Advanced Sustainable BIOfuels for Aviation

Deliverable D4.3: Final Environmental Sustainability Assessment

Consortium:

Acronym	Legal entity	Role
RE-CORD	CONSORZIO PER LA RICERCA E LA DIMOSTRAZIONE SULLE ENERGIE RINNOVABILI	CO
ENI	ENI S.p.A.	BEN
SKYNRG	SKYENERGY BV	BEN
CENER	FUNDACION CENER-CIEMAT	BEN
ETA	ETA – Energia, Trasporti, Agricoltura Srl	BEN
CCE	CAMELINA COMPANY ESPANA S.L.	BEN
JRC	JOINT RESEARCH CENTRE – EUROPEAN COMMISSION	BEN

CO…Coordinator, BEN…Beneficiary

Sarriguren, June 30, 2023

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 789562.

General Information

Call identifier:	H2020-LCE-2017-RES-IA
GA Number:	789562
Topic:	LCE-20-2016-2017
Start date of project:	01/05/2018
Duration:	5 years (30/06/2023)
Work Package:	WP4 – Evaluation
Type:	Deliverable
Number:	D4.3
Title:	Final Environmental Sustainability Assessment
Due Date:	30/06/2023 (Month 62)
Submission date:	30/06/2023
Reference Period:	30/04/2021 – 30/06/2023
Prepared by:	CENER (Lead)
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Dissemination Level:	Public

INTERNAL MONITORING & REVISION TABLE					
REV.	**DATE**	**DESCRIPTION**	**PAGES**	**CHECKED**	**APPROVED**
1	**26-06-2023**	**First Draft**	**37**	**EMM, DC, TB**	**-**
2	**30-06-2023**	**Final Version**	**42**	**EMM, DC**	**DC**
3	**31-07-2023**	**Revised Version**	**39**	**EMM**	

Document Type		
PRO	Technical/economic progress report (internal work package reports indicating work status)	
DEL	Technical reports identified as deliverables in the Description of Work	**X**
MoM	Minutes of Meeting	
MAN	Procedures and user manuals	
WOR	Working document, issued as preparatory documents to a Technical report	
INF	Information and Notes	

Dissemination Level		
PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	
CON	Confidential, only for members of the Consortium	

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Abbreviations

BTU	Biomass Tretament Unit
CCE	Camelina Company España
CO	Camelina Oil
ES	Spain
Ex	Experimental (Referred to the calculation of soil carbon accumulation)
GHG	Grenhouse Gases
HEFA	Hydroprocessed Esters and Fatty Acids
ILUC	Indirect Land Use Change
IT	Italy
REDII	Renewable Energy Directive (Directive (EU) 2018/2001)
SAF	Sustainable Aviation Fuel
SMR	Steam Methane Reforming
Th	Theoretical (Referred to the calculation of soil carbon accumulation)
UCO	Used Cooking Oil

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Executive Summary

Decarbonising the aviation sector is one of the targets of the *Fit for 55* package of the EU, by means of the ReFuel Aviation initiative, which pursues a progressive increase of the share of biofuels in the sector. Despite different technological pathways for the production of Sustainable Aviation Fuel (SAF) are already mature and relatively high blending percentages are allowed, the deployment of large supply chains is still scarce. The Bio4A project addressed this gap, by demonstrating a value chain not only including the industrial production of SAF, but also feedstock supply and logistics for fuel delivery.

This study analysed the GHG emissions of the proposed value chain, which considers the conversion of lipid feedstocks, namely Used Cooking Oil (UCO), animal Tallow and Camelina Oil (CO), by ENI's patented Ecofining™ process, based on the Hydroprocessed Esters and Fatty Acids (HEFA) technology. The study followed the methodological approach for Life Cycle Assessment of biofuels described in the recast of the Renewable Energy Directive (REDII).

An extensive set of cases was analysed by assuming different locations, logistic options and agricultural protocols (particularly the application of different soil amendments) for camelina cultivation, a crop which is being developed as an intermediate crop and as a potential alternative for restoring degraded lands, as the ones in the EU Mediterranean region here considered. As a meaningful contribution of the work, calculations introduced the e_{sca} term (emissions savings from improved agricultural management), included in REDII methodology, whose application has been limited up to now. We applied this term by adopting two different approaches to the quantification of the change in soil carbon stock: i) one based on theoretical calculations, related to the content of fixed carbon in the soil amendments applied and ii) other based on experimental measurements from field trials carried out by Bio4A partners.

Encouraging results were observed for all the studied cases, for the calculated Greenhouse Gas (GHG) emission savings were always >65%, as required by REDII for biofuels to be quantified for national renewable energy objectives. In particular, we estimated 89% and 85% savings respectively for UCO and Tallow.

Camelina cases performed even better, providing savings in the range of 107% - 128%. These were largely contributed by e_{sca} and by the adoption of the degraded land bonus (e_B), also indicated in REDII methodology. When the e_{sca} and the e_B contributions are not taken into consideration, the camelina cases -based on the experimental data obtained from BIO4A field trials in Spain and Italy- provide GHG emission savings ranging from 65% to 74%, depending on the country and cultivation scenario.

Indeed, we observed the relevance of the e_{sca} term to the results in a sensitivity analysis by considering different values for the change in Soil Organic Carbon (SOC) (in which the term is ultimately based). A positive outcome of the study is that the calculated theoretical e_{sca} values for the different camelina cultivation scenarios and the e_{sca} values measured experimentally from soil sampling are aligned.

However, we must emphasize the consideration of e_{sca} necessarily needs to be understood as a preliminary approach or pilot application of the term, once large

uncertainty is involved in soil sampling and SOC measurements. Further experimental work in this sense should be performed to strengthen our results. Although a maximum limit for e_{sca} of 45 g CO_{2eq} MJ^{-1}, as indicated in RED II, was taken into account, it was not reached in the study, given that the soil amendments (assumed as the major contributors to SOC change) were only applied at moderate amounts. Ultimately, we could state Bio4A adopted a conservative approach regarding e_{sca} quantification. Additionally, we also analysed the influence of crop productivity by varying this parameter ±10%, which yielded changes in overall emissions ranging -11% to +13%. Finally, we also carried out an optimisation study, which actually showed that there is room for even improving these results (minimising emissions) if larger amounts of amendment are applied on land.

In summary, we can conclude that the Bio4A value chain and particularly, camelina as feedstock, can be an excellent option providing a synergic positive effect by contributing to decarbonising the aviation sector and reverting soil degradation.

1. Introduction

The Renewable Energy Directive recast (REDII) targets 32% share of renewable sources to the gross final consumption of energy in the European Union by 2030. In the same terms, a specific goal of 14% share for the transport sector is also set. Besides, REDII further regulates how accounting to meeting these targets shall be performed. In particular, amongst other specifications, biofuels produced in facilities with a startup date later than January 2021 are required to provide Greenhouse Gas (GHG) emission savings above 65% when confronted to a fossil reference of 94 g CO_2 MJ^{-1} used fuel. This rule is applicable to aviation biofuels, which can particularly contribute to meeting the target, for aviation is left out of the calculation of the gross final energy consumption (denominator), while accountable and even fostered[1] when calculating the consumption of renewables (numerator).

Further, REDII includes measures to prevent biofuel production incurring in indirect land-use change (ILUC). This is an undesired effect occurring when an increased demand for biofuel feedstocks ultimately leads to agricultural expansion and the conversion of natural lands with high soil carbon stock. The carbon loss, released as CO_2, which might happen when transforming these lands, has the potential to counterbalance GHG emission savings from the use of biofuels. Feedstocks identified as posing high ILUC risk are progressively capped and ultimately banned in 2030. On the other hand, feedstocks certified as low ILUC risk are exempt of such cap. Such low ILUC biofuels are those avoiding the displacement of food and feed crops, either by improved agricultural practices or by using areas not previously used for crop production (ICCT, 2018).

In parallel with REDII, a more specific action on decarbonising the aviation sector is on the track with the ReFuelEU Aviation initiative (European Parliament, 2022), one of the branches of the the *"fit for 55"* package, which seeks reducing net GHG emissions in the EU by at least 55% by 2030[2]. This regulation sets a progressive mandate in the share of SAF delivered by aviation fuel suppliers, starting at 2% (v/v) in 2025 and increasing to 63% in 2050.

Bearing this context in mind, the Bio4A project aims at industrially demonstrating the production and commercial uptake of Sustainable Aviation Fuel (SAF) from alternative (low ILUC) lipid feedstocks.

1.1 Object of this deliverable

This document describes the work and results from T4.3 (WP4) of Bio4A. The purpose of T4.3 was to evaluate the environmental performance, particularly the generated GHG emissions, of the Bio4 value chain, which comprises:

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[1] Specifically, with the exception of those produced from food and feed crops, REDII indicates a multiplier of 1.2 shall be applied to the energy content of aviation biofuels.

[2] Compared with 1990 levels.

1. Feedstock provision.
2. Production of SAF via the Hydroprocessed Esters and Fatty Acids (HEFA) pathway.
3. SAF blending and delivery logistics.
4. SAF utilisation.

Deliverable D4.2 presented a preliminary approach to the task. Still, this was limited for i) only one feedstock, camelina, and one cultivation case were considered, ii) a relevant methodological aspect, GHG savings from improved agricultural management (e_{sca}) was not included, and iii) emissions from the biorefinery stage were based on literature data. In this document, we present a fully redone and more comprehensive study, for which we addressed the following sub-tasks:

1. Re-framing of LCA system boundaries in aspects concerning feedstocks, locations and logistics. These were discussed with the partners and ultimately, cases to be analysed were established. UCO and tallow were included as feedstocks together with camelina. Impacts arising from camelina cultivation were extensively analysed by considering different locations and agricultural protocols (most importantly, the utilisation of different soil amendments). ENI facilities in Gela (Sicily) and Livorno (Tuscany) were defined as locations for the biorefinery stage. Amsterdam-Schiphol and Rome-Fiumicino airports were selected as destinations for SAF consumption.
2. Compilation of a comprehensive Life Cycle Inventory (LCI). An intensive information exchange with all the partners was kept in this sense. Noticeably, first-hand data from ENI facilities were incorporated to model the fuel production stage.
3. Modelling of e_{sca}. This was a quite new and pilot contribution of this task, given other examples of its application, to the best of our knowledge, were not available on the literature by the time of issuing this document. We incorporated two different approaches to the quantification of the change in soil carbon stock: i) one based on theoretical calculations, related to the content of fixed carbon in the soil amendments applied and ii) other based on experimental measurements carried out by our partners. Large uncertainty is however related to this term, so results need to be interpreted in consequence.
4. LCI implementation on Simapro, a dedicated LCA software, (later on MS Excel).
5. Life Cycle Impact Assessment (LCIA) of selected cases.
6. Identifying the most relevant contributions to the overall GHG emissions and comparing the performance between the analysed cases.
7. Determining the potential GHG emissions reduction, if any, of the produced SAF, when compared to its fossil counterpart.
8. Performing a sensitivity analysis, to evaluate the influence of relevant cultivation aspects (namely crop productivity and changes in soil carbon stock) on the calculated emissions.
9. Optimising the addition of soil amendments in the cultivation stage, seeking the minimisation of the calculated emissions.

2. Bio4A value chain

The Bio4A value chain comprehends three main stages: lipid feedstock provision, fuel production (hydroprocessing), and fuel delivery and utilisation. All intermediate logistic operations are also included. The following subsections provide a short overview on these stages.

2.1 Feedstock provision

Three feedstocks have been analysed in this study: Used Cooking Oil (UCO), Tallow and Camelina Oil (CO). We must clarify however that the SAF production demonstration carried out in the framework of Bio4A only utilised UCO, as declared in the proof of sustainability. Nonetheless, ENI facilities have effectively processed Tallow as well. CO is conceptualised in Bio4A and this document as an additional feedstock to boost SAF production by using the same HEFA technology as for UCO and Tallow (see section 2.2).

2.1.1 Used Cooking Oil (UCO)

UCO is a waste[3] generated by the food-processing industry, restaurants, catering services operating in both public and private institutions and households, whose current supply in the EU+UK is estimated at 0.7–1.2 Mt y^{-1}. Together with 30-50% coming from non-EU countries, the total supply potential in the EU+UK is estimated at 3.1–3.3 Mt y^{-1} (van Grinsven, 2020). However, currently, a more significant use of this resource is hindered by its relatively low availability. While collection at restaurants and catering services is easier because of the higher amounts, there is a need for better developed collection schemes from households.

In this work, the provision of UCO was modelled by adopting data reported in JRC (2019). These assume 20% supply from East Asia (transported by ship over 7,000 km), while the rest is collected locally in Italy (100 km as representative travelling distance) (see Table A5).

2.1.2 Tallow

Cattle and sheep slaughtering residues typically undergo the so-called rendering process, in which these are converted into more stable and usable products. In this process two fractions are obtained: a mix of fats, referred to as tallow, and a meal composed of meat and bone.

Some controversy exists regarding the consideration of these animal residues either as a waste or as a co-product of the animal farming industry. In this last case, value chains using tallow as feedstock should include farming activities within their system boundaries (ICAO, 2022). In this study, however, we adopted the approach and input data provided in JRC (2019), which treats tallow as a product being obtained from wastes. Hence, accounted impacts start at waste collection, followed by the rendering process itself, in which those are allocated between the tallow and the meat and bone

[3] Considered a waste under REDII, it is then free of environmental burdens before it is collected.

meal. Modelling data for rendering are compiled in Table A2. Rendered tallow is assumed to be later transported over 162 km to the hydroprocessing facility.

2.1.3 Camelina oil

Camelina (*Camelina sativa*) is a non-food-competing oil crop with a high potential for biofuel production, including SAF. This is due to its resilience, as it is drought resistant, and its low demand for agricultural inputs, including nutrients (fertilisers) and herbicides, and the fact it can be grown under different climatic and soil conditions (CORE-JetFuel Project, 2016). Specifically, its potential to be cultivated on marginal or degraded land poses significant interest on camelina as a low ILUC feedstock, in line with REDII requirements. In Bio4A, this aspect was addressed by D4.4, which mapped potential camelina feedstock production on marginal lands in the EU Mediterranean area.

In this work, we considered two locations for camelina cultivation in degraded land: one in Toledo, central Spain, and other in inner Sicily, Italy. The first location was chosen since cultivation trials carried out by CCE in the context of Bio4A were hosted in that area. Inner Sicily was selected as a reasonable option in Italy, closer to the biorefining facilities, after consultation with the JRC following D4.4 results. For each location, cases reflecting different agricultural protocols, based on field trials, were addressed (Table A7). Spanish cases were referred to the already mentioned CCE trials in Toledo. Italian cases were referred to input data from Re-Cord field trials in Terontola (Tuscany). These agricultural protocols not only reflect different practices in terms of the used amounts of mineral fertilisers, diesel consumption, etc. but also the utilisation of three different soil amendments: biochar from lignocellulosic residues, compost and a mixture of those, referred to as combi[4]. Importantly, the application of these amendments can be considered as an improved agricultural practice, which enables the inclusion of the e_{sca} factor in LCA calculations (see section 3.3.3), which will be later shown as key in the results observed in this work. Also, notice camelina cultivation productivity in this type of degraded land and under this particular harsh climatic conditions can be variable.

Following cultivation, camelina seed is harvested and cleaned (sieved), to separate it from the remaining husk[5]. Drying is not necessary since, if correctly harvested, the moisture content is low (ca. 7%). Then, the seed is transported to an oil extraction facility, where it is crushed to obtain camelina oil. This process yields 0.38 kg oil kg^{-1} dry seed (internal communication from CCE)[6]. Together, camelina meal is produced (0.61 kg kg^{-1} dry seed), which has market value as animal feed. Finally, camelina oil is transported to be utilised as feedstock for the HEFA process.

[4] In this work, combi trials utilised combi (15%), containing 15% (w/w) biochar.

[5] A certain % of the husk is harvested together with the seed (Spain: 20%; Italy: 16.7%).

[6] These yields were taken as representative values from experimental and industrial trials and can be variable depending on the camelina variety and cultivation area.

2.2 Fuel Production

In Bio4A, fuel production takes place via the HEFA technology, which converts lipid feedstocks with hydrogen (hydroprocesing) over catalytic beds into hydrocarbons. The produced fuel cuts are composed of drop-in molecules, which allow their direct blend with conventional fuels without any further adaption (IEA Bioenergy, 2018). HEFA is a mature technology, which since obtaining ASTM certification in 2011, has been successfully tested by numerous airlines (CORE-JetFuel Project, 2016), but still lacks of large-scale deployment.

Bio4A fuel production occurs at ENI facilities in Gela (Sicily) and Livorno (Tuscany), both in Italy. The core of this process is ENI's patented Ecofining^{TM} process, which produces different hydrocarbon products. A general overview of this biorefining process is shown in Figure 1. The following subsections briefly describe the steps depicted.

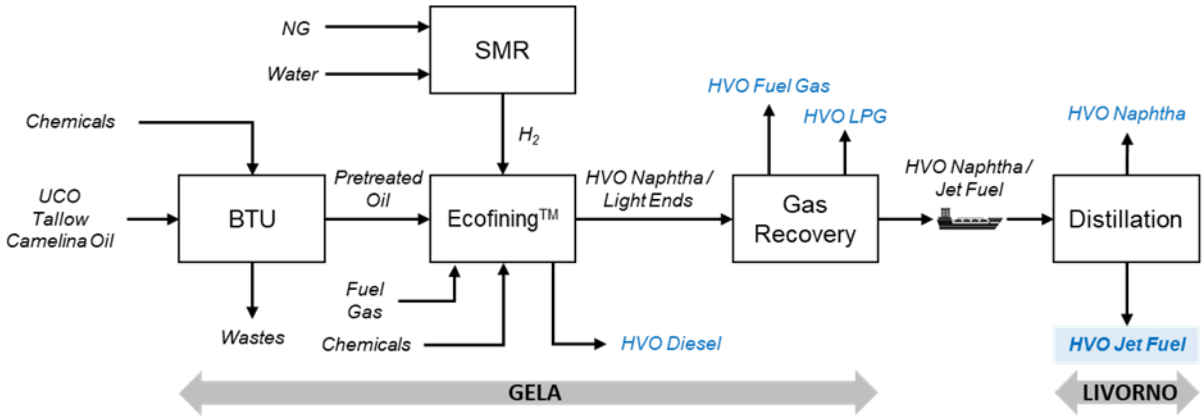

Figure 1. Block chart of the fuel processing stage at ENI facilities. Feedstock hydroprocessing takes place in Gela (Sicily). The Naphtha / Jet Fuel fraction is then transported by ship to Livorno (Tuscany), where it is distilled to produce SAF.

2.2.1 Biomass Treatment Unit (BTU)

Prior to the hydroprocessing step, the lipid feedstock undergoes a pre-treatment consisting of:

1. Acid degumming process, in which hydratable solids (e.g. phosphates, polar gums, saccharides, starches, etc.) are removed (Rincón et al., 2021).
2. Bleaching process, in which so-called bleaching earths are added to remove other impurities, such as metals, soaps, or phospholipids (Rincón et al., 2021).

2.2.2 Steam Methane Reforming Unit (SMR)

Hydrogen for the hydroprocessing step is produced via the steam methane reforming reaction, in which natural gas reacts to produce a mixture of CO and H_2.

The hydrogen production plant at Gela can produce 40,000 $Nm^3\ h^{-1}$ of 99.9% pure hydrogen. Further, the unit also exports superheated steam at medium pressure (18 barg, 260 ºC) and low pressure (6 barg, 220 ºC).

The unit is composed by the following sections:

1. Pre-heating, purification and desulphurization of natural gas.
2. Steam reforming reaction inside the main furnace.

$$CH_4 + H_2O \leftrightarrow CO + 3H_2$$

3. Water Gas Shift reaction for the conversion of resulting quantities of CO from the previous reaction into CO_2 and H_2.

   $CO + H_2O \leftrightarrow CO_2 + H_2$

4. Purification of hydrogen by PSA.

2.2.3 Ecofining™ Unit

The Ecofining™ process consists of two main processes: a deoxygenation stage and an isomerization stage.

2.2.3.1 Deoxygenation stage

In this stage, oxygen is removed from the pre-treated feedstock by means of a reaction with H_2 in presence of a catalyst. This mostly produces aliphatic compounds in the diesel distillation range, together with CO, CO_2, propane and water. The operating conditions also promote saturation, demetallization and denitrogenation reactions. All these are strongly exothermic, which hence requires to control the temperature over the catalytic bed in order to displace the equilibrium towards product formation. This is done by partially recirculating the deoxygenated product, which is mixed with the fresh feedstock in a 1:2 ratio.

2.2.3.2 Isomerization stage

Following deoxygenation, another catalytic process involving H_2 consumption is carried out to promote isomerization reactions. These seek converting n-paraffins (linear hydrocarbon chains) into iso-paraffins (branched hydrocarbon chains) in order to improve cold fuel properties (e.g. the cloud point or the cold filter plugging point).

This stage yields HVO-diesel as the main product, with excellent properties that enable direct blending with diesel. Together, a fraction containing compounds in the naptha/ jet range and lighter compounds is produced, which follows to the gas recovery unit.

2.2.4 Gas Recovery Unit

This unit is dedicated to the stabilization of the gas streams and the naphtha/jet fuel mix from Ecofining™. The unit generates fuel gas and LPG streams, together with a stabilized naphtha/jet fuel mix that is sent to the final distillation stage.

2.2.5 Distillation

The stabilized naphtha/ jet fuel mix is transported to the ENI refinery in Livorno, where it is distillated in a conventional column operating at atmospheric pressure. HVO-naphtha is produced as head product, while the HVO-Jet fuel cut (SAF) is obtained from the bottoms of the column.

2.3 SAF blending and delivery

The ASTM Aviation Fuels committee sets maximums to the amount of SAF that can be blended in aircrafts. For SAF produced via de HEFA pathway, such limit is at 50% (v/v) (IATA, 2021). This maximum has been assumed in this study to calculate the emissions occurring in the transportation of SAF to the airport of destination.

SAF heading to Schiphol airport is transported by ship as neat SAF to Amsterdam port. There, it is blended with fossil jet fuel up to the indicated ratio, and finally delivered by pipe at the airport.

SAF heading to Fiumicino is directly blended at ENI refinery in Livorno and subsequently transported by truck to the airport.

2.4 Recap of Bio4A value chain locations and logistics

Figure 2 shows the most relevant locations in the Bio4A value chain. These include:

- Camelina cultivation in Toledo (Castilla la Mancha), central Spain; and inner Sicily (Italy).
- Valencia, in east Spain, as port for camelina oil exports heading to biorefining in Italy.
- Gela (Sicily), in Italy, which is the location of the ENI facility where feedstock hydroprocessing takes place.
- Livorno (Tuscany), in Italy, which is the location of the ENI refinery in which distillation for the separation of jet fuel from naphtha takes place.
- Amsterdam Schiphol airport (North Holland), in the Netherlands, as final destination of the SAF produced.
- Rome Fiumicino airport (Lazio), in Italy, as final destination of the SAF produced.

Table 1 indicates the logistic steps between the previous locations. More detailed information on these can be found on Table A5.

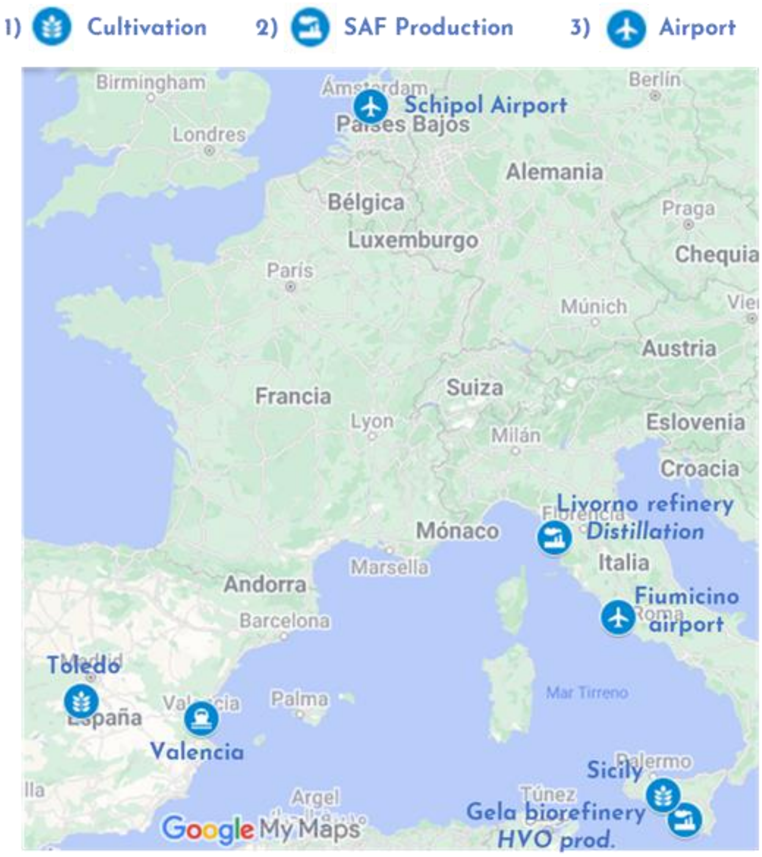

Figure 2. Main locations in the Bio4A value chain.

Table 1. Transportation steps included in the Bio4A value chain.

Product transported	Route	Mode
Feedstock provision		
UCO		
UCO, collected in Italy	Non specified	Truck
UCO, imported from Asia	Non specified	Ship
Tallow		
Tallow, collected in Italy	Non specified	Truck
Camelina, Spain		
Camelina oil	Toledo – Valencia	Truck
Camelina oil	Valencia – Gela	Ship
Camelina, Italy		
Camelina oil	Inner Sicily – Gela	Truck
SAF production		
HVO Jet Fuel / Naphtha mix	Gela – Livorno	Ship
Fuel delivery		
Fuel delivery, Schiphol		
Neat SAF	Livorno – Amsterdam Port	Ship
Blended SAF	Amsterdam Port – Schiphol	Pipe
Fuel delivery, Fiumicino		
Blended SAF	Livorno – Fiumicino	Truck

3. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a standardised methodology used to quantify the environmental impacts of products and services over their lifetime, including extraction of raw materials, manufacturing, utilization and end of life. The regulatory framework for the application of LCA is specified by UNE-ISO standards 14040:2006 and 14044:2006), which includes four stages (Figure 3).

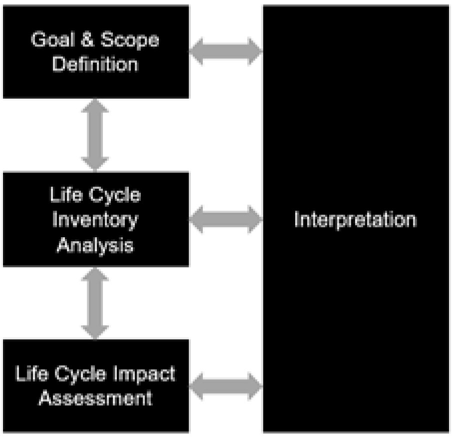

Figure 3. LCA stages as defined by UNE-ISO standards 14040 and 14046.

1. **Goal and scope.**

   In this stage the basic framework of the study is defined, including the following aspects:

   - Objective: intended implementation, the reason for which the study is performed.
   - Target audience.
   - System boundaries: process technological framework (stages) to be analysed, including environmental burdens and benefits from avoided products and processes. These boundaries shall be adapted to the potential accuracy that could be obtained from the available data.
   - Functional Unit (FU): numerical quantity defining the function performed by a particular system, which serves as a reference basis for all process material and energy flows.
   - Reference Flows: quantified amounts of materials and energy necessary for a specific system to deliver the performance described by the functional unit.
   - Required data quality.
   - Technological parameters.

2. **Life Cycle Inventory (LCI).**

   This stage consists in the compilation of all inputs (materials, energy and activities) and outputs (material products, energy, delivered activities, emissions and wastes) of the system, which will be subsequently used to calculate its environmental impacts.

3. **Life Cycle Impact Assessment (LCIA).**

   In this stage, the LCI is transposed into environmental indicators of potential impacts by means of specific methodologies. The selection of a particular methodology should be made in accordance with the defined study goal. Different environmental indicators cover impacts to the environment, human health and availability of natural resources.

4. **Interpretation.**

   Finally, this stage is thought to discuss the obtained results, so as to derive conclusions on the environmental performance of the system (e.g. identifying hotspots). To this end, a continuous revision of the previous stages should be done for consistency purposes. For this reason, LCA is frequently referred to as an iterative process.

3.1 RED II methodological framework

Aside from other technical specifications, REDII, requires biofuels to provide GHG emission savings above 65% when compared to a fossil reference of used fuel. GHG savings are calculated as:

$$\%\ savings = (E_F - E_B)/E_F$$

Where E_B are the total emissions from the biofuel, and E_F are the total emissions of the fossil fuel reference (94 g CO_2 MJ^{-1}).

In Annex V.C, REDII provides the methodology, based on an attributional LCA, to calculate the GHG emissions produced by biofuels, with the aim of proving GHG savings:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr}$$

Table 2 provides the description of the included terms, together with their application referred to the Bio4A value chain.

Table 2. Terms included in the calculation of biofuel GHG emissions in REDII and their application in Bio4A.

Term	Description	Applies to:
E	total emissions from the use of the fuel	
e_{ec}	emissions from the extraction or cultivation of raw materials	Cultivation stage
e_l	annualised emissions from carbon stock changes caused by land-use change	Cultivation stage
e_p	emissions from processing	Tallow rendering Camelina seed sieving Camelina seed crushing Fuel Production
e_{td}	emissions from transport and distribution	All raw materials, semi-manufactured and manufactured products. See Table A5
e_u	emissions from the fuel in use	Fuel combustion
e_{sca}	emission savings from soil carbon accumulation via improved agricultural management	Cultivation stage
e_{ccs}	emission savings from CO_2 capture and geological storage	n/a
e_{ccr}	emission savings from CO_2 capture and replacement	n/a

The following clarifications should be made on the terms from the previous table.

- Both e_l and e_{sca} quantify the change in soil carbon stock, but RED II distinguishes them depending on a decrease or an increase happening. This means these terms are excluding, for obvious reasons (BioGrace II project, 2020). In Bio4A, soil carbon accumulation, both theoretically estimated and experimental, always showed positive values (see section 3.3.3). Hence, the term for soil carbon accumulation in e_l was always zero, and hence, it is not reported in LCA results. This, however, does not affect the application of the degraded land bonus, included in e_l, which was taken into account and reported (see section 3.3.4).
- REDII methodology assumes the same amount of CO_2 is captured in biomass cultivation as it is released in biofuel combustion. Hence, e_u is always equal to zero as per definition. This does not apply to non-CO_2 (CH_4 and N_2O) emissions.
- e_{ccs} and e_{ccr} terms do not apply in the Bio4A value chain, for no carbon capture operations are included.

3.2 Goal and Scope

The goal of the environmental assessment presented in this document was to quantify the GHG emissions generated in the Bio4A value chain for the production of SAF. The selected functional unit was 1 MJ SAF produced, delivered and combusted.

The considered system boundaries included those activities described in section 2, plus the utilisation (combustion) of the fuel, which are synthesised in Figure 4. Results are reported following REDII terminology.

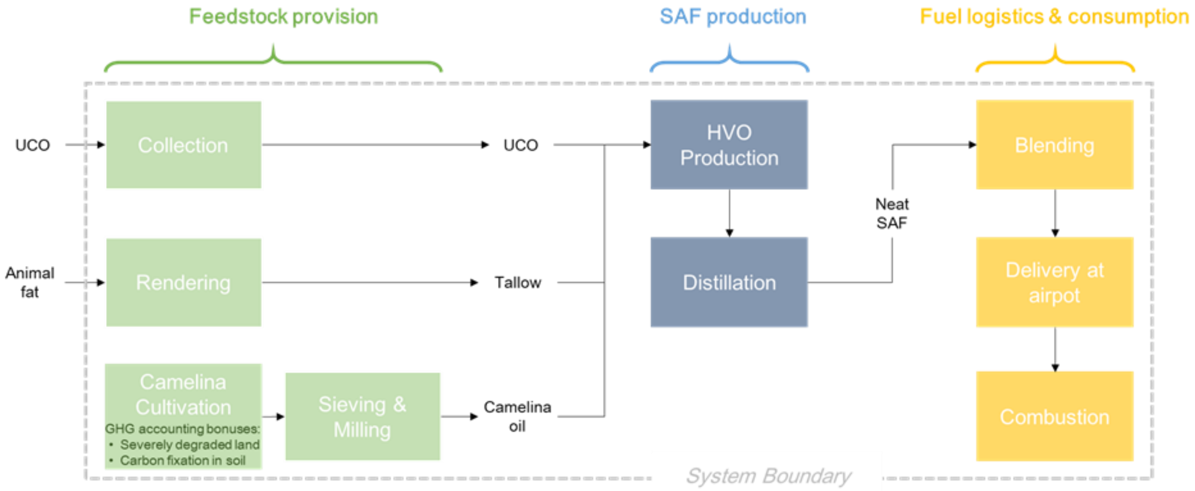

Figure 4. System boundaries for the Bio4A value chain.

3.3 Life Cycle Inventory (LCI)

The LCI for this study, considering the scope presented in the previous section, and organised following RED II terminology (as explained in section 3.1.), is described in Annex I – Life Cycle Inventory, Table A2-Table A9. LCI data are extensively based on first-hand data provided by Bio4 partners and completed whenever necessary with other literature sources. Specific LCI modelling aspects, mostly concerning the cultivation stage, are presented in the following subsections.

3.3.1 N_2O emissions from cultivation

N_2O emissions from the cultivation stage were calculated (included in e_{ec}) following REDII requirements, which refer to Tier 2 of the IPCC methodology (IPCC, 2019). This considers specific emission factors for different environmental conditions, soil conditions and crops, including both direct and indirect emissions from the utilisation of mineral fertilisers, manure, crop residue left in the field, etc.

3.3.2 Emissions from neutralising acidification caused by mineral fertilisers

Commission Implementing Regulation (EU) 2022/996 indicates the emissions resulting from the acidification caused by nitrogen fertiliser use in the field shall be accounted (included in e_{ec}). In this work, we assumed the emission factor indicated for the neutralisation of nitrate fertilisers, 0.783 kg CO_2 kg^{-1} N.

3.3.3 Emission savings from soil carbon accumulation (e_{sca})

We utilised the formula recommended in Commission Implementing Regulation (EU) 2022/996 to calculate e_{sca}:

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

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) by the molecular weight of carbon (12.011 g/mol) in g CO_{2eq}/g C.

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. Values are reported in Table A7.

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

In this work, the term for change in soil carbon stock, $(CS_A - CS_R)$, was calculated in two different ways:

- Theoretically, by considering all the fixed carbon (C_{fix}) contained in the soil amendment is incorporated in the soil.
- Experimentally, from actual measures of CS_A and CS_R in Bio4A field trials, provided by Re-Cord. These were only available for Spanish trials.

REDII further indicates that the maximum possible total value for e_{sca} shall be capped to 45 g CO_{2eq} MJ^{-1} fuel for the entire period of application of the e_{sca} practices if biochar is used as organic soil improver alone or in combination with other eligible e_{sca} practices.

In all other cases, the cap shall be 25 g CO_{2eq} MJ^{-1} fuel for the entire period of application of the e_{sca} practices. These maximum values were taken into account in the calculation of e_{sca} in this work.

We need to emphasize that the quantification of changes in the soil carbon stock for the purpose of considering e_{sca} in this task was a unique distinctive of Bio4A, which should be understood as a pilot experience and further backed-up by more experimental work. Hence, results are still subjected to high uncertainty, and should be interpreted keeping this in mind.

3.3.4 Degraded land bonus (e_B)

The land use change term (e_l) included in REDII methodology for GHG emissions (see section 3.1) is indicated to be calculated as:

$$e_l = (CS_R - CS_A) \times 3.664 \times 10^6 \times \frac{1}{n} \times \frac{1}{p} - e_B$$

As mentioned in section 3.1, once e_{sca} is being accounted, the first term in e_l is not applicable. However, e_l also includes the term e_B, which still might be considered. This is a bonus of 29 g CO_{2eq}/MJ biofuel if biomass is obtained from restored degraded land, if evidence is provided that the land:

a) was not in use for agriculture or any other activity in January 2008;
b) is severely degraded land[7], including such land that was formerly in agricultural use.

The bonus shall apply for a period of up to 20 years from the date of conversion of the land to agricultural use, provided that a steady increase in carbon stocks as well as a sizable reduction in erosion phenomena for land falling under (b) are ensured.

In Southern EU/MED Countries, there is strong evidence of irreversible desertification effects (Figure 5). Under these circumstances, loss of agricultural land directly corresponds to loss of organic carbon in the soil, as forest will not replace agricultural land due to the unfavourable climatic conditions. For instance, 20% of the territory in Spain is degraded and an additional 1% is actively degrading, so a predictive/alert model has been developed for this purpose (Martínez-Valderrama et al., 2016). Given this context, which can be extended to the assumed cultivation areas in inner Sicily for Italian cases, the e_B term was considered in the calculations performed in this work.

[7] Severely degraded land' means land that, for a significant period of time, has either been significantly salinated or presented significantly low organic matter content and has been severely eroded.

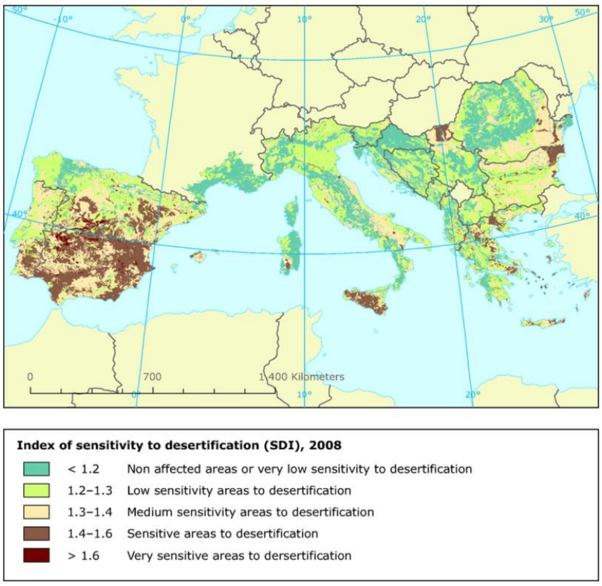

Figure 5. Sensitivity to desertification index in EU Mediterranean region (EEA, 2017).

3.3.5 Other considerations

- Emission factors for the LCI inputs were retrieved, as long as possible, from Commission Implementing Regulation (EU) 2022/996, a document further supporting REDII methodology on the calculation of GHG emissions from biofuels. When not available, emission factors were retrieved from the Ecoinvent database (v3.9) or other literature sources.
- Emission factors were selected so as to reflect as much as possible the geographical scope of the study (e.g. in terms of the selected electricity mix).
- GHG emissions from the production of the metal catalyst used in the hydroprocessing stage were modelled based on literature data from Barbera et al. (2020) and Snowden-Swan et al. (2016). The catalyst was assumed to be replaced every 3 years.
- Annual replacement of 1% was assumed for the thermal carrier utilised in the distillation stage.
- Annual replacement of 3% was assumed for cooling water circuits.
- Environmental burdens from the manufacture of machinery, infrastructure, vehicles, etc. were left out of the scope of the study.

3.4 Allocation of impacts

When a system produces multiple products, the generated environmental impacts must be properly distributed between these. In this regard, REDII indicates:

> *"Where a fuel production process produces, in combination, the fuel for which emissions are being calculated and one or more other products (co-products), greenhouse gas emissions shall be divided between the fuel or its intermediate product and the co-products in proportion to their energy content (determined by lower heating value in the case of co-products other than electricity and heat)."*

The calculated distribution of allocation percentages along the Bio4 value chain, based on the LHV of products, is presented in Table A1 and Figure 6. The figure, when read left-to-right, shows how the energy content is distributed amongst the products in those stages delivering more than one product. Allocation is *back-propagated*, which means it must be traced backwards or, in other words, the figure must be read right-to-left. In our case, the target product of the study is the jet fuel cut obtained at the distillation stage in Livorno. In consequence, from that stage on, processes (i.e. fuel blending and delivery) will be allocated with 100%. On the other hand, upstream processes will be proportionally allocated with less impact, as long as intermediate (semi-manufactured products) involved in jet fuel production also yield products other than this. This is applicable not only to the stages shown in Figure 6, but also to other intermediate stages in which *branching* does not happen (e.g. transportations). In line with this, allocation has been calculated as:

$$A_{i,j}(\%) = \frac{\dot{m}_{i,j} \cdot LHV_j}{\sum_j \dot{m}_{i,j} \cdot LHV_j} \cdot 100$$

$$A_{i,j_{ac.}}(\%) = A_{i+1} \cdot A_{i,j}$$

Where:

$A_{i,j}(\%)$ is the % allocation factor for product *j*, in stage *i*.

$A_{i,j_{ac.}}(\%)$ is the % accumulated allocation factor for product j, in stage *i.*

$\dot{m}_{i,j}$ is the mass flow of product *j* in stage *i*.

LHV_j is the LHV of product *j*.

Notice A_{i+1} refers to the % allocation factor in stage *i+1* of the intermediate product involved in the production of SAF.

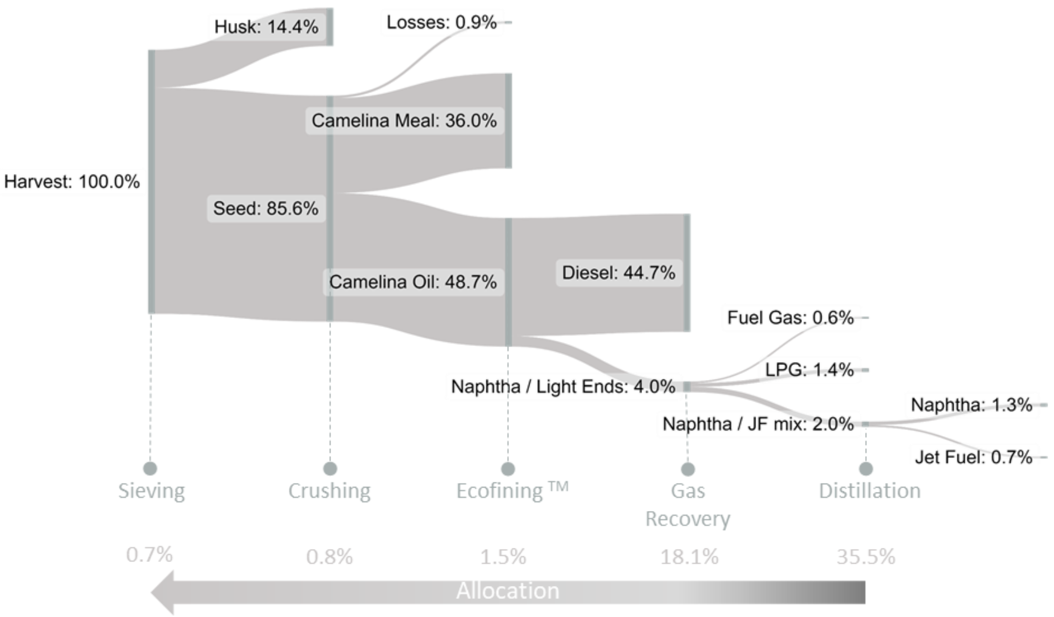

Figure 6. Energy balance (based on LHV of products) and allocation of impacts in the production of SAF along the Bio4A value chain. Cases comprising camelina cultivation. Jet Fuel (bottom right corner) accounts for 0.7% of the energy content of the harvest. Allocation is back-propagated, which results in earlier stages of the value chain proportionally having a lesser allocation percentage.

3.5 Overview of analysed cases

Table 3 presents a recap of all the cases analysed in the study. All of them further comprise two SAF delivery options: Schiphol and Fiumicino.

Table 3. List of analysed cases.

Feedstock	Cultivation		
	Location	**Amendment**	**e_{sca} calculation**
UCO	—	—	—
Tallow	—	—	—
Camelina	Spain	Biochar	Theoretical
Camelina	Spain	Biochar	Experimental
Camelina	Spain	Compost	Theoretical
Camelina	Spain	Compost	Experimental
Camelina	Spain	Combi (15%)	Theoretical
Camelina	Spain	Combi (15%)	Experimental
Camelina	Italy	Biochar	Theoretical
Camelina	Italy	Compost	Theoretical
Camelina	Italy	Combi (15%)	Theoretical

3.6 LCA model implementation

The LCA model was first implemented on Simapro v9.4, one of the most common commercial softwares for LCA. The model was later transposed to a MS Excel Spreadsheet, in order to facilitate parametrisation, which was extensively required for sensitivity analysis calculations.

4. Results and discussion

4.1 Life Cycle Impact Assessment (LCIA)

Figure 7 shows the GHG emissions for the analysed cases. Results are presented according to the terms indicated in REDII, Annex V.C methodology. Cases delivering the produced fuel at Schiphol and Fiumicino are presented jointly (i.e. on the same bar), once all the terms have the same values, with the only exception of e_{td}. Given e_{td} values for Schiphol are higher than those for Fiumicino, e_{td} is presented as:

- $e_{td,Fiumicino}$: emissions from transport and distribution when SAF is delivered at Fiumicino.
- $e_{td,Schiphol}$: difference (*additional* emissions), when SAF is delivered at Schiphol airport, with respect to $e_{td,Fiumicino}$.

As observed, in any case, the difference between the SAF being delivered at one or other airport is minimum (<0.1 g CO_{2eq} MJ^{-1}), once e_{td} is the term showing the less contribution to the overall results.

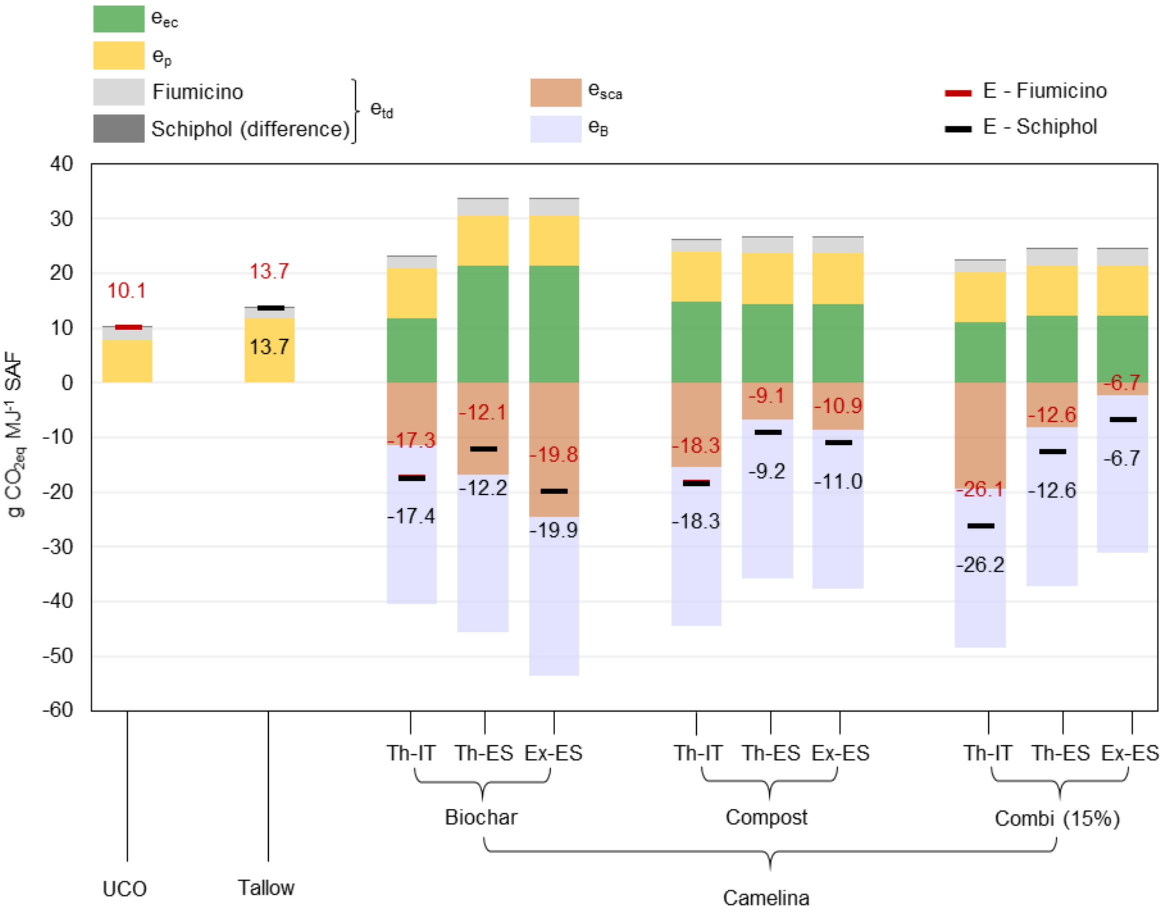

Figure 7. Greenhouse gas emissions of analysed SAF production value chains. Emissions from transport and distribution (e_{td}) are jointly presented for SAF delivery at Fiumicino airport and Schiphol ($e_{td\ Fiumicino}$ + difference). Th: e_{sca} calculated from theoretical fixed carbon addition. Ex: e_{sca} calculated from experimental measures of change in soil carbon stock. IT: Italy. ES: Spain.

Cases utilising UCO and Tallow as feedstock are mostly contributed by processing activities (i.e. biorefining), with just a minor contribution from logistics. Tallow shows increased emissions with respect to UCO, because of the addition of the rendering process, whose emissions are quantified ca. 4 g CO_{2eq} MJ^{-1}. These cases respectively attain 89% and 85% GHG emission savings when compared to the fossil fuel reference of 94 g CO_{2eq} MJ^{-1}.

Taking a closest look at biorefining activities, Figure 8 shows the distribution of impacts in the fuel production stage, which are dominated by the production of H_2 (SMR) consumed by Ecofining^{TM}.

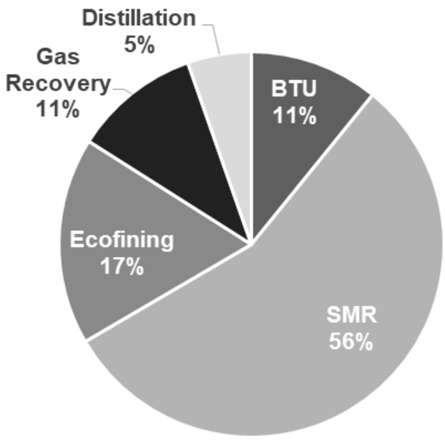

Figure 8. Distribution of GHG emissions in the fuel processing stage.

Cases based on camelina cultivation present a more complex *composition* of their overall emissions. Positive contributions are in fact higher than those observed for UCO and Tallow cases, due to the inclusion of the cultivation stage, represented by the e_{ec} term. However, in all these cases such increase is largely counterbalanced by negative contributions (e_{sca} and e_B), which ultimately results in negative E values, ranging 107% (Combi Ex-ES) to 128% (Combi Th-IT) GHG savings. Considering e_{td}, e_p and e_B have the same values in all these cases, results are in fact driven by the e_{ec} / e_{sca} binomial (as further explained in section 4.2.2). On its side, the magnitude of e_{sca}, is directly proportional to the annualised change in soil carbon stock and inversely proportional to crop productivity. This effect is observed in Table 4, in which cases are listed by their increasing (absolute) value of e_{sca}.

Table 4. e_{sca} values and their relation with the change in soil carbon stock and crop productivity. Cases are listed by decreasing value of e_{sca}.

Case	(CS_A-CS_R) kg Cf_{ix} ha^{-1} y^{-1}	Productivity MJ ha^{-1} y^{-1}	e_{sca} g CO_{2eq} MJ^{-1}
Combi(15%), Ex-ES	34.63	417.11	-2.19
Compost, Th-ES	83.75	325.59	-6.79
Combi(15%), Th-ES	128.24	417.11	-8.11
Compost, Ex-ES	105.85	325.59	-8.58
Biochar, Th-IT	120.54	287.17	-11.41
Compost, Th-IT	104.27	184.53	-15.36
Biochar, Th-ES	187.78	296.20	-16.73
Combi(15%), Th-IT	224.81	313.43	-19.49

To better understand *the whole picture*, the breakdown of contributions for e_{ec} is shown in Figure 9. In consonance with differences in the applied agricultural protocols and the reported crop productivity (see Table A7), a significant variation is observed in such breakdown. This is mostly related to the production of mineral fertilisers and N_2O emissions, coming from the volatilisation and leaching of mineral fertilisers and the crop residue left on the field. Biochar production and diesel utilisation are also significant to a lesser extent. In spite of these variations, global e_{ec} values are very similar for compost and combi cases in Italy and Spain. Nevertheless, a larger difference is observed for biochar, in which the Spanish protocol almost doubles the emissions of the Italian one. Of course, when interpreting these results, one should always keep in mind that the comparison is being established between distant locations, which might were subjected to external variables rather than the ones reflected in the agricultural protocols (i.e. rain or erosion). In the end, these could affect crop productivity, which obviously plays a major role when reporting the numbers in terms of emissions per MJ SAF produced.

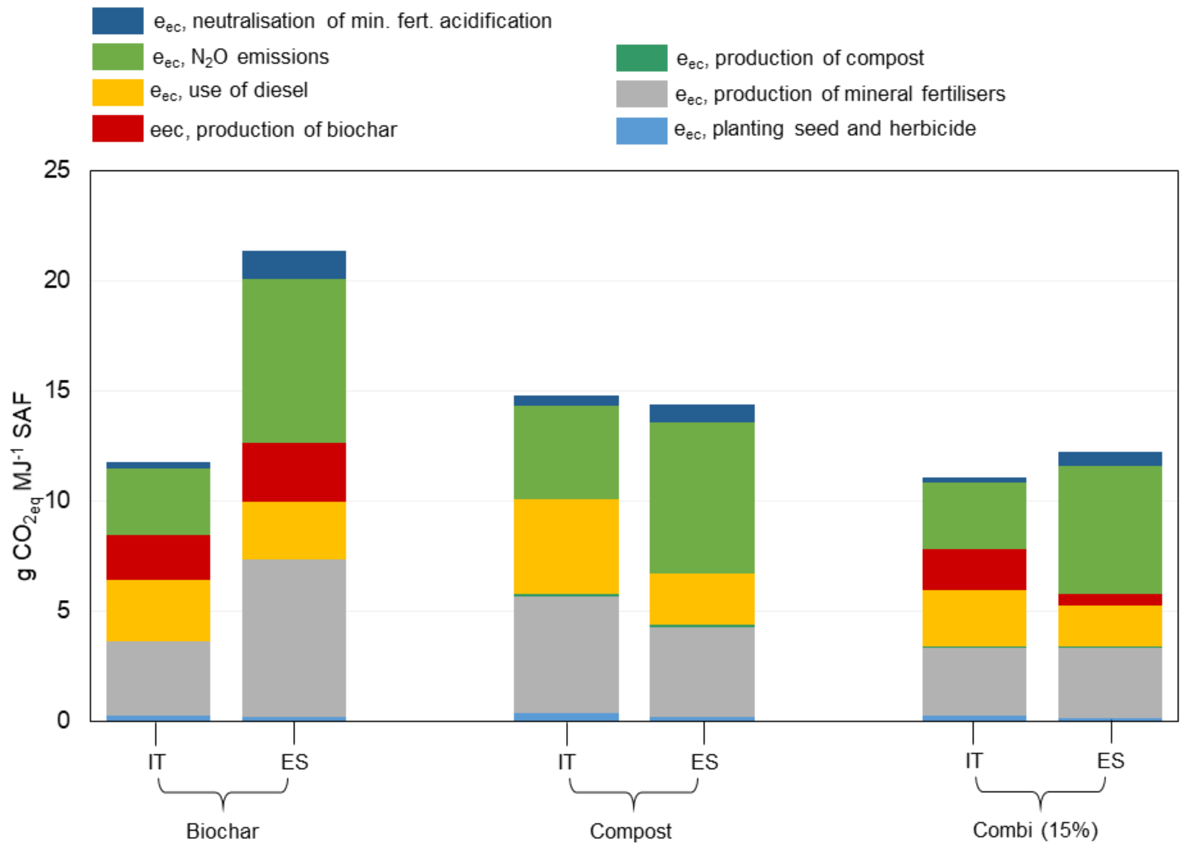

Figure 9. Breakdown of emissions derived from crop cultivation (e_{ec}) in camelina scenarios. IT: Italy. ES: Spain.

Ultimately, going back to Figure 7, despite the differences mentioned, homogenous trends are observed for each of the three amendments. This is derived from the fact that total emissions in cases in which e_{sca} values were based on theoretical C_{fix} addition are quite in line with those observed for the experimental cases, which supports our theoretical calculation as a reasonable approach for e_{sca}.

Finally, when the e_{sca} and the e_B contributions are not taken into consideration, all the camelina cases – based on the experimental data obtained from BIO4A field trials in Spain and Italy – provide GHG emission savings above 65%. In particular, the camelina cases delivering the produced fuel at Fiumicino produce total emissions E between 22,2 and 32,5 g CO_{2eq} MJ^{-1}, depending on the country and cultivation scenario, equivalent to GHG savings ranging from 65% to 74% (when the e_{sca} and the e_{B} contributions are not considered).

4.2 Sensitivity Analysis

We further explored the sensitivity of the results with two key parameters in camelina cultivation scenarios: crop productivity and the % fixed carbon incorporated in soil (when calculating e_{sca} theoretically).

4.2.1 Crop productivity

Figure 10 shows the effect on camelina cultivation scenarios when assuming ±10% variation in crop productivity. Overall, results indicate E varying from -11% to +13%. The extent of the variation is observed in the order biochar<compost<combi, with the Combi(15%) Ex-ES case showing the most sensitivity. Interestingly, some scenarios show an inversion of the logically expected behaviour (decrease of E when crop productivity is increased and vice-versa). To understand this, attention must be paid not only to e_{ec}, but to the combined value of e_{ec}+e_{sca}. In these *inverted* cases, the absolute value of e_{sca} is greater than that of e_{ec} (hence, $e_{ec}+e_{sca}<0$). Then, when crop productivity increases, the value e_{ec}+e_{sca} also increases, which utterly reflects an increase of E. This is more clearly depicted in Figure 11, which compares an *inverted* case (E increase with productivity) vs. a *normal* one (E decrease with productivity). Once again, this makes clear than the joint interpretation of e_{ec} and e_{sca} is crucial to interpret the results, instead of analysing these terms separately.

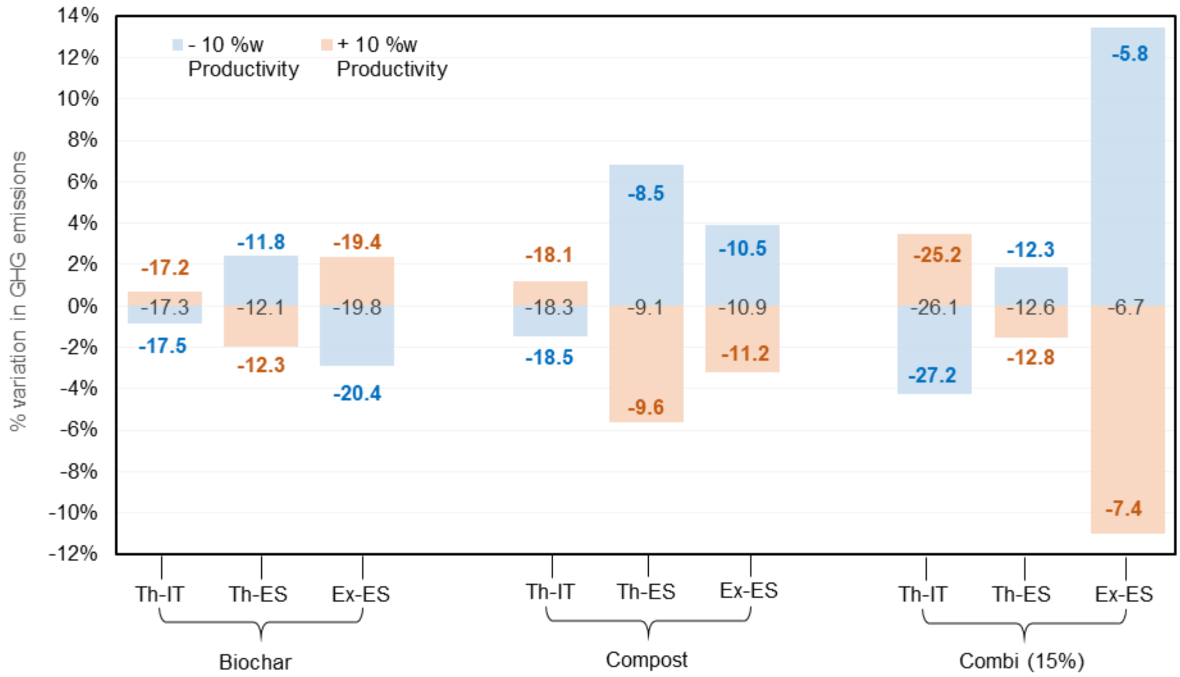

Figure 10. Sensitivity of E (g CO_{2eq} MJ^{-1}) to crop mass productivity (camelina cultivation scenarios, SAF delivered at Schiphol airport). Base values are indicated in the middle of each bar. Sensitivity values are indicated next to bar edges. Th: e_{sca} calculated from theoretical fixed carbon addition. Ex: e_{sca} calculated from experimental measures of change in soil carbon stock. IT: Italy. ES: Spain.

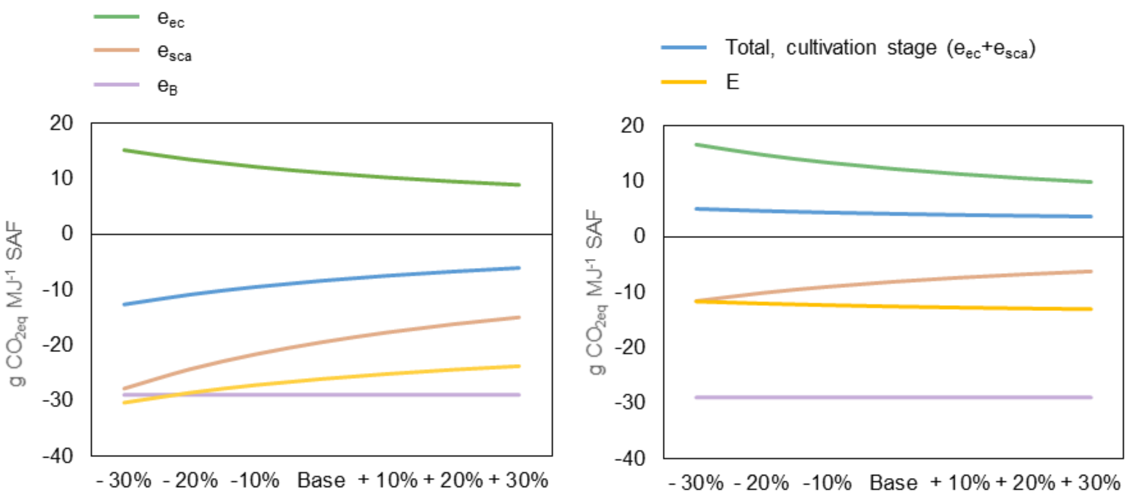

Figure 11. Sensitivity of E (g CO_{2eq} MJ^{-1}) to crop mass productivity. Left: Example of E increasing with crop productivity (Combi (15%), Th-IT). Right: Example of E decreasing with crop productivity (Combi (15%), Th-ES).

4.2.2 Theoretical change in soil carbon stock

We further analysed to what extent our assumptions for theoretically calculating e_{sca} could affect the global emissions for SAF production. In principle, we assumed the change in soil organic carbon to calculate the term would correspond to the amount of fixed carbon contained in the amendment (either biochar, compost or combi). However, this consideration neglects the fact of complex soil dynamics, erosion, and other phenomena that might occur in the field, which are indeed reflected in experimental measures. Then, we evaluated the sensitivity on total emissions when assuming lesser percentages of C_{fix} incorporated in soil (Figure 12). Results indicate a linear increase of emissions when less C_{fix} is assumed to be incorporated in soil. Variations are in the range of +(5-10)% when C_{fix} incorporation percentage is assumed to be 50% of the total.

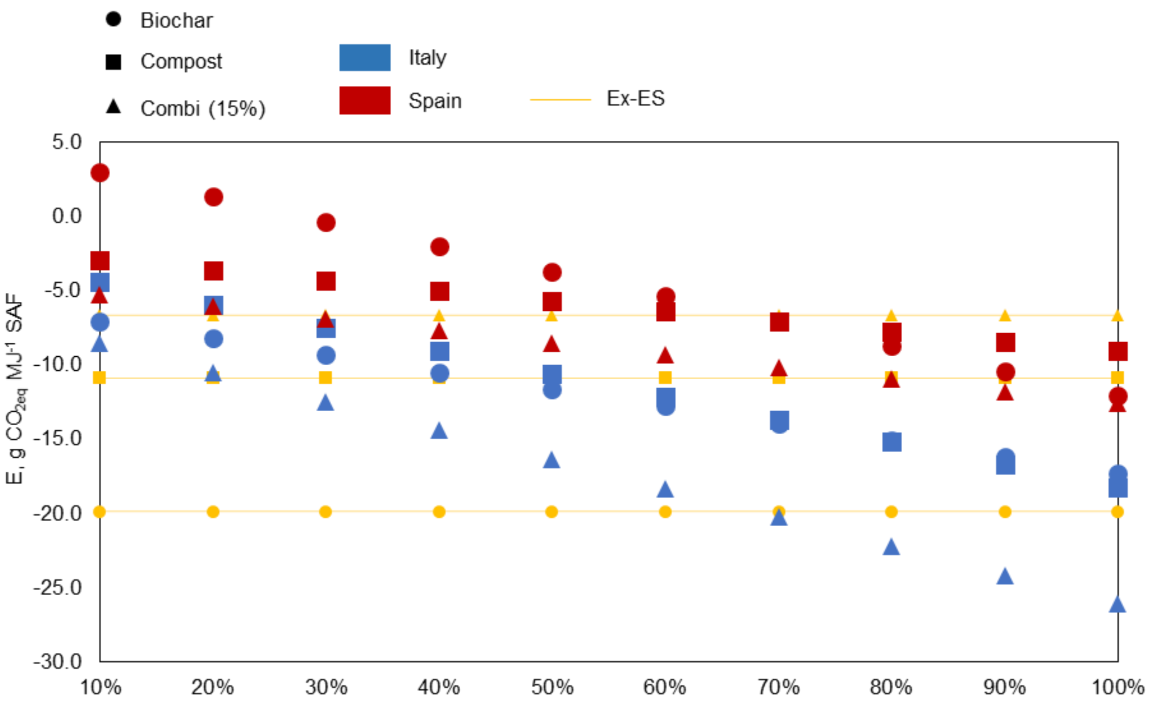

Figure 12. Sensitivity of E (g CO_{2eq} MJ^{-1}) to the % C_{fix} in the amendment assumed to be incorporated in soil.

4.3 Optimisation of soil amendment addition

As already seen, the amount of the applied soil amendment is key to the e_{sca} value and utterly, to the total emissions calculated for the SAF production value chain. Bearing in mind the cap values set by REDII to e_{sca}, we performed an optimisation study seeking to minimise the total emissions while keeping constant the amounts of nutrients (NPK) applied, by varying the amount of applied amendment. This study was obviously only performed for the cases considering theoretical calculation of e_{sca}. Results are shown in Table 5.

Table 5. Optimised addition of soil amendments in camelina cultivation cases.

	Original						Optimised					
	Biochar		Compost		Combi		Biochar		Compost		Combi	
	Th-IT	Th-ES	Th-IT	Th-ES	Th-IT	Th-ES	Th-IT	Th-ES	Th-IT	Th-ES	Th-IT	Th-ES
Emissions, g CO_{2eq} MJ^{-1} SAF												
E	-17.3	-12.1	-18.3	-9.1	-26.1	-12.6	-44.9	-35.8	-18.3	-14.0	-47.2	-43.8
e_{ec}	11.8	21.4	14.8	14.4	11.1	12.2	17.8	25.9	14.8	13.5	15.5	17.9
e_b	-29.0	-29.0	-29.0	-29.0	-29.0	-29.0	-29.0	-29.0	-29.0	-29.0	-29.0	-29.0
e_p	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2
e_{td}	2.0	3.1	2.0	3.1	2.0	3.1	2.0	3.1	2.0	3.1	2.0	3.1
e_{sca}	-11.4	-16.7	-15.4	-6.8	-19.5	-8.1	-45.0	-45.0	-15.4	-10.7	-45.0	-45.0
Application of mineral fertilizer and soil amendment												
N, kg ha^{-1} y^{-1}	14.6	66.0	14.6	50.0	14.6	50.0	14.6	66.0	14.6	41.5	14.4	48.1
P, kg ha^{-1} y^{-1}	58.5	40.0	58.5	7.0	58.5	7.0	58.5	40.0	58.5	3.9	57.9	6.8
K, kg ha^{-1} y^{-1}	14.6	30.0	14.6	7.0	14.6	7.0	14.6	30.0	14.6	0.0	12.9	5.8
Biochar, t ha^{-1} †	4.3	4.8			4.3	1.3	16.9	12.9			14.5	16.0
Biochar, t ha^{-1} y^{-1}*	0.4	0.5			0.4	0.1	1.7	1.3			1.4	1.6
Compost, t ha^{-1} ‡			27.0	20.0	27.0	18.7			27.0	31.6	28.9	20.9
Compost, t ha^{-1} y^{-1}*			2.7	2.0	2.7	1.9			2.7	3.2	2.9	2.1

† Wet base. % moist: IT = 30%; ES = 4.2%
‡ Wet base. % moist: IT = 26%; ES = 60%
* 10 years basis

The results indicate that the total emissions attributed to the production and utilisation of SAF (E) can be effectively further diminished by optimising the amount of applied amendment. As expected, what these indicate is that by applying more amendment, larger GHG savings could be attained. In the case of biochar, the optimal amounts would be in the range of 1.7 – 1.3 wet t $ha^{-1}y^{-1}$ (amount annualised over 10 years), as compared to 4.3 – 4.8 used in the field trials of the project. The same is observed for combi, which would increase to 2.1 – 2.9 wet t $ha^{-1}y^{-1}$ and the compost case in Spain, which would increase to 3.2 wet t $ha^{-1}y^{-1}$. In these cases, the application of mineral fertilisers is partially displaced by the amendment, which covers a higher share of the total supply of nutrients. In general, we observe optimised results tend to increase the amount of amendment up to the allowed maximum of e_{sca} of 45 g CO_{2eq} MJ^{-1} for biochar and combi. For compost, the cap of 25 g CO_{2eq} MJ^{-1} is not attained, because the cap on the amount of nutrients act as a constraint in this case (in fact, for Compost Th-IT the tool could not find an improved result because of this).

These results, however, should be taken carefully, since other effects were not considered in the study, such as that of the addition of amendment on crop productivity. Also, no limit was imposed to the maximum available amount of amendment that could be applied, which in practice could be limited due to e.g. supply issues or other practical reasons concerning works on the field.

5. Conclusions

This study analysed the GHG emissions of Sustainable Aviation Fuel (SAF) produced following the value chain proposed in Bio4A. This considers the conversion of lipid feedstocks, namely Used Cooking Oil (UCO), animal Tallow and Camelina Oil (CO), by ENI's patented Ecofining^{TM} process, based on the Hydroprocessed Esters and Fatty Acids (HEFA) technology. The study followed the methodological approach for Life Cycle Assessment of biofuels described in the recast of the Renewable Energy Directive (REDII).

An extensive set of cases was analysed by assuming different locations, logistic options and agricultural protocols (particularly the application of different soil amendments) for camelina cultivation, a crop which is being developed as an intermediate crop and as a potential alternative for restoring degraded lands, as the ones in the EU Mediterranean region here considered. As a meaningful contribution of the work, calculations introduced the e_{sca} term (emissions savings from improved agricultural management), included in REDII methodology, whose application has been limited up to now. We applied this term by adopting two different approaches to the quantification of the change in soil carbon stock: i) one based on theoretical calculations, related to the content of fixed carbon in the soil amendments applied and ii) other based on experimental measurements from field trials carried out by our Bio4A partners.

Encouraging results were observed for all the studied cases, for the calculated Greenhouse Gas (GHG) emission savings were always >65%, as required by REDII for biofuels to be quantified for national renewable energy objectives. In particular, we estimated 89% and 85% savings respectively for UCO and Tallow.

Camelina cases performed even better, providing savings in the range of 107% - 128%. These were largely contributed by emission savings from improved agricultural management (e_{sca}) and by the adoption of the degraded land bonus (e_B) indicated in REDII methodology. When the e_{sca} and the e_B contributions are not taken into consideration, the camelina cases -based on the experimental data obtained from BIO4A field trials in Spain and Italy- provide GHG emission savings ranging from 65% to 74%, depending on the country and cultivation scenario.

Indeed, we observed the relevance of the e_{sca} term to the results in a sensitivity analysis by considering different values for the change in Soil Organic Carbon (SOC) (in which the term is ultimately based). A positive outcome of the study is that the calculated theoretical e_{sca} values for the different camelina cultivation scenarios and the e_{sca} values measured experimentally from soil sampling are aligned.

However, we must emphasize the consideration of e_{sca} necessarily needs to be understood as a preliminary approach or pilot application of the term, once large uncertainty is involved in soil sampling and SOC measurements. Further experimental work in this sense should be performed to strengthen our results. Although a maximum limit for e_{sca} of 45 g CO_{2eq} MJ^{-1}, as indicated in RED II, was taken into account, it was not reached in the study, given that the soil amendments (assumed as the major contributors to SOC change) were only applied at moderate amounts. Ultimately, we could state Bio4A adopted a conservative approach regarding e_{sca} quantification. Additionally, we also analysed the influence of crop productivity by varying this parameter ±10%, which yielded changes in overall emissions ranging -11% to +13%. Finally, we also carried out an optimisation study, which actually showed that there is room for even improving these results (minimising emissions) if larger amounts of amendment are applied on land.

In summary, we can conclude that the Bio4A value chain and particularly, camelina as feedstock, can be an excellent option providing a synergic positive effect by contributing to decarbonising the aviation sector and reverting soil degradation.

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Annex I – Life Cycle Inventory

Table A1. Allocation of impacts along the Bio4A value chain. Intermediate products taking part in SAF production are indicated in italics below each stage.

Product	Amount, kg MJ^{-1} SAF	LHV, MJ kg^{-1}	Allocation (stage)	Allocation (accumulated)	Source of LHV
Sieving					
Seed, dry	4.43	25.42	85.6%	0.7%	CCE
Husk, dry	1.11	17.13	14.4%		CCE
Crushing					
Camelina oil	1.68	37.03	56.9%	0.8%	CCE
Camelina meal	2.70	17.08	42.1%		CCE
Losses	0.04	25.42	1.0%		CCE
Ecofining ™					
Naphtha / Light ends	0.12	45.35	8.2%	1.5%	Calculated
Diesel	1.41	44	91.8%		REDII, Annex III
Gas Recovery					
Naphtha / JF mix	6.31E-02	44.64	50.9%	18.1%	Calculated
Fuel Gas	1.68E-02	46.40	14.1%		Propane assumed
LPG	4.21E-02	46.00	35.0%		REDII, Annex III
Distillation					
Jet Fuel	2.27E-02	44.00	35.5%	35.5%	REDII, Annex III
Naphtha	4.04E-02	45.00	64.5%		REDII, Annex III

Table A2. Life Cycle Inventory (non-allocated) for e_p, tallow rendering. Functional Unit: 1 MJ SAF produced, delivered and used. Based on JRC (2019).

Item	Value	Unit	Comments	Reference process for emission factor
Electricity	0.05	kWh	Medium voltage, Italy	Commission Implementing Regulation 2022/996, Annex IX
Natural Gas	3.25	MJ		Commission Implementing Regulation 2022/996, Annex IX
Fuel oil	0.40	MJ		Commission Implementing Regulation 2022/996, Annex IX

Table A3. Life Cycle Inventory (non-allocated) for e_p, processing of camelina seed. Functional Unit: 1 MJ SAF produced, delivered and used.

Item	Value	Unit	Comments	Reference process for emission factor
Sieving (Separation of seed from husk)				
Electricity	2.86E-03	kWh	Medium voltage, Italy. Cultivation in Italy.	Commission Implementing Regulation 2022/996, Annex IX
Electricity	2.86E-03	kWh	Medium voltage, Spain. Cultivation in Spain.	Commission Implementing Regulation 2022/996, Annex IX
Crushing	1.5	g CO_{2eq}	Communication to CCE by commercial operator as average market value	

Table A4. Life Cycle Inventory (non-allocated) for e_p, fuel production stage (hydroprocessing + distillation). Functional Unit: 1 MJ SAF produced, delivered and used.

Item	Value	Unit	Comments	Reference process for emission factor
Biomass Treatment Unit (BTU)				
Acid	0.01	kg	Assumed phosphoric acid	Commission Implementing Regulation 2022/996, Annex IX
Water	0.04	kg		Ecoinvent 3.8 - Water, decarbonised {ES}| market for water, decarbonised | Cut-off, S
Bleaching Earth	0.04	kg		Commission Implementing Regulation 2022/996, Annex IX
Electricity	0.03	kg	Medium voltage, Italy	Commission Implementing Regulation 2022/996, Annex IX
Gums outlet	0.04	kg	Assumed to undergo Anaerobic Digestion	Ecoinvent 3.8 - Biowaste {RoW}| treatment of biowaste by anaerobic digestion | Cut-off, S
Spent cake	0.06	kg	Assumed to be disposed of in landfill	Ecoinvent 3.8 - Waste zeolite {RoW}| treatment of, inert material landfill | Cut-off, S
Steam Methane Reforming (SMR)				
Direct CO_2 emissions	0.35	kg	From NG combustion	
Natural Gas provision	0.28	m^3		Ecoinvent 3.8 - Natural gas, high pressure {IT}| market for | Cut-off, S
Water	1.47	kg		Ecoinvent 3.8 - Water, deionised {Europe without Switzerland}| market for water, deionised | Cut-off, U
Heat (steam), avoided	-2.43	MJ		Ecoinvent 3.8 - Heat, from steam, in chemical industry {RER}| steam production, as energy carrier, in chemical industry | Cut-off, U
Electricity	0.02	kWh	Medium voltage, Italy	Commission Implementing Regulation 2022/996, Annex IX
Ecofining™				
Fuel Gas	0.77	MJ		Commission Implementing Regulation 2022/996, Annex IX
Water	0.40	kg		Ecoinvent 3.8 - Water, deionised {Europe without Switzerland}| market for water, deionised | Cut-off, U
Dimethyl sulphide	2.10E-03	kg		Ecoinvent 3.8 - Dimethyl sulfide {GLO}| market for | Cut-off, S
Catalyst	1.18E-04	kg	Assumed replacement every 3 years	Barbera et al. Snowden-Swan et al. 2016.
Electricity	0.11	kWh	Medium voltage, Italy	Commission Implementing Regulation 2022/996, Annex IX
Gas recovery				
Electricity	1.37E-02	kWh	Medium voltage, Italy	Commission Implementing Regulation 2022/996, Annex IX
Distillation				
Natural Gas	1.46E-02	MJ	Used to heat thermal oil	Commission Implementing Regulation 2022/996, Annex IX
Thermal oil		kg	Assumed Dowtherm™	
Diphenyl oxide	1.33E-05	kg	73.5% of thermal oil. Diphenylether as proxy.	Ecoinvent 3.8 - Diphenylether-compound {GLO}| market for | Cut-off, S
Biphenyl	4.78E-06	kg	26.5% of thermal oil. Benzene as proxy.	Ecoinvent 3.8 - Benzene {GLO}| market for | Cut-off, S
Water	4.76E-05	kg	Cooling water. Closed circuit with 6 hours autonomy. 3% annual replacement.	Ecoinvent 3.8 - Water, decarbonised {ES}| market for water, decarbonised | Cut-off, S
Electricity	1.37E-04	kWh	Medium voltage, Italy	Commission Implementing Regulation 2022/996, Annex IX

Table A5. Life Cycle Inventory (non-allocated) for e_{td}, emissions from transportation. Functional Unit: 1 MJ SAF produced, delivered and used.

Item	Value	Unit	Comments	Reference process for emission factor
UCO collection			Based on JRC (2019)	
Truck	0.13	tkm	100 km (80% of UCO)	See Table A6
Ship	2.36	tkm	7,000 km (20% of UCO imported from Asia)	See Table A6
Tallow collection			Based on JRC (2019).	
Truck	0.27	tkm	162 km	See Table A6
Harvest (seed+husk), cultivation site – crushing facility				
Truck, ES	0.24	tkm	50 km Assumed	See Table A6
Truck, IT	0.24	tkm	50 km Assumed	See Table A6
Camelina oil, Central Spain – Valencia				
Truck	0.62	tkm	371 km. Toledo assumed as departing point	See Table A6
Camelina oil, Valencia – Gela				
Ship	2.18	tkm	1,296 km. Estimated with https://sea-distances.org/	See Table A6
Camelina oil, Inner Sicily – Gela				
Truck	0.17	tkm	100 km Assumed	See Table A6
Jet fuel/Naphtha mix, Gela – Livorno				
Ship	0.05	tkm	856 km. Estimated with https://sea-distances.org/	See Table A6
Neat SAF, Livorno – Amsterdam port				
Ship	0.09	tkm	4,171 km. Estimated with https://sea-distances.org/	See Table A6
Blended SAF, Amsterdam port – Schiphol airport				
Pipe	7.27E-04	tkm	16 km	See Table A6
Blended SAF, Livorno – Fiumicino airport				
Truck	0.02	tkm	387 km	See Table A6

Table A6. Emission factors from selected transportation modes. Source: Commission Implementing Regulation 2022/996, Annex IX.

Item	Value	Unit	Reference process for emission factor
Ship transportation	**15.07**	**g CO_{2eq} tkm^{-1}**	
Heavy fuel oil consumption	0.16	MJ tkm^{-1}	Chemical/product tanker, 15 kt (fuel oil) for FAME and HVO transport
Emissions from fuel combustion	94.20	g CO_{2eq} MJ^{-1}	Heavy fuel oil
Truck transportation	**77.51**	**g CO_{2eq} tkm^{-1}**	
Diesel consumption	0.81	MJ tkm^{-1}	Truck (40 tonne) for dry product (Diesel)
Emissions from fuel combustion	95.10	g CO_{2eq} MJ^{-1}	
CH_4, exhausted	8.40E-02	g CO_{2eq} tkm^{-1}	Truck (40 tonne) for dry product (Diesel)
N_2O, exhausted	0.40	g CO_{2eq} tkm^{-1}	Truck (40 tonne) for dry product (Diesel)
Pipe transportation	**0**	**g CO_{2eq} tkm^{-1}**	Local (10 km) pipeline

GWP CH_4: 28 g CO_{2eq} g^{-1}
GWP N_2O: 265 g CO_{2eq} g^{-1}

Table A7. Agricultural protocols (non-allocated) used in the calculation of e_{ec}, emissions from cultivation, and e_{sca}, emission savings from soil carbon accumulation. Data sources for inputs and outputs: Spain, CCE trials in Toledo/Ciudad Real; Italy, Re-Cord trials in Terontola.

Item	Unit	Comments	Spain			Italy		
			Biochar	Compost	Combi (15%)	Biochar	Compost	Combi (15%)
Outputs								
Harvest								
Seed yield	kg ha^{-1} y^{-1}	Wet base. 7% moisture	1,411.00	1,551.00	1,987.00	1,367.98	879.07	1,493.08
Harvest	kg ha^{-1} y^{-1}	Wet base. Seed + Husk	1,763.75	1,938.75	2,483.75	1,641.58	1,054.88	1,791.69
Productivity	MJ SAF ha^{-1} y^{-1}	0.23 MJ SAF produced kg^{-1} (dry) seed	296.20	325.59	417.11	287.17	184.53	313.43
Crop residue								
Above ground total residue	kg ha^{-1} y^{-1}	Dry base. All assumed to be left in field	3,254.58	3,577.46	4,582.98	2,652.93	1,806.42	2,632.89
Below ground total residue	kg ha^{-1} y^{-1}	Dry base. Assumed 22% of Above Ground	716.01	787.04	1,008.26	583.64	397.41	579.23
N returned with crop residue	kg N ha^{-1} y^{-1}	Above ground: 0.006 kg N kg^{-1} Below ground: 0.009 kg N kg^{-1}	25.97	28.55	36.57	21.17	14.42	21.01
Inputs								
Planting seed	kg ha^{-1} y^{-1}		8	8	8	12.4	12.4	12.4
Herbicides	kg ha^{-1} y^{-1}		0.075	0.075	0.075	0	0	0
Diesel								
Diesel, first year	L ha^{-1}		36.00	56.50	56.50	36.00	56.50	56.50
Diesel, additional, annual	L ha^{-1} y^{-1}		29.00	27.50	27.50	29.00	27.50	27.50
Mineral fertiliser application		Mineral fertiliser is applied annually						
N	kg N ha^{-1} y^{-1}		66.00	50.00	50.00	14.63	14.63	14.63
P	kg P ha^{-1} y^{-1}		40.00	7.00	7.00	58.52	58.52	58.52
K	kg K ha^{-1} y^{-1}		30.00	7.00	7.00	14.63	14.63	14.63
Soil amendment application		Applied once, at the beginning of the cultivation						
Compost	kg ha^{-1}	Wet base. Moist %: ES, 60%; IT, 26%		20,000.00	18,653.91		20,000.00	27,027.03
	kg ha^{-1} y^{-1}	Dry base. Annualised along 20 years cultivation		405.00	365.50		740.00	1,000.00
Biochar	kg ha^{-1}	Wet base. Moist %: ES, 4.17%; IT, 30%	4,800.00		1,346.09	4,285.71		4,285.71
	kg ha^{-1} y^{-1}	Dry base. Annualised along 20 years cultivation	230.00		64.50	150.00		150.00
Emissions								
N_2O emissions	kg N_2O ha^{-1} y^{-1}	See calculation in Section 3.3.1	1.16	1.16	1.27	0.44	0.39	0.48
Neutr. of fertiliser acidification	kg CO_2 ha^{-1} y^{-1}	See calculation in Section 3.3.2	51.68	39.15	39.15	11.46	11.46	11.46
e_{sca}								
Calculated from C_{fix} addition								
(CS_a – CS_r), Change in soil carbon stock	kg ha^{-1} y^{-1}	The change in soil carbon stock is assumed equal to the C_{fix} applied with soil amendment. Annualised along 20 years cultivation	187.78	83.75	128.24	120.54	104.27	224.81
CO_2 *captured*	kg ha^{-1} y^{-1}	All C_{fix} from amendment incorporated in soil	688.01	306.87	469.88	441.66	382.03	823.69
Calculated from experimental data								
(CS_a – CS_r)	kg ha^{-1}	Change in soil carbon stock (3 years). Averaged value for locations in Ciudad Real and Toledo.	5,497.51	2,117.05	692.55	—	—	—

$(CS_a – CS_r)$	kg ha^{-1} y^{-1}	Annualised along 20 years cultivation	274.88	105.85	34.63	—	—	—
CO_2 *captured*	kg ha^{-1} y^{-1}		1,007.14	387.84	126.88	—	—	—

Table A8. Composition of amendments applied in camelina cultivation.

Item	Unit	Spain			Italy		
		Biochar	Compost	Combi (15%)	Biochar	Compost	Combi (15%)
Moisture, Compost	%		59.50%	60.81%		26.00%	26.00%
Moisture, Biochar	%	4.17%		4.17%	30.00%		30.00%
N	kg kg^{-1}		0.04	0.04		3.51E-03	3.05E-03
P	kg kg^{-1}		3.78E-03	0.00		8.34E-03	7.25E-03
K	kg kg^{-1}		0.03	0.02		0.02	0.02
C_{total}	kg kg^{-1}	0.86	0.41	0.47	0.87	0.36	0.43
$C_{organic}$	kg kg^{-1}	0.86	0.40	0.46	0.86	0.36	0.42
C_{fix}	kg kg^{-1}	0.82	0.21	0.30	0.80	0.10	0.20

Table A9. Life Cycle Inventory for biochar production. Functional Unit: 1 kg biochar produced. Data provided by Re-Cord.

Item	Value	Unit	Comments	Reference process for emission factor
Wood Chips	3.76	kg		Ecoinvent 3.8 - Wood chips, dry, measured as dry mass {RER}| market for | Cut-off, S
Natural Gas	1.23	MJ		Commision Implementing Regulation 2022/996, Annex IX
Electricity	0.64	kWh	Medium voltage, Italy	Commision Implementing Regulation 2022/996, Annex IX
			Medium voltage, Spain	