Carina

D3.4

Report on Environmental Assessment

Roundtable on Sustainable Biomaterials (RSB)

31/10/2025

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ABBREVIATIONS

AC	Acidification
CC	Climate change
EU	European Union
FEC	Ecotoxicity, freshwater
FEU	Eutrophication, freshwater
GHG	Greenhouse gas
HTC	Human toxicity, cancer
HTN	Human toxicity, non-cancer
IR	Ionising radiation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LU	Land use
MEU	Eutrophication, marine
OD	Ozone depletion
PEF	Product Environmental Footprint
P&C	Principles and Criteria
PM	Particulate matter
POF	Photochemical ozone formation
R&D	Research and Development
RSB	Roundtable on Sustainable Biomaterials
RUF	Resource use, fossil
RUM	Resource use, minerals and metals
TEU	Eutrophication, terrestrial
VC	Value Chain
WU	Water use

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1. Executive summary

This report presents the methodological foundations of the environmental assessment applied to the selected innovative bio-based Value Chains (VCs) of the CARINA project, carried out within WP3 (Sustainability Assessment) and specifically linked to T3.4 (Environmental assessment of selected CARINA concepts). In this context, a set of environmental indicators was defined in T3.1 (Identification of sustainability indicators) as part of the overall project framework. To address these indicators comprehensively and ensure a holistic evaluation, the environmental impacts of the chosen CARINA VCs were assessed through a Life Cycle Assessment (LCA), complemented by additional evaluations based on the 12 Principles and Criteria (P&C) established by the Roundtable on Sustainable Biomaterials (RSB).

This document reports exclusively on those indicators examined from a life cycle perspective, presenting a first-round assessment. The preliminary results serve a dual purpose: (i) to identify environmental hotspots across the different phases of the selected CARINA VCs, thereby providing decision support for developing more sustainable process routes, and (ii) to refine both the data inputs and the methodological framework applied.

A second-round assessment will be presented in a forthcoming deliverable (D3.5), in which the full set of environmental indicators will be evaluated as part of a broader Integrated Sustainability Assessment (i.e., T3.5). This will be complemented by an economic assessment (T3.2) and a social evaluation (T3.3), ensuring a multidimensional perspective on sustainability performance.

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2. Environmental assessment of the CARINA project

The sustainability assessment to be conducted within the CARINA project, including the evaluation of the environmental pillar, was based on a process for a participatory indicators' selection under a multi-stakeholder perspective to be applied to innovative bio-based Value Chains (VCs). In this sense, four consecutive steps were followed, two of them considering a top-down approach, in which a series of sustainability principles and targets were established. In contrast, the other two considered a bottom-up approach, selecting a set of preliminary indicators which were finally validated. Concerning the environmental dimension of sustainability, 15 preliminary indicators were selected, and finally, 10 of them were chosen. More information about the methodological description can be found in D3.1.

Focusing on the environmental, the selected environmental indicators (see **Table 1**) aim to ensure that the sustainability assessment robustly captures the ecological dimension of bio-based VCs, in alignment with global environmental priorities and sustainability frameworks. The indicators span global, terrestrial, water-related, and systemic environmental impacts, reflecting both biophysical realities and regulatory expectations.

The environmental indicators are to be assessed through quantitative metrics from the Product Environmental Footprint (PEF) method[1] combined with qualitative and semi-quantitative indicators drawn from the Roundtable on Sustainable Biomaterials (RSB)'s 12 Principles and Criteria (P&C) for a sustainable bioeconomy[2]. These frameworks are widely recognised as scientifically robust and practically applicable to guide the sustainable transition of bio-based industries[3]. The 10 selected indicators are structured to reflect this comprehensive scope. Global impacts are captured through Greenhouse Gas (GHG) emissions (indicator #1) and Soil Management and Carbon Accumulation (indicator #2), the former assessed via the PEF climate change impact category[4,5] and RSB P&C Nr. 3, and the latter through RSB P&C Nr. 8, focusing on potential soil carbon sink functions. Terrestrial system pressures are addressed by Land Use Impacts (indicator #3), which includes the PEF land use category (soil quality index) and potential low-iLUC impacts, and conservation (indicator #4), capturing biodiversity effects via RSB P&C Nr. 7 and other key standards, such as from the European Sustainability Reporting Standard[6], the Global Reporting Initiative[7] or Joint Research Centre[8]. Water-related issues are assessed through a sequence of indicators: Water Availability (indicator #5), measured using PEF water use[9] and regionalised water stress analysis; Water Management (indicator #6), assessed via RSB P&C Nr. 9; and Eutrophication (indicator #7), which evaluates nutrient loading impacts across marine, freshwater, and terrestrial systems[10]. Freshwater Ecotoxicity (indicator #8) and Acidification (indicator #9), both part of the PEF impact categories, extend the analysis to chemical stressors and broader atmospheric effects[11]. Finally, Resource Use and Waste Management (indicator #10) integrates input use efficiency and waste reduction strategies, drawing from RSB P&C Nr. 11 and the PEF resource use category. Taken together, the selected environmental indicators allow for a systemic yet operationalisable assessment of environmental risks and opportunities along the new bioeconomic VCs. Their alignment with EU sustainability metrics and bioeconomy strategies ensures academic relevance, policy, and market applicability.

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Table 1. Overview of environmental indicators considered in this study.

#	Indicator	Calculation method	Unit	Covered in this report?
1	GHG emissions	RSB GHG Calculator Tool	kg CO_2 eq.	✗
		Life cycle indicator: Climate change Environmental Footprint (EF) method, version 3.1[5,12]	kg CO_2 eq.	✓
2	Water management and saving	RSB Principle #9: Water stress index Water management: The water management plan (both for rain-fed and irrigated crops) shall contain good water management practices to optimise water use	Yes/No	✗
		RSB Principle #9: Water stress index Water saving: Implementation of water saving practices	Yes/No	✗
3	Water availability and quality	RSB Principle #9: Water stress index Water availability: Operations are located in a region with medium, high or extremely high water stress	High/medium/low	✗
		RSB Principle #9: Water stress index Water quality: Wastewater or runoff that contains potential organic and mineral contaminants is treated or recycled to prevent any negative impact on humans, wildlife, and natural compartments (water, soil)	Yes/No	✗
		Life cycle indicator: Water use Environmental Footprint (EF) method, version 3.1[5,12]	m^3	✓
4	Eutrophication	Life cycle indicator: Marine eutrophication Environmental Footprint (EF) method, version 3.1[5,12]	kg N eq.	✓
		Life cycle indicator: Freshwater eutrophication Environmental Footprint (EF) method, version 3.1[5,12]	kg P eq.	✓
		Life cycle indicator: Terrestrial eutrophication Environmental Footprint (EF) method, version 3.1[5,12]	mol N eq.	✓
5	Soil management and soil carbon accumulation	RSB Principle #8: Soil Increase of soil organic matter content due to soil management practices (organic matter content measure (>1%))	%	✗
6	Land use impacts: land use, soil quality index and direct/indirect Land Use Change (LUC) vs. Induced LUC (ILUC)	Life cycle indicator: Land use Environmental Footprint (EF) method, version 3.1[5,12]	Pt	✓
		Soil quality index based on LANCA (soil quality index)[13]	-	✗
		Land use change: GHG Tool, GTAP-BIO Model (Nuseed CARINATA), operations contribute to land use change	-	✗
7	Biodiversity conservation of natural protected areas and deforestation risk	RSB Principle #7: Conservation Biodiversity conservation: Ecological corridors are protected, restored or created to minimize habitat fragmentation	Yes/No	✗
		RSB Principle #7: Conservation Natural protected areas: Operations avoid negative impacts on biodiversity, ecosystems, and conservation values. Is the operation located in any nationally/regionally or internationally legally protected area?	Yes/No	✗
		RSB Principle #7: Conservation Deforestation risk: Risk of forest decrease in the area where crop is located	High/Medium/Low	✗
8	Freshwater ecotoxicity	Life cycle indicator: Ecotoxicity, freshwater Environmental Footprint (EF) method, version 3.1[5,12]	CTUe	✓
9	Acidification	Life cycle indicator: Acidification Environmental Footprint (EF) method, version 3.1[5,12]	mol H^+ eq.	✓
10	Depletion of abiotic resources & resource use, minerals and metals	Life cycle indicator: Resource use, fossil and resource use Environmental Footprint (EF) method, version 3.1[5,12]	MJ	✓
		Life cycle indicator: Resource use, minerals and metals Environmental Footprint (EF) method, version 3.1[5,12]	kg SB eq.	✓

Within the scope of this report, solely the indicators related to the PEF method were selected, with the purpose of obtaining some preliminary results and conclusions, while for the others, related to the RSB P&C framework, will be addressed in an upcoming deliverable (D3.5). The ones that will be addressed in this document are shown in **Table 1**.

The life cycle approach considered is shown in **Section 2.1**, with a further description provided in **Section 3** (the methodology section). The P&C of the RSB is shown in **Section 2.2** for descriptive purposes. Lastly, **Section 2.3** explains the list of case studies to be evaluated in this deliverable.

2.1 Overview of the life cycle approach

A cradle-to-factory gate approach was considered when performing the LCA for selected camelina and carinata VCs. Additionally, individual assessments were performed for each phase for camelina and carinata, considering different scenarios to provide detailed decision support for project partners (see **Figure 1**). Particularly, three main phases were distinguished: (i) field phase (cradle-to-gate approach), (ii) seed crushing phase (gate-to-gate approach), and (iii) industrial phase (gate-to-factory gate approach).

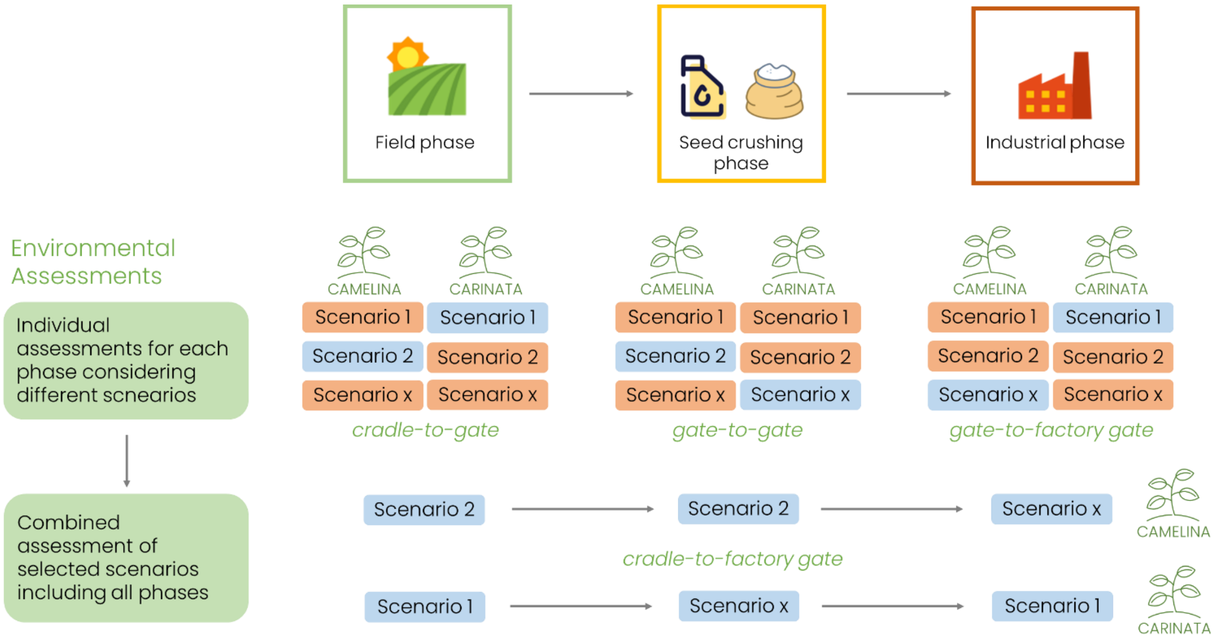

Figure 1. Overview of the three phases of the camelina and carinata value chains considered in the environmental assessments performed in the CARINA project. After individual assessments for all phases, a combined evaluation considering selected scenarios from each phase was conducted.

2.2 Principles & Criteria of the Roundtable on Sustainable Biomaterials

The RSB 12 P&C framework has been defined to provide a sustainability structure that ensures sustainable social, legal, environmental and management practices for production in the circular bioeconomy. These appear depicted in **Figure 2**.

Bio-based products that align with the 12 RSB P&C can obtain the RSB's best-in-class certification. To get RSB certified, products must comply with RSB standards, procedures, and guidance documents such as the RSB Standard for Advanced Products (non-energy use)[14], the RSB Standard for Advanced Fuels[15] and the RSB GHG (greenhouse gas) Calculation Methodology[16]. This ensures that all operators participating in the RSB certification system use a standardised methodology to calculate GHG emissions employing the RSB GHG Tool.

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In the scope of the WP4 of the CARINA project, guidelines and new standards for certification of low iLUC (indirect Land Use Change) feedstocks will be developed based on existing RSB standards for low iLUC feedstocks[17]. Given that the CARINA VCs and products are in an early stage of development, certification of CARINA products based on RSB standards is not in the project's scope. However, the in-depth sustainability assessments conducted play a crucial role in demonstrating the CARINA VCs' social, economic, and environmental impacts, laying the foundation for future certification.

Figure 2. The 12 Principles and Criteria (P&C) proposed by the Roundtable on Sustainable Biomaterials (RSB) for sustainable production[2].

2.3 Selection of case studies

Within the field phase of CARINA project (WP1), a set of cropping systems was considered for the environmental assessment. They have been designated with a letter for clarity:

A: Camelina as a cash-cover crop in double cropping.

B: Camelina intercropping and relay cropping.

C: Camelina on marginal land.

D: Carinata as a cash-cover crop in double cropping.

E: Carinata intercropping and relay cropping.

F: Carinata on marginal land.

A detailed overview of the field phase scenarios is provided in **Table 2**, including information on location, the responsible project partner, and the campaign year. The scenarios are structured around two types of system: reference scenarios and CARINA scenarios. The latter are characterised by the integration of camelina or carinata in different cropping systems: (i) as cash-cover crops in double cropping systems (scenarios A and D), (ii) through intercropping or relay cropping (scenarios B and E), and (iii) on marginal land (scenarios C and F).

Table 2. List of the field phase scenarios of the CARINA project.

Scenario	Sub-scenario	Location	CARINA partner	Reference crop system	CARINA crop system	Campaign	Area (ha)
A	A-1.1	France (Centre-Val de Loire, Bainvilliers)	TI	Barley	Barley & camelina	2024	1
	A-1.2			Pea	Pea & camelina	2024	1
	A-2.1	France (SW)	ARVALIS	Sunflower	Sunflower & camelina	2024	1
	A-2.2			Sorghum	Sorghum & camelina	2024	1
	A-3.1	Italy (experimental site in Bologna)	UNIBO	Sunflower	Sunflower & camelina	2023 & 2024	0.1314 0.285
	A-3.2			Sorghum	Sorghum & camelina	2023 & 2024	0.1314 0.285 0.16
	A-4.1	Serbia (Rimski sancevi)	IFVNCS	Sunflower	Sunflower & camelina	2024	0.1314
	A-4.2			Sorghum	Sorghum & camelina	2024	0.1314
	A-5	**Spain (Lleida)**	**CCE**	**Soybeans & barley**	**Soybeans & camelina**	**2024**	**2.7**
B	B-1	Poland (not known)	PULS	NA (fallow)	Barley & camelina	2023 & 2024	0.35
	B-2	Serbia (Rimski sancevi)	IFVNCS	NA (fallow)	Pea & camelina	2023	0.1314
C	**C-1.1**	**Spain (Ciudad Real)**	**CCE**	**Wheat, barley & pea (with fallow)**	**Wheat, barley & pea (with camelina)**	**2023**	**1.38**
	C-1.2	**Spain (Burgos)**		**Sunflower, barley, pea & wheat (with fallow)**	**Sunflower, barley, pea & wheat (with camelina)**	**2023**	**36**
	C-2	Poland (not known)	PULS	NA (marginal land)	Camelina in marginal land	2023 & 2024	0.35
	C-3.1	Italy (Emilia-Romagna, Ozzano dell'Emilia)	UNIBO	NA (marginal land)	Camelina in marginal land	2023	0.168
	C-3.2			NA (marginal land)	Camelina in marginal land	2024	0.24
E	E-1	Italy (experimental site in Bologna)	UNIBO	Chickpea	Chickpea & carinata	2024	0.076 0.162
	E-2	Italy (Lemmo rino)	Novamont	NA	Chickpea & carinata	2024	1
	E-3	Poland (not known)	PULS	NA	Barley & carinata	2023 & 2024	0.35
F	F-1	Poland (not known)	PULS	NA (marginal land)	Carinata in marginal land	2023 & 2024	0.35

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An internal selection criterion was applied, based on both the minimum cultivated area (set at 1 ha to ensure representativeness) and the availability of primary data, which enhances the robustness of the results. Additionally, depending on the outcomes of the field phase, at least one of the scenarios will subsequently be assessed in detail within the CARINA VC. In this context, the production of biostimulants is foreseen to be integrated during the third industrial phase.

Following these criteria, three case studies located in Spain were selected:

- one from scenario A (A-5) and
- two from scenario C (C-1.1 and C-1.2).

However, for ease of reference, these cases have been renamed as scenario A, C-1 and C-2, and their descriptions are provided in the following sections.

Not all scenarios are addressed in this deliverable because not enough data was available for all cases. In this regard, it is essential to note that all scenarios selected are related to Camelina, apart from scenario D, which was not included in **Table 2**. These two aspects are based on a lack of reliable information. Then, the idea will be to address at least one case study of each scenario to provide a more appropriate scope of the CARINA project sample, including both camelina and carinata crops in every cropping system situation (i.e., cash-cover cropping with double cropping, intercropping and relay cropping, and cropping on marginal land).

Case A: Camelina cash-cover cropping with double cropping in Lleida, Spain

The first case study is a cropping system type A (camelina cash-cover cropping with double cropping) performed in the province of Lleida (Spain) during 2023/24. With an extension of 2.7 ha, the reference scenario (winter barley and soybeans) was compared to the CARINA scenario (camelina and soybeans).

Case C-1: Camelina on marginal land in Ciudad Real, Spain

The second case study is a cropping system type C (camelina on marginal land) performed in the province of Ciudad Real (Spain) during 2022/23. With an extension of 1.28 ha, the reference scenario (winter barley, fallow, winter wheat, and winter pea) was compared to the CARINA scenario (winter barley, camelina, winter wheat, and winter pea).

Case C-2: Camelina on marginal land in Burgos, Spain

The third case study is a cropping system type C (camelina on marginal land) performed in the province of Burgos (Spain) during 2022/23. With an extension of 36 ha, the reference scenario (sunflower, winter barley, fallow, winter wheat and winter pea) was compared to the CARINA scenario (sunflower, winter barley, camelina, winter wheat and winter pea).

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3. Methodology

For conducting the Life Cycle Assessment (LCA) study, the two associated international standards were taken into consideration, thus establishing the principles and framework (ISO 14040:2006[18]), as well as the requirements and guidelines (ISO 14044:2006[19]). In this regard, the four interrelated steps were covered: (i) goal and scope, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation. Therefore, the methodological description of the LCA is described below, divided into steps (see **Sections 3.1-3.4**).

3.1 Goal and scope

The overall objective was to perform an environmental assessment while following a life cycle approach for the camelina and carinata cropping systems associated with the CARINA project. However, different goals and scopes were defined depending on the phase evaluated (i.e., field, seed crushing, industrial, or combined) and whether the whole VC was addressed. Consequently, these were collected in **Table 3** as short descriptions or bullet points for facilitating purposes, along with other key features like the system boundaries, functional units and the target group associated. For the appropriate life cycle modelling, the system boundaries vary depending on the scenario being evaluated (see **Figure 3**).

Table 3. Main features related to the goal and scope step of the Life Cycle Assessment (LCA) conducted in CARINA.

Goal	Field phase: Identification and analysis of environmental hotspots occurring during the field phase of camelina and carinata cropping systems of the CARINA project to obtain crops, as well as changes in the environmental impact considering between the CARINA scenario (i.e., those that integrate camelina or carinata in the cropping system) and the reference scenario (i.e., those that do not integrate camelina or carinata in the cropping system). Seed crushing phase: Identification and analysis of environmental hotspots occurring during the seed crushing phase of camelina and carinata cropping systems of the CARINA project to obtain cake and oil fractions. Industrial phase: Identification and analysis of environmental hotspots occurring during the conversion phase of camelina and carinata cropping systems of the CARINA project, from cake and oil fractions to bio-based products. Combined assessment: Identification and analysis of environmental impacts occurring during the whole VCs of the CARINA project, comprising all phases and transportation in between.
Scope	Several scenarios were explored within the CARINA project. Of all of them, some were selected to be evaluated. This selection was based mainly on two different criteria. On the one hand, field size. Areas larger than 1 ha were selected, thus excluding experimental field trials to obtain more realistic results. On the other hand, primary data availability. In this sense, in those case studies in which primary information was available, they were prioritised to be selected compared to other cases where there may have been some data gaps. This was a selection process conducted in close collaboration with the project partners.

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Table 3 (cont.). Main features related to the goal and scope step of the Life Cycle Assessment (LCA) conducted in CARINA.

System boundaries	Field phase: Cradle-to-gate. Seed crushing phase: Gate-to-gate. Industrial phase: Gate-to-factory gate. Combined assessment: Cradle-to-factory gate.
Functional units	A "perfect conditions" situation was assumed to select functional units. This means that all basic physicochemical requirements are met so that each product fully delivers its intended function in every phase of the system: Field phase: • 1 kg of camelina or carinata grain from a specific country and cropping system in perfect conditions to be further crushed. • 1 ha of cropping system (to perform comparisons between CARINA and reference scenarios). Seed crushing phase: • 1 kg of camelina or carinata cake in perfect conditions to be further processed. Industrial phase and combined assessment: • 1 L of biostimulant (from camelina or carinata cake) in perfect conditions to be sold.
Target group	The CARINA project consortia were selected as the primary target group, since the main aim was to evaluate the results of the chosen case studies and draw conclusions from them. The CARINA case studies under evaluation are also intended to serve as a methodological reference for conducting life cycle approaches related to the production of added-value bio-based products from crops. Therefore, the secondary target group was defined as academia, particularly researchers or practitioners of LCAs.

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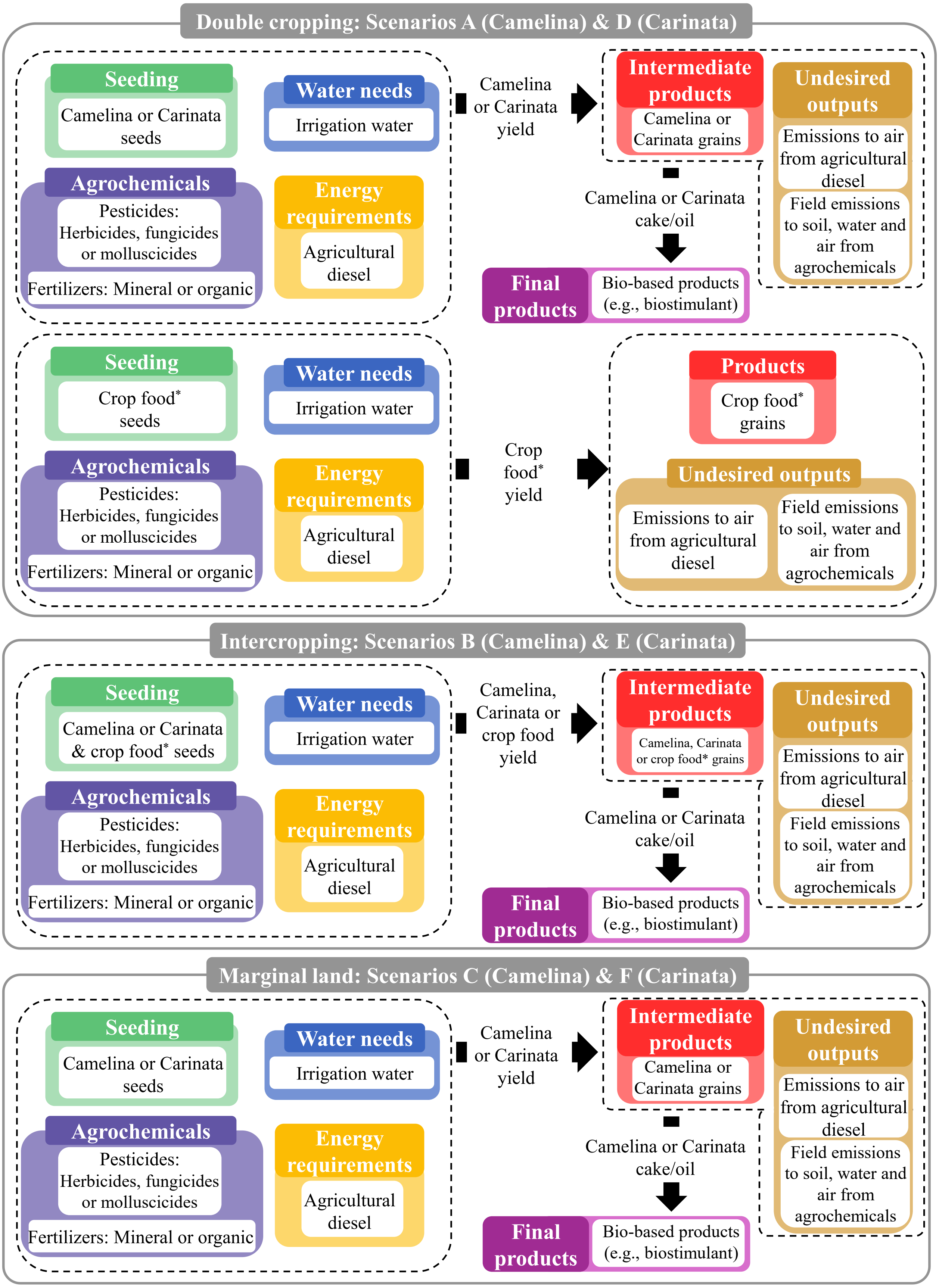

* Barley, chickpea, pea, sorghum, soy, sunflower or wheat

Figure 3. System boundaries of the different scenarios during the field phase covered in the CARINA project.

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3.2 Inventory analysis

During the inventory analysis, the Life Cycle Inventories (LCIs) for the field phase were mainly compiled from primary quantitative and qualitative data from the Systerre® (https://www.arvalis.fr/outils-et-services/outils-et-fiches/systerre) tool, resulting from field trials and additional bilateral meetings. Where information was missing, such as litres of fuel per hour or average crop yields in the territory, estimations were made based on the expertise of the CARINA partners. However, when primary information was unavailable and estimations could not be made, secondary quantitative and qualitative data were collected through literature review papers and LCA databases (e.g., Ecoinvent).

For the seed crushing phase, due to confidentiality constraints, project partners were unable to provide direct data. Consequently, this phase was modelled predominantly using secondary sources.

In contrast, the industrial processing phase benefited from detailed input data, including the types and quantities of materials and energy required, enabling a more precise LCI compilation.

Likewise, different modelling assumptions were considered depending on the phase evaluated: field (**Section 3.2.1**), seed crushing (**Section 3.2.2**) or industrial (**Section 3.2.3**), apart from when the full CARINA VC was addressed (see **Section 3.2.4**).

3.2.1 Field modelling assumptions

Starting from the field phase, it is essential to mention the need of addressing the variability of the system being studied (i.e., the field itself), as this will vary throughout time under different scenarios (A-F). This variability influences the quantity of inputs required since it depends on the seeds sown before and after each trial, for instance. However, although this data was not collected as primary information from the CARINA partners, the associated processes of transforming and occupying the lands to be studied were considered. Consequently, both the previous status of the field and its current function or situation must be covered (e.g., a change from a crop field to fallow or from one crop field to another). Additionally, the time the current status was occupied was taken into account as well. All these possible situations were considered as “inputs from nature”.

Additionally, two recurring processes were included under this category in the modelling of cropping systems:

- Biogenic CO_2 sequestration, referred to the uptake of CO_2 during photosynthesis, resulting in carbon fixation within the biomass. This entails a negative flow that balances the carbon cycle compared with the positive CO_2 emissions from the combustion of fuels, fertiliser production, etc. For its estimation, equations can be applied. Nevertheless, this has been overlooked in this report, although soil carbon accumulation practices will be covered in a following deliverable (D3.5) by the end of the CARINA project.
- Energy content of the biomass, defined as the amount of heat released by the complete combustion of a unit mass of biomass, usually expressed in terms of MJ per kg of dry matter. For its estimation, **Eq 1** was applied (see Annex).

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Land management

Starting from the land preparation, the tillage process requirements were accounted for depending on the extension of the crop field. For the sowing process, it was able to identify dedicated inputs in most cases, though some were missing. Therefore, some assumptions were necessary. For chickpeas and sorghum, the related processes for peas and maize, respectively, were considered as proxies. The same occurred for camelina and carinata. Some authors have used the rapeseed sowing process as a proxy for camelina and carinata in their modelling, since production data for the Brassicaceae family was generalised[21]. Others accounted for the seeds used for sowing by subtracting part of the yield[22]. The latter assumption is based on the fact that camelina and carinata seed production reports similar agrochemical, water and energy requirements to those of the grains themselves. Consequently, the same primary data was used in the case studies of the CARINA project as a proxy for producing the seeds needed to produce camelina or carinata grains.

Fertilisation

According to the fertilisation, the total bulk mass of the product was considered for accounting for the impact associated to both the application and production processes, while the amount of nutrient provided to the field, which was available as primary data (i.e., kg of P_2O_5 or kg of N), was bear in mind when quantifying for the emissions associated to the different environmental compartments, thus ensuring consistency when aligning with emissions models (which refer to nutrient content, not fertiliser weight).

IPCC guidelines were followed when accounting for field emissions from the application of fertilisers (all equations appear collected in Annex):

- In this regard, from N fertilisers, part of the N is directly emitted as N_2O to air due to nitrification/denitrification (see **Eq 2** and **Eq 3**). Another part volatilizes: 90% of that as NH_3 and 10% as NO_x to air[23] (see **Eq 4**, **Eq 5** and **Eq 6**). Additionally, volatilised N can later contribute to indirect N_2O emissions to air (see **Eq 7** and **Eq 8**).
- Regarding the emissions from P fertilisers, these were estimated following specific guidelines[24]: PO_4^{3-} (leaching to ground water, **Eq 9**, and run-off to surface water, **Eq 10**) and P (erosion to surface water, **Eq 11**).

Pesticides

Concerning the pesticides, its application was under consideration based on the total amount of the product applied to the field, apart from the pesticide manufacturing. For the former, the application technique was considered, while for the latter, the production of the associated quantities of the constituent active ingredients was covered. Likewise, the pesticide emissions were accounted for by allocating them across different environmental compartments, taking as a reference the PestLCI Consensus Model developed under the OLCA-Pest project[29].

In this way, the model estimates distribution fractions of pesticides to: (i) air, (ii) agricultural soil, (iii) crop surfaces (for food and non-food purposes), and (iv) off-field surfaces (i.e., from agricultural soil which fraction remains here, and which goes to freshwater and other natural soil like forests).

For the split of the pesticides emissions modelling, the tier 1A method was selected, which uses default initial emissions distribution fractions depending on the target class and the crop system (see **Table 4** below). Moreover, as no information was available on buffer zones, these were unconsidered in the modelling process.

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Table 4. Percentage distribution between the environmental compartment of the active ingredients from the emissions of the pesticides. Hrb-post (Herbicide, post-emergence), Ins (Insecticide), Fun (Fungicide), PGR (Plant growth regulator), Ac/Mi (Acarcide or Miticide), Hrb-pre (Herbicide, pre-emergence (applied on bare soil)).

Target class	Crop system	Pest-class	Air, low population density	Soil, agricultural	Soil, natural/forest	Water, surface/river	Crop
Pooideae	Barley & wheat	Hrb-post	10%	67%	1%	0%	22%
		Ins	10%	27%	1%	0%	62%
		Fun	10%	27%	1%	0%	62%
		PGR	10%	9%	1%	0%	80%
		Ac/Mi	10%	45%	1%	0%	44%
		Hrb-pre	10%	89%	1%	0%	0%
Pulses	Pea & chickpea	Hrb-post	10%	67%	1%	0%	22%
		Ins	10%	18%	1%	0%	71%
		Fun	6%	19%	1%	0%	74%
		PGR	6%	28%	1%	0%	65%
		Ac/Mi	10%	27%	1%	0%	62%
		Hrb-pre	10%	88%	2%	0%	0%
Panicoideae	Sorghum	Hrb-post	10%	67%	1%	0%	22%
		Ins	10%	18%	1%	0%	71%
		Fun	6%	19%	1%	0%	74%
		PGR	6%	28%	1%	0%	65%
		Ac/Mi	10%	27%	1%	0%	62%
		Hrb-pre	10%	88%	2%	0%	0%
Oil-bearing crops	Soybean, camelina, carinata & sunflower	Hrb-post	8%	73%	1%	0%	18%
		Ins	10%	9%	1%	0%	80%
		Fun	10%	9%	1%	0%	80%
		PGR	10%	36%	1%	0%	53%
		Ac/Mi	10%	36%	1%	0%	53%
		Hrb-pre	10%	89%	1%	0%	0%

Additionally, according to the crop surfaces, these should be included to cover the entire mass balance. To this end, it is recommended to model this additional compartment by using the dynamiCROP model[30,31]. In this regard, the EFSA plans to categorise which pesticides are more suitable for food use. However, this is outside the scope of CARINA, according to the system boundaries and objective established during the LCA study. Still, since some CARINA project scenarios intersperse camelina and carinata cultivation with other food crops, special attention will be given to the toxicity impact categories of the applied pesticides to determine the most suitable ones for food purposes.

Packaging

The packaging requirements for both fertilisers and pesticides were modelled using the corresponding Ecoinvent processes. Packaging inputs were estimated on a mass basis, applying a ratio of primary packaging weight to product weight (kg packaging per kg product). For pesticides, a value of 0.06 kg·kg⁻¹ was assumed, reflecting typical distribution in small bottles or jerrycans of 1–5

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L. A ratio of 0.006 kg·kg^{-1} was applied for fertilisers, corresponding to solid products packaged in 25 kg bags.

Water use and energy requirements

Lastly, dedicated Ecoinvent processes were selected to address water withdrawal and the necessary energy for pumping water. For the water withdrawal, the regional irrigation market was selected, while for the energy requirements, not only the environmental burdens associated with diesel production, but also the combustion of diesel in agricultural machinery were considered. Crops do not normally need water, as they are rain-fed, with the exception of soybeans.

3.2.2 Seed crushing modelling assumptions

The second phase of the CARINA VC is "seed crushing", this encompasses all processes related to the drying, cleaning, preheating, flaking, cooking, pressing and extracting oil and protein cake from camelina or carinata. Due to industrial confidentiality issues, primary process details from project partners could not be shared. However, partners' recommendations were based on considering already existing LCA databases and using the rapeseed crushing process as a plausible proxy. In this regard, given that the final product is a biostimulant obtained from camelina meal, the following Ecoinvent process was selected: "Rape meal {Europe without Switzerland}| rape oil mill operation | Cut-off, U". The reason behind this selection is that this includes solvent extraction using hexane (not just a simple pressing process), as is the case with the original camelina crushing process. However, to better reflect the camelina seed crushing process used in the selected case studies, two key modifications were applied:

1. The rapeseed seeds used for obtaining the cake were replaced by the process modelled for the camelina seeds.
2. The quantity of the seed-per-meal ratio was modified according to camelina's specifications. To do so, it was considered rapeseed's particularities, which contain around 55% of seed mass[32], as well as those from camelina, having estimated the meal fraction as 65%, based on its average oil content: 45%[33]. Therefore, a factor of 0.84615 ($0.55 \cdot 0.65^{-1}$) was multiplied by the amount of rapeseed used in the original Ecoinvent process to approximate the camelina seed required to produce each kg of meal.

3.2.3 Industrial modelling assumptions

For the industrial phase, the biostimulant production process was selected, as it was the one for which the CARINA project partners provided the most comprehensive primary information. Detailed process steps were available, together with the corresponding inputs such as water requirements and the chemical substances consumed. A diagram of the process is depicted in **Figure 4**, where specific substances were selected by choosing dedicated Ecoinvent processes for their appropriate modelling. In this regard, the camelina meal is used as feedstock, which comes from the camelina grains of the crop fields (phase 1), once they are crushed (phase 2), and it goes through a four-step process until the final product is obtained. The different steps of the biostimulant production process can be summarised as follows:

1. **Hydrolysis**: The process begins with two consecutive hydrolyses carried out in separate batches. In the first hydrolysis, camelina cake (from the previous seed-crushing step) is combined with water, a specific enzyme, and HCl to adjust the pH to 4.5. The second hydrolysis involves the addition of a different enzyme and KOH to adjust the pH to 9. Both

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stages require energy inputs in the form of electricity and heat, reaching a temperature of 50 °C, with a duration of 1 hour for the first hydrolysis and 5 hours for the second.

2. **Decantation**: Following hydrolysis, a decantation step is performed using electricity from the grid to separate the flow into two fractions. Approximately one-fifth of the output is considered waste and removed from the process.
3. **Concentration**: The remainder of the amount obtained from decantation proceeds to a concentration stage, in which 25% of it is obtained as hydrolysate using both electricity and heat.
4. **Formulation**: The hydrolysate from the concentration is mixed with additional chemicals, such as preservatives, minerals or amino acids, to obtain the final biostimulant.

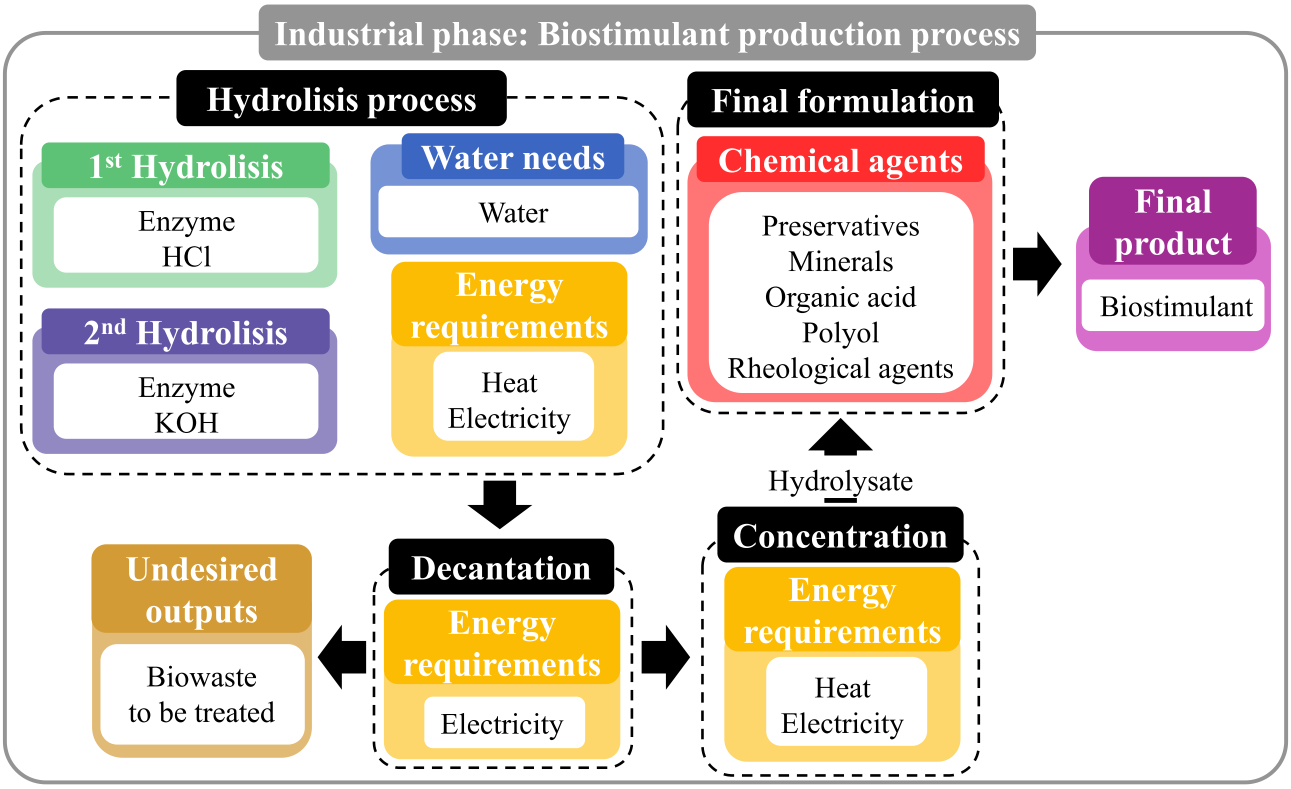

Figure 4. System boundaries of the biostimulant production process considered.

3.2.4 CARINA value chain modelling assumptions

When modelling the full CARINA VC, apart from considering each dedicated phase, some assumptions were taken according to the transportation stage. For the transport of camelina seeds from the field to the oil/cake processing facility (i.e. seed crushing phase), the material is assumed to be delivered in bulk form. Accordingly, the process was modelled using the “lorry >16 t, EURO6, RER” transport dataset, which reflects modern heavy-duty freight transport in the European context. This choice represents large-capacity trucks commonly used for bulk agricultural commodities, ensuring consistency with the logistical characteristics of seed transport.

For the subsequent transport of camelina cake from the oil/cake facility to the industrial biostimulant production plant, different transport scenarios were considered depending on the packaging and scale of the material flow. In cases where the cake is transported locally in pallets or bags, the transport was modelled using the “lorry 7.5–16 t, EURO6, RER” dataset, which reflects medium-duty freight vehicles typically employed for regional distribution of packaged goods. Alternatively, when the cake is transported in bulk quantities, the “lorry >16 t, EURO6, RER” dataset was again applied to represent heavy-duty long-haul bulk transport.

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3.3 Impact assessment

Table 5. Description and CARINA selection of the environmental impact indicators from the Environmental Footprint (EF) method (version 3.1).

Impact category	Acronym	Indicator description	Unit	CARINA selection
Climate change	CC	Radiative forcing as Global Warming Potential in a 100 years' time horizon (GWP100)	kg CO_2 eq.	Evaluation and final selection
Ozone depletion	OD	Stratospheric Ozone Depletion Potential (ODP)	kg CFC11 eq.	Evaluation
Ionising radiation - human health	IR	Health effects from ionising radiation exposure	kBq U-235 eq.	Evaluation
Photochemical ozone formation - human health	POF	Increase in ground-level (tropospheric) ozone concentrations (smog formation)	kg NMVOC eq.	Evaluation
Particulate matter	PM	Health impact from inhalation of fine particulate matter and related pollutants	disease inc.	Evaluation
Human toxicity - cancer	HTC	Human health impact potential: cancer effects	CTUh (Comparative Toxic Unit for humans)	Evaluation
Human toxicity - non-cancer	HTN	Human health impact potential: non-cancer effects	CTUh	Evaluation
Acidification	AC	Accumulated Exceedance (AE) of acidifying substances	mol H+ eq.	Evaluation and final selection
Eutrophication - freshwater	FEU	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq.	Evaluation and final selection
Eutrophication - marine	MEU	Fraction of nutrients reaching marine end compartment (N)	kg N eq.	Evaluation and final selection
Eutrophication - terrestrial	TEU	AE of N on terrestrial ecosystem	mol N eq.	Evaluation and final selection
Ecotoxicity - freshwater	FEC	Comparative Toxic Unit for ecosystems (CTUe) on freshwater	CTUe	Evaluation and final selection
Land use	LU	Soil quality index (resilience to erosion, mechanical filtration, biotic production)	Pt (Points)	Evaluation and final selection
Water use	WU	User-deprivation potential (deprivation-weighted water consumption)	m^3 depriv.	Evaluation and final selection
Resource use - fossils	RUF	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	Evaluation and final selection
Resource use - minerals and metals	RUM	Abiotic resource depletion – minerals and metals (ADP ultimate reserves)	kg Sb eq.	Evaluation and final selection

All the information compiled in the LCIs were transformed into life cycle impacts by using the 16 indicators of the Environmental Footprint (EF) method, version 3.1 (latest available). This method was chosen because it represents the reference framework promoted by the European Commission for ensuring harmonization and comparability of environmental assessments across products and

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systems.

By applying the EF approach, the study aligns with the Product Environmental Footprint (PEF) guidelines, thus contributing to a common European marketplace for environmentally sustainable products[24,25]. Notwithstanding, some of them will be depicted for information purposes, while nine of them will be finally selected when conducted the whole environmental study (including additional methodologies like the RSB Principles and Criteria framework), which are: Climate change (CC), acidification (AC), marine eutrophication (MEU), terrestrial eutrophication (TEU), freshwater eutrophication (FEU), freshwater ecotoxicity (FEC), land use (LU), water use (WU), as well as use of fossil resources (FRU) and minerals and metals (MRU) as shown in **Table 5**. In addition, the SimaPro software was used as a computational tool.

3.4 Interpretation

Once the environmental LCA results have been obtained, they have been interpreted to draw conclusions. The focus is on carrying out a hotspot analysis to identify the most relevant impact categories, stages, processes, and elementary flows in the life cycle of Camelina cropping systems. Based on this, several potential improvement strategies are proposed during the discussion section (see **Section 5**) to be implemented, with the possibility of conducting a sensitivity analysis in further deliverables to evaluate their environmental benefits.

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4. Initial results

The initial results of the environmental assessment described in **Section 3** are shown in the following section divided per phase: Field (**Section 4.1**), which encompasses two different cropping systems relative to camelina: (i) as a cash cover crop with double cropping system (case A), and (ii) crop on marginal land (cases C-1 and C-2); seed crushing (**Section 4.2**); and industrial (**Section 4.3**). In addition, the environmental impacts related to the whole VC, encompassing the three phases abovementioned, are collected in **Section 4.4**.

4.1 Field phase

The environmental performance of the three selected case studies was assessed using the 16 mid-point impact categories defined by the PEF method. **Figure 5** illustrates the percentage contribution of each impact category, allowing for a clearer understanding of how different stages of the VC influence the overall environmental burden. To facilitate interpretation, the environmental impacts were grouped into six distinct categories:

(i) **crop field** – representing not only the land occupation due to specific crop yields, but also the transformation between one crop field and another;

(ii) **land preparation** – related to the tillage practices needed before sowing;

(iii) **sowing** – accounting for the processes involved in the crop seed production, such as land requirements, application of fertilisers and pesticides, among others;

(iv) **fertilisation** – encompassing the fertilisation application process, the production of the fertilisers used, as well as the nutrient balance once the fertilisers are applied to the soil;

(v) **plant protection** – considering the pesticide application process, the production of the pesticides applied, apart from the distribution of the active ingredients between the soil, water and air compartments; and

(vi) **fuel requirements** – mainly from the agricultural machinery.

Attending to **Figure 5**, for all case studies, fertilisation is the main hotspot in almost all impact categories. However, there are some exceptions as is the case of the crop field contribution for the LU impact category in all case studies, as well as the ratio that represents the fuel requirements in case C-1 and sowing in case study C-2 for HTN. In a second position is land preparation in case A, which varies between 11-27% in seven impact categories, energy requirements in case C-1, ranging from 16% (OD) up to 68% (HTN) in eight impact categories, as well as sowing in case C-2 with contributions above 25% in up to 10 different impact categories. This can be attributed to the considerably larger area of C-2 (36 ha) compared to the other case studies (2.7 ha for A and 1.8 ha for C-1), since the input requirements considered in this process reflect not only the quantity of seeds needed but also the total area to be sown.

On the opposite side is plant protection, with nearly no environmental impacts recorded in the categories analysed for all three case studies, except for OD, which represents 9% (case A), 25% (case C-1), and 20% (case C-2).

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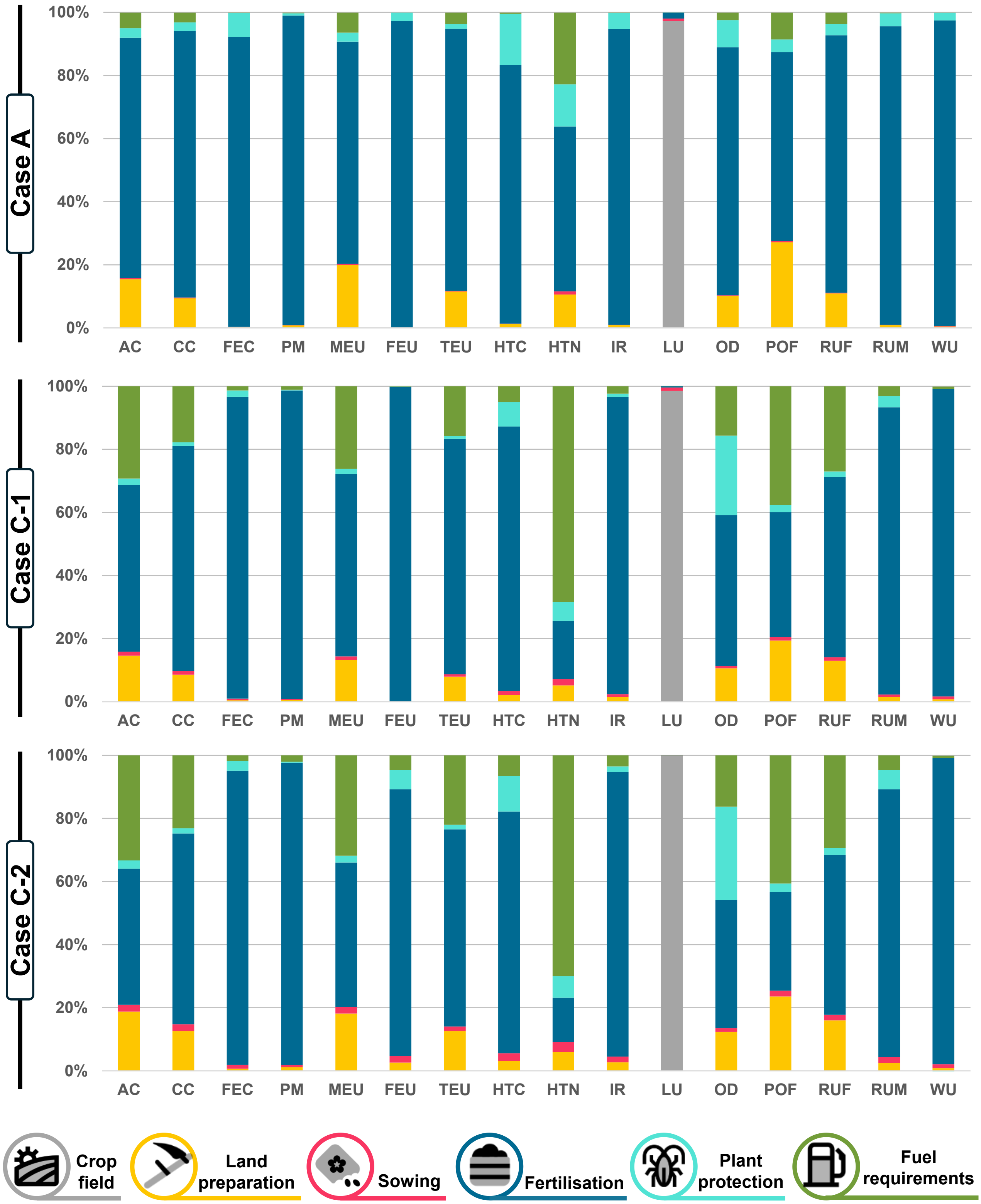

Figure 5. Contribution of each impact category of the Environmental Footprint method for the field phase of each case study, having selected 1 kg of camelina as the functional unit. AC (acidification), CC (climate change), FEC (ecotoxicity, freshwater), PM (particulate matter), MEU (eutrophication, marine), FEU (eutrophication, freshwater), TEU (eutrophication, terrestrial), HTC (human toxicity, cancer), HTN (human toxicity, non-cancer), IR (ionising radiation), LU (land use), OD (ozone depletion), POF (photochemical ozone formation), RUF (resource use, fossil), RUM (resource use, minerals and metals), WU (water use).

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On the other hand, for the common camelina sowing process, it was identified that the energy requirements are the main contributor with almost four tenths of the total impacts, encompassing diesel, electricity and natural gas. In a second position are the production process of the fertilisers (28% on average), in which those of N origin entails more than half of this impact. In the middle position are the seeds needed (18%), as well as the associated nutrient emissions (13%), while both plastics and transport solely contribute 5%.

If the evaluation is conducted per ha, differences are seen when comparing the reference and CARINA scenarios for each cropping system. In this regard, 10 out of 16 impact categories are reduced by more than 25% when moving to CARINA scenario, standing out FEU (50%) and POF (40%), while on the opposite side are IR, RUM and WU with lower than 5% reduction. The same trend is not replicated when moving to camelina on marginal land scenarios, since cases C-1 and C-2 show an increase in impacts due to fallow period replacement (worse environmental performance for CARINA scenarios), with PM (25%) and CC (13%) especially affected for case C-1, while in case C-2 these increases are lower (e.g., PM 16% and CC 9%). However, the emissions related to the fallow land period have not been considered in this analysis, but will be included in the final one.

The overall contribution of both scenarios can also be shown in percentage terms for each impact category in **Figure 6**. Additionally, the contribution of each crop was also shown. Attending to this, barley is in case A the most contributor in the reference scenarios for almost all impact categories, excepting RUM and WU, being the latest due to the fact that soybean is the only crop which needs external water irrigation. The substitution of barley for camelina is translated into lower overall environmental impacts in the CARINA scenario, in addition to almost equal impacts like in IR or even lower when compared to soybean, such as in HTN or LU.

In C cases, three different types of crops can be differentiated according to its environmental performance:

- High-impactful crops: In this category are included barley and wheat, since both represent around 80% of the total impacts for both the reference and CARINA scenarios.
- Low-impactful crops: Sunflower and pea are located in this lower position, since their impacts are considerably lower than those classified as “high-impactful”.
- Environmentally friendly crop: Camelina is achieved to be categorised as “environmentally friendly" since, although it contributes a similar amount to that of the low-impactful crops, its inclusion in both cases accounts for less than 5% in the CARINA scenario for almost all impact categories. Moreover, this study has not yet taken soil carbon accumulation into account, so the benefits of the CC impact category should be reviewed.

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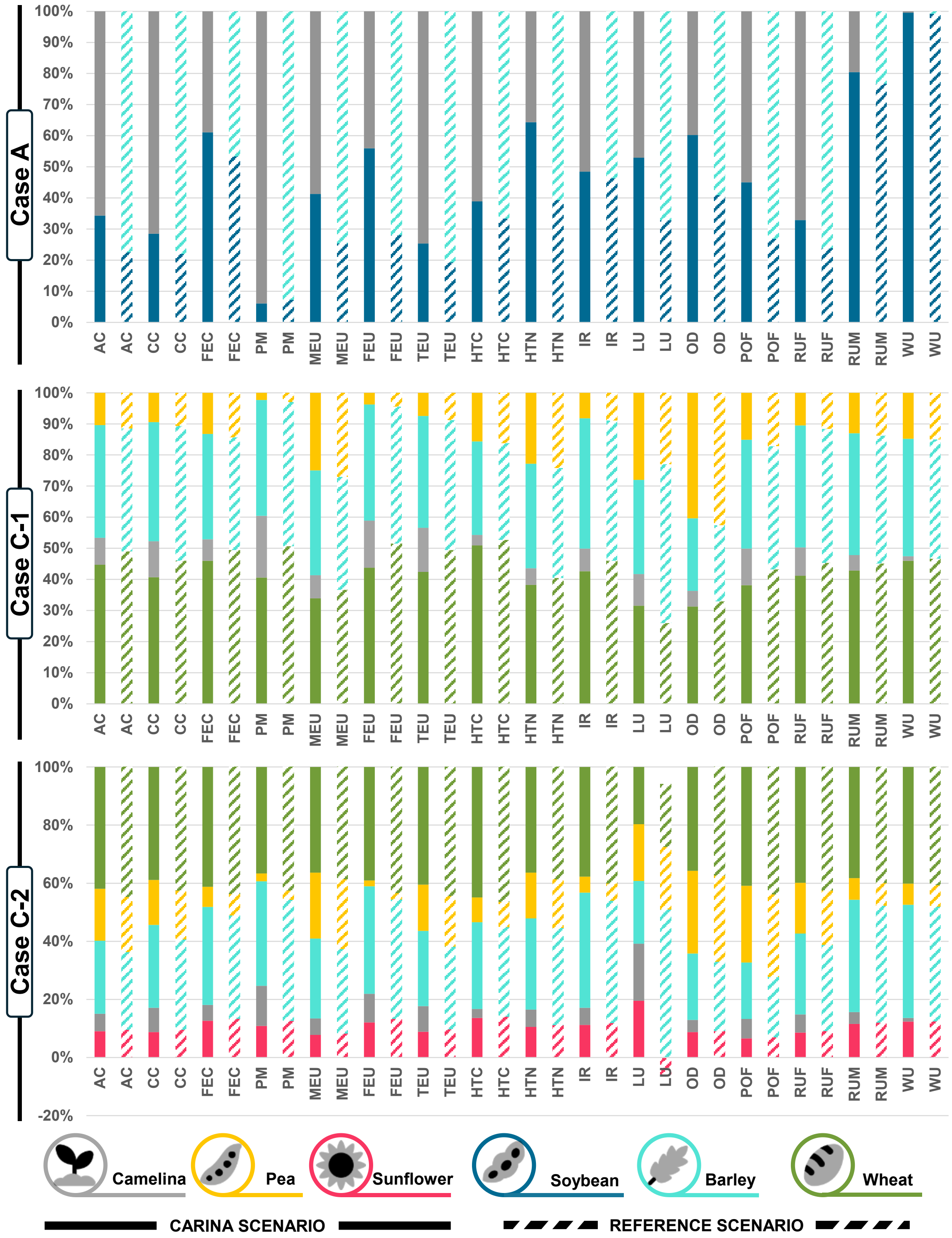

Figure 6. Contribution of each impact category of the Environmental Footprint method for the field phase for both reference and CARINA scenarios of each case study, having selected 1 ha of crop as the functional unit. AC (acidification), CC (climate change), FEC (ecotoxicity, freshwater), PM (particulate matter), MEU (eutrophication, marine), FEU (eutrophication, freshwater), TEU (eutrophication, terrestrial), HTC (human toxicity, cancer), HTN (human toxicity, non-cancer), IR (ionising radiation), LU (land use), OD (ozone depletion), POF (photochemical ozone formation), RUF (resource use, fossil), RUM (resource use, minerals and metals), WU (water use).

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4.2 Seed crushing phase

Impact categories' results from the PEF method regarding the camelina seed crushing phase have been collected in **Table 6**. In addition, with the purpose of elucidating which can be the potential environmental hotspots, these figures were converted into percentage contributions for each impact category, divided by:

- Seeds, from the previous camelina cropping system studied. These are used as the raw material of the process.
- Emissions, mainly from hexane use and combustion of heat/steam sources.
- Solvent agent, hexane is used for such a purpose, contributing to separate the remaining oil content of the camelina press cake after pressing.
- Energy, relative to electricity and heat for performing the pressing process.
- Auxiliary agents, including phosphoric acid and activated bentonite for degumming and bleaching purposes, which entail the removal of phospholipids, metals, pigments and impurities.
- Wastewater, produced mainly from the seed cleaning and conditioning process.

According to **Figure 7**, seeds are by far the most critical contributors for all impact categories, surpassing 90% of the total impact in most of them. In the second position are the energy requirements, represented by electricity and heat, which vary between 5% and 20% for the following impact categories: FEU, IR, OD, and RUF. Lastly, although on a lower scale, it can be mentioned that auxiliary agents accounted for more than 20% of RUM, apart from 5% for both FEU and HTC.

Table 6. Results relative to 1 kg of camelina meal for each impact category of the Environmental Footprint method during the seed crushing phase. AC (acidification), CC (climate change), FEC (ecotoxicity, freshwater), PM (particulate matter), MEU (eutrophication, marine), FEU (eutrophication, freshwater), TEU (eutrophication, terrestrial), HTC (human toxicity, cancer), HTN (human toxicity, non-cancer), IR (ionising radiation), LU (land use), OD (ozone depletion), POF (photochemical ozone formation), RUF (resource use, fossil), RUM (resource use, minerals and metals), WU (water use).

Damage category	AC	CC	FEC	PM	MEU	FEU	TEU	HTC
Unit	mol H+ eq.	kg CO_2 eq.	CTUe	disease inc.	kg N eq.	kg P eq.	mol N eq.	CTUh
Value	$3.08 \cdot 10^{-3}$	0.54	2.02	$2.50 \cdot 10^{-8}$	$1.41 \cdot 10^{-3}$	$2.13 \cdot 10^{-5}$	0.02	$1.39 \cdot 10^{-10}$
Damage category	HTN	IR	LU	OD	POF	RUF	RUM	WU
Unit	CTUh	kBq U-235 eq.	Pt	kg CFC11 eq.	kg NMVOC eq.	MJ	kg Sb eq.	m^3 depriv.
Value	$6.83 \cdot 10^{-9}$	0.01	147.90	$6.93 \cdot 10^{-9}$	$3.49 \cdot 10^{-3}$	4.84	$9.40 \cdot 10^{-8}$	0.08

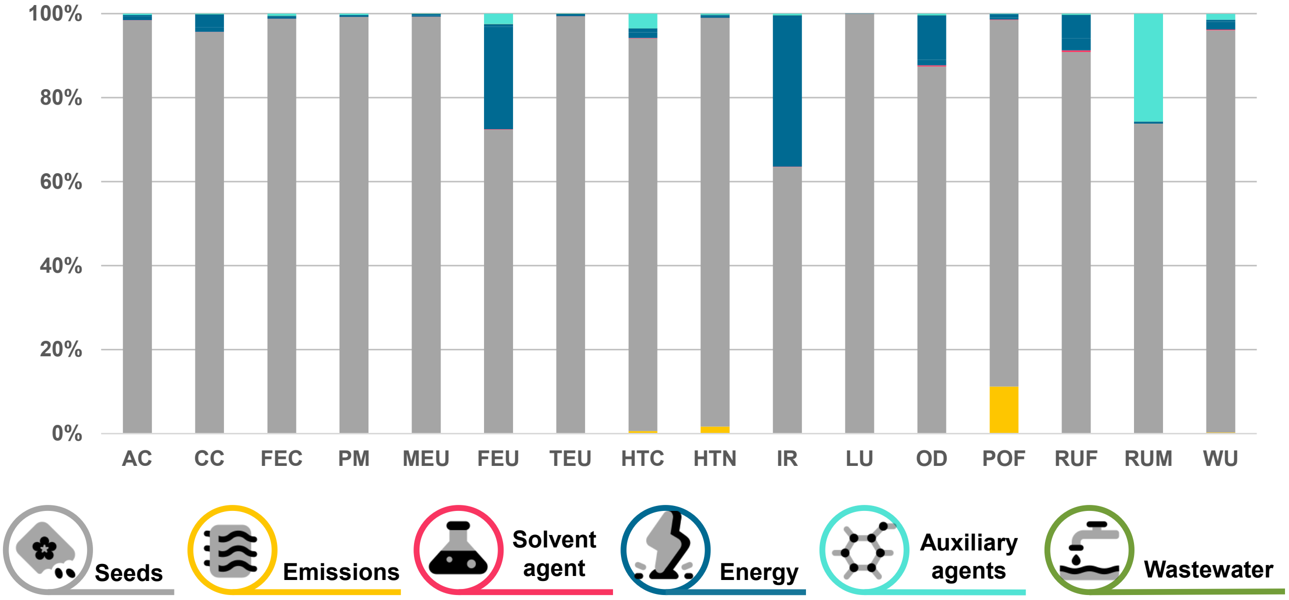

Figure 7. Contribution of each impact category of the Environmental Footprint method for the seed crushing phase, having selected 1 kg of camelina meal as the functional unit. AC (acidification), CC (climate change), FEC (ecotoxicity, freshwater), PM (particulate matter), MEU (eutrophication, marine), FEU (eutrophication, freshwater), TEU (eutrophication, terrestrial), HTC (human toxicity, cancer), HTN (human toxicity, non-cancer), IR (ionising radiation), LU (land use), OD (ozone depletion), POF (photochemical ozone formation), RUF (resource use, fossil), RUM (resource use, minerals and metals), WU (water use).

4.3 Industrial phase

The life cycle results of the industrial phase are presented in two distinct ways. First, life cycle impacts divided by industrial stage, having been divided into six consecutive steps in **Table 7**: (i) raw materials, (ii) 1st hydrolysis, (iii) 2nd hydrolysis, (iv) decantation, (v) concentration, and (vi) formulation. Second, life cycle impact results divided by consumables requirements, grouping them in the form of percentual contributions for each EF mid-point category (see **Figure 8**).

Table 7 shows that formulation is one of the key steps in the industrial phase in terms of environmental impact, accounting for 40–60% of the total contribution. This stage encompasses inputs such as minerals, polyols, preservatives, amino acids, and rheological agents. With roughly half of this contribution, both second hydrolysis and decantation also stand out, being consistently represented across all impact categories. Finally, it is noteworthy that raw materials present a significant contribution to the LU category, while the concentration stage shows a negative contribution to WU.

Looking at **Figure 8**, the chemicals & reagents are distinguished as a hotspot, representing around half of the total impacts in almost all impact categories. Apart from this, two types of inputs could be allocated in a second position. On the one hand, the extraction of the raw materials refers to the camelina cake, which contributes considerably to LU, POF and TEU. On the other hand, electricity consumption stands out in IR, RUF, CC, OD and POF, with higher environmental burdens than 15%. Waste to treatment also accounts for a considerable portion of the eutrophication impacts categories, along with AC, CC and FEC. On the opposite side, water consumption, additives & functional agents, and heat requirements contribute about 5% on average terms.

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Table 7. Results relative to 1 kg of biostimulant for each impact category of the Environmental Footprint method during the industrial phase. AC (acidification), CC (climate change), FEC (ecotoxicity, freshwater), PM (particulate matter), MEU (eutrophication, marine), FEU (eutrophication, freshwater), TEU (eutrophication, terrestrial), HTC (human toxicity, cancer), HTN (human toxicity, non-cancer), IR (ionising radiation), LU (land use), OD (ozone depletion), POF (photochemical ozone formation), RUF (resource use, fossil), RUM (resource use, minerals and metals), WU (water use).

Damage category	Unit	Total	Raw materials	1st hydrolysis	2nd hydrolysis	Decantation	Concentration	Formulation
AC	mol H+ eq.	$5.79\cdot10^{-3}$	$6.99\cdot10^{-4}$	$1.24\cdot10^{-4}$	$1.04\cdot10^{-3}$	$9.86\cdot10^{-4}$	**$2.25\cdot10^{-5}$**	**$2.92\cdot10^{-3}$**
CC	kg CO_2 eq.	0.91	0.12	0.03	**0.27**	$1.88\cdot10^{-1}$	**$1.41\cdot10^{-2}$**	$2.80\cdot10^{-1}$
FEC	CTUe	19.11	0.46	0.11	2.90	4.62	**$1.22\cdot10^{-1}$**	**10.90**
PM	disease inc.	$4.21\cdot10^{-8}$	$5.65\cdot10^{-9}$	$5.38\cdot10^{-10}$	$7.94\cdot10^{-9}$	$6.30\cdot10^{-9}$	**$6.78\cdot10^{-11}$**	**$2.16\cdot10^{-8}$**
MEU	kg N eq.	$3.29\cdot10^{-3}$	$3.19\cdot10^{-4}$	**$3.47\cdot10^{-5}$**	$2.55\cdot10^{-4}$	$3.36\cdot10^{-4}$	$5.19\cdot10^{-5}$	**$2.29\cdot10^{-3}$**
FEU	kg P eq.	$1.78\cdot10^{-4}$	$5.40\cdot10^{-6}$	$4.47\cdot10^{-6}$	$5.56\cdot10^{-5}$	$3.70\cdot10^{-5}$	**$3.57\cdot10^{-6}$**	**$7.18\cdot10^{-5}$**
TEU	mol N eq.	$2.21\cdot10^{-2}$	$3.60\cdot10^{-3}$	$3.10\cdot10^{-4}$	$2.44\cdot10^{-3}$	$4.10\cdot10^{-3}$	**$7.52\cdot10^{-5}$**	**$1.16\cdot10^{-2}$**
HTC	CTUh	$1.23\cdot10^{-9}$	$3.20\cdot10^{-11}$	$2.13\cdot10^{-11}$	$5.30\cdot10^{-10}$	$5.69\cdot10^{-11}$	**$5.62\cdot10^{-12}$**	**$5.80\cdot10^{-10}$**
HTN	CTUh	$1.24\cdot10^{-8}$	$1.54\cdot10^{-9}$	**$1.62\cdot10^{-10}$**	$1.15\cdot10^{-9}$	$1.50\cdot10^{-9}$	$1.85\cdot10^{-10}$	**$7.83\cdot10^{-9}$**
IR	kBq U-235 eq.	0.16	**0.00**	0.02	**0.11**	$7.93\cdot10^{-3}$	$2.25\cdot10^{-3}$	$1.51\cdot10^{-2}$
LU	Pt	50.12	**33.33**	0.09	0.51	$2.41\cdot10^{-1}$	**$3.33\cdot10^{-3}$**	15.90
OD	kg CFC11 eq.	$1.84\cdot10^{-8}$	$1.58\cdot10^{-9}$	$1.04\cdot10^{-9}$	$4.10\cdot10^{-9}$	$5.38\cdot10^{-10}$	**$2.74\cdot10^{-10}$**	**$1.09\cdot10^{-8}$**
POF	kg NMVOC eq.	$2.99\cdot10^{-3}$	$7.88\cdot10^{-4}$	$9.66\cdot10^{-5}$	$7.98\cdot10^{-4}$	$2.89\cdot10^{-4}$	**$3.57\cdot10^{-5}$**	**$9.78\cdot10^{-4}$**
RUF	MJ	11.46	1.11	0.85	**5.42**	$6.23\cdot10^{-1}$	**$2.56\cdot10^{-1}$**	3.21
RUM	kg Sb eq.	$2.76\cdot10^{-7}$	$2.37\cdot10^{-8}$	$3.28\cdot10^{-9}$	$5.30\cdot10^{-8}$	$7.57\cdot10^{-9}$	**$1.98\cdot10^{-9}$**	**$1.87\cdot10^{-7}$**
WU	m^3 depriv.	0.52	**0.20**	0.02	0.10	$5.97\cdot10^{-3}$	**$-1.07\cdot10^{-1}$**	$3.07\cdot10^{-1}$

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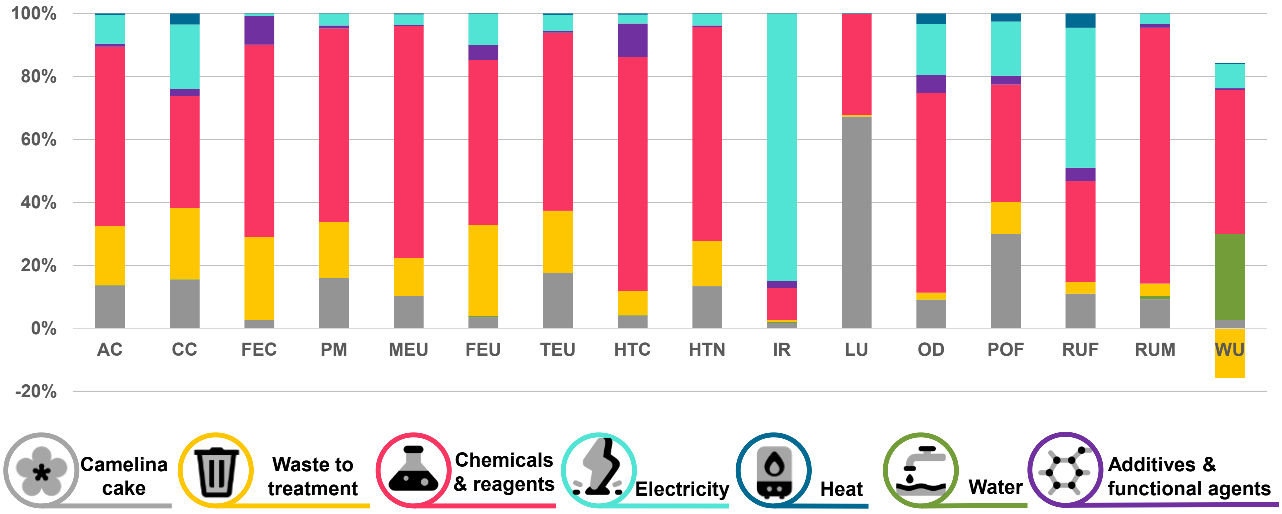

Figure 8. Contribution of each impact category of the Environmental Footprint method for the industrial phase, having selected 1 kg of biostimulant as the functional unit. AC (acidification), CC (climate change), FEC (ecotoxicity, freshwater), PM (particulate matter), MEU (eutrophication, marine), FEU (eutrophication, freshwater), TEU (eutrophication, terrestrial), HTC (human toxicity, cancer), HTN (human toxicity, non-cancer), IR (ionising radiation), LU (land use), OD (ozone depletion), POF (photochemical ozone formation), RUF (resource use, fossil), RUM (resource use, minerals and metals), WU (water use).

4.4 CARINA value chain

The contributions in terms of percentage for the full CARINA VC relative to the case A (i.e., camelina cash-cover cropping with double cropping), for each of the 16 mid-point impact categories of the PEF method, are represented in **Figure 9**, divided by phase. In addition, the transportation between one phase and another was accounted for and included in phase II (transport from phase I to phase II) and phase III (from phase II to phase III). Specific values, being differentiated per CARINA VC, as well as transportation steps, can be found in **Table A1** in the Annex. Attending to the results obtained, the industrial phase represents more than 80% of the environmental burden in almost all impact categories. Notwithstanding, its environmental impact varies depending on the impact category considered. Likewise, the field phase is fundamental when referring to LU (more than 60% contribution). In contrast, the second phase, relative to the seed crushing, only accounts for about 2% in both RUM and POF, while its contribution is almost negligible for the other impact categories.

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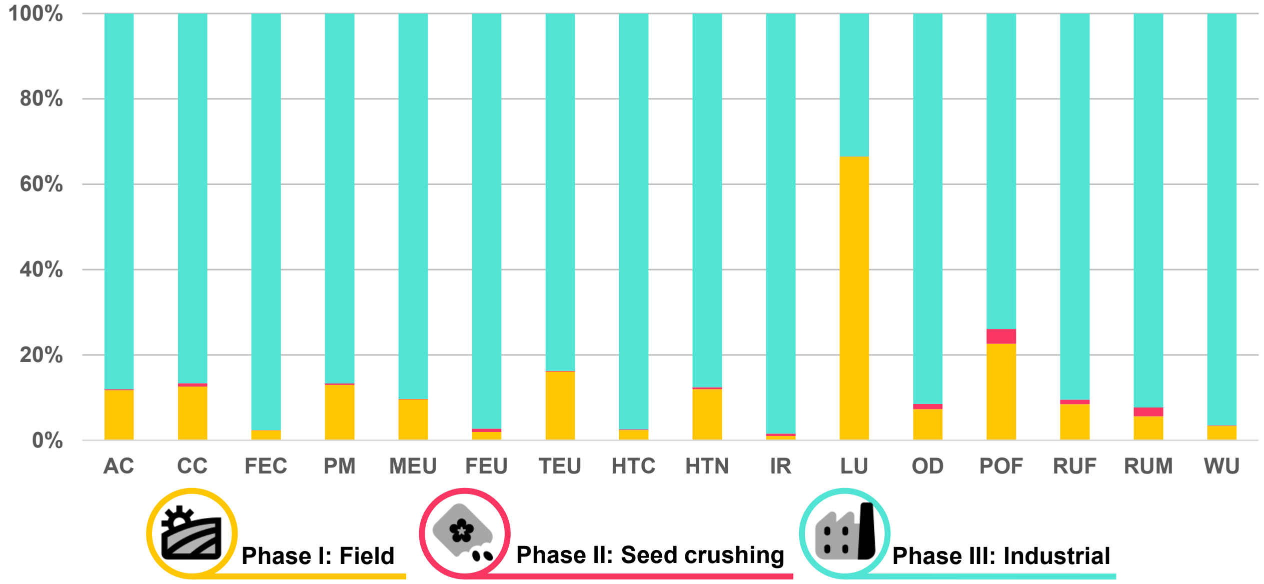

Figure 9. Contribution per phase of each impact category of the Environmental Footprint method for full CARINA value chain, having selected 1 kg of biostimulant produced thanks to the camelina seeds obtained from case A as the functional unit. AC (acidification), CC (climate change), FEC (ecotoxicity, freshwater), PM (particulate matter), MEU (eutrophication, marine), FEU (eutrophication, freshwater), TEU (eutrophication, terrestrial), HTC (human toxicity, cancer), HTN (human toxicity, non-cancer), IR (ionising radiation), LU (land use), OD (ozone depletion), POF (photochemical ozone formation), RUF (resource use, fossil), RUM (resource use, minerals and metals), WU (water use).

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5. Discussion

This study evaluated two distinct camelina cropping systems during the field phase: (i) Camelina as a cash cover crop within a double cropping system (case A), and (ii) camelina cultivated on marginal land (cases C-1 and C-2). The results suggest that growing camelina on marginal land is environmentally more favourable than using it as a cash cover crop, despite its lower yields. However, further case studies are necessary to validate the robustness of this conclusion.

The results show that fertilisation is the most significant contributor to environmental impact across all the evaluated case studies. In addition, it was identified that the main hotspot is primarily attributed to the production stage of agrochemicals, along with their use. These processes account for nutrient emissions to the different environmental compartments: air, soil and water. Therefore, information on these processes is of the utmost importance when reporting results. In this regard, more specific information about the products used in the fertilisation process should be evaluated, as opposed to the generic Ecoinvent processes for N, P and K fertilisers. The same applies to the primary information collected from Systerre, which should include, among other things, fallow period soil labours that have not been considered in this analysis. Regarding the associated nutrient emissions, the process used is internationally recognised as a good proxy and has been widely used in the literature. These findings highlight how a few key agricultural practices dominate the overall environmental profile of camelina cultivation.

Nevertheless, the relative importance of hotspots varies depending on the production system, as certain processes, such as land preparation or fuel requirements, become more significant in certain situations or plots. Particularly, one of the PEF indicators, LU, warrants further discussion due to its pivotal importance from a biofuel certification perspective, which is one of the most promising pathways for introducing camelina into the market.

When camelina is introduced during a period that is normally left fallow, the LU indicator shows higher impacts even though no additional land is converted. In fact, in cases C-1 and C-2, camelina simply replaces fallow land without expanding the agricultural area, meaning there is no increase in iLUC risk. The PEF LU indicator penalises active land occupation compared with fallow, but it does not account for regenerative or soil-improving practices.

In this regard, camelina is officially recognised under the EU Common Agricultural Policy as a soil-improving species due to its benefits for soil structure, erosion control, and water infiltration due to its pivotal root, advantages that bare fallow cannot provide. Additionally, many fallow lands are tilled and left without vegetative cover, which increases erosion risk and also contributes to GHG emissions through soil disturbance. By ignoring these factors, the LU indicator may misrepresent the actual environmental performance of such systems.

Consequently, a higher LU score in PEF does not necessarily indicate real soil degradation. Instead, it reflects the lack of weighting for regenerative practices within the LU characterisation model. This nuance is essential when interpreting results for crops like camelina, particularly in the context of biofuel certification.

Moving to make a comparison between CARINA and reference scenarios, the integration of camelina into conventional cropping systems (i.e., case A) tends to reduce the overall environmental impact. In contrast, its introduction to marginal land, as in case C-1 and case C-2, can sometimes lead to a higher burden when impacts are calculated per kg of grain produced, since the yield in marginal lands tends to be lower, highlighting the context-dependent nature of its environmental performance. Moreover, when placed within multi-crop systems, cereals like barley and wheat

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represent the highest environmental burdens, while crops such as sunflower and pea show comparatively lower contributions. Camelina, in turn, can be considered environmentally favourable, since its share of impacts remains relatively minor in most categories and soil carbon accumulation (which is not taken into account in the analysis) will further contribute to emission savings. This reinforces its potential role as a sustainable crop option, provided that management practices are optimised and site-specific conditions are carefully considered.

Likewise, the seed crushing process highlights the importance of the field phase in the CARINA VC, as camelina seeds used as feedstock make a significant contribution across all PEF impact categories. In this regard, the rest of the consumables in terms of solvent and auxiliary agents, energy requirements or associated emissions (i.e., air-polluting emissions from combustion or wastewater streams for cleaning and conditioning purposes) play a comparative minor role. A similar pattern is observed for the rapeseed crushing process, which is used as a proxy for camelina seed crushing process modelling, with rapeseed seeds representing the main environmental hotspot. Notwithstanding, several differences in environmental performance per impact category arise in a one-to-one comparison.

Additionally, those significant differences between camelina and rapeseed seeds crushing processes extend to subsequent phases of the CARINA VC, such as the industrial one, in which camelina cake accounts for the primary hotspot (around 50% or more of the environmental burden) in half of the total number of impact categories evaluated. According to the rest of the biostimulant industrial process steps, the formulation steps stand out, having a contribution around three times higher in comparison with the others. These differences come mainly from the consumption rates of amino acids and rheological agents. However, it is essential to note that for their modelling, some were assumed to have similar chemical components or to be associated with specific substances due to a lack of primary information for confidentiality issues of the industrial process provided by the CARINA partners. Given their relative importance, it is strongly recommended to obtain primary data for these elements in future assessments.

When evaluating the entire CARINA VC, the seed crushing process contributes only marginally, whereas the industrial phases dominate in almost all impact categories. However, the field phase is particularly relevant for categories such as PM, arising from tillage and soil management as well as secondary atmospheric formation from agricultural machinery emissions; eutrophication, driven by N and P losses to water and air; and LU, linked to land occupation and transformation for crop cultivation. In contrast, the industrial phase, where crops are processed into higher-value products such as biostimulants, dominates in CC, OD, POF, and IR, largely due chemical inputs needs, apart from energy requirements for processing. It also drives RUF, associated with the demand for chemical agents, and WU, resulting from direct water consumption during manufacturing.

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6. Preliminary conclusions and next steps

Following the establishment of the methodological framework and the analysis of selected case studies, along with the discussion presented in this report, a set of preliminary conclusions has been drawn and is summarised below:

- It has been seen that camelina on marginal land performs environmentally better than the cash-cover double cropping system, despite lower yields. However, further case studies are needed to confirm the robustness of this finding.
- Fertilisation is the dominant hotspot during the field phase, driven by upstream production and use of agrochemicals and associated nutrient emissions. Consequently, primary data on fertiliser types and use rates are needed instead of relying on generic database processes.
- Incorporating camelina into conventional systems tends to lower overall environmental impacts, whereas its introduction into marginal lands replacing fallow and producing an additional biomass (cases C) can increase burdens (when comparing reference vs CARINA scenarios), highlighting strong context-dependence. However, this preliminary conclusion should be reviewed by incorporating additional case studies.
- The environmental profile is mainly determined by the seed feedstock in the seed crushing phase. In general terms, camelina shows much lower environmental impacts when compared to rapeseed crushing (reference case). Still, these first results should be considered with caution based on the assumptions considered.
- In the biostimulant production during the industrial phase, chemicals and reagents account for more than half of the total impacts, with the formulation step being a major contributor due to its high chemical demands.

In the overall assessment of the VC, the seed crushing phase contributes only marginally to environmental impacts. In contrast, the industrial phase is the dominant contributor across nearly all impact categories. However, the field phase can still play a significant role in certain categories—particularly LU—where its contribution ranges from approximately 10% to over 60%.

Given the main drawbacks and improvement points identified, the following next steps have been defined:

- ✓ Refine and validate data used in the three case studies presented in this document.
- ✓ Account for additional biomass production and emission savings associated with ESCA in the soil in CARINA scenarios.
- ✓ Compile additional information to assess at least one case study for each scenario (i.e., at least six in total, from A to F).
- ✓ Integrate the RSB P&C framework to evaluate the sample of 10 indicators selected for the environmental assessment.
- ✓ Ensure incorporation of these actions into the forthcoming deliverable (D3.5) by the end of the CARINA project.
- ✓ Organise workshops and bilateral meetings with stakeholders to validate data, cross-check

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information, and jointly develop assumptions and modelling approaches. These activities will enhance the robustness of the results and foster more reliable outcomes.

- ✓ Conduct a sensitivity analysis to identify opportunities for adopting more environmentally sustainable practices based on the main environmental hotspots identified.

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7. Annex

Equations

Eq 1

$$\mathbf{Energy\ in\ biomass} = \mathbf{Crop\ yield} \cdot \mathbf{Crop\ area} \cdot \mathbf{GCV}$$

Where:

$Energy\ in\ biomass$	Energy content of a specific crop (MJ).
$Crop\ yield$	Yield of a specific crop in a dry basis (kg·ha^{-1}).
$Crop\ area$	Area of a specific crop (ha).
GCV	Gross calorific value (MJ·kg^{-1}).

Eq 2

$$\mathbf{N_2O_{direct}} = \mathbf{N_2O_{direct}} - \mathbf{N} \cdot \frac{\mathbf{MW_{N_2O-N}}}{\mathbf{MW_{N_2O}}}$$

Where:

N_2O_{direct}	Annual direct N_2O emissions produced from managed soils (kg N_2O·yr^{-1}).
$N_2O_{direct} - N$	Annual direct N_2O–N emissions produced from managed soils (kg N_2O–N·yr^{-1}).
MW_{N_2O-N}	Molecular weight of N_2O-N, 44.
MW_{N_2O}	Molecular weight of N_2O, 28.

Eq 3

$$\mathbf{N_2O_{direct}} - \mathbf{N} = \mathbf{N_{applied}} \cdot \mathbf{EF1_N}$$

Where:

$N_2O_{direct} - N$	Annual direct N_2O–N emissions produced from managed soils (kg N_2O–N·yr^{-1}).
$N_{applied}$	Annual amount of both organic and synthetic fertilisers N applied to soils (kg N·yr^{-1}).
$EF1_N$	Emission factor for N_2O emissions from N inputs, kg N_2O–N (kg N input), 1%[25].

Eq 4

$$\mathbf{NH_3} = \mathbf{N_{volatilised}} \cdot \mathbf{DF1_N}$$

Where:

NH_3	Annual NH_3 emissions produced from N volatilised (kg NH_3·yr^{-1}).
$N_{volatilised}$	Annual emissions of N volatilised (kg N·yr^{-1}).
$DF1_N$	Distribution factor of NH_3 emissions from N volatilised, 90%[23].

Eq 5

$$\mathbf{NO_x = N_{volatilised} \cdot DF2_N}$$

Where:

NO_x	Annual NO_x emissions produced from N volatilised (kg $NO_x \cdot yr^{-1}$).
$N_{volatilised}$	Annual emissions of N volatilised (kg $N \cdot yr^{-1}$).
$DF2_N$	Distribution factor of NO_x emissions from N volatilised, 10%[23].

Eq 6

$$\mathbf{N_{volatilised} = \left[\left(NS_{applied} \cdot FS\right) + \left(NO_{applied} \cdot FO\right)\right]}$$

Where:

$N_{volatilised}$	Annual emissions of N volatilised (kg $N \cdot yr^{-1}$).
$NS_{applied}$	Annual amount of synthetic fertiliser N applied to soils (kg $N \cdot yr^{-1}$).
FS	Fraction of synthetic fertiliser N that volatilises as NH_3 and NO_x, kg N volatilised (kg of N applied)$^{-1}$, 11%[25].
$NO_{applied}$	Annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils (kg $N \cdot yr^{-1}$).
FO	Fraction of applied organic N fertiliser materials that volatilises as NH_3 and NO_x, kg N volatilised (kg of N applied)$^{-1}$, 21%[25].

Eq 7

$$\mathbf{N_2O_{indirect} = N_2O_{indirect} - N \cdot \frac{MW_{N_2O-N}}{MW_{N_2O}}}$$

Where:

$N_2O_{indirect}$	Annual amount of N_2O produced from atmospheric deposition of N volatilised from managed soils (kg $N_2O \cdot yr^{-1}$).
$N_2O_{direct} - N$	Annual amount of N_2O-N produced from atmospheric deposition of N volatilised from managed soils (kg N_2O–$N \cdot yr^{-1}$).
MW_{N_2O-N}	Molecular weight of N_2O-N, 44.
MW_{N_2O}	Molecular weight of N_2O, 28.

Eq 8

$$\mathbf{N_2O_{indirect} - N = \left[\left(NS_{applied} \cdot FS\right) + \left(NO_{applied} \cdot FO\right)\right] \cdot EF2_N}$$

Where:

$NS_{applied}$	Annual amount of synthetic fertiliser N applied to soils (kg $N \cdot yr^{-1}$).
FS	Fraction of synthetic fertiliser N that volatilises as NH_3 and NO_x, kg N volatilised (kg of N applied)$^{-1}$, 11%[25].
$NO_{applied}$	Annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils (kg $N \cdot yr^{-1}$).

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FO	Fraction of applied organic N fertiliser materials that volatilises as NH_3 and NO_x, kg N volatilised (kg of N applied)$^{-1}$, 21%[25].
$EF2_N$	Emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, [kg N–N_2O (kg NH_3–N + NO_x–N volatilised)$^{-1}$], 1%[25].

Eq 9

$$\mathbf{PO_4^{3-}}_{\mathbf{lgw}} = \mathbf{CA \cdot P_{lgw}}$$

Where:

$PO_4^{3-}{}_{lgw}$	Amount of PO_4^{3-} (kg·(ha·yr)$^{-1}$) leaching to ground water.
CA	Cultivated area of the crop field (ha).
P_{lgw}	Annual amount of PO_4^{3-} (kg·yr^{-1}) leaching to ground water, 0.386[24].

Eq 10

$$\mathbf{PO_4^{3-}}_{\mathbf{row}} = \mathbf{CA \cdot P_{row}}$$

Where:

$PO_4^{3-}{}_{row}$	Amount of PO_4^{3-} (kg·(ha·yr)$^{-1}$) runoff to surface water.
CA	Cultivated area of the crop field (ha).
P_{row}	Annual amount of PO_4^{3-} (kg·yr^{-1}) runoff to surface water, 0.965[24].

Eq 11

$$\mathbf{P = CA \cdot 1000 \cdot R \cdot k \cdot LS \cdot c_1 \cdot c_2 \cdot P \cdot P_{sc}}$$

Where:

P	Amount of P (kg·(ha·yr)$^{-1}$) emitted through water erosion to surface water.
CA	Cultivated area of the crop field (ha).
R	Erosivity factor (MJ·mm·(ha·year)$^{-1}$), 0.0073[24].
k	Erodibility factor (t·h·(MJ·mm)$^{-1}$), type of soil Cambisol[26] equivalent to Inceptisol[27], 0.04 (generic to all case studies).
LS	Slope factor (dimensionless), 0.1[28].
c_1	Crop factor (dimensionless), 0.4[28].
c_2	Tillage factor (dimensionless), 1[24].
P	Practice factor (dimensionless), 1[24].
P_{sc}	Soil capacity to hold P (kg P·kg soil^{-1}), 0.00095[24].

Tables

Table A1. Results relative to 1 kg of biostimulant for each impact category of the Environmental Footprint method during the full CARINA value chain (case A was considered for phase I). AC (acidification), CC (climate change), FEC (ecotoxicity, freshwater), PM (particulate matter), MEU (eutrophication, marine), FEU (eutrophication, freshwater), TEU (eutrophication, terrestrial), HTC (human toxicity, cancer), HTN (human toxicity, non-cancer), IR (ionising radiation), LU (land use), OD (ozone depletion), POF (photochemical ozone formation), RUF (resource use, fossil), RUM (resource use, minerals and metals), WU (water use).

Damage category	Unit	Phase I: Field	Transport (from phase I to phase II)	Phase II: Seed crushing	Transport (from phase II to phase III)	Phase III: Industrial
AC	mol H+ eq.	$6.83\cdot10^{-4}$	$2.14\cdot10^{-6}$	$1.13\cdot10^{-5}$	$1.87\cdot10^{-5}$	$5.10\cdot10^{-3}$
CC	kg CO_2 eq.	0.12	$1.83\cdot10^{-3}$	0.01	0.02	0.78
FEC	CTUe	0.45	$8.27\cdot10^{-4}$	0.01	0.01	18.66
PM	disease inc.	$5.58\cdot10^{-9}$	$1.08\cdot10^{-10}$	$4.53\cdot10^{-11}$	$7.95\cdot10^{-10}$	$3.65\cdot10^{-8}$
MEU	kg N eq.	$3.16\cdot10^{-4}$	$4.77\cdot10^{-7}$	$2.32\cdot10^{-6}$	$4.09\cdot10^{-6}$	$2.97\cdot10^{-3}$
FEU	kg P eq.	$3.47\cdot10^{-6}$	$1.32\cdot10^{-8}$	$1.32\cdot10^{-6}$	$1.17\cdot10^{-7}$	$1.73\cdot10^{-4}$
TEU	mol N eq.	0.00	$5.18\cdot10^{-6}$	$2.23\cdot10^{-5}$	$4.47\cdot10^{-5}$	0.02
HTC	CTUh	$2.94\cdot10^{-11}$	$1.28\cdot10^{-13}$	$2.04\cdot10^{-12}$	$1.05\cdot10^{-12}$	$1.19\cdot10^{-9}$
HTN	CTUh	$1.50\cdot10^{-9}$	$1.22\cdot10^{-11}$	$4.14\cdot10^{-11}$	$9.03\cdot10^{-11}$	$1.08\cdot10^{-8}$
IR	kBq U-235 eq.	0.00	$9.22\cdot10^{-6}$	$9.16\cdot10^{-4}$	$8.13\cdot10^{-5}$	0.16
LU	Pt	33.31	$5.42\cdot10^{-5}$	0.01	$4.77\cdot10^{-4}$	16.79
OD	kg CFC11 eq.	$1.36\cdot10^{-9}$	$3.74\cdot10^{-11}$	$1.97\cdot10^{-10}$	$3.29\cdot10^{-10}$	$1.69\cdot10^{-8}$
POF	kg NMVOC eq.	$6.86\cdot10^{-4}$	$4.63\cdot10^{-6}$	$1.00\cdot10^{-4}$	$4.04\cdot10^{-5}$	$2.20\cdot10^{-3}$
RUF	MJ	0.99	0.02	0.10	0.21	10.36
RUM	kg Sb eq.	$1.56\cdot10^{-8}$	$6.05\cdot10^{-11}$	$5.55\cdot10^{-9}$	$5.33\cdot10^{-10}$	$2.55\cdot10^{-7}$
WU	m^3 depriv.	0.02	$1.03\cdot10^{-5}$	$7.64\cdot10^{-4}$	$9.06\cdot10^{-5}$	0.50

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