Biorefineries for the valorisation of macroalgal residual biomass and legume processing by-products to obtain new protein value chains for high-value food and feed applications

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D4.1. Life Cycle Methodology definition and template

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PROJECT INFORMATION

Project full title: Biorefineries for the valorisation of macroalgal residual biomass and legume processing by-products to obtain new protein value chains for high-value food and feed applications

Acronym: ALEHOOP

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List of participants:

Partner no.	Type of partner	Name	Acronym	Country
1 (Coordinator)	SME	Contactica	CTA	Spain
2	SME	Isanatur	ISA	Spain
3	SME	Biozoon	BZN	Germany
4	SME	Biosurya	BIOYA	Spain
5	SME	Centiv	CENTIV	Germany
6	SME	Garlan	GARLAN	Spain
7	SME	Alginor	ALGI	Norway
8	LE	Nuscience	NUS	Belgium
9	LE	Indukern	IK	Spain
10	RTO	The Flanders Research Institute for agriculture, fisheries and food	EV-ILVO	Belgium
11	RTO	Anfaco	ANFACO	Spain
12	RTO	Tecnalia	TECNA	Spain
13	RTO	Technological University Dublin	TUDublin	Ireland
14	RTO	Universidad de Cádiz	UCA	Spain
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16	RTO	Universidad de Vigo	UVIGO	Spain

DELIVERABLE DETAILS

Document Number:	D4.1
Document Title:	Life Cycle Methodology definition and template
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Task:	Task 4.1. Methodology definition for ALEHOOP sustainability assessment and Product Category Rule
Author:	Contactica
Abstract:	A Life Cycle Sustainability Assessment (LCSA) will be performed within the project ALEHOOP. It includes Life Cycle Assessment (LCA) to assess the environmental impacts, Life Cycle Costing (LCC) analysis to assess the economic feasibility and Social Life Cycle Assessment (S-LCA) to evaluate the social impacts of the products developed. Furthermore, the processes will be modelled for simulation and multi-objective optimization by using the own-developed tool by CTA, eco2des. The LCSA should allow further comparisons with products developed after the optimization and for products from other processes or feedstocks. With that aim, the methodology is defined in this deliverable for LCA, LCC and S-LCA, including standards and guidelines to use in the development of the LCSA, functional unit, system boundaries, data needs, data sources and impact assessment methods. Templates for collecting data from partners are included as annex.

1 LCSA methodology ALEHOOP

The Life Cycle Sustainability Assessment (LCSA) methodology will be based on the general recommendations from UNEP (United Nations Environmental Program (UNEP), 2011) and Walter Kloepffer (Kloepffer, 2008). It will consist of three interconnected assessments: Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA). In consequence, the three pillars of sustainability (environmental, economic and social) will be included. As they all have a holistic and life cycle perspective, and they are based on the same normative (ISO 14040), it is possible to interconnect them keeping some common aspects of the goal and scope, life cycle inventories and independent impact assessment methods and providing an interpretation that will gather the results of the 3 studies. The interconnection among LCA, LCC and S-LCA during the development of S-LCA can be represented as shown in Figure 1.

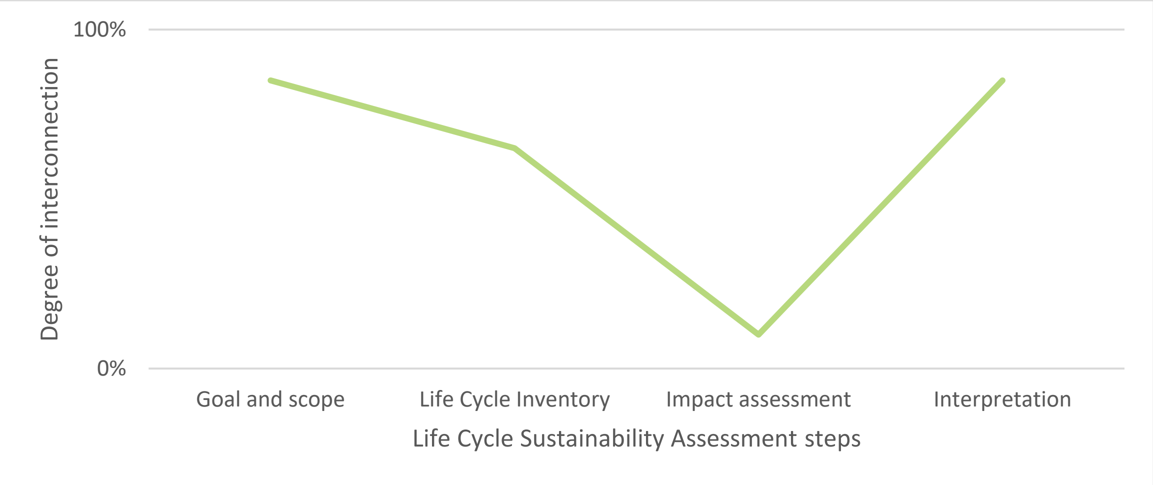

Figure 1. Level of interconnection of LCA, LCC and S-LCA during the LCSA development.

The structure in ISO 14040, main standard for LCA, will be followed for all the three assessments. In the following sections, the approach to develop the goal and scope, the life cycle inventory (LCI), the life cycle impact assessment (LCIA) and the interpretation will be explained. The explanation will include the overall perspective, from the point of view of the sustainable development and the specifications of each assessment will be detailed for each section.

The LCA is the most developed methodology of the three included in LCSA. There are schemes to declare the environmental impacts of products voluntary (type III eco-labels) based on LCAs verified by a third party. These documents are called Environmental Product Declarations (EPDs) and they must be developed under product LCA specific rules: Product Category Rules (PCRs). PCRs can be found for different products under the general rules of several program operators.

In the framework of ALEHOOP, a research of PCRs will be carried out and a draft PCR for protein isolates products, classified with the UN CPC 23999 other foods not elsewhere classified, will be developed. This task feeds from the LCSA methodology definition, particularly from the definition of the LCA.

2 Goal and scope

The goal and scope of the LCSA will be the section with more similarities among the three assessments. It will be based on the attributional approach (avoiding consequential impacts)

The products to be assessed in the ALEHOOP project are functional ingredients extracted from biomass. The processes will be developed at laboratory and pilot scale. The biomass is obtained from the agriculture and aquaculture sectors and the protein isolates will be used in food and feed products. The process and value chain will be tested within the ALEHOOP project and the results obtained will be used for further upscaling of the production processes and improvement of the value chain to ensure product quality.

2.1 Goals of the LCSA

The objectives of the three sustainability assessments are listed below:

- The first goal of the LCSA will be to evaluate and comprehend the environmental, economic and societal impacts and hotspots of the products developed within the ALEHOOP project.
- Then, the processes will be modelled, eco-designed and scaled up in order to optimize the overall sustainability of the functional ingredients production processes and avoid burden shifting among impact categories and sustainability compartments (environment, economic and society).
- Testing S-LCA methodologies and approaches for innovative bio-based products.
- The assessment will aim to find the optimal operational parameters to optimize the overall sustainability of the processes at larger scales.
- One specific goal for the LCA will be to evaluate current methodologies and Product Category Rules (PCRs) and, if there are no existing PCRs for ALEHOOP products, develop draft PCRs.

2.2 Target audience

The LCSA will be addressed for the developers of protein isolate extraction process to inform them about the most relevant hotspots in their processes in order to improve the sustainability associated in further upscaling plans. In addition, the LCSA will also be addressed to relevant stakeholders in the value chain, such as consumers or retailers. In addition, further reporting could be made to inform the public about the environmental impacts of the products developed.

2.3 Geographical scope

The LCSA will be located in Europe, considering that the protein will be extracted in different countries depending on the raw material used. In consequence, the electricity grid mix will be specific for the country where the processes take places. The economic impacts will also be influenced by specific country taxes and salaries and average European values will be used when possible. The social assessment will be fully localized in the specific country where the process take phase for the assessment of job creation and retention potential, while the hotspot analysis will be performed on the social aspects along the whole life cycle.

2.4 Main references

The definition of the methodology has been based on specific standards and guidelines in order to allow comparability and provide results with scientific robustness. Many references have been consulted but the following list collects main documents regarding methodological issues of LCA, LCC and S-LCA used for the methodology definition.

- LCSA:
  - Towards a Life Cycle Sustainability Assessment: Making informed choices on products, 2011, UNEP ((United Nations Environmental Program (UNEP), 2011))
- LCA:
  - ISO 14040, ISO 14044 (ISO, 2006a) (ISO, 2006b)
  - Product Environmental Footprint (PEF) guide, 2019, European Commission (Zampori & Pant, 2019)
- LCC
  - Environmental life-cycle costing: a code of practice (Swarr et al., 2011)

Common and normalized methodologies for products is missing. Only Standards regarding the LCC of buildings is currently released. The mentioned reference has been consulted to link the results of LCC with LCA and S-LCA results.

- S-LCA
  - Guidelines for Social Life Cycle Assessment of Products and Organizations, UNEP 2020. (Benoît Norris et al., 2020)
  - Product Social Impact Assessment Handbook, by the Roundtable for Social Product Metrics - (Goedkoop, M.J.; de Beer, I.M; Harmens, 2020)
  - A Product Social Impact Life Cycle Assessment Database version 3 Documentation, KirillMaister, Claudia Di Noi, Andreas Ciroth, Michael Srocka (all GreenDelta) 2020 (Maister et al., 2020)
  - Social Hotspot Database[1] (NewEarth B, 2015)
  - Social life cycle assessment framework for evaluation of potential job creation with an application in the French carbon fiber aeronautical recycling sector, Pillain et al., 2019).

The document provided by UNEP has been used as main reference to develop the S-LCA methodology to be followed. The other guidelines consulted were used given that they are compliant with the document from UNEP and they provide useful information about the impact assessment, data needs, reference scale method, data sources, the interpretation of results and communication of results.

2.5 Functional unit

The functional unit for LCSA will be based on physical properties and quality specifications: 1 kg of pure protein. The packaging will not be included in the LCSA of the products assessed given the marketable packaging design is not decided yet.

2.6 System boundaries

The system boundaries of the assessment will be cradle-to-gate. The inputs and outputs included in the assessment of each stage will be selected for each assessment (social, economic and environmental) based on relevancy and data availability. The raw material production, collection, transport and the protein extraction stages

[1] http://www.socialhotspot.org/

be shared among the three assessments. The scheme presented in Figure 2, extracted from United Nations Environmental Program (UNEP), 2011 gives an example of the LCSA system boundaries establishment.

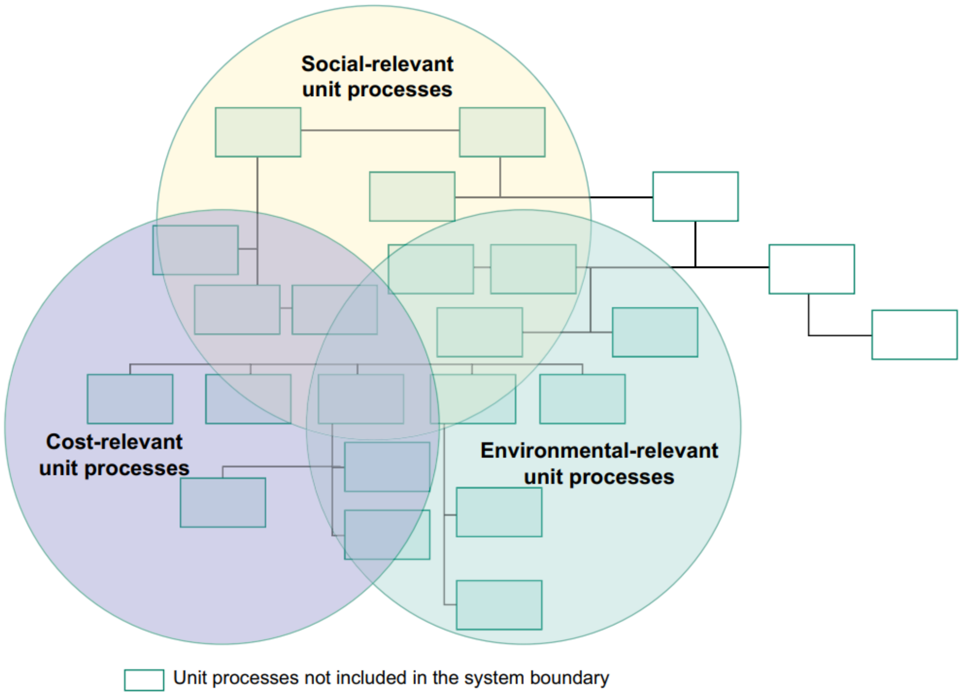

Figure 2. System boundaries for LCSA (United Nations Environmental Program (UNEP), 2011).

Some unit processes will be assessed in from the social perspective and not included in the economic assessment nor environmental depending on their relevancy and data availability.

In Figure 3, the life cycle stages of a bio-based protein concentrate product is presented. The impacts related to sustainability will be assessed in a holistic view but the LCA, LCC and S-LCA will consider different stages or aspects of the functional ingredients' life cycle.

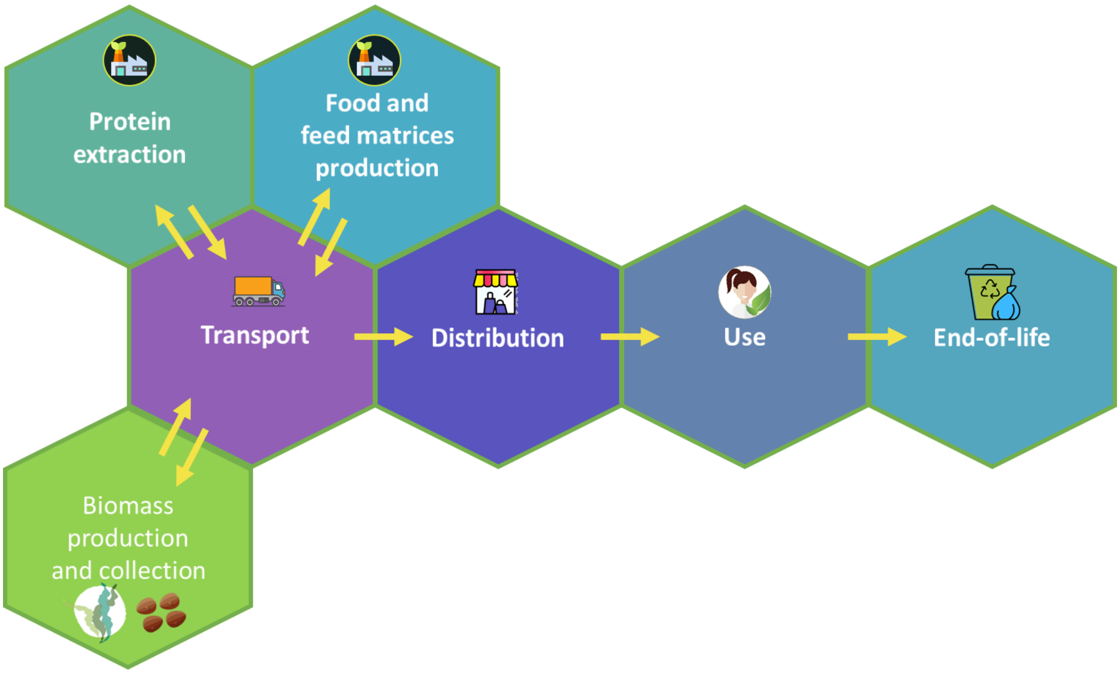

Figure 3. Life cycle of ALEHOOP products

The final food and feed products production stage is included in the ALEHOOP project to validate the proteins extracted in different matrixes. Not all the stages of the life cycle will be included in the LCSA, which system boundaries are set as cradle-to-gate:

Stages included in the LCSA:

- Biomass production and harvest: two scenarios are differentiated:
  - Legumes as raw materials: the production of legumes will be modelled using generic data.
  - Seaweed production and harvest: seaweeds are collected as a current waste stream of seafood production process. Following a cut-off approach, the impacts of production stage will be allocated to seafood. On the other hand, harvest stages are sometimes exclusively performed to harvest seaweed. In this case, the impacts produced during the harvesting phase will be included in the assessment.
- Transport: the transport from the cultivation fields and the coastal areas where the seaweed is collected to the treatment facility will be included. The transport to the food and feed matrixes production facilities will also be included for the matrixes tested within the projectFood and feed matrixes production: Given that final food and feed matrices are not yet fully developed, and they will not be fully developed within ALEHOOP project, the inclusion of the protein into the matrixes will not be included in the LCSA, due to the low availability and quality of the data potentially collected.

Stages not included in the LCSA:

- Distribution: the impacts of distribution of the commercialized products will not be included in this LCSA.
- Use: The use stage will not be included neither in the assessments given the potential low impact of this stage (products will not be to be cooked and will not lead to any washing phase). In the potential PCR

developed, it must be included given that other products of the same UN CPC code may present impacts associated to this phase.

- End-of-life: this stage will not be included in the LCSA given lack of data on products rate getting the end-of-life scenario as well as the packaging used.

2.6.1 LCA

The direct emissions of each life cycle stage included in the LCSA will be estimated. The indirect emissions will be estimated using generic data on materials and energy production, waste treatment, etc.

2.6.2 LCC

It will address the viability of extraction processes, considering also upstream costs (raw materials anad energy costs, etc.)

2.6.3 S-LCA

The S-LCA is divided in three steps:

- Hotspot analysis: using the SHDB and SimaPro, the more relevant social issues, life cycle stages and unit processes will be identified.
- Job creation potential assessment. It will be performed following the methodology used in Pillain et al., 2019. Input-Output (IO) economic tables will be used to evaluate the potential number of jobs created in the upstream life cycle stages, using the same inventory for the LCC, IO tables and Full Time Equivalent (FTE) data for each sector.
- Additional information: evaluation of S-LCA performance using suitable indicators from Guidelines for Social Life Cycle Assessment of Products and Organizations, UNEP 2020. The pre-selected indicators are contribution to economic development and health and safety of customers. The latter will affect the use life cycle stage, but given its high relevancy could be added as additional information

2.7 Selected impact categories

The categories selection is based on relevancy and data availability criteria.

2.7.1 LCA

Impact categories included in the EF method v3 (or most updated version at the moment) will be used. Each impact category will be quantified under a specific method selected by a panel of experts at European level during the Single Market for Green Products (still in course).

Table 1. Environmental impact categories from EF method v3.0.

Impact category	Indicator	Unit	Method and description
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO2 eq	Baseline model of 100 years of the IPCC 2013
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC11 eq	Steady-state ODPs (WMO 2014)

Ionising radiation, human health	Human exposure efficiency relative to U235	kBq U-235 eq	Human health effect model based on Dreicer et al. 1995 (Frischknecht et al, 2000)
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS model (Van Zelm et al, 2008) - ReCiPe 2008
Particulate matter	Impact on human health	disease inc.	PM method recommended by UNEP (UNEP 2016)
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	CTUh	USEtox model 2.1 (Fankte et al, 2017)
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	CTUh	USEtox model 2.1 (Fankte et al, 2017)
Acidification	Accumulated Exceedance (AE)	mol H+ eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model (Struijs et al, 2009) - ReCiPe
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (P)	kg N eq	EUTREND model (Struijs et al, 2009) - ReCiPe
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	USEtox model 2.1 (Fankte et al, 2017)
Land use	Soil Quality Index Biotic production erosion resistance Mechanical filtration	Pt	Soil quality index (LANCA v2.2 by JRC)
Water use	User deprivation potential (deprivation-weighted water consumption)	m3 depriv.	Available WAter REmaining (AWARE). Recommended by UNEP, 2016
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002.

Deeper analysis will be done on the impact categories identified as most relevant in the hotspot analysis, using single score results after weighing and normalization using EF method factors.

2.7.2 LCC

The costs will be classified in type of costs categories. Each category will include:

- CAPEX: equipment used in the production of the functional ingredients
- Depreciation: reduction of the value of equipment
- OPEX: products, raw materials, energy, water, salaries, renting, logistics and maintenance
- Taxes: taxes that the company will pay in function of their incomes related to the products assessed

Then, the Net Present Value (NPV) will be calculated, considering all the costs along the lifetime, to estimate the final Levelised Cost of Production (LCOP). The LCOP will be the main indicator to evaluate the economic feasibility as it represents the minimum price of the product to equalize the costs along a lifetime pre-defined. The lifetime of the study will be 5, 10 or 20 years, depending on data quality and availability.

2.7.3 S-LCA

First, a hotspot analysis using SHDB will be performed to evaluate the main hotspots. A literature review will be performed to identify most relevant indicators assessed in similar value chains. Ultimately, the impact categories will be extracted from Guidelines for Social Life Cycle Assessment of Products and Organizations by UNEP, 2020. The job creation/retention indicators have been included following the recommendations of the European Commission for BBI projects, which demands these indicators as a diagnosis to measure the impact of the project. The methodology selected to evaluate it is the one developed by Pillain et al., 2019, which uses Input-Output (IO) tables to assess the influence of one activity along the value chain:

- Hotspot analysis: all the impact categories and indicators used in SHDB will be considered, although only those accounting with more than 80% of the weighed impacts will be analysed with special focus. The damage and impact categories in the SHD are presented in Table 2. The social issues included in SHDB have different influence in different impact categories.

Table 2. Damage category and impact categories included in SHDB.

Damage Category	Impact category
Labor Rights & Decent Work	Wage
	Poverty
	Child labor
	Forced labor
	Excessive WkTime
	Freedom of assoc
	Migrant labor
	Social benefits
	Labor Laws/Convs
	Discrimination
	Unemployment
Health & Safety	Occ Tox & Haz
	Injuries & Fatalities
Human Rights	Indigenous Rights
	Gender Equity
	High Conflict Zones

	Non-Communicable Diseases Communicable Diseases
Governance	Legal System Corruption
Community	Access to drinking water Access to Sanitation Children out of School Access to Hospital Beds Smallholder v Commercial Farms

- Job creation potential: the job creation potential will be divided in upstream jobs (direct and indirect) and jobs created within the production life cycle stage.
- Additional social information: the UNEP guidelines and current S-LCA methodologies are designed for products on the market and not products in the research and development phase. In consequence, in R&D projects, only few indicators and categories are suitable. A variety of factors determine the selection of categories and indicators for the social assessment: the location of economic activity, the system boundaries, the scope of the study and the availability of high-quality data. The selection also depends on the type of product and value chain to assess. In Alehoop, the selected indicator is the health and safety of users following the criteria set by RPSM, given the availability of documents and studies addressed to evaluate the benefits or harms to human health of proteins.

The categories and indicators selected shall be representative and valid to assess R&D projects. This consideration is important when selecting categories and indicators from recognised international methodologies, such as the ones developed by UNEP or by RSMP. Firstly, some concepts need to be defined:

- **Stakeholder category: "**cluster of stakeholders that are expected to have shared interests due to their similar relationship to the investigated product systems. Stakeholder categories provide a comprehensive basis foar the articulation of the subcategories. The proposed stakeholder categories are deemed to be the main group categories potentially impacted by the life cycle of the product" (Benoît et al., 2013).
- **Social topic:** social areas related to stakeholder groups that should be measured and assessed such as working hours, community engagement, child labour, etc. (Goedkoop, M.J.; de Beer, I.M; Harmens, 2020).
- **Performance indicator:** performance markers for each of the social topics, for example, number of working hours per week, minimum wage paid, etc. (Goedkoop, M.J.; de Beer, I.M; Harmens, 2020)

Table 3.Selected stakeholders, social topics and performance indicators (based on Goedkoop, M.J.; de Beer, I.M; Harmens, 2020).

STAKEHOLDER	SOCIAL TOPIC	DEFINITION	PERFORMANCE INDICATOR	DEFINITION
Consumers	Health and safety	Products are expected to perform their intended functions satisfactorily and not pose a risk to consumers' health and safety. This social topic addresses both risks and the positive impacts that products may have on the health and safety of the end-users of products	Presence of certifications or labels for the product/sites sector	

In addition, some positive impacts could be addressed. Positive social impacts can be addressed in different ways, depending on the scenario that fits the better the types of positive impact according to UNEP, 2020.

In this methodology, type B positive social impacts will be considered. Product life cycles also create positive social impacts through their presence. Products generate impacts on employment, capacity building or infrastructure improvement. These impacts are positive if the company is present in a location and may disappear if there are modifications in the product life cycle, aimed at reducing other negative impacts.

2.8 Treatment of multi-functionality

Functionality will be dealt following the hierarchy described in ISO 14040 and ISO 14044. First, system expansion or sub-division will be used if possible. If this first approach is not feasible, physical allocation will be used unless economic allocation is preferred. In some cases, the products and co-products sharing some units of the production process have very different functions and mass allocation is not relevant anymore. For example, most food products from agriculture normally use economic allocation due to different function of waste streams, energy produced or final food product. In the case of seaweed production and harvest, the impacts of production are fully allocated to the main product (seafood). The harvesting impacts of seaweed harvest are allocated to different types of seaweed harvested (brown, green or red) using mass allocation.

3 Life Cycle Inventory (LCI)

One LCI will be developed to ask for the data for the LCSA.

The data will be collected from partners through physical interviews and/or online meetings and by using the LCI templates in excel format. The templates have been prepared by CONTACTICA and they are presented in annexes. Note that templates could be modified during the project if the processes suffer any change.

The data needs and sources are described in the following section for each assessment. There will always be two types of data: primary data and secondary data. Primary data are provided by the stakeholders involved in the protein extraction stage. Amounts of materials, energy, output streams (waste, emissions, products and co-products), operational data (materials, quantities, duration, people involved, etc.) or data to describe the value chain are considered as primary data. Secondary data are obtained from generic databases and includes information that project partners are not able to provide accurately, like the emissions embodied in the materials used or inputs and outputs of downstream and upstream processes.

3.2 Source of data

3.1.1 LCA

The data required for the LCA will be obtained from the following sources:

- Primary data: description of extraction process and value chain, including materials and energy used, amounts, input and output streams, waste streams management scenarios, delivery distance of products used, etc will be provided by partners involved. Data will be asked using the LCI templates found in Annex 1: LCI templates.
- Secondary data: LCA databases will be used to include the emissions associated to the use of materials, energy, industrial processes and transport. Ecoinvent, ELCD, Agribalyse, World Food Database and Industry data (World steel, Plastics Europe, etc) will be used as sources. Default scenarios for end of life or transport will be extracted from PEF guide when no data is available. Additional data can be sought in scientific literature if needed.

Data needed from partners for the LCA will be asked through the template found in Table A 1.

3.1.2 LCC

Costs will be obtained from partners, who must fill the template from Table A 1. with actual cost data. When data is not available, market price will be used. Data concerning taxes or interest rates will be consulted with partners and compared to official indicators for the specific country in which the process takes place.

3.1.3 S-LCA

During the hotspot analysis, the data obtained in the LCI regarding the costs of the inputs and services for the protein extraction will be used together with the SHDB.

Data used to evaluate job creation and job retention potential will be collected from partners (same data used in LCA and LCC) and from specific country data (IO tables).

Data needed for the assessment of the impact categories extracted from S-LCA methodologies and standards will be directly asked to partners. Data gaps will be filled with data from literature and secondary databases. All the sources previously identified are collected in Table 3.

Table 4. Data sources for S-LCA.

STAKEHOLDER	SOCIAL TOPIC	PERFORMANCE INDICATOR	TYPE OF DATA FOR ALEHOOP	SOURCE OF DATA
Consumers	Health and safety/Transparency	Presence of certifications or labels for the product/sites sector	Primary	Partner

The data that need to be collected from partner, will be asked by sending the template found in Table A 2.

4 Life Cycle Impact Assessment (LCIA)

In this third step of the LCSA, the results will be extracted. The impacts will be classified into environmental impact categories (LCA), types of costs (LCC) and social indicators (S-LCA). The methods to calculate the impacts for different categories are presented below for each type of assessment.

4.1 LCA

The LCIA method for the LCA will be EF method 3.0 for current scenarios analysis given that it uses the most updated LCIA methods for each category, selected by a panel of European experts. The emissions will be classified and characterized by the use of Characterization Factors (CFs) provided by the method. Normalization and weighting factors included in EF method will also be used to calculate single score results (excluding toxicity categories). The SimaPro software which includes the EF method 3.0 will be used. The categories and impact methods are gathered in Table 1.

4.2 LCC

The LCC will be based on the calculation of the Net Present Value (NPV) and the LCOP. This cost represents the value of the final product to equalize costs and sales in a pre-defined time framework. Only exceeding the LCOP, benefits can be obtained. It is a reference value to compare with market price of competence products.

The costs of all categories or type of costs (see section 2.7.2) will be used to calculate the Net Present Value (PV):

$$NPV = \sum_{i=1}^{l} \frac{Costs}{(1+i)^t}$$

Costs: annual operational costs and capital costs performed in year *t*.

$$Costs = EBITDA + taxes$$

$$EBITDA = CAPEX + OPEX + Maintenance + Sales$$

l: lifespan defined: 5, 10 or 20 years.

i: nominal discount rate. It is assumed to be 5%, equal to the real discount rate. In consequence, the inflation is not considered.

CAPEX: it includes the cost of equipment used in the extraction processes.

OPEX: it includes workers, materials and utilities (water and energy).

4.3 S-LCA

The S-LCA impacts will be different for job creation and job retention potential and for the other impact categories selected (section 2.7). Job creation potential will be evaluated using following formulas:

- Potential Jobs Created = (WH each input * G stock available)/FTE
- Gstock: t/year
- FTE (Full-time equivalent): h/year for all sectors
- WH input = f*Y (h)
- Y: cost from inventory for all the inputs (€)
- f = S*$(I-A)^{-1}$
- S: direct working h/€
- $(I-A)^{-1}$: Input-Output tables for Spanish economy

Regarding the evaluation of categories and social topics included in specific S-LCA methodologies and standards, the impact assessment method will be based on a scale-based approach to identify social risks or hotspots. The selected social topics will be assessed individually and no weighting will be applied to obtain a single score result. Every social topic result will be presented in terms of risks and scale levels. The scales levels are defined differently from (Goedkoop, M.J.; de Beer, I.M; Harmens, 2020) to (Maister et al., 2020). In both cases the highest risk corresponds to red colour and green corresponds to lowest risk.

In the methodology developed by Goedkoop et al. the scale levels go from -2 (highest risk and red colour) to +2 (green colour and lowest risk) (see Table 4). To identify the scale level, performance indicators need to be defined based on data collected from stakeholders and from secondary data sources. Several performance indicators can be used to identify the scale level. Some performance indicators are defined on quantitative approach, defining minimum or maximum values to fulfil the criteria, and other performance indicators are based on qualitative justifications.

Table 5. Scale reference impact assessment method. Health and safety of users.

Stakeholder group / category	Social topic	Scale level description	Performance indicator	Score
Users	Health and Safety	There is solid science-based evidence that normal use of the product can contribute very significantly to a better health and safety AND the product or service is marketed and managed in such a way that it does reach the most vulnerable groups who would benefit most from this product and service.	The evidence must contain two parts: • Scientific evidence or opinions from independent experts or independent organisations that are specialised in this area, confirming the product has properties that can significantly improve the health and safety of users • Opinions from independent experts who confirm that the product indeed is marketed and managed in such a way that it reaches the most vulnerable groups In a B2B situation a description of the efforts to design components and/or support the design of the final product that contributes to this achievement.	+2
		The company has a dossier or other evidence that shows how the product or service has been successfully designed to create a maximum contribution to health and safety of the user and that the recommended use of the product contributes to a better health and safety for the intended users.	A dossier or evidence that contains elements such as: • The company has assessed how the product can optimise or harm the health and safety of the user; for instance, through reduction of salt, saturated fats or calories, or significantly improved ergonomics. • The product developers have a verifiable audit trail on the efforts and decisions to optimise the health and safety of the user. In a B2B situation a description of the efforts to design components and/or support the design of the final product that contributes to this achievement	+1
		The normal use product and the way it is marketed and managed does not have any significant detrimental effect on the	Absence of verifiable claims by authorities, consumer organisations and user groups that there is a significant detrimental health and safety impact (for B2B and B2C situations).	0

		health and safety of the user.	Reports from authoritative sources that confirm there is no or a negligible health impact, in the way the product is used (for B2B and B2C situations)	
		The normal use of the product has negative health or safety impacts, but the producer has developed a corrective action plan to improve the product and to influence the way the product is used in order to significantly reduce the negative impacts.	Verifiable information that the health and safety issue is recognised by the company and that the product and the way it is managed and marketed is being improved with a clear and credible timeline In a B2B context: verifiable information that the health and safety issue is recognised and that the component or ingredient and the way it is applied is being improved with a clear and credible timeline.	-1
		Any use of the product has direct negative health or safety impacts on short or long term.	Reports from consumer organisations, NGOs, watchdogs and authorities that describe the negative impacts The product does not conform to the legal requirements and is not approved by the authorities.	-2

In conclusion, each social topic will be assessed individually and no aggregation or weighting of results will be performed, due to low robustness of methods and lack use of this approach by the industry stakeholders who tested the methodology developed by The Roundtable for Product Social Metrics. Each social topic result will represent a risk (higher or lower) according to the criteria described by the methodology in which the indicator was obtained from.

5 Interpretation of results

An individual interpretation will be performed and the final conclusions will interconnect the results of the three assessments.

5.1 LCA

The environmental impact results will be interpreted throughout a hotspot analysis. The **hotspot analysis** is a methodology to interpret the LCA results according to the PEF Guide. It aims to identify the most relevant impact categories, stages, processes and elementary flows of the life cycle of a product or activity. The definition of most relevant relies on the 80% criteria, i.e., the most relevant impact categories, stages, processes and elementary flows are those which contribute to the greatest 80% of the normalized and weighed impacts. The following steps must be followed to do a hotspot analysis:

1) First, characterized results are calculated by classification and using characterization factors to obtain the results for each impact category.
2) The categories related to toxicity impacts are excluded due to the low robustness of their characterization factors.
3) The remaining impact categories results are normalized to the average global person emissions for each impact category (EF method normalization factors).

4) Then, the impacts are weighted using the weighting impacts provided by the European Commission (EF method), converting all the results into one common unit (points).
5) The results are sorted from greatest to lowest and the greatest values are summed until the greatest 80% of the impacts is achieved. The impact categories which results are part of this 80%, are considered as most relevant impact categories.
6) The same methodology is used to identify the most relevant stages for each most relevant impact category and the most relevant processes and elementary flows.
7) In this study, the most relevant elementary flows will not be identified due to the final application of this LCA. The stakeholders involved and parties interested in this LCA do not have influence on the elementary flows although they have it on the processes, that is why the hotspot analysis identify the most relevant impact categories, stages and processes.

5.2 LCC

A similar criterion than the established for the LCA will be used for the economic analysis. The same threshold of 80% will be used to identify the most relevant costs, i.e., the types of cost with highest contribution within the whole-time framework of the assessment.

In addition, the feasibility of the processes can be evaluated in terms of NPV and Internal Rate of Return (IRR).

The results of LCOP will be interpreted comparing them with current competitors' price in the market. In addition, interviews with protein producers and food and feed matrices producers will be performed to evaluate the LCOP towards a final market price.

Also, sensitivity analysis on certain parameters with higher uncertainty will be performed to evaluate different scenarios.

5.3 S-LCA

Job creation and job retention potential will be interpreted considering the amount of feedstock available and the potential production with the developed extraction processes. Also, the hotspot analysis results performed with SHDB and by literature review will be assessed using a hotspot analysis perspective, as used for LCA and LCC.

Regarding the impacts in categories from specific S-LCA methodologies, the results will be interpreted in function of the quality of data. A data quality assessment will be performed according to the criteria defined by UNEP (see Table 6).

Table 6. Data quality assessment criteria and score description (Benoît Norris et al., 2020).

Score	1	2	3	4	5

Reliability of the source(s)	Statistical study, or verified data from primary data collection from several sources	Verified data from primary data collection from one single source or non-verified data from primary sources, or data from recognized secondary sources	Non-verified data partly based on assumptions or data from non-recognized sources	Qualified estimate (e.g. by expert)	Non-qualified estimate or unknown origin
Completeness conformance	Complete data for country-specific sector/ country	Representative selection of country-specific sector / country	Non-representative selection, low bias	Non-representative selection, unknown bias	Single data point / completeness unknown
Temporal conformance	Less than 1 year of difference to the time period of the dataset	Less than 2 years of difference to the time period of the dataset	Less than 3 years of difference to the time period of the dataset	Less than 5 years of difference to the time period of the dataset	Age of data unknown or data with more than 5 years of difference to the time period of the dataset
Geographical conformance	Data from same geography (country)	Country with similar conditions or average of countries with slightly different conditions	Average of countries with different conditions, geography under study included, with large share, or country with slightly different conditions	Average of countries with different conditions, geography under study included, with small share, or not included	Data from unknown or distinctly different regions
Further technical conformance	Data from same technology (sector)	Data from similar sector, e.g. within the same sector hierarchy, or average of sectors with similar technology	Data from slightly different sector, or average of different sectors, sector under study included, with large share	Average of different sectors, sector under study included, with small share, or not included	Data with unknown technology / sector or from distinctly different sector

A score will be obtained for every data collected by doing the average of all criteria. Subsequently, the average score among all the results for all data used will serve as reference to estimate the quality of results for every social topic.

Finally, all the conclusions from LCA, LCC and S-LCA will be interpreted together. All the hotspots will be compared to identify the origin of sources and provide recommendations to avoid burden shifting among categories and pillars of sustainability. This means that no decision to improve the environmental performance should compromise the social or economic performance of the process in the upscaling.

6 Eco2des tool

The scaling-up process will be evaluated using the tool developed in CONTACTICA by an Industrial PhD program financed by the Community of Madrid (Spain) in 2017 (García-Casas, M. et al. 2020). The LCA, LCC and S-LCA methodologies previously described will be embedded into the tool, which will link them with the virtual plant simulation of the ALEHOOP process. Then, a multi-objective optimization problem will be defined and resolved using genetic algorithms to optimize technical, economic, environmental and social indicators.

6.1 Introduction.

Industry is a key sector to achieve worldwide sustainability with a prosperous society, with a modern, resource-efficient and competitive economy; and where there are no net emissions of greenhouse gases. Therefore, new value chains must be studied and developed, as well as, the current ones must be optimized in terms of sustainable key performance indicators. However, during the development of new innovative processes, there are no industrial data that can support any life cycle assessment, LCA, or life cycle cost, LCC, analysis, which gives rise to numerous trial-and-error phases during technology upscaling, exorbitantly increasing time-to-market and costs, while achieving solutions that may not be optimized or, even, feasible in sustainable terms.

Predictive models and process simulations, however, are able to compute, through physicochemical relationships, the behaviour of that technology under development at industrial scale and formulate scenarios for environmental or cost optimization. Even so, process simulation, LCA and LCC methodologies are well structured and there are many options of commercial software specialized in these areas. Nowadays, at the best of our knowledge, there is no current research combining them in a holistic way for their application in the economic and environmental optimization of any industrial design of process under research and/or development. With this premise, the **eco2des** framework was born. It is an object-oriented Python framework for sustainability-based optimization of industrial processes. The tool takes advantage of the full feature set of Python, such as its facilities for fast prototyping and the several available libraries for data processing, data analysis, scientific computing and data visualization. **Eco2des** is a descriptive tool, which documents life cycle inventories and characterizes them through their environmental impact and associated costs. It is a predictive tool, since it uses as inputs physicochemical models for process simulation in the research phase; and adaptive, since it automates process design selections based on multi-objective optimization algorithms. As a result, the framework is able to take a process simulation, such an aspen plus file (Figure 1), linking it with a LCA and a LCC models and optimize its sustainable objectives changing operational variables, topology or supply chain decisions.

Figure 4. eco2des concept

6.2 Process modelling design and plantwide simulation methodology.

The aim of this task is to generate feasible and industrially realistic basis, information/data to optimize the ALEHOOP concept before scaling it up to a real plant.

All the processes steps will be explicitly modelled and considered in the simulation by CONTACTICA. For each of the steps a first-principles based predictive model will be selected to simulate the physical, chemical and biological phenomena taking place. Moreover, when necessary, machine learning techniques will be applied to develop predictive regression models.

Finally, these models will be implemented in a plant wide simulation built in Aspen Plus software, in which downstream processes will be also considered to perform mass and energy balances according to target scale-up capacity. The simulation will provide inventory data in different scales to perform subsequent LCSA studies and to solve multi-objective optimization problems.

6.3 Life Cycle Sustainability Assessment methodology.

In order to preserve the harmony between LCSA of reference systems, simulated processes and real plant analysis, the LCSA methodology implemented in **eco2des** will be analogue to that described below Section 6.3.1.1. The data used for simulation and optimization will be collected from partners using data collected in templates found in Annex 1: LCI templates.

6.3.1 Multi-objective optimization methodology.

First, sustainable key performance indicators (S-KPI) will be defined as objectives of the optimization problem:

- Environmental objective: Those shown in Table 1 normalized and weighted into a single score following the PEF methodology.
- Economic objective: NPV of the ALEHOOP bio-process.
- Social objectives: job creation potential.

After the definition of the optimization objectives, key operational and value chain variables will be identified carrying out sensitivity analysis in the virtual plant and value chain models developed. Then, their boundaries and principal constraints will be defined.

For solving multi-objective optimization problems finding reasonable solutions, **eco2des** offers a set of different genetic algorithms. In this case study, multi-objective evolutionary algorithm with decomposition, MOEA/D, (Zhang and Li, 2007) and non-dominated sorting genetic algorithm II, NSGA-II, (Deb et al., 2002) will be used to find the Pareto front of the problem, in which a set of solutions will be presented. Between them, that which better fulfils the KPIs of the call will be selected as optimal solution to be tested and scaled-up in real plants.

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8 Annex 1: LCI templates

Table A 1. Data collection template for LCA, LCC and S-LCA (Tecnalia).

Life Cycle stage	Input	Quantity input	Unit	Cost (€/unit)	Output	Quantity output	Unit	Duration stage (h)	CAPEX (€)	Number of workers	Cost of workers (€/h)	Comments
Milling	Raw material		kg		Milled raw material		kg					
	electricity		kWh		Losses		kg					
Dispersion	Water		kg		Dispersed solution		kg					
	Milled raw material		kg									
	electricity		kWh									
pH adjustment	electricity		kWh		liquid protein		kg					
	Acid agent		kg		solid residues (specify)		kg					
Centrifugation	electricity		kWh		Solution		kg					
					solid residues (specify)		kg					
Centrifugation 2	electricity		kWh		Protein concentrate		kg					
					Liquid waste stream		kg					
Washing	Protein concentrate		kg		filtrated red seaweed		kWh					
	Water		l		solid residues (specify)		kg					
Centrifugation 3	electricity		kWh		Protein concentrate		kg					
					Liquid waste stream		kg					
Freeze drying	Dry protein concentrate				water		kg					
	electricity				protein concentrate		kg					
					protein content		%					

Table A 2. Data collection template for LCA, LCC and S-LCA (Anfaco).

Life Cycle stage	Input	Quantity input	Unit	Cost (€/unit)	Output	Quantity output	Unit	Duration stage (h)	CAPEX (€)	Number of workers	Cost of workers (€/h)	Comments
Harvesting #1	diesel		l		green seaweed		kg					
	electricity		kWh									
Washing (lab)	Water		kg		Washed green seaweed		kg					
	Green seaweed						kg					
Washing (pilot)	Water		kg		Washed green seaweed		kg					
	Green seaweed		kg		Water		kg					
Fragmentation	electricity		kWh		fragmented seaweed		kg					
					losses		kg					
Enzymatic hydrolysis	electricity		kWh		protein solution		kg					
	fragmented seaweed		kg									
	Water		kg									
	enzyme		kg									
Sieving	electricity		kWh		Protein solution sieved		kg					
	Protein solution				Solid residue (specify)		kg					
Filtration	Protein solution sieved		kg		Filtered solution		kg					
	electricity		kWh		Solid residue (specify)		kg					
Ultra/nano-filtration	Filterd solution		kg		Filtered solution 2							
	electricity		kWh		Solid residue (specify)		kg					
Spray drying	electricity				water		kg					
					protein concentrate		kg					
					protein content		%					

Table A 3. Data collection template for LCA, LCC and S-LCA (Alginor).

Life Cycle stage	Input	Quantity input	Unit	Cost (€/unit)	Output	Quantity output	Unit	Duration stage (h)	CAPEX (€)	Number of workers	Cost of workers (€/h)	Comments
Harvesting #1	diesel		l		red seaweed		kg					
	electricity		kWh		brown seaweed		kg					
Harvesting #2	diesel		l		red seaweed		kg					
	electricity		kWh		brown seaweed		kg					
Stabilization	Water		kg		red seaweed + alkaline solution		kg					
	Basic agent		kg				kg					
Heating	electricity		kWh		water		kg					
					dry red seaweed							
Solid-liquid separation	electricity		kWh		liquid protein		kg					
					solid residues (specify)		kg					
Ultrafiltration	electricity		kWh		filtrated red seaweed		kWh					
					Solid residue (specify)		kg					
Spray drying	electricity				water		kg					
					protein concentrate		kg					
					protein content		%					