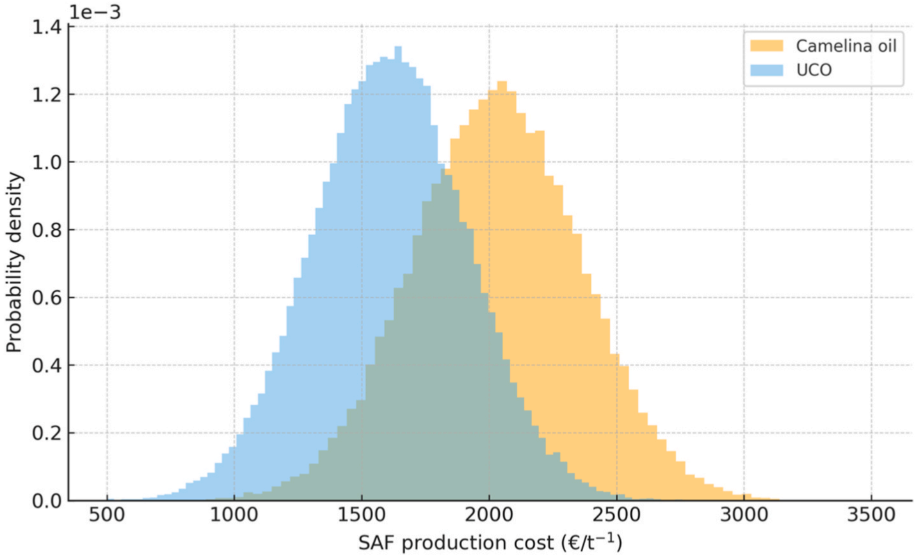

Fig. 1. Probability density distribution of SAF production cost for camelina and UCO, obtained from a Monte Carlo simulation with 50,000 iterations.

GHG emissions reduction is required to consider the biofuels eligible for certification purposes according to the RED. For CORSIA, it is required that eligible fuels reduce GHG emissions by more than 10 % compared to standard baseline fuels (set at 89 $gCO_2eq\ MJ^{-1}$) to contribute to CORSIA's goal of capping CO_2 emissions for international flights.

RED and its IR 2022/996 (European Commission (EC), 2022) allow to claim GHG emissions credits based on both positive changes in soil carbon stock (emission savings from soil carbon accumulation via improved agricultural management, e_{sca}) over 10 years of improved crop managements (e.g. no tillage, use of intermediate crops, soil improvement with biochar or digestate, etc.) and cultivating biomass on severely degraded lands (included within annualized emissions from carbon stock changes due to land-use change, e_l).

For e_{sca}, this study considers the benefits of applying the agricultural practices proposed by CAM-BAR and estimates the GHG emissions credit by means of the formula recommended in the RED IR 2022/996 (European Commission (EC), 2022) as shown in eq. (6).

$$e_{sca} = (CS_A - CS_R) \times 3.664 \times 10^6 \times \frac{1}{n} \times \frac{1}{p} - e_f \qquad \text{(eq.6)}$$

Where:

CS_R is the mass of soil carbon stock per unit area associated with the reference crop management practice in Mg of C per ha.

CS_A is the mass of soil estimated carbon stock per unit area associated with the actual crop management practices after at least 10 years of application in Mg of C per ha.

3.664 is the quotient obtained by dividing the molecular weight of CO_2 (44.010 g mol^{-1}) by the molecular weight of carbon (12.011 g mol^{-1}) in g $CO_2eq\ gC^{-1}$.

n is the period (in years) of the cultivation of the crop considered. 20 years assumed.

P is the productivity of the crop, measured as MJ biofuel or bioliquid energy per ha per year.

e_f emissions from the increased fertilizers or herbicide use. Zero in this study.

The term for change in soil carbon stock is calculated according to the CAM-BAR results (Schillaci et al., 2023) as shown in eq. (4). According to the RED guidelines, the cap shall be 25 $gCO_2eq\ MJ^{-1}$ fuel for the entire period of application of the e_{sca} practices. As regards the credit for cultivating biomass in severely degraded lands, the cultivation system proposed in CAM-BAR considers the requirements set in the EC guidelines (European Commission (EC), 2022; Guidehouse Netherlands, 2024) to classify the lands as such (as explained in section 2.2). Therefore, a bonus of 29 $gCO_2eq\ MJ^{-1}$ fuel can be claimed if biomass is obtained from restored degraded land, if evidence is provided that the land was not used for agriculture or any other activity (e.g. fodder lands).

Differently, carbon farming crediting mechanisms within CORSIA are based on considering both ILUC and DLUC emissions. Specifically, ILUC emissions are accounted by adding a default value depending on the region, fuel feedstock and pathway specification (International Civil Aviation Organization, 2024b) while DLUC emissions are calculated considering a specific methodology (International Civil Aviation Organization, 2024a) similar to the RED scheme.

While this study is a transparent model exercise based on geospatial and measured data, biofuels operators have to certify their supply chains using voluntary and national certification schemes available for EU countries (European Commission website, 2024b), which verify the compliance with the EU/International sustainability and GHG saving criteria for both RED and CORSIA purposes.

3.3. *Life cycle inventory*

In conducting the life cycle inventory for the supply chain considered within this study, a rigorous collection of complementary information and data on feedstock properties, energy inputs, use of materials, and technological specifications (as explained in section 2.2) have been collected for the scope of performing the calculation of SAF carbon intensity.

As regards the emissions from agricultural activities, N_2O emissions from the cultivation stage follow the RED II requirements, which refers to Tier 2 of the IPCC methodology (Intergovernmental Panel on Climate Change (IPCC), 2019). This considers specific emission factors for different environmental conditions, soil conditions and crops, including both direct and indirect emissions from the utilization of mineral fertilizers, crop residue left in the field, etc. As regards the emissions from neutralizing acidification caused by mineral fertilizers, the IR 2022/996 (European Commission (EC), 2022) indicates that the acidification caused by nitrogen fertilizer use in the field shall be accounted. Therefore, this work assumes the emission factor indicated for the neutralization of nitrate fertilizers equal to 0.783 kg $CO_2eq\ kg^{-1}$ N. All other agro-based data are retrieved from the LCA within Bio4A project (Medina Martos and Chiaramonti, 2023), except N input and diesel consumptions for agro-machineries as described in section 2.2.

Specifically, from the present scenario, diesel input for agro-machineries is calculated equal to 43.08 l ha^{-1} and 39.4 l ha^{-1} for innovative and standard practices, respectively. Unlike the standard scenario where the agro-machineries are fuelled by diesel, in the best scenario, the agro-machineries are considered to be fuelled by the HVO co-produced in the SAF production process.

As regards processing, this study considers the scheme of inputs/outputs proposed by Chu et al. (2017) as described in section 2.2, including the thermal and electricity demand. The GHG emissions from this step are allocated to all valuable co-products—liquefied petroleum gas (LPG), naphtha, kerosene, and diesel—based on energy allocation principles. The process consumes 0.03 kg of fossil-based hydrogen per kg of camelina oil, with an hydrogen carbon intensity of 99.3 g CO_2eq MJ^{-1} assumed from "GMCH1" pathway (sourced from JECv5 (Prussi et al., 2020b)) for the standard scenario with emissions for "conditioning and distribution" excluded since hydrogen is used and produced within the refinery. Differently, for the best scenario renewable hydrogen comes with zero carbon intensity being produced from renewable electricity only, according to RED. The electricity used in the process has a carbon intensity of 83 g CO_2eq MJ^{-1} (mid voltage for the EU grid mix in 2019 (European Commission (EC), 2022)) in the standard scenario and 72 g CO_2eq MJ^{-1} (high RES share in 2030 as in JECv5 (Prussi et al., 2020b)) for the best scenario. The heat supplied to the conversion process has a carbon intensity of 77.9 g CO_2eq MJ^{-1} (natural gas combustion, GPHT2b (Prussi et al., 2020b)) for the standard scenario and the carbon intensity of the co-produced bio-LPG combusted with 90 % efficiency for the best scenario. Emissions related to catalyst use during hydroprocessing, sourced from ecoinvent v3.10, are considered negligible.

Finally, emissions for transport of biomass and SAF distribution are assumed as for Bio4A project (Medina Martos and Chiaramonti, 2023), which proposed camelina supply chains in Spain and Italy, biorefineries located in Italy, and Schipol (Netherlands) and Fiumicino (Italy) as airports. It has been demonstrated that different scenarios across EU do not affect this contribution of emissions.

4. Results and discussion

4.1. Available areas for producing camelina

Table 1 shows the available area in EU where camelina seeds yield above 1.4 t ha^{-1} in lands with SOC $\leq$1.7 % classified under CLC 211 and 241,242,243 (without agroforestry). The results of the selected areas are reported per selected EU Member States, showing the effect of each selected filter on CAM-BAR. The results of applying the same filters beyond the proposed thresholds are also reported.

The analysis reveals significant disparities in both production capacity and contribution to renewable fuel targets across EU Member States: Italy emerges as the dominant contributor, showing that almost one fifth of its overall surface is suitable for camelina cultivation (about one third of the overall agricultural area). Spain, Greece, France and Portugal show significant contributions as well, representing almost the remaining part. In contrast, smaller member states such as Hungary, Slovenia, Croatia and Bulgaria demonstrate minimal contributions, which shows how challenging the implementation of this agricultural model would be. The geographic variability in CAM-BAR model applicability reflects the complex interplay between soil conditions, climate parameters, and agronomic management requirements for successful crop rotations in degraded lands. Mediterranean regions show high adaptability for CAM-BAR implementation because cereals (in this case, barley) are largely used in the arid and semi-arid Mediterranean environments and camelina confirms high performances in low-quality soils with harsh climate conditions (Schillaci et al., 2023).

However, the model's effectiveness varies significantly due to soil physical properties affecting water infiltration and retention, nutrient availability influenced by pH and organic matter content, and climate factors determining seasonal water stress patterns. Besides Italy, where the individuated areas are distributed among the whole area, other concentrated areas for CAM-BAR applicability are in south-west of Spain and France, south of Portugal and north of Greece as shown in Fig. 2. There are no substantial differences of the individuated areas considering various CLC levels: the first map (CLC211, non-irrigated arable land) shows a larger surface due to the presence of enough rainfalls during the growing season to support the crop without needing irrigation; differently, the second map, which contains agricultural areas but excludes agroforestry areas, shows that Portugal has a different distribution of high-yield camelina areas. The latter indicates that while some of the non-irrigated arable land is suitable, a significant portion of the land with high yield potential is a mix of agricultural and natural land covers suggesting less degradation in marginal areas or land with constraint to agricultural use. This land use pattern is common in the Iberian Peninsula, where many agricultural plots are small and fragmented, and are often mixed with natural vegetation, particularly in rural and semi-arid regions. The specific CLC level (241 and 242) for these mixed areas means that Portugal's landscape is better suited to camelina cultivation in a more heterogeneous land use context rather than just large, continuous plots of non-irrigated farmland. Specific GIS data have been provided as supplementary material.

4.2. Sustainable aviation fuel potential

Agricultural production data are reported for the selected countries, showing grains productivity, vegetable oil production, and Sustainable Aviation Fuel (SAF) productivity (as shown in Table 2) alongside their respective contributions to EU totals.

Table 1

Available areas in EU for the proposed classifications. Specifically, the last column aggregates the results where productivity of camelina seeds yield above 1.4 t ha^{-1} in lands with SOC $\leq$1.7 % classified under CLC 211 and 241,242,243 (without agroforestry).

Country	Country area	CLC211 SOC <1.7 % Yield <1.4 t ha^{-1}	CLC211 SOC >1.7 Yield <1.4 t ha^{-1}	CLC211 SOC <1.7 % Yield >1.4 t ha^{-1}	CLC211 SOC >1.7 % Yield >1.4 t ha^{-1}	CLC24x SOC <1.7 % Yield <1.4 t ha^{-1}	CLC24x SOC >1.7 % Yield <1.4 t ha^{-1}	CLC24x SOC <1.7 % Yield >1.4 t ha^{-1}	CLC24x SOC >1.7 % Yield >1.4 t ha^{-1}	Overall area SOC <1.7 % Yield >1.4 t ha^{-1}
-	*thousand km^2*	*km^2*	*km^2*	*km^2*	*km^2*	*km^2*	*km^2*	*km^2*	*km^2*	*km^2*
Hungary	93	423	160	75	37	37	14	5	2	79
Portugal	89	120	35	4,404	1,971	228	89	5,848	7,700	10,252
Croatia	56	1	8	2	11	0	17	4	58	6
Bulgaria	111	3	1	20	4	5	4	10	4	30
Spain	499	61,769	7,473	17,198	4,345	10,414	4,398	4,424	4,380	21,622
Greece	132	1,970	386	7,590	1,631	1,230	756	5,867	9,402	13,457
Slovenia	20	0	43	1	119	0	858	1	726	2
France	549	87	645	7,224	2,533	39	1,063	4,041	6,859	11,265
Italy	301	2,267	2,457	44,461	29,967	646	2,217	15,049	26,611	59,510
EU	1,850	66,641	11,207	80,973	40,617	12,599	9,416	35,249	55,739	116,223

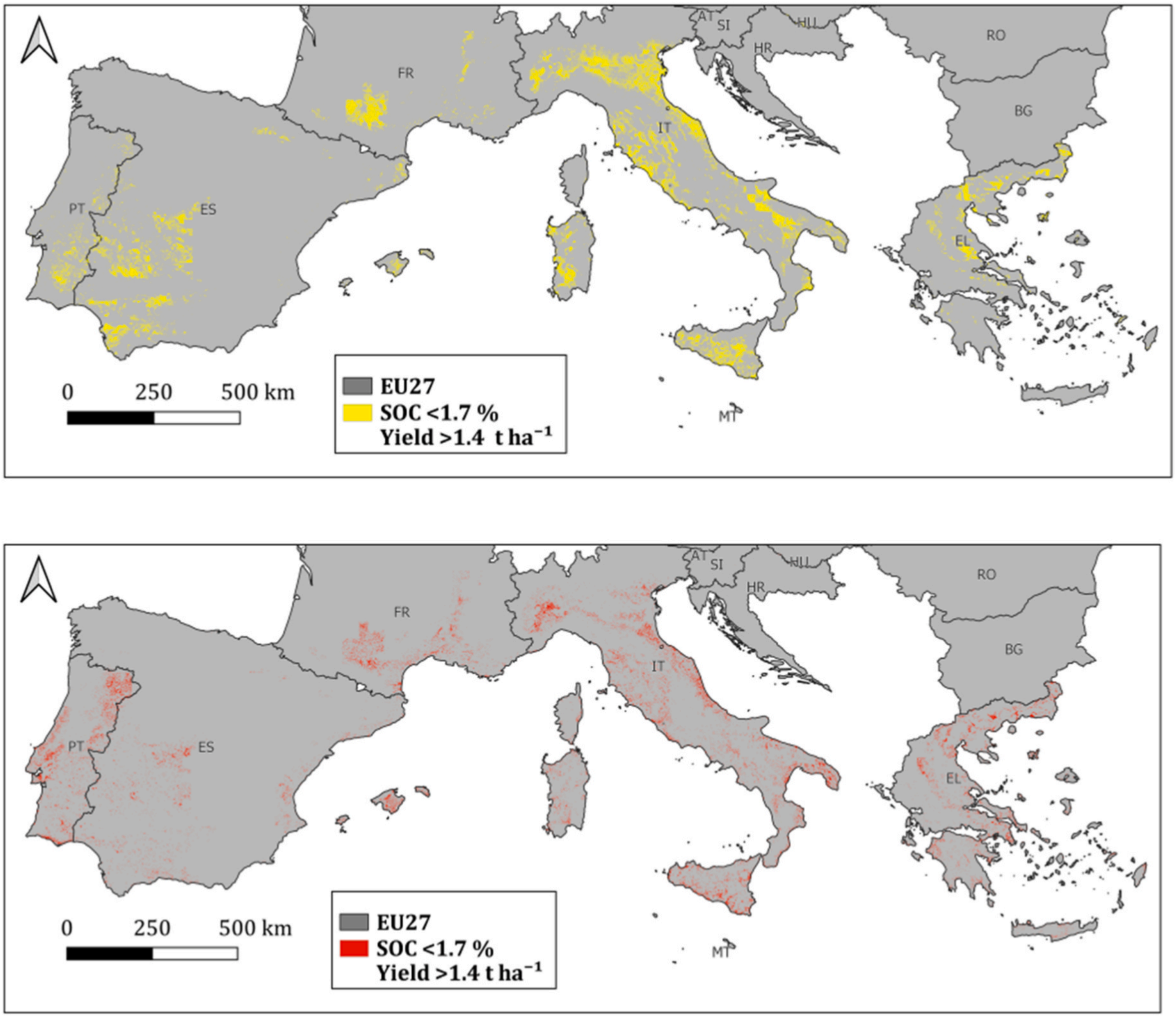

Fig. 2. Geographic position of the areas indicated by CAM-BAR applicability where camelina seeds yield above 1.4 t ha^{-1} in lands with SOC ≤1.7 % classified under CLC 211 (top – yellow-coloured distribution) and 241,242,243 (without agroforestry) (bottom – red-coloured distribution). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Productivity of camelina seeds, vegetable oil and SAF referring to the areas identified in Table 1. Data used for the calculations derives from the LCI: camelina seeds productivity 1.4 t ha^{-1} (1.3 t ha^{-1} dry seeds), vegetable oil extraction efficiency from dry oilseed, 38 %; SAF yield, 53.5 % as mass fraction.

Country-	Grains productivity	Vegetable Oil productivity	SAF productivity		
	kt	*kt*	*kt*	*EJ*	*Mtoe*
Hungary	10.29	3.91	2.09	0.09	0
Portugal	1,335	507	271	11.87	0.28
Croatia	0.75	0.28	0.15	0.01	0
Bulgaria	3.84	1.46	0.78	0.03	0
Spain	2,815	1,070	572	25.03	0.60
Greece	1,752	666	356	15.58	0.37
Slovenia	0.29	0.11	0.06	0	0
France	1,467	557	298	13.04	0.31
Italy	7,748	2,944	1,575	68.90	1.65
EU	15,132	5,750	3,076	134.56	3.21

The SAF productivity analysis indicates varying potentials across member states, with Italy that produces over 1.6 Mt of SAF, corresponding to over 50 % of the total. Also Spain shows notable performance at about 570 kt and about 20 % contribution to EU total, while Greece, France and Portugal integrate the EU SAF production capacity with 926 kt, i.e. 30 % of the total. Central EU countries, despite their significant agricultural base, contributes less than 0.1 % to the EU aggregate.

The total SAF output across the assessed Mediterranean countries reaches approximately 3.2 Mtoe, corresponding to 353 % of the REFuelEU Aviation mandate for 2025 (0.91 Mtoe) and 175 % to the target for 2030 (considering 1.83 Mtoe maximum for bio-SAF and 0.55 Mtoe minimum for renewable fuel of non-biological origin (RFNBO), as estimated from POTEnCIA CETO 2024 scenario (Neuwahl et al., 2024). Among the countries analyzed, Italy stands out as the dominant contributor, producing nearly 1.65 Mtoe of SAF—theoretically being able to cover alone more than the target of SAF for the 2025 and 90 % of the 2030 target.

These results highlight a geographically uneven, but regionally significant, capacity for SAF deployment, underlining the strategic importance of southern European countries in meeting near-term decarbonization targets in aviation. These findings do not overestimate the real potential since the maximum oilseeds productivity is kept at 1.4 t ha^{-1} even though the model estimates areas where productivity exceeds 3 t ha^{-1}. In support of this, recent trials performed by Zanetti et al. (2024b) showed that transitioning from crop-growth models to actual field-measured data in areas with various forms of marginality, including steep slopes, low soil fertility, adverse terrain, shallow, stony soils, and extreme soil textures (sandy and clay-rich) show clear signs of reduced camelina productivity. As regards the infrastructure to produce SAF through the HRJ process, in the EU, there are already several HVO plants that are either operational or in the process of being converted to HRJ production. These facilities are typically located within oil refineries, which have established logistics systems to efficiently manage the volumes of feedstocks and fuels produced. It is worth noting that the HRJ production also yields significant quantities of co-products at the EU scale—approximately 506 kt of LPG, 730 kt of naphtha, and 805 kt of diesel—which represent additional opportunities for decarbonization in the transport sector.

4.3. Carbon intensity of SAF

The results of the GHG emissions assessment are reported as different emission contributions as in the RED framework in the form of actual values and including the GHG emissions savings generated by cultivating on severely degraded lands and performing carbon farming (as shown in Fig. 3). UCO and tallow deliver GHG emissions of 19.4 and 23.4 $gCO_2eq\ MJ^{-1}$ respectively, with both cases primarily impacted by fuel processing emissions (e_p) and minor contributions from transport and distribution (etd), while there are no upstream emissions associated with feedstock production, both being biowastes. These values translate to emissions savings of 79 % for UCO and 75 % for tallow under the RED, and 78 % (UCO) and 74 % (tallow) under CORSIA, also consistent with their respective default values.

In contrast, the camelina-based SAF scenario at standard conditions demonstrates higher baseline emissions due to the substantial contribution of emissions for cultivation. The small difference in diesel inputs of agro-machineries for the two scenarios investigating different harvesting techniques for camelina (described in section 2.2) does not significantly affect the carbon intensity of SAF (resulting in less than 0.1 $gCO_2eq\ MJ^{-1}$ offset). Therefore, the overall carbon intensity is 39.5 $gCO_2eq\ MJ^{-1}$, which is above the REDII eligibility threshold for advanced biofuels.

However, when accounting for emission savings from improved soil carbon management (e_{sca}, capped at 25 $gCO_2eq\ MJ^{-1}$ maximum) and the degraded land bonus, in line with the provisions of REDII Annex V and IR 2022/996, the net GHG intensity of camelina SAF improves significantly. For the standard scenario, the SAF includes an e_{sca} value calculated at 13.71 $gCO_2eq\ MJ^{-1}$, consisting in a median value of the regions performing carbon farming reported in Schillaci et al. (2023), and results in a net emission of −3.2 $gCO_2eq\ MJ^{-1}$ (details of calculations are reported in the Annexes). In the areas classified as severely degraded lands where carbon does not accumulate over the years, other agricultural practices such as cover crops or biochar/digestate intake, can cover the gap to ensure sufficient soil carbon intake (not considered within this study). Finally, the “camelina best” case—featuring decarbonized inputs and reduced energy demand—achieves −30.8 $gCO_2eq\ MJ^{-1}$, accounting the maximum e_{sca} savings corresponding to 2.5 tonnes of carbon per ha over the 20 years of cultivation. According to the CAM-BAR results, this threshold can be reached in some areas individuated by the model (Schillaci et al., 2023). These results show that SAF from camelina in the standard scenario does not achieve the minimum GHG emission savings requirements for biofuels (58 % vs 65 % as minimum requirements), while in the other cases the GHG emissions reduction is well above 100 % (103 % for standard with credits and 133 % for the best scenario).

These values demonstrate strong alignment with those calculated within the CORSIA default values, where camelina SAF leads to 42 $gCO_2eq\ MJ^{-1}$ with a default iLUC value of −13.4 $gCO_2eq\ MJ^{-1}$ when feedstock is grown as a secondary crop that avoids other crops displacement (International Civil Aviation Organization, 2024b). While for the RED scenario, an annual monocrop cultivation scenario of camelina alternated with barley was investigated, the CORSIA’ iLUC bonus considers camelina used as an intermediate crop, which is also a possible solution within the RED (not evaluated in this study) for producing SAF as advanced biofuels. For SAF certification proposals under CORSIA, however, the actual value calculated in this study (equivalent, as mentioned, to the ore LCA value) can be used, and a bonus for soil organic carbon accumulation can also be considered, which does not have a cap as in the case of RED. Therefore, the carbon intensity of SAF can be reduced to extremely low values that vary on a case-by-case basis, and it is recommended to evaluate these case by case, alongside specific SOC measurements.

The present results highlight the critical role of carbon accumulation practices and land restoration strategies in enabling ultra-low or even negative emission pathways for SAF, particularly when using a low iLUC

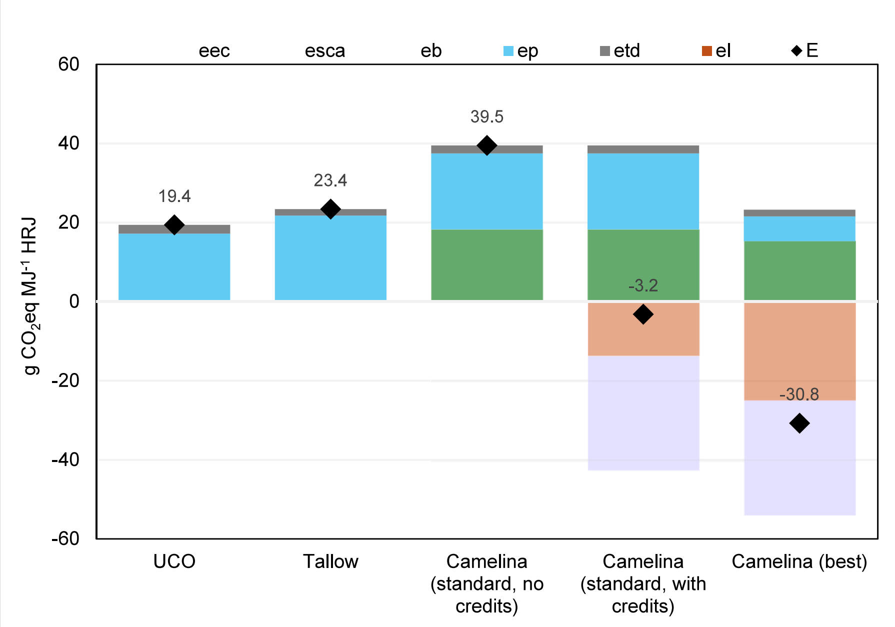

Fig. 3. Carbon intensities of SAF pathways from different feedstocks: Used Cooking Oil (UCO), Tallow, and Camelina under three scenarios: standard, with credits or not, and best case. Emissions contribution consist in: eec – Emissions from cultivation; esca – Emission savings from improved agricultural practices; eb – Emission savings from degraded land restoration; ep – Emissions from processing; etd – Emissions from transport and distribution. Values are expressed as net totals, summing all contributions. Negative total emissions in the camelina cases with credits show the effect of practices introducing carbon accumulation.

crop such as camelina. The accounting under both RED and CORSIA regulations thus demonstrate that, under specific conditions, such biofuel pathways can perform soil carbon accumulation—an outcome that underscores the need for harmonized methodologies and coordinated, sustainable strategies (Roux et al., 2024) supporting environmental benefits and deployment of aviation biofuels.

4.4. Quantifying the GHG reduction cost for SAF production

To quantify the current gap between jet fuel price and GHG emissions reduction, Fig. 4 shows the costs and carbon intensities of conventional jet fuel, UCO SAF and different variants of SAF from camelina. Costs are retrieved from the techno-economic assessment proposed in section 2.4. For GHG emissions, the previous section showed the possibility to reduce the carbon intensity calculated according to RED of camelina SAF simply by growing it on severely degraded land with the methodology proposed in this paper, and this leads to a significant reduction in carbon intensity without altering the economics (for the standard scenario). The orange line that intersects the “Conventional Jet Fuel” and “UCO SAF” represents the GHG reduction cost of UCO SAF of approximately 287 € t^{-1} CO_2eq. The point individuating “Camelina SAF, standard”, nearly lies on the orange line, demonstrating a similar GHG reduction cost. Because camelina SAF cost uncertainty is quite large (including its standard deviation), its potential GHG reduction costs—provided that GHG credits for production on degraded land are recognized—fall within the same range as UCO SAF. While the uncertainty in carbon intensity is not accounted, it may offsets the range of possible GHG reduction costs.

Considering the median cases for SAF costs, if no credits are obtained for camelina, the GHG reduction cost would be around 612 € t^{-1} CO_2eq, and for the best practice around 268 € t^{-1} CO_2eq, compared to 317 € t^{-1} CO_2eq for UCO. Even if the camelina SAF produced with the best sustainable practices may introduce some additional costs (e.g. renewable electricity, etc.), the blue line indicates that there is room to maintain GHG reduction costs at the same level as UCO. In the best case scenario, this approach offers additional benefits to various policies such as the EU Biodiversity Strategy by contributing to biodiversity restoration (thus supporting a new agro-system capable of covering the identified marginal areas), the EU Soil Strategy by enhancing soil health, and the LULUCF regulation by promoting carbon accumulation. Therefore, the proposed scheme would introduce a novel mechanism based on rewarding GHG emissions reduction, which can offset the extra costs incurred while providing the discussed benefits. Finally, it is worth mentioning that this system has been developed for an EU scenario, but with updated data on costs and carbon intensities, it could be easily adapted to the ICAO-CORSIA’ scheme as well.

5. Conclusions

5.1. Findings

This study presented a comprehensive scenario assessment of using camelina as a sustainable feedstock to produce Sustainable Aviation Fuel (SAF) within the EU, with a focus on Southern EU and Mediterranean countries. The research showed the potential of camelina cultivation on “severely degraded lands” as defined in the EU framework of the Renewable Energy Directive and proposed a low indirect land-use change (iLUC) risk feedstock cultivation protocol tailored for Southern EU Mediterranean countries to recover lands already degraded or at risk of marginalization. By using the CAM-BAR model with specific boundary conditions, significant areas suitable for camelina cultivation have been identified, notably in Italy, Spain, Greece, France, and Portugal: Italy emerged as the dominant contributor, capable of producing more than 50 % of the total potential SAF output. Overall, the Mediterranean countries could reach approximately 3.2 Mtoe of SAF, achieving 175 % of the REFuelEU Aviation 2030 target. Camelina SAF demonstrated significantly lower carbon intensity compared to traditional UCO-based SAF when accounting for carbon savings from improved agricultural practices and degraded land restoration. The “best case” scenario achieved a carbon intensity of −30.8 gCO_2eq MJ^{-1}, showcasing the potential for ultra-low or even negative emission pathways under specific conditions. The study also proposed an economic assessment of SAF pricing compared to the GHG emissions savings, identifying how these parameters are interconnected. This scheme aims to bridge the economic gap between camelina-based SAF and conventional or UCO-based SAF by demonstrating how improved cultivation practices and land-use

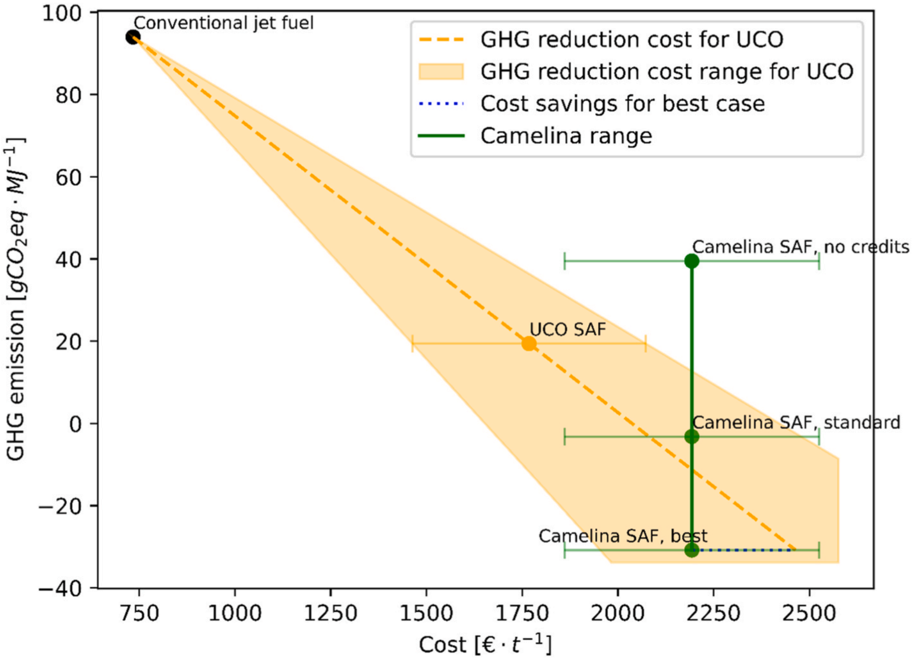

Fig. 4. Chart showing a relation between Sustainable Aviation Fuel (SAF) price (in Euro per t) and its carbon intensity (gCO_2eq MJ^{-1}). Uncertainties are based on the standard deviation of the SAF production price.

choices can significantly reduce GHG emissions.

5.2. Future directions

While camelina SAF has different cost dynamics, this approach highlights opportunities to maintain comparable GHG reduction costs and deliver additional environmental co-benefits—such as biodiversity restoration, soil health improvement, and carbon accumulation—that strengthen the overall sustainability of the supply chain. This cross-disciplinary synthesis provides not only scientific insights but also a practical, policy-relevant framework for implementing the proposed agronomic and biofuel certification schemes in Europe. By linking carbon farming, sustainable crop rotations, GHG emissions offset and advanced biofuel pathways within the current RED and ICAO-CORSIA contexts, the study offers actionable evidence to inform both policy-makers and industry stakeholders. The findings also underscore the strategic importance of Southern European countries in contributing to sustainable biomass supply, where large concentrations of degraded land represent a significant and underutilized resource for low-iLUC feedstock production. Countries with high camelina suitability could promote targeted support measures to accelerate deployment of the proposed scheme.

5.3. Study limitations and implications for future research

Although the study provides a robust framework for the developed supply chains, further assessments are needed to validate technical and economic assumptions through real-world experiences to enhance the applicability and reliability of the proposed solutions. For instance, the focus on a continuous barley-camelina rotation for 20-year remains a shortcoming: in a real case, the authors suggest the need for a more diversified crop rotation strategy to better achieve long-term sustainable agricultural practices. These limitations open new avenues for future work. Models such as CAM-BAR could be expanded to include a broader portfolio of low-iLUC crops and region-specific rotations, enabling more realistic assessments of land-use dynamics across Europe. Future works may integrate real-farm data on yields, soil improvements and farmer adoption, as well as techno-economic data from emerging camelina-to-SAF value chains, to improve the applicability and reliability of the proposed system. Finally, future analyses could explore how policy instruments—carbon crediting, soil-restoration actions, RED multipliers or iLUC-risk mitigation schemes—can be optimized to support the economic viability of camelina SAF and scale its deployment in a scale aligned with EU climate and energy targets.

CRediT authorship contribution statement

M. Buffi: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **S. Bergonzoli:** Writing – review & editing, Validation, Methodology, Data curation. **E. Medina-Martos:** Validation, Software, Methodology, Data curation. **O. Hurtig:** Writing – review & editing, Resources, Investigation, Data curation, Conceptualization. **D. Chiaramonti:** Writing – review & editing, Validation, Supervision, Project administration. **F. Tozzi:** Visualization, Resources, Data curation. **A. Monti:** Writing – review & editing, Validation, Supervision. **M.G. Sessa:** Visualization, Resources, Formal analysis. **C. Thiel:** Writing – review & editing, Validation, Supervision. **C. Schillaci:** Writing – original draft, Visualization, Methodology, Investigation, Conceptualization.

Disclaimer

The views expressed here are purely those of the authors and may not, under any circumstances, be regarded as an official position of the European Commission.

Declaration of competing interest

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.enpol.2025.115043.

Data availability

Data will be made available on request.

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