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Chloé Thomas, Cécile Gremy-Gros, Aurélie Perrin, Ronan Symoneaux, Isabelle Maître. Implementing LCA early in food innovation processes: Study on spirulina-based food products. Journal of Cleaner Production, 2020, 268, 10.1016/j.jclepro.2020.121793 . hal-02615773

HAL Id: hal-02615773

<https://hal.science/hal-02615773>

Submitted on 22 Aug 2022

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1 Implementing LCA early in food innovation processes: study on spirulina-based
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1. Introduction

In 2015, the United Nations announced its sustainable development goals (SDGs) with a view to increasing the commitment to sustainability within political and economic systems worldwide. The protection of environmental ecosystems, resources and human health have become a global priority. In Europe, food production accounts for 20–30% of all anthropogenic impacts on the environment (Notarnicola et al., 2017). Consumers increasingly demand for healthier and more sustainable products. For example, expectations for "clean labels" products grew, and the market share of organic products has been growing (FiBL and IFOAM Organics International, 2019) as consumers consider such products as more environmentally friendly (Azzurra and Paola, 2009). This context enhances agri-food industries to consider their role in protecting the environment, and most of them are striving to achieve greater sustainability.

The 21st century sees the great evolution of sustainability research (Medicine et al., 2019). Many methods and tools are currently available to assess the environmental impacts of objects, agricultural productions of food transformations. Some are qualitative (e.g., checklists and guidelines), others are quantitative and monocriteria (e.g. Carbon Footprint) or multicriteria (e.g. Life Cycle Assessment) (Rousseaux et al., 2017). Even though monocriteria assessment, like water use (Hashemi et al., 2019), water allocation (Sedghamiz et al., 2018) in crops, or climate change (Pandey et al., 2011), are often used in first approach, quantitative methods such as the recognized Life-cycle assessment (LCA) standardized method (ISO 14040) are more reliable tools to characterize and assess multiple environmental impacts of products and services.

Past studies that performed LCAs for agri-food products have been quite diverse in nature (Perrin et al., 2014) and generally hard to compare (Roy et al., 2009). The food transformation sectors like meat (e.g. chicken meat: Skunca et al., 2018; red meat: Colley et al., 2020) and dairy (Baldini et al., 2017) are more and more studied. The studies on the full value chain of food sectors have progressed. Some studies think beyond the factory gate and deal with the environmental impact of the life cycle of products (e.g. vegetables: Moreno et al., 2018), meals, restaurants (Calderón et al., 2018), meals (Stylianou et al., 2017) and even dietary changes (Hallström et al., 2015).

The life cycle thinking is believed to be a key concept for supporting sustainability transition (Sala et al., 2017).

Some literature mention that LCA can play a role in decision-making contexts (Moro Piekarski et al., 2013), particularly as a prospective tool for product and process design during development (Tillman, 2000), such as in eco-design. LCA can help identify key actions for reducing the product's impact during the design of innovative products or redesign of existing products (i.e. eco-design and eco-innovation: Cluzel et al., 2014), in order to answer sustainability challenges (Yannou-Le Bris and Ferrandi, 2016). Eco-design, as defined by the International Organization for Standardization standard number 14006:2011, is the "integration of environmental aspects into product design and development, with the aim of reducing adverse environmental impacts throughout a product's life cycle". Eco-design approaches were applied in manufacturing firms from the 1970s (Notarnicola et al., 2015). By contrast, eco-design methods and tools in agri-food industry were used more recently because of the challenges to apply LCA in this context (Notarnicola et al., 2017).

The literature presenting application of eco-design in agri-food industry is scarce and heterogenous. Some studies focus in particular on the simplification of the assessment tools for the evaluation of agricultural sectors (Renouf et al., 2018). Some studies show that modularizing LCA is particularly efficient to reduce the complexity of assessing food product systems (Brondi and Carpanzano, 2011), product design alternatives (Gabrisch et al., 2019), and identify hotspots in relation to consumers' point of view (Jungbluth et al., 2000). However, practitioners still face challenges in making LCA suitable for assessing complex food systems. Three factors can influence the integration of LCA in design processes. First, the frequency of creation of new products in the food industry is very high. Second, the LCA method must be improved to better adapt to the complexity of food systems (Sala et al., 2017). Data are extremely variable (Roy et al., 2009), and there is a need to consider the entire food chain (Sonesson et al., 2010).. Third, as a consequence of the second factor, the incorporation of environmental resource management into pre-existing organizational models is perceived as time and energy intensive on the part of business managers and collaborators (Petala et al., 2010). Fourth, multiple functional units are possible (e.g. quantities are most used, otherwise

the nutrient units can also be used: McAuliffe et al., 2019) and every product, process (Roy et al., 2009) and packaging (Verghese et al., 2012) has its own particularities, leading to extensive inventories. Most agri-food companies are therefore not equipped with sufficient expertise and knowledge to deal with the diversity of eco-design tools available (Rousseaux et al., 2017), and guidelines are lacking for eco-design practices using assessment tools (Hospido et al., 2010).

While facing those challenges, it seems relevant that the research in LCA should consider the environment earlier in the innovation process of food industries, before the development stage where eco-design is usually used, i.e. during what is called the ideation stage (from the five-stages innovation process drawn upon the model of Cooper et al. (2004): ideation, conceptualization, development, validation, launch). During the ideation stage, commercial opportunities are identified, and brainstorming generates possible concepts that are referred to as pre-concepts. A pre-concept can simply be a type of a product that meets some consumer expectations that are identified, e.g. “a drink that provides health benefits”. At this early stage, also called “fuzzy front-end”, information flows are complex and diverse. They nonetheless determine the direction of future product development (Kim and Wilemon, 2002), in particular when the product is discontinuous (i.e. totally new) (Reid and Brentani, 2004). Pre-concepts are therefore highly imprecise. Their characteristics (e.g., ingredients, packaging) are deliberately poorly defined – fuzzy – to enable some flexibility in the choice of product characteristics upstream of its development (Takey and Carvalho, 2016). Using an environmental assessment tool at this fuzzy early stage of the innovation process was never done. The difficulty of carrying out LCA so early in the innovation process is precisely that LCA requires precise input data while the characteristics of the pre-concept are imprecise (specified in the Product Environmental Impact Guide: European Commission, 2012). This challenge adds to the challenges regarding the use of LCA in the agri-food context. Furthermore, the LCA assessments are built on the basis of existing data, which makes it difficult to use them for early design purposes (Skerlos, 2015). However, carrying LCA very early would help to anticipate the product attributes with regard to the expected environmental impacts, prior to the development stage. What the literature lacks, and which would be useful to agri-food companies, is an improved framework for conducting

LCA during the early stages of an innovation process. The present study intends to fill this gap.

The research question that the present paper addresses is the following: How can LCA be used to assess the environmental impacts of imprecise food pre-concepts during the early stage of an innovation process? The objective of this study was to develop a methodological framework for integrating modular LCA into the early ideation stage of an innovation process, so that food companies could consider environmental impacts of the imprecise pre-concepts before developing them. The present paper proposes a framework composed of three steps that was applied to a case study in which innovative spirulina-based foods were being developed by a French SME.

This article is structured as follows: firstly, the methodological framework and the case study are detailed in the materials and methods section. Then, the obtained results are presented according to each of the three steps of the methodology: 1) generate scenarios for imprecise pre-concepts, 2) analyze modules to identify hotspots and compare pre-concepts, 3) communicate the results to guide the company decision-making. Results are discussed as they occur. Finally, the conclusion expresses the main result and lessons learned from the case study, and draw the need for future research.

2. Materials and methods

2.1. Proposed methodological framework for assessing the environmental impacts of pre-concepts

2.1.1. General approach

Product creation begins with the ideation stage, in which the goal is to generate as many innovative pre-concepts as possible. Subsequently, the project team compares and ranks the pre-concepts based on a list of criteria. During the subsequent stage—conceptualization stage—the top pre-concepts are transformed into marketable concepts. The proposed method for assessing the environmental impacts of pre-concepts before the decision has three basic steps (Figure 1).

The first step is to establish modules focused on key sources of environmental impacts (see section 2.1.2) and then generate different possible scenarios within each module

for each pre-concept. The second step is to carry out LCAs to identify hotspots and inform decision-making. Using transversal analyses, the impacts of different scenarios and combinations of scenarios can be compared. By analyzing the contributions of the different scenarios to the environmental impacts of the pre-concepts, hotspots can be identified. The scenarios with the smallest environmental impacts can then be chosen for each pre-concept, which can then be compared to each other. The third step is to translate the results of these analyses into single scores for each pre-concept, which can then be communicated to the company. The goal is to help company stakeholders (1) understand the environmental impacts of the pre-concepts so that they can be prioritized accordingly during the decision-making process and (2) implement appropriate ecodesign approaches during product development.

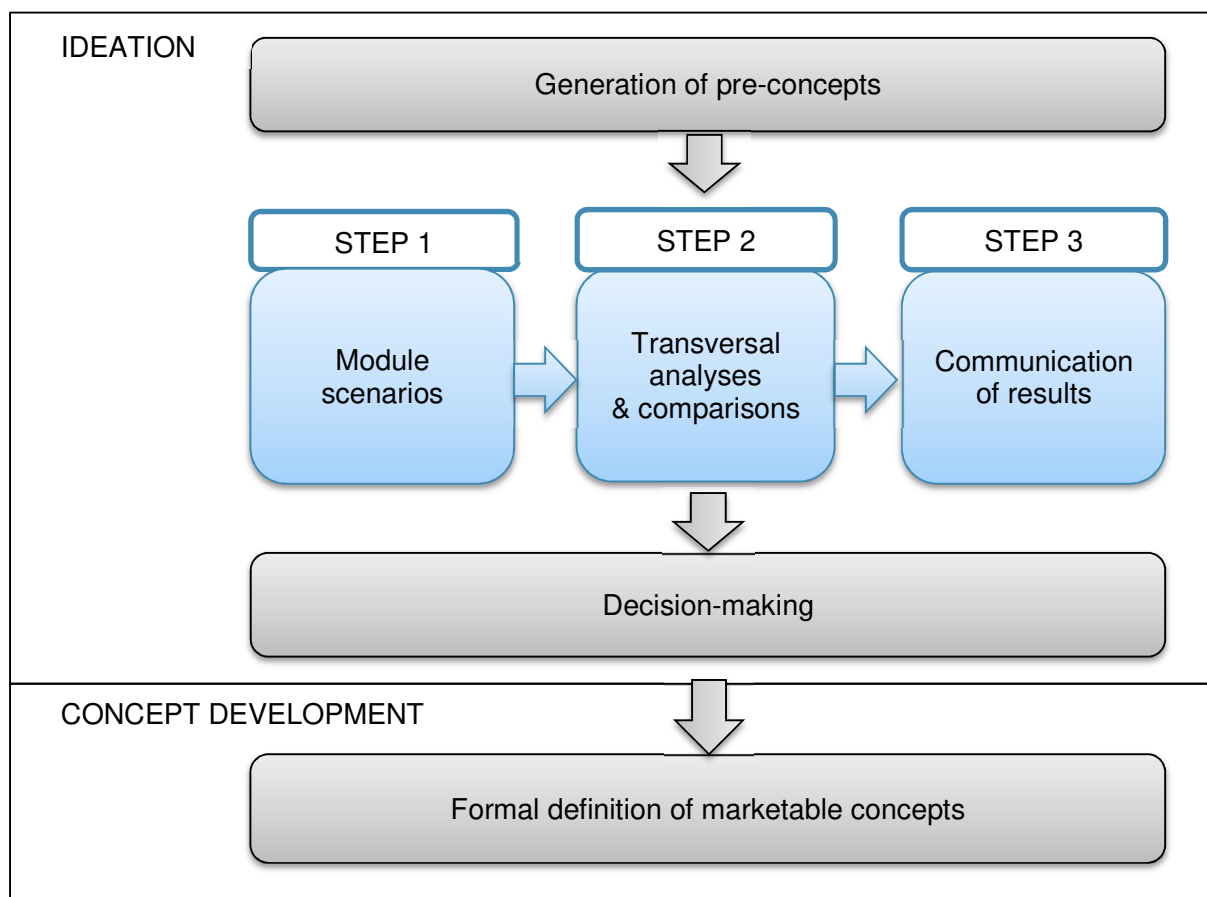


Figure 1: Three-step method for assessing the environmental impacts of agri-food pre-concepts during the ideation stage and disseminating the results to company stakeholders

2.1.2. Creation of modules and module scenarios for the different pre-concepts

To function reliably, LCA requires detailed inventory data. However, the characteristics of pre-concepts are, by nature, only vaguely defined. To deal with this situation, the proposed method utilizes a modular approach. More specifically, agri-food pre-concepts are broken down into different modular elements.

Jungbluth et al. (2000) and Roy et al. (2009) identified the factors that most greatly influenced the impacts of food products: agricultural production, the type of ingredients, food transformation, packaging, the means of transportation, consumption, and energy + water usage. These factors thus appeared to be best suited to the modular LCA of agri-food pre-concepts.

Since Jungbluth et al. (2000) performed modular analyses that focused on each of the factors identified, the research team decided to create modules according to the chosen factors: ingredients (that includes production), packaging, transportation, and energy/water.

Within each module, there are various possible scenarios. For example, in the "ingredients" module, different ingredients can be employed to create the food; in the "packaging" module, the food can be packaged in different materials and/or sizes; in the "transportation" module, means and distances of transportation can differ; and in the "energy + water" module, quantities and sources of each resource can differ (Figure 2).

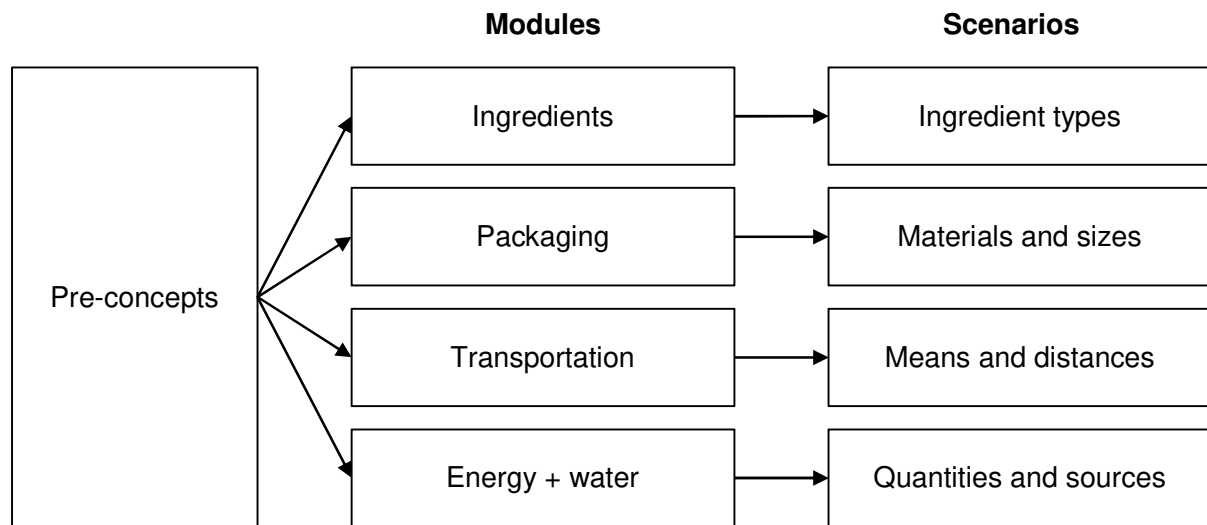


Figure 2: Defining the modules and module scenarios for the pre-concepts

2.2. The case study

The method framework was applied to a new product development (NPD) process being carried out by GlobeXplore (a French agri-food SME) with the help of a food company (MidCap), a technical institute, and a research team, who formed the project's steering committee. Communication took place directly with the company's director and its head of R&D, whose backgrounds were exclusively in agri-food; they had no previous familiarity with procedures for assessing environmental impacts. Results were always presented to the project's steering committee. The NPD process followed the five stages described by Cooper et al. (2004).

Spirulina is a microalga that has nutritional benefits (Habib et al., 2008) because of its high protein, vitamin, and mineral contents. The company wished to incorporate fresh (i.e., non-dehydrated) spirulina into perishable products sold in the cold aisle of supermarkets. The target market was consumers within France. The pre-concepts were products in which spirulina had been added to a plant-based food (fruits, vegetables, legumes, or oilseeds). Some pre-concepts were drinks, while others were products with more texture. They differed in many of their traits (e.g., appearance, texture, type of ingredients, and packaging). For reasons of confidentiality, the authors cannot provide a more detailed description of all the pre-concepts here. To illustrate the analyses, the authors focused on three of the pre-concepts: spirulina-based milk, jam, and apple

compote; each provided a daily serving of 12 g of fresh spirulina and its associated nutritional benefits.

In this NPD project, the company needed to rapidly select the top two to three pre-concepts from among the eight pre-concepts that had emerged during the ideation stage. The relative performance of the different pre-concepts had been assessed by the consortium based on information provided by stakeholders during meetings of the project's steering committee. Performance estimates related to market potential and technical and economic feasibility were assessed and presented by the company. The research team presented the LCA method and the results of the transversal/comparative analyses for the pre-concepts. An analysis of the exchanges among the consortium members during meetings helped us assess the potential of the modular LCA proposed here.

2.3. Application of life-cycle analysis to the case study

2.3.1. Objectives and functional units

In this study, the objective of the LCA was to assess the environmental impacts of eight imprecise pre-concepts with a view to informing company decision-making upstream of product development. To help identify key differences in the module scenarios (step 1 of the method), module-specific functional units were chosen. Ingredients were compared based on mass. Packaging was compared based on a fixed quantity of packaged product (e.g. 1L of spirulina-based milk, 200g of jam). Transportation means and distances were compared based on payload-distance (tkm/kg of packaged product). Energy was compared in kWh, and water was compared in m³. To assess the different pre-concepts (step 2 of the method), the functional unit was a serving containing 12 g of fresh spirulina, which meets 100% of the daily requirement for vitamin B12.

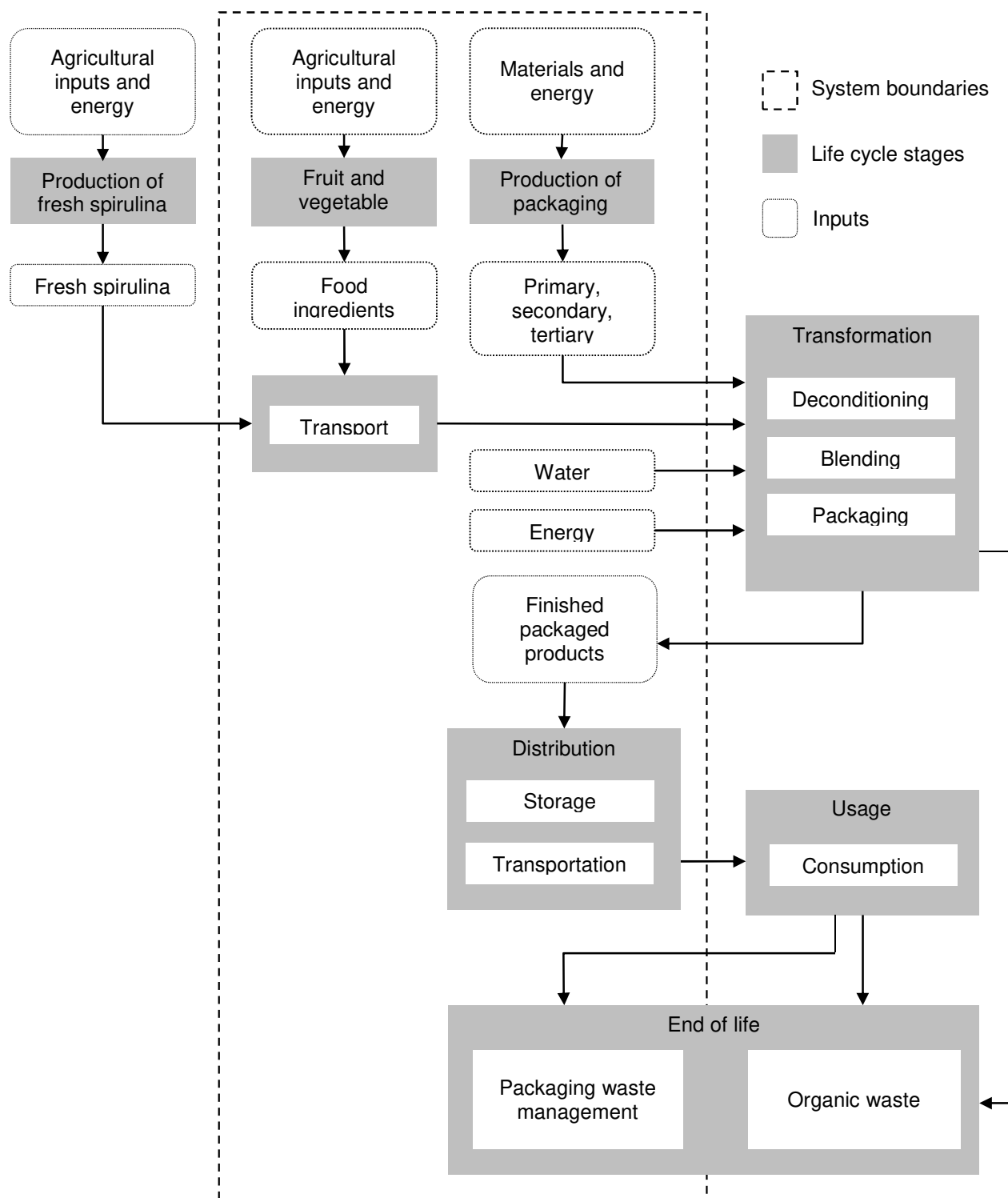
2.3.2. Study system

The study system incorporated almost the entire life cycle of the potential products resulting from the pre-concepts: from the production of the ingredients and the packaging materials to the treatment of the waste produced. The Figure 3 shows the study system, its boundaries, and the stages that fall outside the boundaries. This system included the agricultural production of the ingredients, the manufacturing of the

packaging materials, the energy and water used to create the finished products, the transportation of the products, and the treatment of the packaging waste. The different scenarios for recycling packaging waste in France were defined based on information published in the annual report by Eco-Emballages (data from 2016).

Certain stages were left out of the study system to simplify the assessment of the pre-concepts—the elements that differed among potential products or between the potential products and a standard of reference were solely included (Hospido et al., 2010).

- The production of spirulina was treated as a constant parameter. The pre-concepts contained the same daily serving of spirulina. Furthermore, the authors did not have access to any inventory data for fresh spirulina production.
- The processes for transforming the potential products were treated as constant parameters. First, the LCA databases currently contain little information on transformation processes, making it impossible to more explicitly incorporate them without heavy data collection work. Second, the same production line (already in place within the factory) would be used regardless of the product selected, so there would be no differences in the infrastructure associated with the different pre-concepts. Third, the mean consumption of electricity and water by the factory to generate each kg of potential product is already taken into account within the analysis and allowed us to estimate the resources used during product transformation.
- Product use by consumers, including purchasing, storage, cooking, was unknown. The imprecision and diversity of the pre-concepts resulted in a high degree of uncertainty with regards to consumer behavior (e.g., shelf life). In addition, during the end-of-life stage, only the packaging waste treatment was accounted for.
- It was difficult to estimate the waste produced by product transformation (rejection), transport (breakage) or storage (expired).



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236 *Figure 3: Stages and boundaries of the life-cycle analysis of the pre-concepts*

2.3.3. Inventory data and the characterization of environmental impacts

To run the LCAs, SimaPro® software (v. 8.5) was used. The European ReCiPe methodology was employed with the Hierarchist model (v. 1.13) (Goedkoop et al., 2013) in tandem with the Agribalyse® database (v. 1.3) and the EcolInvent3 database (v. 3.3). The environmental impacts of the pre-concepts were expressed using the midpoint results and the single scores. The 18 categories of midpoint results obtained using the ReCiPe method are listed in Table 1.

Table 1: Categories of impacts associated with the midpoint results obtained with the ReCiPe method (Hierarchist model; v. 1.13)

Impact categories	Units
Climate change	kg CO ₂ -eq
Ozone depletion	kg CFC-11-eq
Terrestrial acidification	kg SO ₂ -eq
Freshwater eutrophication	kg P-eq
Marine eutrophication	kg N-eq
Human toxicity	kg 1,4-DB-eq
Photochemical oxidant formation	kg NMVOC
Particulate matter formation	kg PM10-eq
Terrestrial ecotoxicity	kg 1,4-DB-eq
Freshwater ecotoxicity	kg 1,4-DB-eq
Marine ecotoxicity	kg 1,4-DB-eq
Ionizing radiation	kBq U235-eq
Agricultural land occupation	m ² a
Urban land occupation	m ² a
Natural land transformation	m ²
Water depletion	m ³
Metal depletion	kg Fe-eq
Fossil fuel depletion	kg oil-eq

3. Results and discussion

3.1. Scenarios for the pre-concepts

To deal with the uncertainty associated with the imprecise pre-concepts, the first methodological step was to generate different simple scenarios for the possible products. These scenarios were created within each of the four modules "ingredients", "packaging", "transportation," and "energy + water," which represented the main sources of environmental impacts over a food product's life cycle.

Ingredients module: There were several different ingredient options for each pre-concept (Table 2). For example, the jam was composed of sugar and a type of fruit, and the milk could use soy, oat, almond, or cow milk. An inventory of the ingredients that could be employed to make each pre-concept was thus created.

Table 2: Different ingredient scenarios for the three example pre-concepts (spirulina-based milk, jam, and apple compote)

Pre-concepts	Milk	Jam	Apple compote
Ingredients	Soy milk	Kiwi	Additional sugar
	Oat milk	Pear	No additional sugar
	Almond milk	-	-
	Cow milk	-	-
Number of options	4	2	2

Packaging module: There were several packaging scenarios for each pre-concept based on commercially available packaging. For example, for the spirulina-based milk, the types of possible packaging were glass bottles, plastic bottles made of high-density polyethylene (HDPE), or plastic bottles made of polyethylene terephthalate (PET). The bottles could also come in different sizes, from 250 mL to 1 L. An example inventory of all the different packaging scenarios for the three illustrative pre-concepts is presented in Table 3.

Table 3: Different packaging scenarios shown for three example pre-concepts (spirulina-based milk, jam, and apple compote); Alu. = aluminum; PP = polypropylene (plastic)

Type	Jars						Bottles						Lids			
Material	Glass			Plastic - PET			Glass			Plastic - HDPE			Tinplate screw top	Alu. seal	Paper seal	PP screw top
Size	400 g	90 g	20 g	125 g	500 g	1 kg	250 mL	500 mL	1 L	250 mL	500 mL	1 L				
Milk							x	x	x	x	x	x		x		x
Jam	x												x			
Apple compote	x	x		x									x		x	

Transportation module: The transportation scenarios took into account the transportation of the spirulina from its production site to the factory where the products would be manufactured and the transportation of the final products to four purchasing centers in different parts of France. The loads in the trucks filled with the potential products were calculated based on packaging type and truck carrying capacity. The trucks were assumed to be empty upon the return trip. The company chose to use the same means of transportation for all the pre-concepts: a 28-tonne truck pulling a

refrigerated semi-trailer (kept at 4°C). The mean estimated roundtrip payload-distance was 4.7 tkm/kg of packaged product. It was the same for all the pre-concepts because they would all use the same distribution chain.

Energy + water module: Energy and water consumption were estimated by taking the factory's annual energy and water consumption in 2016 and dividing it by the mean total mass of products manufactured over the year. This calculation yielded a mean energy usage of 0.4 kWh of electricity and 0.007 m³ of water for each kg of product manufactured.

By using a modular LCA to assess pre-concepts, it is possible to deal with a certain amount of uncertainty in the data, which could otherwise lead to a faulty interpretation of the results and unreliable recommendations for the company. The ingredients found in lesser quantities in food products can generally be ignored unless they have previously been identified as hotspots for environmental impacts (e.g., animal proteins, non-seasonal produce). If LCA databases lack information on ingredients present in larger quantities, similar ingredients can be used as substitutes in the analyses. Simple tools, like checklists about key trends in ingredients, could be developed for R&D teams. Developing decision-making guidelines based on the literature would also benefit the companies.

This state of affairs underscores that LCA databases for food ingredients and transformation processes remain incomplete. Even if they are expanding, the databases do not include data for all the ingredients of potential interest to the agri-food industry. For example, no information is available for additives such as xanthan gum, which is used to thicken the matrices of plant-based foods. As a result, analyses may be skewed and thus biased for or against a given pre-concept when it is compared to others whose life-cycle data are more complete and/or accurate.

3.2. Transversal analyses, module contribution, and pre-concept comparisons

The transversal analyses (contribution of modalities, comparison of modalities, contributions of modules to the impacts of pre-concepts) generated diverse knowledge about the environmental impacts of the pre-concepts. These results are presented below.

3.2.1. Module scenarios with the smallest impacts

Ingredients module

For the ingredients' module, the environmental impacts of using different ingredients to make the pre-concepts were compared and contrasted.

For example, for the spirulina-based milk (Figure 4), it was clear that using an ingredient of animal origin (cow milk) led to greater environmental impacts than using ingredients that were plant based, except in the case of almond milk, which had greater impacts in the categories water depletion and human toxicity (because most of the almonds on the market come from California and are irrigated). Previous research has shown that the consumption of animal products has a greater environmental impact than the consumption of plant products, such that a vegetarian diet reduces carbon emissions by 20–39% (Hallström et al., 2015; Pernollet et al., 2017). The use of oat milk and soy milk led to the smallest impacts, except in the case of marine eutrophication (because oat crops need to be fertilized).

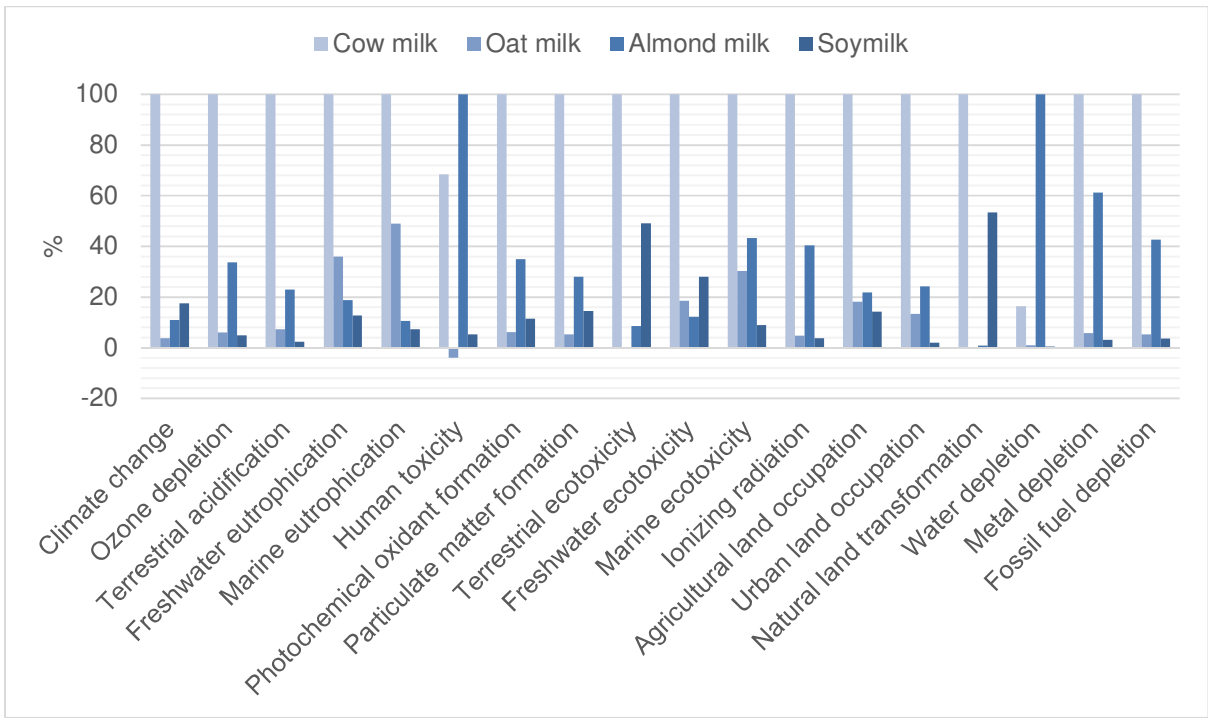


Figure 4: Comparison of the four ingredient scenarios for 1 kg of the spirulina-based milk pre-concept: (from left to right) cow milk, oat milk, almond milk, and soy milk (the midpoint results for the impact categories)

There were large differences in the impacts associated with different produce types. For example, for the spirulina-based jam, the use of kiwi resulted in smaller environmental impacts than the use of pear, except in the categories climate change and fossil fuel depletion, for which the results were similar (Figure A.1). It could be that pear trees are more vulnerable to pest and diseases and are thus treated more frequently with pesticides. In contrast, other scenarios did not make much of a difference. For the spirulina-based apple compote, there was little difference in the environmental impacts associated with the two sugar scenarios (no additional sugar versus additional sugar equivalent to 8% of cooked mass) (Figure A.2). Sugar addition thus appears to have no influence on the environmental performance of the product.

To dissect the origin of these impacts, it was necessary to assess the contributions associated with the different ingredients. Frequently, companies lack the expertise to perform these types of analyses. Databases often only provide inventories and no information regarding the interpretation of impacts. As a consequence, it is advisable to provide interpreted results associated with databases in supplementary report to make it easier for the user to understand the variation in the impacts of the product being analyzed.

Packaging module

For the packaging module, the environmental impacts of using different packaging sizes and materials were compared and contrasted. First, glass bottles of different sizes (1 L, 500 mL, and 250 mL) were compared, all with tinplate screw top lids; the basis for comparison was the packaging needed to hold 1 L of liquid. The results revealed that there was an effect of packaging size: one 1-L bottle had less of an environmental impact than two 500-mL bottles or four 250-mL bottles (Figure 5). Similar results were obtained for the PET bottles (Figure A.3) and the HDPE bottles (Figure A.4), both with polypropylene (PP) pop top lids. Second, bottles of the same size made with different materials (HDPE, PET, and glass) were compared. The results showed that an HDPE bottle had 0–15% of the environmental impact of a glass bottle (Figure A.5) because of its lighter mass and less energy costly waste treatment. The PET bottle had an environmental impact in between those of the HDPE bottle and the glass bottle.

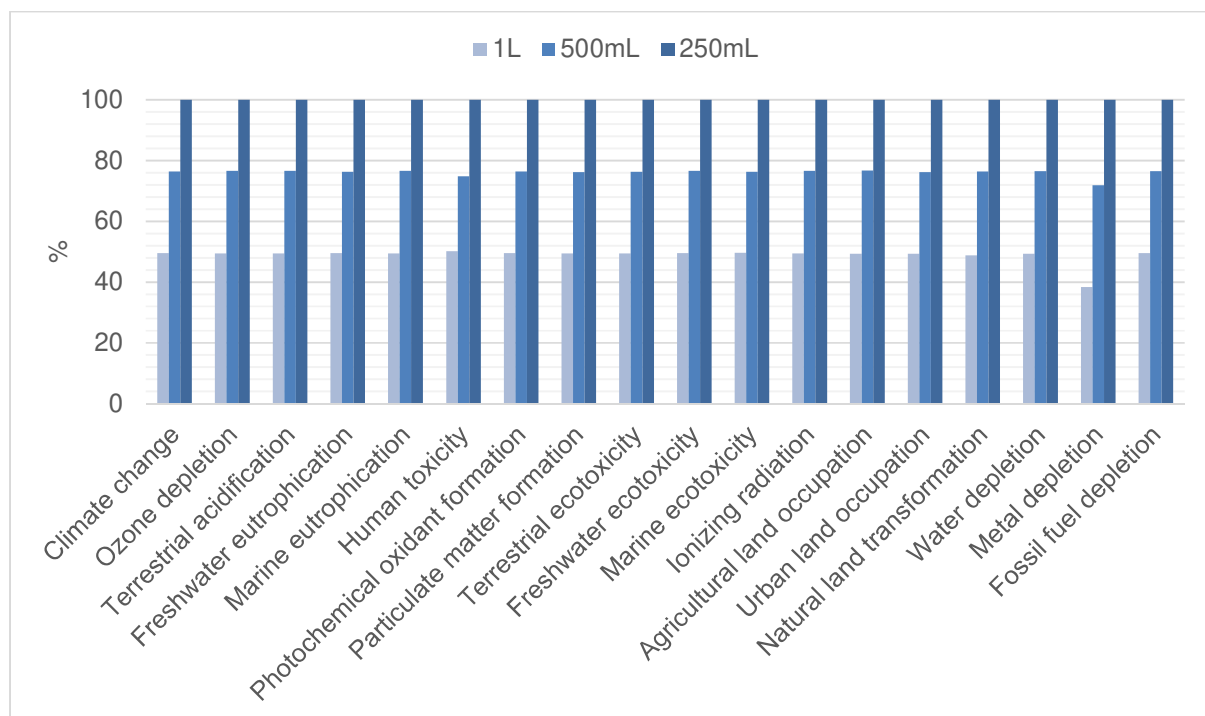


Figure 5: Comparison of the three sizes of glass bottles, 1 L, 500 mL, and 250 mL, based on the packaging needed to hold 1 L of liquid (Hierarchist model; midpoint results)

It is generally straightforward to assess packaging options using LCA in a way that is customized to company circumstances because LCA databases contain ample information about the direct impacts of packaging (Molina-Besch et al., 2019), and literature exists on how to optimize the packaging design (Park et al., 2014). In contrast to the guidelines used by (Verghese et al., 2012), the LCA of packaging allows different packaging scenarios to be compared and to assess the environmental impacts associated with the quantity of packaged product. Discussions about packaging size raise questions about food waste. Here, the results revealed that larger packaging had less of an environmental impact than did smaller packaging. However, this finding does not take into account indirect effects involving consumer behavior. For example, packages that contain a quantity of food that exceeds consumer needs may result in the food product going bad and being thrown away, which increases food waste (Molina-Besch et al., 2019). When designing food products, it is important to keep in mind that reducing impacts by increasing packaging size can increase impacts at the product's end of life.

As the market shifts towards new packaging solutions, there will be contrasting consequences for LCAs. On the one hand, because single-material packaging is coming back into favor and is more easily recycled, LCAs will be simplified. On the other hand, because of the arrival of new types of materials that are absent from the databases, LCAs will become more complex.

Transportation and energy + water modules

The product transformation process was treated as a constant parameter. It was characterized using the estimated amount of energy and water used to produce a kg of product, based on the factory's figures for the previous year. While these mean values convey the likely magnitude of energy and water consumption, they are not necessarily reflective of the real usage associated with future products because those figures will depend on production volumes and actual resource consumption by the equipment used. It is crucial to characterize the impacts of the food transformation process in greater detail, especially when the pre-concepts would lead to products that would not necessarily use the same individual operations. The company could install electricity and water meters on each piece of industrial equipment to measure the resource consumption associated with each individual operation. It would therefore be possible to characterize the transformation process for each new food product and thus limit the factory's environmental impacts by reducing unnecessary resource use. In France, projects like Agribalyse® v.3 is working to expand LCA databases by adding more information on transformation processes in various industries, including the beef and dairy industries.

3.2.2. Module contributions to pre-concept environmental impacts

The modules that contributed the most to the pre-concepts' environmental impacts by comparing the modules' results for a given combination of scenarios were identified. More specifically, to represent each module, the scenarios with the smallest environmental impacts were chosen, as estimated in the transversal analyses.

It was found that the ingredients module, followed by the transportation module, contributed the most to the environmental impacts of the eight pre-concepts in this case study. In the example of the spirulina-based kiwi jam pre-concept (Figure 6), the

ingredients module is the main source of environmental impacts (accounting for 15–95% of impacts depending on the category). The transportation module was second greatest source of environmental impacts; it was followed by the packaging module (which examined primary, secondary, and tertiary packaging) and the energy + water module. The results varied depending on the pre-concept.

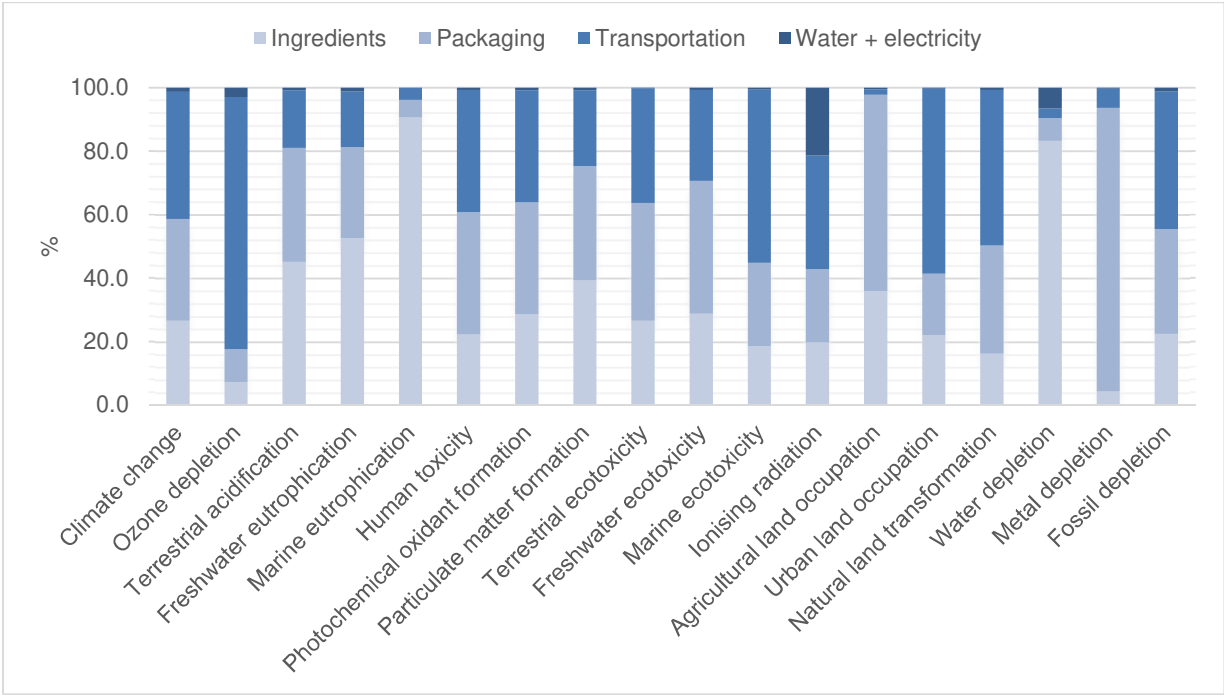


Figure 6: Environmental impacts of a functional unit of the spirulina-based kiwi jam pre-concept: contributions made by the ingredients, packaging, transportation, and energy + water modules (ReCiPe method, Hierarchist model, midpoint results)

The ingredients module contributed to major differences in environmental impacts because agricultural commodities differ significantly in their impacts. Past research has indicated that agricultural production plays a greater role than packaging and transportation in defining the environmental impacts of food products (Pernollet et al., 2017). The contribution of transportation is determined by product quantity and packaging mass.

Given that pre-concepts are generally imprecise, ingredient choice can have a large influence on and modify a potential product's impacts. The end results will be very sensitive to the choice of ingredients, which can have a negative effect when the company makes decisions without finalizing the product recipe. However, removing the

ingredients module because of its degree of uncertainty may result in the severe underestimation of the pre-concepts' environmental impacts. These results highlight that despite the great uncertainty it carries out, the ingredient module is of major importance for the environmental assessment.

3.3. Communicating the results of the pre-concept comparisons

The pre-concepts were subsequently compared to each other using single scores (Figure 7). This comparison showed that certain pre-concepts had greater environmental impacts than did others. Pre-concepts 4 and 7 had the greatest impacts and were both liquid products. The transversal analyses showed that their impacts were due to their ingredients and transportation (their size and mass were greater). Pre-concepts 2, 5, and 6 had the smallest impacts. In particular, pre-concept 6 was composed of almost pure spirulina, for which there was no inventory (i.e., spirulina production was outside the boundaries of the study system). Consequently, the environmental impacts for pre-concept 6 arose exclusively from the packaging, transportation, and energy + water modules. This result highlights the limit of the functional unit used which favors pre-concepts involving no or few additional ingredients. With another functional unit such as calories or added value, the result could have been very different.

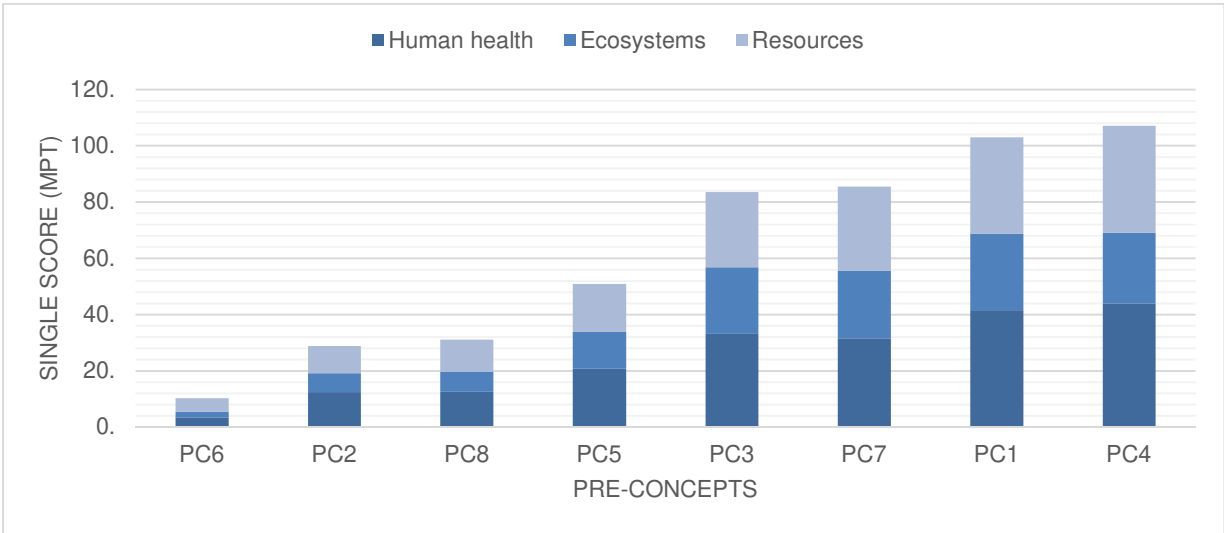


Figure 7: Comparison of the environmental impacts of the NPD project's eight pre-concepts using single scores (millipoints [mpt]) resulting from the categories human health, ecosystems, and natural resources (Hierarchist model; endpoint results). Functional

Pre-concepts are inherently uncertain and could give rise to a range of possible products. As a result, it is difficult to reliably estimate the environmental impacts of a given future product. Here, a single representative scenario per pre-concept was chosen to facilitate the comparisons. The goal was to help the company identify which pre-concepts could have the smallest environmental impacts upstream of product development. Then, as products are being developed, it is necessary to adapt inventories along with the definition of product characteristics.

The LCA results for this case study were shared with the company during a meeting of the project's steering committee. It was expressed that the graph with the single scores for the eight pre-concepts was the best visual representation of the results and would allow rapid decisions to be made about the pre-concepts to prioritize. The company's director explicitly noted "This form of conveying the data is the easiest to understand.", which is in line with the need for endpoint and scores mentioned by the literature for an effective decision-making support (Kägi et al., 2016).

The single scores also raised questions, and it was necessary to discuss the transversal (midpoint) results in detail to clarify the key sources of environmental impacts so that they could be addressed. This process was more complicated than simply discussing the single scores. Consequently, the results of the transversal analyses — notably the contributions of the module scenarios to the environmental impacts of the pre-concepts — were presented during the same steering committee meeting. The company was surprised by some of the findings because they seemed counterintuitive, notably that impacts were greater for glass versus plastic packaging, and that locally sourced ingredient such as apple and cucumber have more impacts than imported foods like banana. The literature shows that transportation contribute significantly to the carbon footprint of products (Striebig et al., 2019), but other assessments suggest that some local situations may be worse than non-local because of different modes of transport, storage and consumption (Edwards-Jones, 2010). Consequently, the LCA results caused the company to question some of its previously held assumptions. For example, a common assumption is that organic products are better for the environment. However, past research using LCA has shown that there are only small differences in the environmental impacts of organically versus conventionally produced foods: organic

foods have lower impacts on a per area basis but not on a per product unit basis (Tuomisto et al., 2012). The effects of consumption of chemical pesticides included into conventional foods are not included into LCA.

At present, the tools (i.e., LCA and the LCA databases) are not sufficiently developed to deal with eco-design challenges in the food sector. In particular, criteria that differentiate products need to be accounted for in inventories (for example, organic versus conventional production, local versus non-local sourcing, or seasonal versus non-seasonal production) because the absence of this information can bias the results. Additional indicators are also lacking to assess the overall impacts of products (e.g. soil carbon changes in milk production: Knudsen et al., 2019), biodiversity in particular, which remains complex to assess (Winter et al., 2017). For example, although single-use glass containers have a greater environmental impact than single-use plastic containers, plastics release compounds during use may pose health risks (Yang et al., 2019).

Finally, as illustrated in this case study, modular LCA can be used as an information provider tool for agri-food industries. Even though results were found useful for the decision of the company to prioritize concepts for the following stages of innovation process (conceptualization, development), the company found that the LCA method remains too complex and time-consuming to be used in business-as-usual. The multiple steps, the need for precise inventories, and the required expertise to analyze the results were the major issues mentioned by the stakeholders, in accordance to Sala et al. (2017).

4. Perspectives

There are several ways in which the modular LCA method presented here could be improved. First, one should include the use stage of the life cycle, since the use of the products by the consumers at home may have a strong impact and alter the decision made on the product characteristics (Notarnicola et al., 2017). Second, further work should incorporate a sensitivity analysis for the pre-concepts that expresses the results of pre-concept comparison and the variability associated with the different possible module scenarios. For example, Cluzel et al. (2014) suggested providing baseline

scenarios, best-case scenarios, and worst-case scenarios. Third, the study system's complexity, the degree of uncertainty of pre-concepts, and the lack of data in databases does not make it easy to generate precise scenarios for the ingredients' module.

5. Conclusion

The early stage of the innovation process is critical to the determination of the characteristics of a future food product, and the environmental criterion should be included to the company's decisions. The main scientific contribution of this document is the proposition of a modular LCA methodology to assess the environmental impacts of imprecise food pre-concepts in the early stage of the innovation process. More precisely, the framework proposed in this manuscript answers the difficulty of life cycle inventory and analysis with three steps: creation of modules to simplify the inventories, transversal analyses (contributions and comparisons) to identify hotspots to be addressed through eco-design, and communication with single scores to the decision makers.

In the studied case of spirulina-based food products, the four modules created were ingredients, packaging, transportation, water & energy consumption. The transversal analyses showed that the ingredients module contributed the most to the environmental impacts of the pre-concepts, and was the most variable and uncertain. The comparison of pre-concepts with single scores was relevant to the non-expert stakeholders in assisting their decisions. However, some expertise was required to inform them about the origin of impacts and their variations. Finally, the modular LCA contributed to change mindset by revealing to the company the inaccuracy of their assumptions about environmental impacts.

Further research is needed to add open agri-food data into LCA databases in order to facilitate rapid inventories for agri-food companies that wish to implement design for environment in their innovation process.

Acknowledgements

The present study was part of the “Spilife” project, funded by the Région Bretagne (France) and initiated by the company GlobeXplore. The present study was carried out with the facilities of the Senso’Veg platform.

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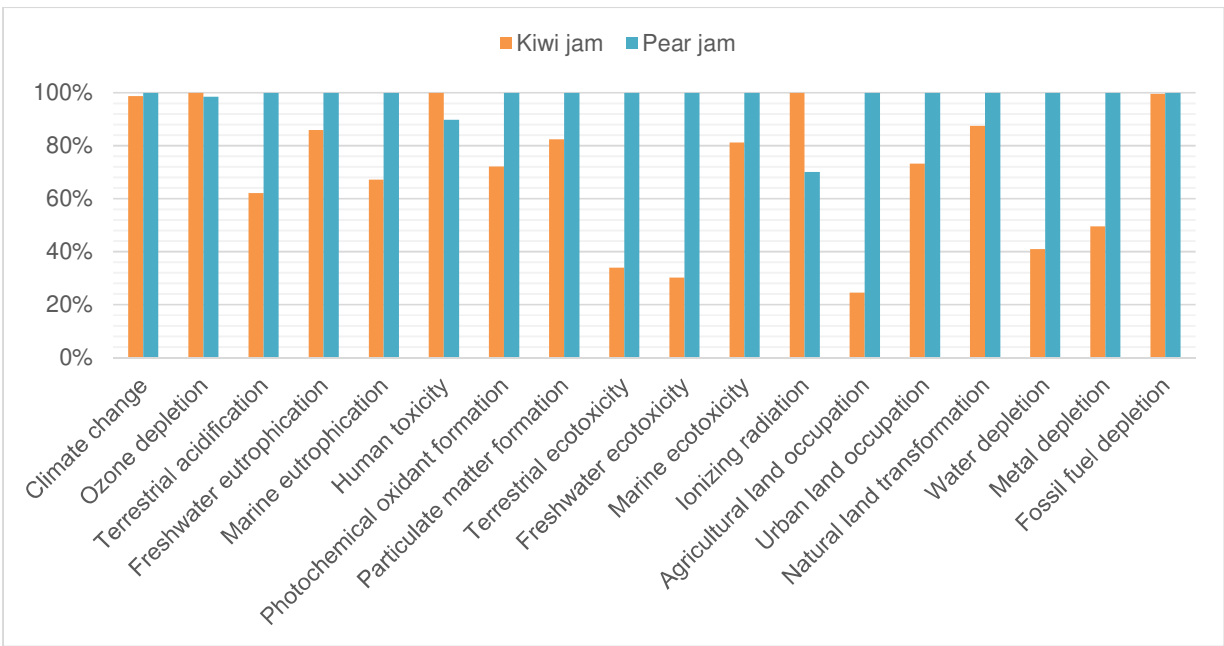
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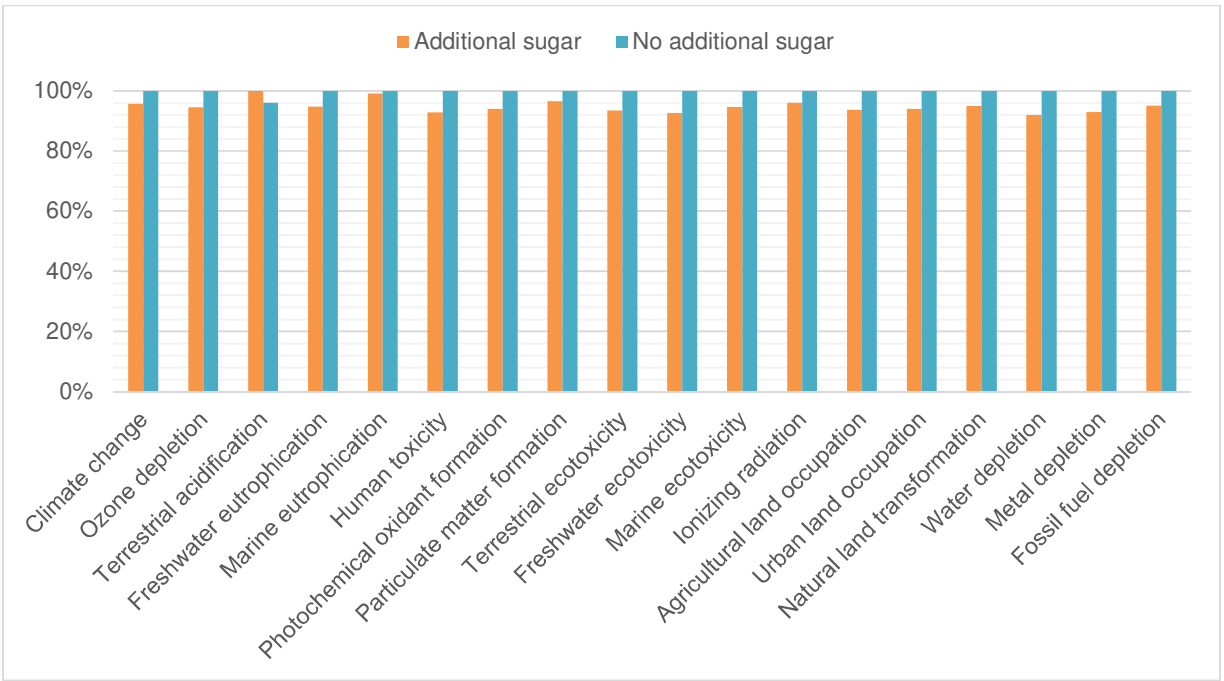
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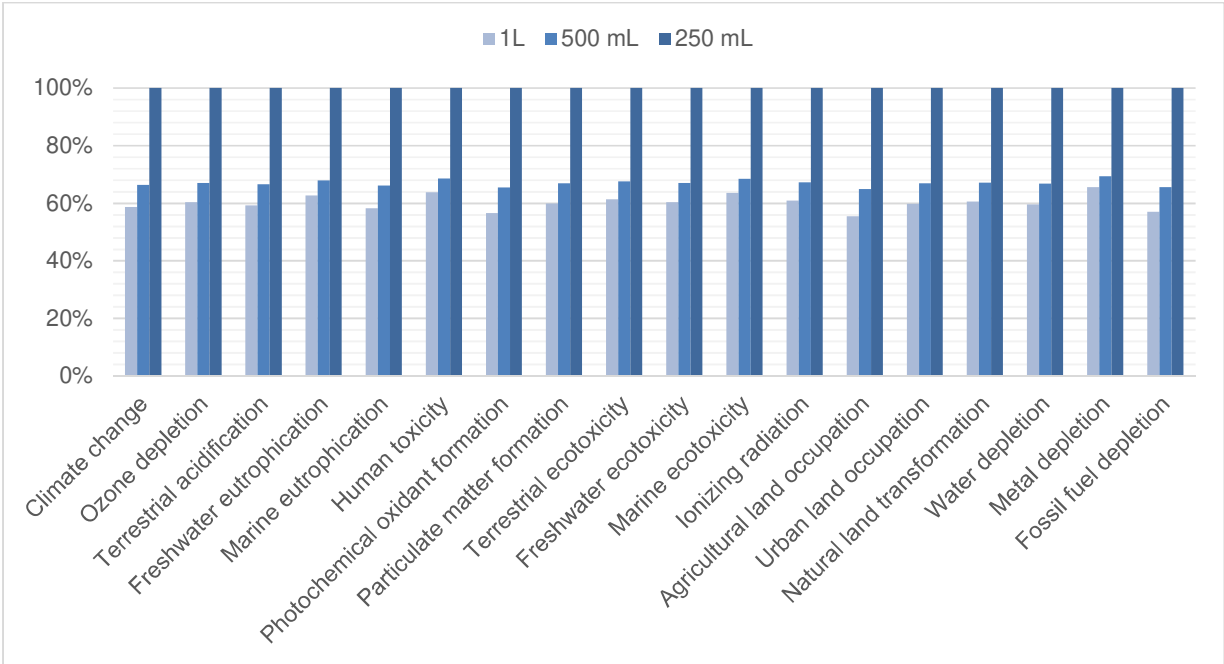
744 **Appendices**



745
746 *Figure A.1: Comparison of two ingredient scenarios for 1 kg of the spirulina-based jam pre-concept (based*
747 *on the midpoint results for the impact categories): kiwi jam (in blue) and pear jam (in green)*

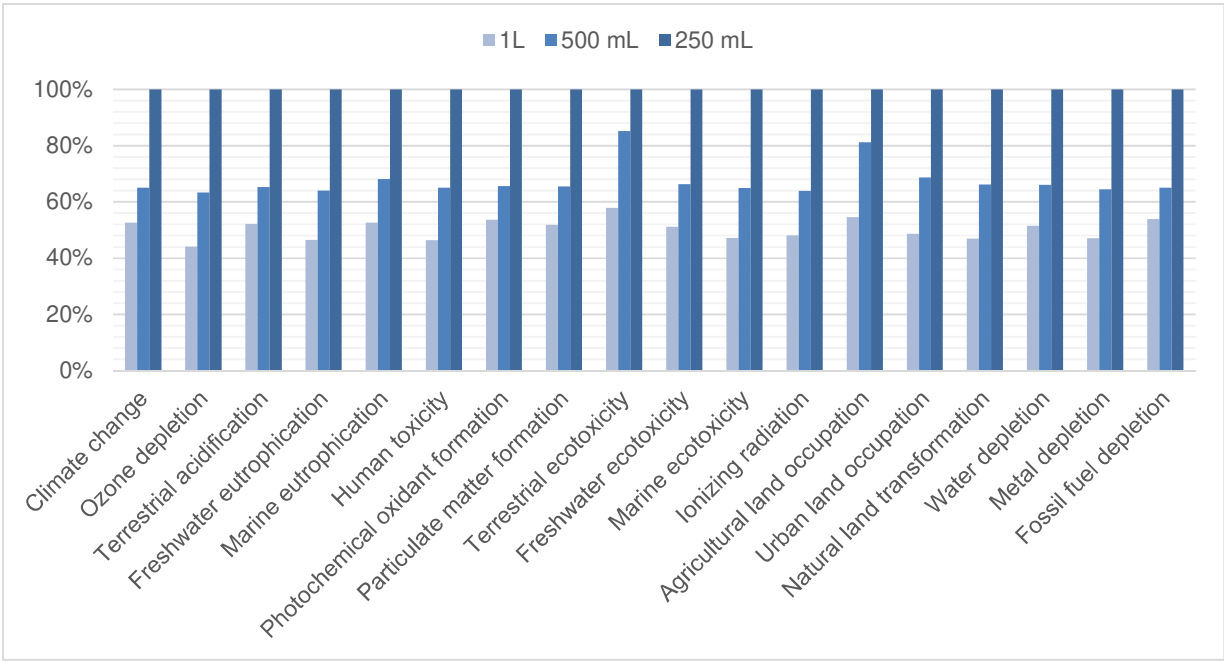


748
749 *Figure A.2: Comparison of two ingredient scenarios for 1 kg of the spirulina-based apple compote pre-*
750 *concept (based on the midpoint results for the impact categories): apple compote with additional sugar*
751 *(8% of cooked mass; in blue) and apple compote without additional sugar*



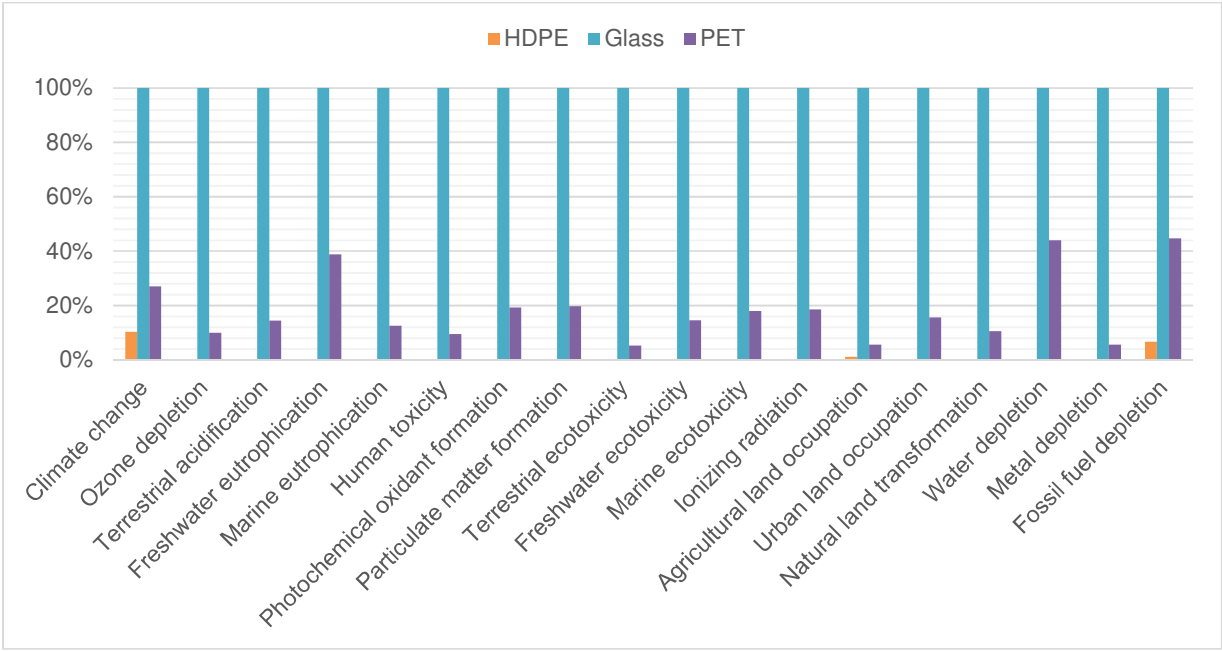
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753 *Figure A.3: Comparison of the three sizes of plastic bottles made from PET: 1 L (in dark blue), 500 mL (in*
 754 *green), and 250 mL (in light blue) (Hierarchist model; midpoint results); the basis for comparison was the*
 755 *packaging needed to hold 1 L of liquid*



756

757 *Figure A.4: Comparison of the three sizes of plastic bottles made from HDPE: 1 L (in dark blue), 500 mL*
 758 *(in green), and 250 mL (in light blue) (Hierarchist model; midpoint results); the basis for comparison was*
 759 *the packaging needed to hold 1 L of liquid*



760

761 *Figure A.5: Comparison of the three materials used to make 1-L bottles: plastic – HDPE (in dark blue),*

762 *plastic – PET (in green), and glass (in light blue) (Hierarchist model; midpoint results)*