



HAL
open science

Implementing LCA early in food innovation processes: Study on spirulina-based food products

Chloé Thomas, Cécile Gremy-Gros, Aurélie Perrin, Ronan Symoneaux, Isabelle Maître

► To cite this version:

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-02615773v1>

Submitted on 22 Aug 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY-NC 4.0 - Attribution - Non-commercial use - International License

1 **Implementing LCA early in food innovation processes: study on spirulina-based**
2 **food products**

3

4 Chloé Thomas^{a*}, Cécile Grémy-Gros^{ab}, Aurélie Perrin^a, Ronan Symoneaux^a, Isabelle
5 Maître^a

6 ^aUSC 1422 GRAPPE, Ecole Supérieure d'Agricultures (ESA), SFR 4207 QUASAV,
7 INRAE, 55 rue Rabelais, 49007 Angers, France

8 ^bLARIS, EA 7315, University of Angers, SFR MathSTIC, Polytech Angers, 62 Avenue
9 Notre Dame du Lac, 49000 Angers, France

10 *c.thomas@groupe-esa.com

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).

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

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

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

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

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

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

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

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

110 **2. Materials and methods**

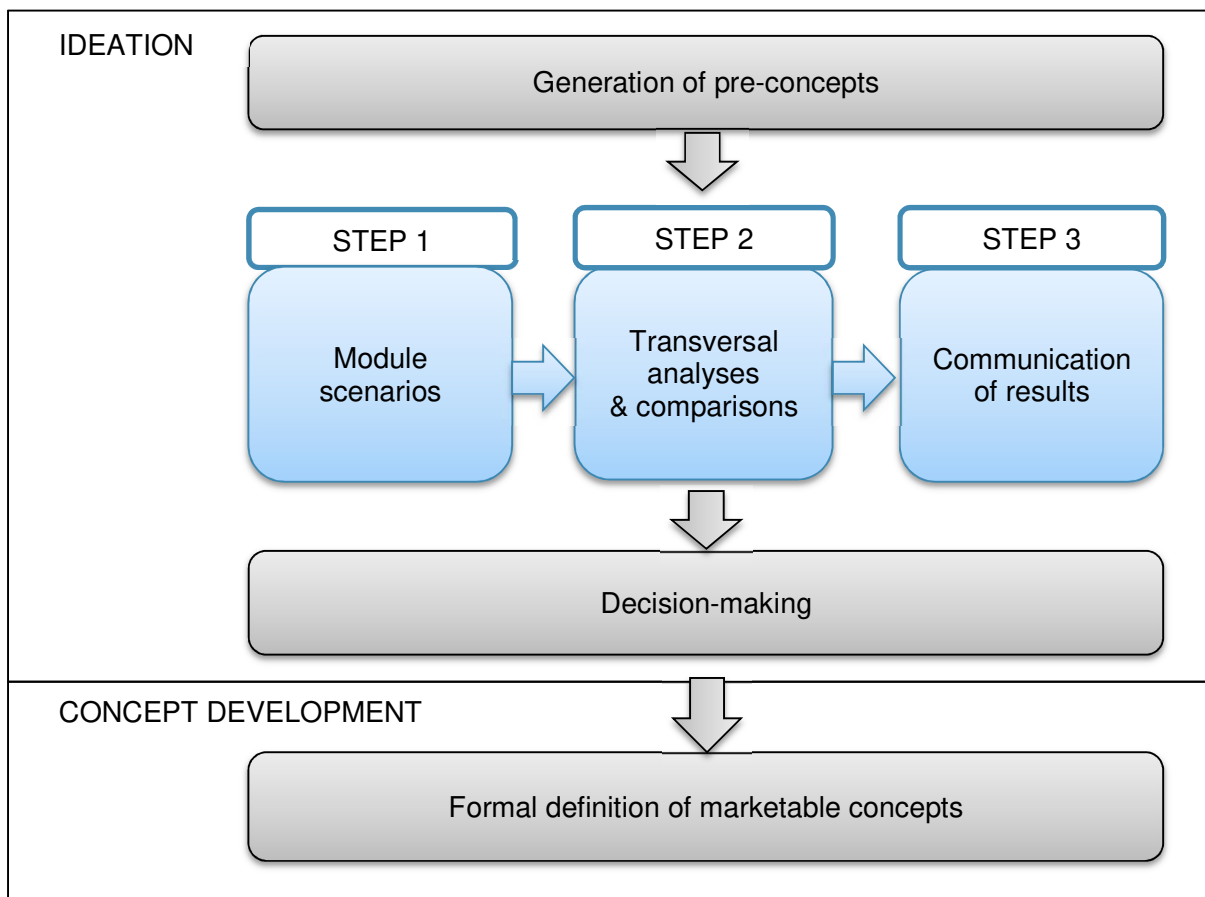
111 **2.1. Proposed methodological framework for assessing the environmental** 112 **impacts of pre-concepts**

113 **2.1.1. General approach**

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

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

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



133
134 *Figure 1: Three-step method for assessing the environmental impacts of agri-food pre-concepts during the*
135 *ideation stage and disseminating the results to company stakeholders*

136

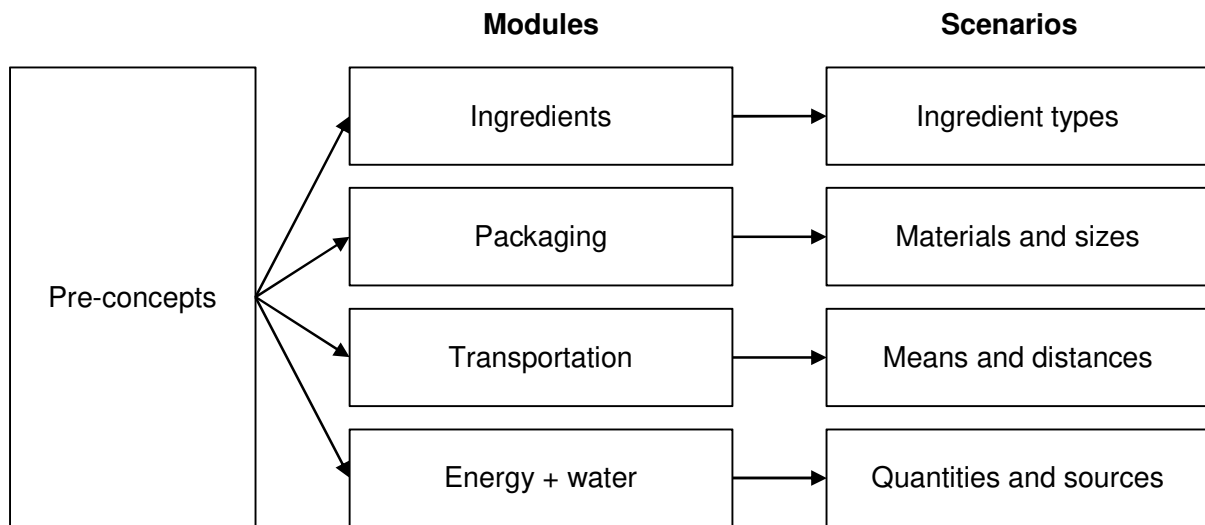
2.1.2. Creation of modules and module scenarios for the different pre-concepts

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).



157

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

159 **2.2. The case study**

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

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

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

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

190 **2.3. Application of life-cycle analysis to the case study**

191 **2.3.1. Objectives and functional units**

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

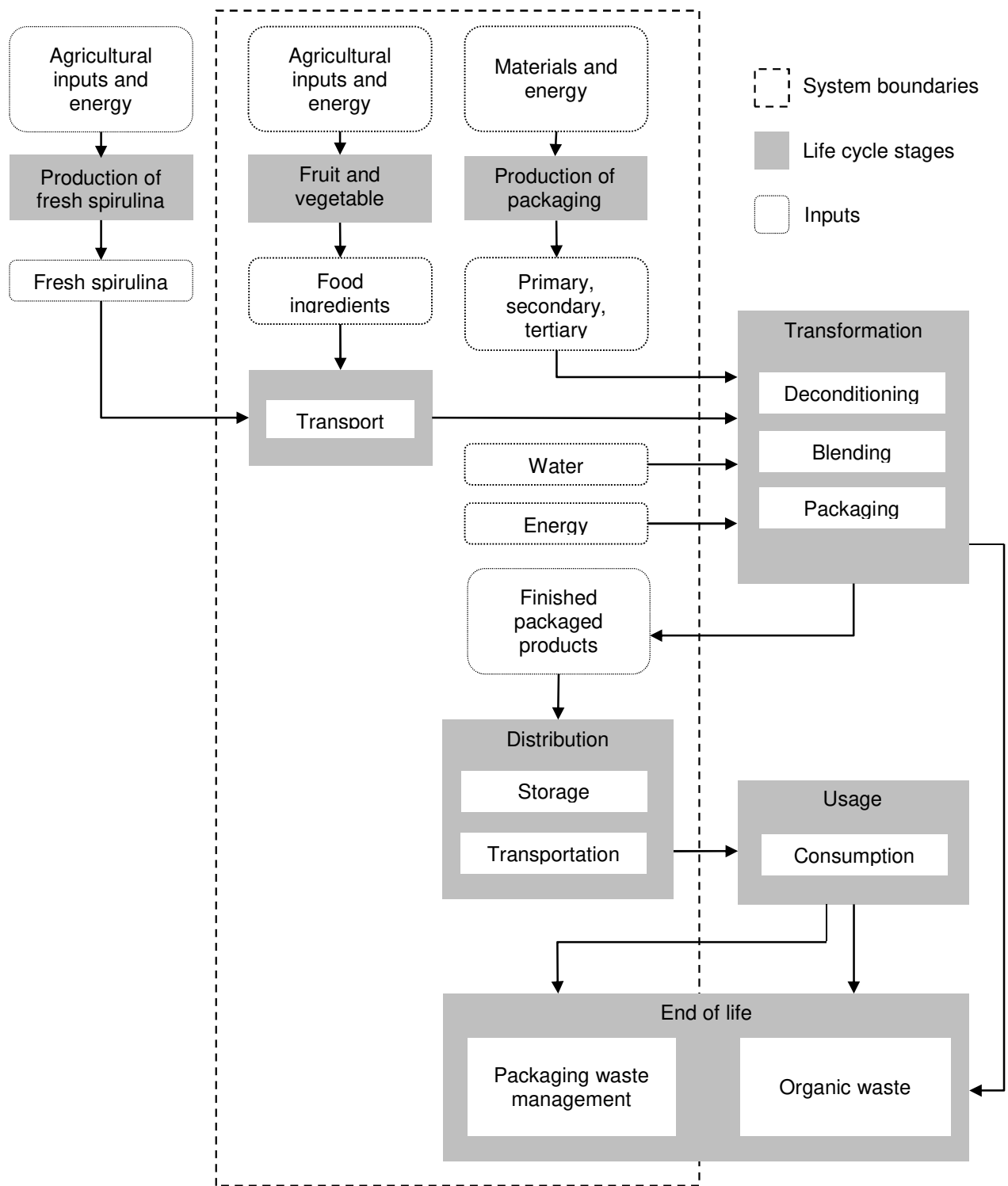
202 **2.3.2. Study system**

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

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

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

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



235

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

237 **2.3.3. Inventory data and the characterization of environmental impacts**

238 To run the LCAs, SimaPro® software (v. 8.5) was used. The European ReCiPe
239 methodology was employed with the Hierarchist model (v. 1.13) (Goedkoop et al., 2013)
240 in tandem with the Agribalyse® database (v. 1.3) and the EcoInvent3 database (v. 3.3).
241 The environmental impacts of the pre-concepts were expressed using the midpoint
242 results and the single scores. The 18 categories of midpoint results obtained using the
243 ReCiPe method are listed in Table 1.

244 *Table 1: Categories of impacts associated with the midpoint results obtained with the ReCiPe method*
245 *(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

246

247 **3. Results and discussion**

248 **3.1. Scenarios for the pre-concepts**

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

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

258 *Table 2: Different ingredient scenarios for the three example pre-concepts (spirulina-based milk, jam, and*
 259 *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

260

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

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

Type Material	Jars						Bottles						Lids			
	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	

270

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

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

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

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

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

303 **3.2. Transversal analyses, module contribution, and pre-concept comparisons**

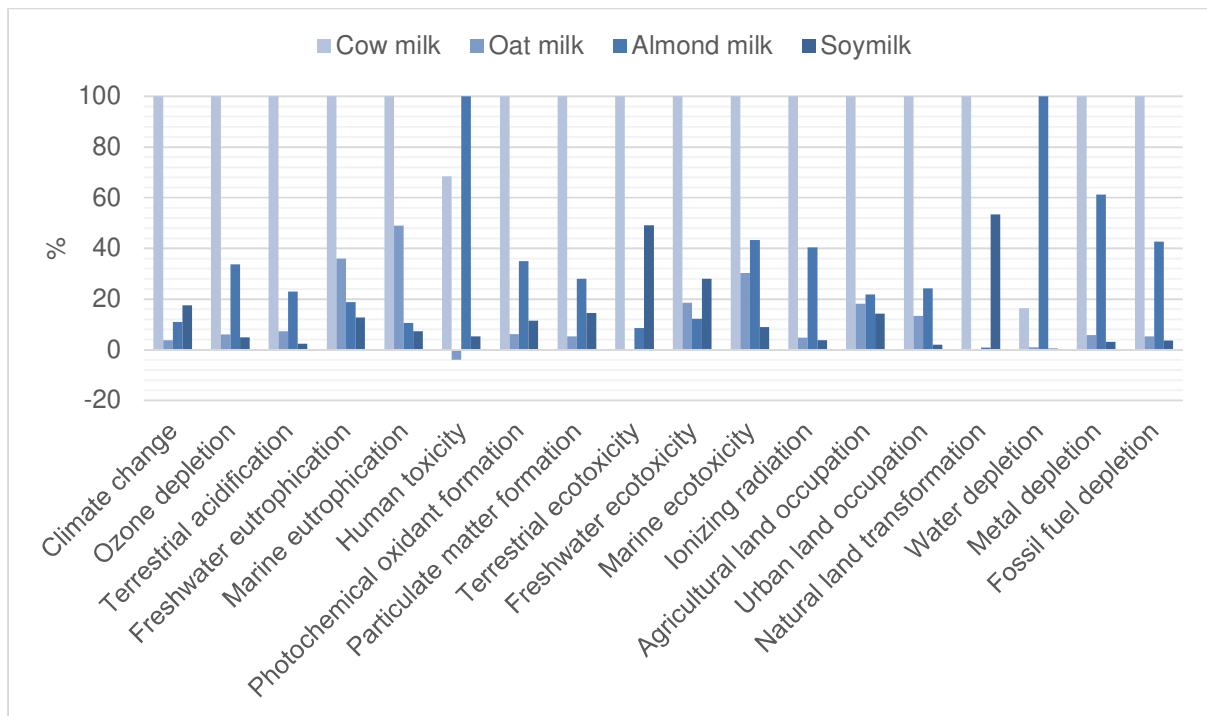
304 The transversal analyses (contribution of modalities, comparison of modalities,
305 contributions of modules to the impacts of pre-concepts) generated diverse knowledge
306 about the environmental impacts of the pre-concepts. These results are presented
307 below.

308 **3.2.1. Module scenarios with the smallest impacts**

309 **Ingredients module**

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

312 For example, for the spirulina-based milk (Figure 4), it was clear that using an ingredient
313 of animal origin (cow milk) led to greater environmental impacts than using ingredients
314 that were plant based, except in the case of almond milk, which had greater impacts in
315 the categories water depletion and human toxicity (because most of the almonds on the
316 market come from California and are irrigated). Previous research has shown that the
317 consumption of animal products has a greater environmental impact than the
318 consumption of plant products, such that a vegetarian diet reduces carbon emissions by
319 20–39% (Hallström et al., 2015; Pernollet et al., 2017). The use of oat milk and soy milk
320 led to the smallest impacts, except in the case of marine eutrophication (because oat
321 crops need to be fertilized).



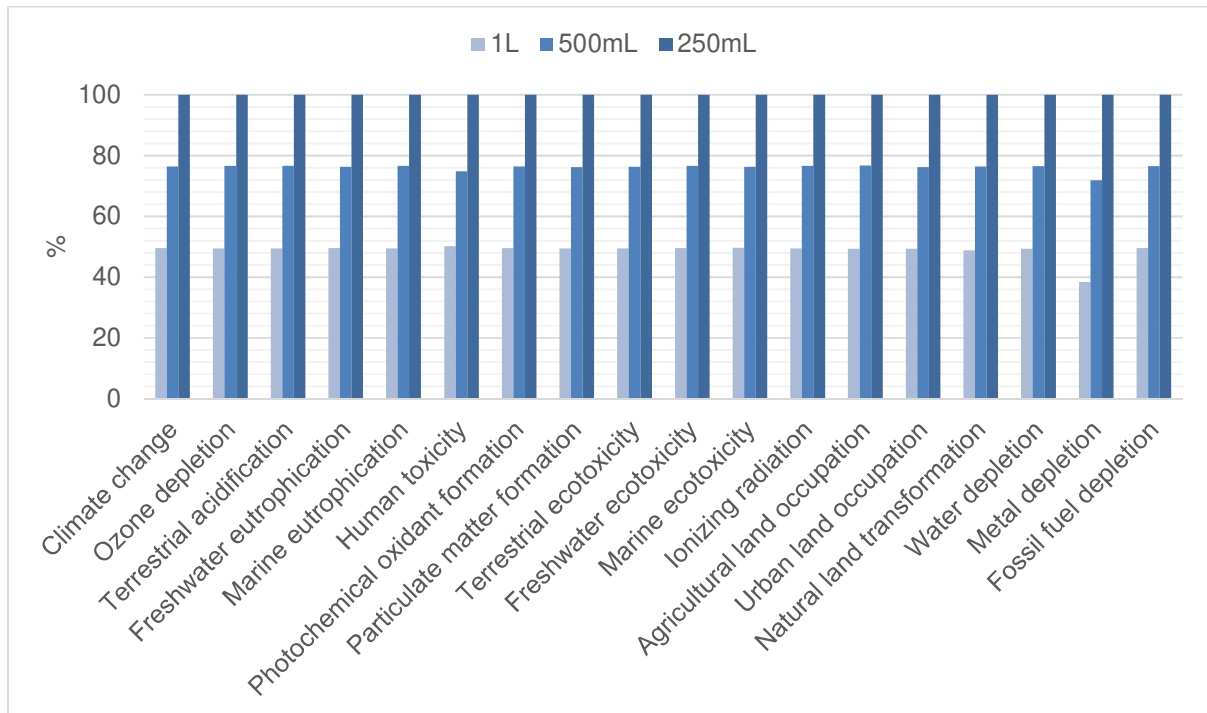
322
323 *Figure 4: Comparison of the four ingredient scenarios for 1 kg of the spirulina-based milk pre-concept:*
324 *(from left to right) cow milk, oat milk, almond milk, and soy milk (the midpoint results for the impact*
325 *categories)*

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

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

343 **Packaging module**

344 For the packaging module, the environmental impacts of using different packaging sizes
345 and materials were compared and contrasted. First, glass bottles of different sizes (1 L,
346 500 mL, and 250 mL) were compared, all with tinplate screw top lids; the basis for
347 comparison was the packaging needed to hold 1 L of liquid. The results revealed that
348 there was an effect of packaging size: one 1-L bottle had less of an environmental
349 impact than two 500-mL bottles or four 250-mL bottles (Figure 5). Similar results were
350 obtained for the PET bottles (Figure A.3) and the HDPE bottles (Figure A.4), both with
351 polypropylene (PP) pop top lids. Second, bottles of the same size made with different
352 materials (HDPE, PET, and glass) were compared. The results showed that an HDPE
353 bottle had 0–15% of the environmental impact of a glass bottle (Figure A.5) because of
354 its lighter mass and less energy costly waste treatment. The PET bottle had an
355 environmental impact in between those of the HDPE bottle and the glass bottle.



356

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

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

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

379 **Transportation and energy + water modules**

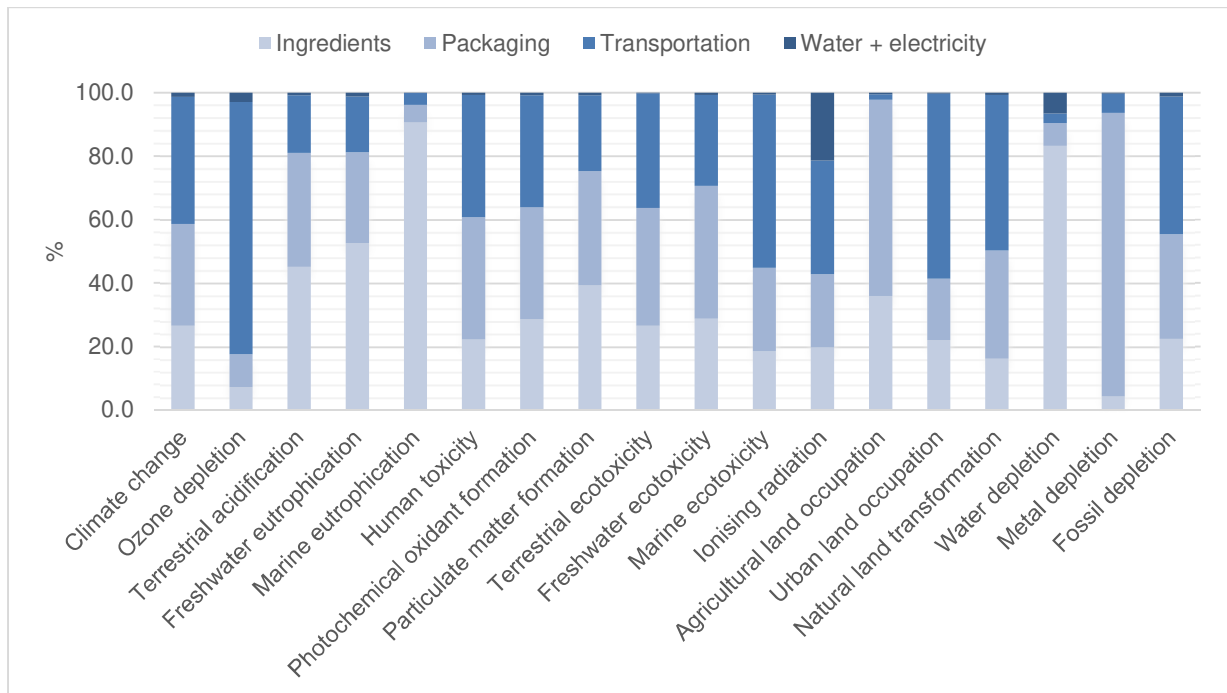
380 The product transformation process was treated as a constant parameter. It was
381 characterized using the estimated amount of energy and water used to produce a kg of
382 product, based on the factory's figures for the previous year. While these mean values
383 convey the likely magnitude of energy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

396 **3.2.2. Module contributions to pre-concept environmental impacts**

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

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

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



409
 410 *Figure 6: Environmental impacts of a functional unit of the spirulina-based kiwi jam pre-concept:*
 411 *contributions made by the ingredients, packaging, transportation, and energy + water modules (ReCiPe*
 412 *method, Hierarchist model, midpoint results)*

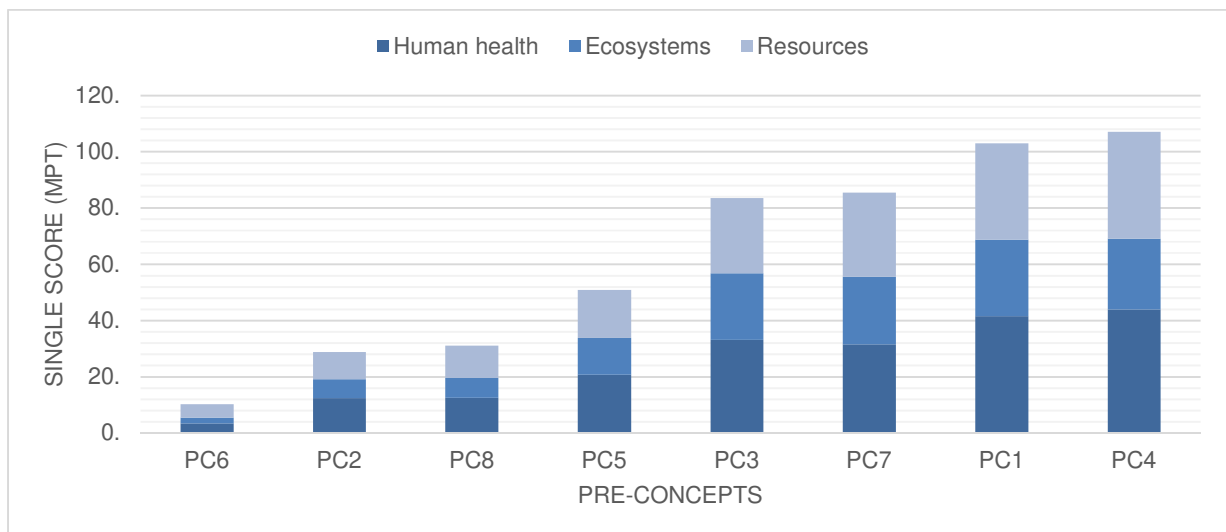
413 The ingredients module contributed to major differences in environmental impacts
 414 because agricultural commodities differ significantly in their impacts. Past research has
 415 indicated that agricultural production plays a greater role than packaging and
 416 transportation in defining the environmental impacts of food products (Pernollet et al.,
 417 2017). The contribution of transportation is determined by product quantity and
 418 packaging mass.

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

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

427 3.3. Communicating the results of the pre-concept comparisons

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



440
441 *Figure 7: Comparison of the environmental impacts of the NPD project's eight pre-concepts using single*
442 *scores (millipoints [mpt]) resulting from the categories human health, ecosystems, and natural resources*
443 *(Hierarchist model; endpoint results). Functional*

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

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

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

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

478 At present, the tools (i.e., LCA and the LCA databases) are not sufficiently developed to
479 deal with eco-design challenges in the food sector. In particular, criteria that differentiate
480 products need to be accounted for in inventories (for example, organic versus
481 conventional production, local versus non-local sourcing, or seasonal versus non-
482 seasonal production) because the absence of this information can bias the results.
483 Additional indicators are also lacking to assess the overall impacts of products (e.g. soil
484 carbon changes in milk production: Knudsen et al., 2019), biodiversity in particular,
485 which remains complex to assess (Winter et al., 2017). For example, although single-
486 use glass containers have a greater environmental impact than single-use plastic
487 containers, plastics release compounds during use may pose health risks (Yang et al.,
488 2019).

489 Finally, as illustrated in this case study, modular LCA can be used as an information
490 provider tool for agri-food industries. Even though results were found useful for the
491 decision of the company to prioritize concepts for the following stages of innovation
492 process (conceptualization, development), the company found that the LCA method
493 remains too complex and time-consuming to be used in business-as-usual. The multiple
494 steps, the need for precise inventories, and the required expertise to analyze the results
495 were the major issues mentioned by the stakeholders, in accordance to Sala et al.
496 (2017).

497 **4. Perspectives**

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

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

508 **5. Conclusion**

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

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

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

530 **Acknowledgements**

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

534 **References**

- 535 Azzurra, A., Paola, P., 2009. Consumers’ behaviours and attitudes toward healthy food
536 products: The case of Organic and Functional foods. Presented at the 113th
537 EAAE Seminar: A resilient European food industry and food chain in a
538 challenging world, Greece, p. 16.
- 539 Baldini, C., Gardoni, D., Guarino, M., 2017. A critical review of the recent evolution of
540 Life Cycle Assessment applied to milk production. *Journal of Cleaner Production*,
541 *Towards eco-efficient agriculture and food systems: selected papers addressing*
542 *the global challenges for food systems, including those presented at the*
543 *Conference “LCA for Feeding the planet and energy for life” (6-8 October 2015,*
544 *Stresa & Milan Expo, Italy)* 140, 421–435.
545 <https://doi.org/10.1016/j.jclepro.2016.06.078>
- 546 Brondi, C., Carpanzano, E., 2011. A modular framework for the LCA-based simulation of
547 production systems. *CIRP Journal of Manufacturing Science and Technology*,
548 *Production Networks Sustainability* 4, 305–312.
549 <https://doi.org/10.1016/j.cirpj.2011.06.006>
- 550 Calderón, L.A., Herrero, M., Laca, A., Díaz, M., 2018. Environmental impact of a
551 traditional cooked dish at four different manufacturing scales: from ready meal
552 industry and catering company to traditional restaurant and homemade. *Int J Life*
553 *Cycle Assess* 23, 811–823. <https://doi.org/10.1007/s11367-017-1326-7>
- 554 Cluzel, F., Vallet, F., Bertoluci, G., Leroy, Y., 2014. Eco-design vs eco-innovation: an
555 industrial survey, in: *International Design Conference*. Presented at the Design
556 2014, Dubrovnik, Croatia.
- 557 Cluzel, François, Yannou, B., Millet, D., Leroy, Y., 2014. Exploitation scenarios in
558 industrial system LCA. *Int J Life Cycle Assess* 19, 231–245.
559 <https://doi.org/10.1007/s11367-013-0631-z>
- 560 Colley, T.A., Birkved, M., Olsen, S.I., Hauschild, M.Z., 2020. Using a gate-to-gate LCA to
561 apply circular economy principles to a food processing SME. *Journal of Cleaner*
562 *Production* 251, 119566. <https://doi.org/10.1016/j.jclepro.2019.119566>
- 563 Cooper, R.G., Edgett, S.J., Kleinschmidt, E.J., 2004. Benchmarking Best NPD
564 Practices—I. *Research-Technology Management* 47, 31–43.
565 <https://doi.org/10.1080/08956308.2004.11671606>
- 566 Eco-Emballages, 2016. Rapport annuel [WWW Document]. *EcoEmballages*. URL
567 <http://www.ecoemballages.fr/eco-emballages/qui-sommes-nous/rapport-annuel>
568 (accessed 10.9.19).
- 569 Edwards-Jones, G., 2010. Does eating local food reduce the environmental impact of
570 food production and enhance consumer health? *Proceedings of the Nutrition*
571 *Society* 69, 582–591. <https://doi.org/10.1017/S0029665110002004>

572 European Commission, 2012. Product Environmental Footprint (PEF) Guide:
573 consolidated version (No. Ares(2012)873782). European Commission, Italy.

574 European Commission, 2006. Environmental Impact of Products (EIPRO): Analysis of
575 the life cycle environmental impacts related to the final consumption of the EU-25
576 (No. EUR 22284 EN), Technical Report Series.

577 FiBL, IFOAM Organics International, 2019. The world of organic agriculture.

578 Gabrisch, C., Cerdas, F., Herrmann, C., 2019. Product System Modularization in LCA
579 Towards a Graph Theory Based Optimization for Product Design Alternatives, in:
580 Schebek, L., Herrmann, C., Cerdas, F. (Eds.), Progress in Life Cycle
581 Assessment, Sustainable Production, Life Cycle Engineering and Management.
582 Springer International Publishing, Cham, pp. 37–44. [https://doi.org/10.1007/978-](https://doi.org/10.1007/978-3-319-92237-9_5)
583 [3-319-92237-9_5](https://doi.org/10.1007/978-3-319-92237-9_5)

584 Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., van Zelm, R.,
585 2013. ReCiPe 2008: A life cycle impact assessment method which comprises
586 harmonised category indicators at the midpoint and the endpoint level (First
587 edition (version 1.08) No. Report 1: Characterisation).

588 Habib, M.A.B., Humtington, T.C., Hasan, M.R., 2008. Review on culture, production and
589 use of Spirulina as food for humans and feeds for domestic animals and fish.
590 FAO Fisheries and Aquaculture Circular.

591 Hallström, E., Carlsson-Kanyama, A., Börjesson, P., 2015. Environmental impact of
592 dietary change: a systematic review. *Journal of Cleaner Production* 91, 1–11.
593 <https://doi.org/10.1016/j.jclepro.2014.12.008>

594 Hashemi, M., Zadeh, H.M., Arasteh, P.D., Zarghami, M., 2019. Economic and
595 Environmental Impacts of Cropping Pattern Elements Using Systems Dynamics.
596 *Civil Engineering Journal* 5, 1020-1032–1032. [https://doi.org/10.28991/cej-2019-](https://doi.org/10.28991/cej-2019-03091308)
597 [03091308](https://doi.org/10.28991/cej-2019-03091308)

598 Hospido, A., Davis, J., Berlin, J., Sonesson, U., 2010. A review of methodological issues
599 affecting LCA of novel food products. *Int J Life Cycle Assess* 15, 44–52.
600 <https://doi.org/10.1007/s11367-009-0130-4>

601 Jungbluth, N., Tietje, O., Scholz, R.W., 2000. Food purchases: Impacts from the
602 consumers' point of view investigated with a modular LCA. *Int. J. LCA* 5, 134.
603 <https://doi.org/10.1007/BF02978609>

604 Kägi, T., Dinkel, F., Frischknecht, R., Humbert, S., Lindberg, J., De Mester, S.,
605 Ponsioen, T., Sala, S., Schenker, U.W., 2016. Session “Midpoint, endpoint or
606 single score for decision-making?”—SETAC Europe 25th Annual Meeting, May
607 5th, 2015. *Int J Life Cycle Assess* 21, 129–132. [https://doi.org/10.1007/s11367-](https://doi.org/10.1007/s11367-015-0998-0)
608 [015-0998-0](https://doi.org/10.1007/s11367-015-0998-0)

609 Kim, J., Wilemon, D., 2002. Focusing the fuzzy front–end in new product development.
610 *R&D Management* 32, 269–279. <https://doi.org/10.1111/1467-9310.00259>

611 Knudsen, M.T., Dorca-Preda, T., Djomo, S.N., Peña, N., Padel, S., Smith, L.G.,
612 Zollitsch, W., Hörtenhuber, S., Hermansen, J.E., 2019. The importance of
613 including soil carbon changes, ecotoxicity and biodiversity impacts in
614 environmental life cycle assessments of organic and conventional milk in Western
615 Europe. *Journal of Cleaner Production* 215, 433–443.
616 <https://doi.org/10.1016/j.jclepro.2018.12.273>

- 617 McAuliffe, G.A., Takahashi, T., Lee, M.R.F., 2019. Applications of nutritional functional
618 units in commodity-level life cycle assessment (LCA) of agri-food systems. *Int J*
619 *Life Cycle Assess.* <https://doi.org/10.1007/s11367-019-01679-7>
- 620 Medicine, N.A. of S., Engineering, and, Engineering, N.A. of, Sciences, D. on E. and P.,
621 Studies, D. on E. and L., Board, W.S. and T., Board, O.S., Programs, N.O. of,
622 Sciences, B. on L., Toxicology, B. on E.S. and, Resources, B. on E.S. and,
623 Systems, B. on E. and E., Technology, B. on C.S. and, Climate, B. on A.S. and,
624 Resources, B. on A. and N., Century, C. on the G.C. and O. in E.E. for the T.-F.,
625 2019. *Environmental Engineering for the 21st Century: Addressing Grand*
626 *Challenges.* National Academies Press.
- 627 Molina-Besch, K., Wikström, F., Williams, H., 2019. The environmental impact of
628 packaging in food supply chains—does life cycle assessment of food provide the
629 full picture? *Int J Life Cycle Assess* 24, 37–50. [https://doi.org/10.1007/s11367-](https://doi.org/10.1007/s11367-018-1500-6)
630 [018-1500-6](https://doi.org/10.1007/s11367-018-1500-6)
- 631 Moreno, J., Pablos, C., Marugán, J., 2018. Quantitative Methods for Life Cycle
632 Assessment (LCA) Applied to the Vegetable Industry, in: Pérez-Rodríguez, F.,
633 Skandamis, P., Valdramidis, V. (Eds.), *Quantitative Methods for Food Safety and*
634 *Quality in the Vegetable Industry, Food Microbiology and Food Safety.* Springer
635 International Publishing, Cham, pp. 255–293. [https://doi.org/10.1007/978-3-319-](https://doi.org/10.1007/978-3-319-68177-1_12)
636 [68177-1_12](https://doi.org/10.1007/978-3-319-68177-1_12)
- 637 Moro Piekarski, C., Mendes da Luz, L., Zocche, L., de Francisco, A.C., 2013. Life Cycle
638 Assessment as Entrepreneurial Tool for Business Management and Green
639 Innovations. *Journal of technology management & innovation* 8, 44–53.
640 <https://doi.org/10.4067/S0718-27242013000100005>
- 641 Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The
642 role of life cycle assessment in supporting sustainable agri-food systems: A
643 review of the challenges. *Journal of Cleaner Production, Towards eco-efficient*
644 *agriculture and food systems: selected papers addressing the global challenges*
645 *for food systems, including those presented at the Conference “LCA for Feeding*
646 *the planet and energy for life” (6-8 October 2015, Stresa & Milan Expo, Italy)* 140,
647 399–409. <https://doi.org/10.1016/j.jclepro.2016.06.071>
- 648 Notarnicola, B., Salomone, R., Petti, L., Renzulli, P.A., Roma, R., Cerutti, A.K., 2015.
649 *Life Cycle Assessment in the Agri-food Sector: Case Studies, Methodological*
650 *Issues and Best Practices,* 2015th ed. Springer.
- 651 Pandey, D., Agrawal, M., Pandey, J.S., 2011. Carbon footprint: current methods of
652 estimation. *Environ Monit Assess* 178, 135–160. [https://doi.org/10.1007/s10661-](https://doi.org/10.1007/s10661-010-1678-y)
653 [010-1678-y](https://doi.org/10.1007/s10661-010-1678-y)
- 654 Park, S.-I., Lee, D.S., Han, J.H., 2014. Chapter 22 - Eco-Design for Food Packaging
655 Innovations, in: Han, J.H. (Ed.), *Innovations in Food Packaging (Second Edition),*
656 *Food Science and Technology.* Academic Press, San Diego, pp. 537–547.
657 <https://doi.org/10.1016/B978-0-12-394601-0.00022-9>
- 658 Pernollet, F., Coelho, C.R.V., van der Werf, H.M.G., 2017. Methods to simplify diet and
659 food life cycle inventories: Accuracy versus data-collection resources. *Journal of*
660 *Cleaner Production, Towards eco-efficient agriculture and food systems: selected*
661 *papers addressing the global challenges for food systems, including those*
662 *presented at the Conference “LCA for Feeding the planet and energy for life” (6-8*

663 October 2015, Stresa & Milan Expo, Italy) 140, 410–420.
664 <https://doi.org/10.1016/j.jclepro.2016.06.111>

665 Perrin, A., Basset-Mens, C., Gabrielle, B., 2014. Life cycle assessment of vegetable
666 products: a review focusing on cropping systems diversity and the estimation of
667 field emissions. *Int J Life Cycle Assess* 19, 1247–1263.
668 <https://doi.org/10.1007/s11367-014-0724-3>

669 Petala, E., Wever, R., Dutilh, C., Brezet, H., 2010. The role of new product development
670 briefs in implementing sustainability: A case study. *Journal of Engineering and*
671 *Technology Management* 27, 172–182.
672 <https://doi.org/10.1016/j.jengtecman.2010.06.004>

673 Reid, S.E., Brentani, U.D., 2004. The Fuzzy Front End of New Product Development for
674 Discontinuous Innovations: A Theoretical Model. *Journal of Product Innovation*
675 *Management* 21, 170–184. <https://doi.org/10.1111/j.0737-6782.2004.00068.x>

676 Renouf, M.A., Renaud-Gentié, C., Perrin, A., van der Werf, H.M.G., Kanyarushoki, C.,
677 Jourjon, F., 2018. Effectiveness criteria for customised agricultural life cycle
678 assessment tools. *Journal of Cleaner Production* 179, 246–254.
679 <https://doi.org/10.1016/j.jclepro.2017.12.170>

680 Rousseaux, P., Gremy-Gros, C., Bonnin, M., Henriel-Ricordel, C., Bernard, P., Flourey,
681 L., Staigre, G., Vincent, P., 2017. “Eco-tool-seeker”: A new and unique business
682 guide for choosing ecodesign tools. *Journal of Cleaner Production* 151, 546–577.
683 <https://doi.org/10.1016/j.jclepro.2017.03.089>

684 Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., Shiina, T., 2009. A
685 review of life cycle assessment (LCA) on some food products. *Journal of Food*
686 *Engineering* 90, 1–10. <https://doi.org/10.1016/j.jfoodeng.2008.06.016>

687 Sala, S., Anton, A., McLaren, S.J., Notarnicola, B., Saouter, E., Sonesson, U., 2017. In
688 quest of reducing the environmental impacts of food production and consumption.
689 *Journal of Cleaner Production, Towards eco-efficient agriculture and food*
690 *systems: selected papers addressing the global challenges for food systems,*
691 *including those presented at the Conference “LCA for Feeding the planet and*
692 *energy for life” (6-8 October 2015, Stresa & Milan Expo, Italy) 140, 387–398.*
693 <https://doi.org/10.1016/j.jclepro.2016.09.054>

694 Sedghamiz, A., Heidarpour, M., Nikoo, M.R., Eslamian, S., 2018. A Game Theory
695 Approach for Conjunctive Use Optimization Model Based on Virtual Water
696 Concept. *Civil Engineering Journal* 4, 1315-1325–1325.
697 <https://doi.org/10.28991/cej-0309175>

698 Skerlos, S.J., 2015. Promoting Effectiveness in Sustainable Design. *Procedia CIRP, The*
699 *22nd CIRP Conference on Life Cycle Engineering* 29, 13–18.
700 <https://doi.org/10.1016/j.procir.2015.02.080>

701 Skunca, D., Tomasevic, I., Nastasijevic, I., Tomovic, V., Djekic, I., 2018. Life cycle
702 assessment of the chicken meat chain. *Journal of Cleaner Production* 184, 440–
703 450. <https://doi.org/10.1016/j.jclepro.2018.02.274>

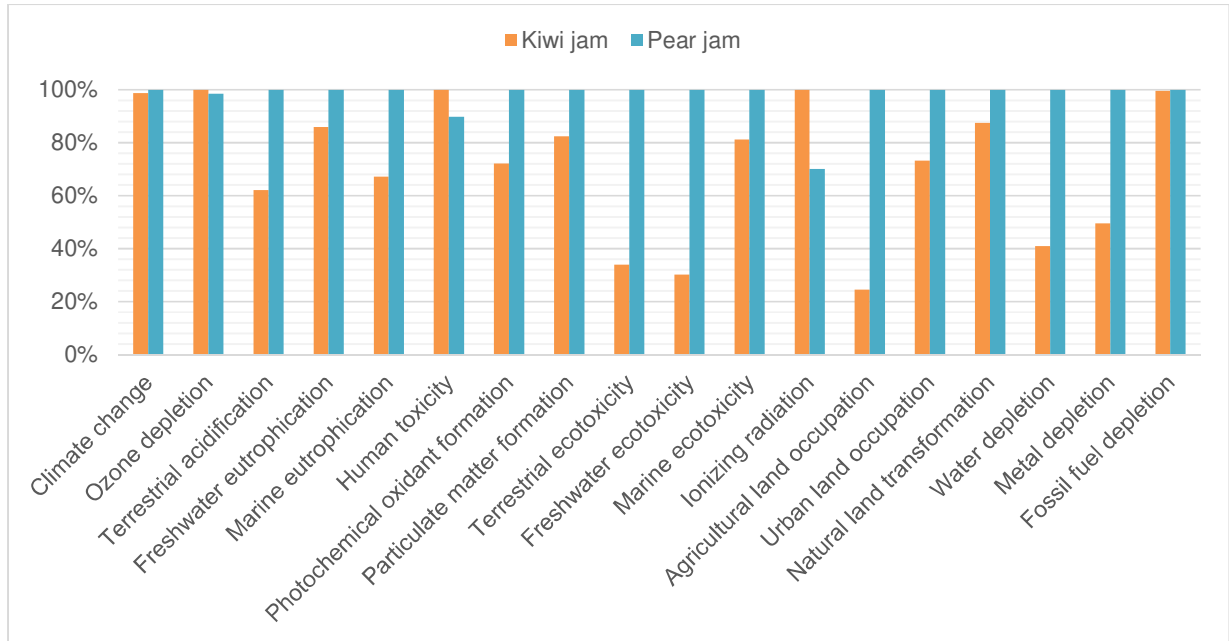
704 Sonesson, U., Berlin, J., Hospido, A., 2010. 9 - Towards sustainable industrial food
705 production using Life Cycle Assessment approaches, in: Sonesson, U., Berlin, J.,
706 Ziegler, F. (Eds.), *Environmental Assessment and Management in the Food*
707 *Industry, Woodhead Publishing Series in Food Science, Technology and*
708 *Nutrition. Woodhead Publishing, pp. 165–176.*
709 <https://doi.org/10.1533/9780857090225.3.165>

- 710 Striebig, B., Smitts, E., Morton, S., 2019. Impact of Transportation on Carbon Dioxide
711 Emissions from Locally vs. Non-locally Sourced Food. *Emerg Sci J* 3, 222–234.
712 <https://doi.org/10.28991/esj-2019-01184>
- 713 Stylianou, K.S., Nguyen, V.K., Fulgoni, V.L., Jolliet, O., 2017. Environmental Impacts of
714 Mixed Dishes: A Case Study on Pizza. *The FASEB Journal* 31, lb386–lb386.
715 https://doi.org/10.1096/fasebj.31.1_supplement.lb386
- 716 Takey, S.M., Carvalho, M.M., 2016. Fuzzy front end of systemic innovations: A
717 conceptual framework based on a systematic literature review. *Technological*
718 *Forecasting and Social Change* 111, 97–109.
719 <https://doi.org/10.1016/j.techfore.2016.06.011>
- 720 Tillman, A.-M., 2000. Significance of decision-making for LCA methodology.
721 *Environmental Impact Assessment Review* 20, 113–123.
722 [https://doi.org/10.1016/S0195-9255\(99\)00035-9](https://doi.org/10.1016/S0195-9255(99)00035-9)
- 723 Tuomisto, H.L., Hodge, I.D., Riordan, P., Macdonald, D.W., 2012. Does organic farming
724 reduce environmental impacts? – A meta-analysis of European research. *Journal*
725 *of Environmental Management* 112, 309–320.
726 <https://doi.org/10.1016/j.jenvman.2012.08.018>
- 727 Verghese, K., Lockrey, S., Clune, S., Sivaraman, D., 2012. 19 - Life cycle assessment
728 (LCA) of food and beverage packaging, in: Yam, K.L., Lee, D.S. (Eds.), *Emerging*
729 *Food Packaging Technologies*, Woodhead Publishing Series in Food Science,
730 *Technology and Nutrition*. Woodhead Publishing, pp. 380–408.
731 <https://doi.org/10.1533/9780857095664.4.380>
- 732 Winter, L., Lehmann, A., Finogenova, N., Finkbeiner, M., 2017. Including biodiversity in
733 life cycle assessment – State of the art, gaps and research needs. *Environmental*
734 *Impact Assessment Review* 67, 88–100.
735 <https://doi.org/10.1016/j.eiar.2017.08.006>
- 736 Yang, J., Song, W., Wang, X., Li, Y., Sun, J., Gong, W., Sun, C., 2019. Migration of
737 phthalates from plastic packages to convenience foods and its cumulative health
738 risk assessments. *Food Additives & Contaminants: Part B* 12, 151–158.
739 <https://doi.org/10.1080/19393210.2019.1574909>
- 740 Yannou-Le Bris, G., Ferrandi, J.-M., 2016. Eco-concevoir et éco-innover : Deux
741 stratégies essentielles pour répondre aux enjeux sociétaux à venir. *IAA* 19–21.

742

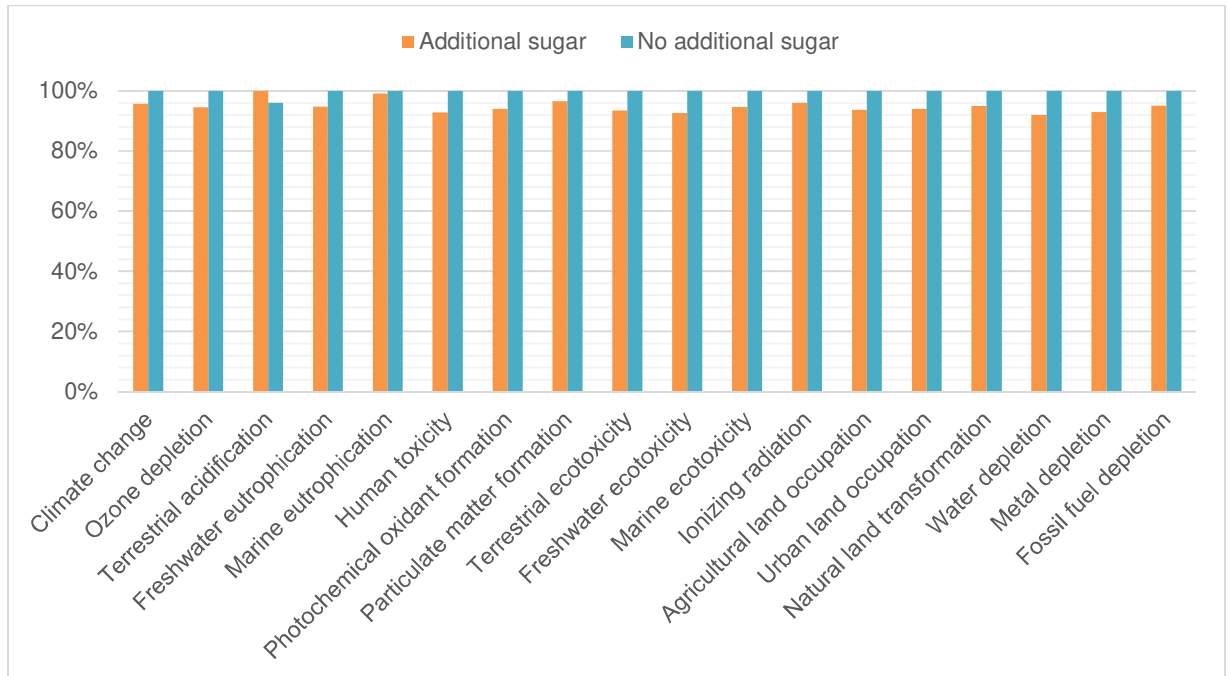
743

744 **Appendices**



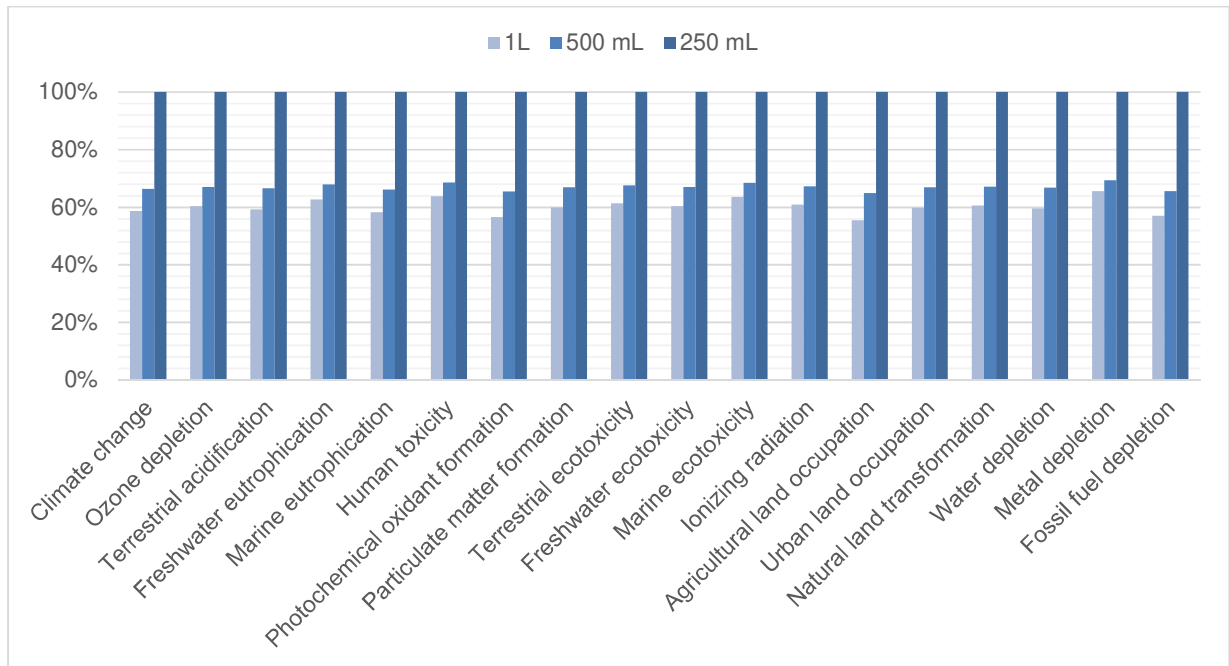
745

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)*



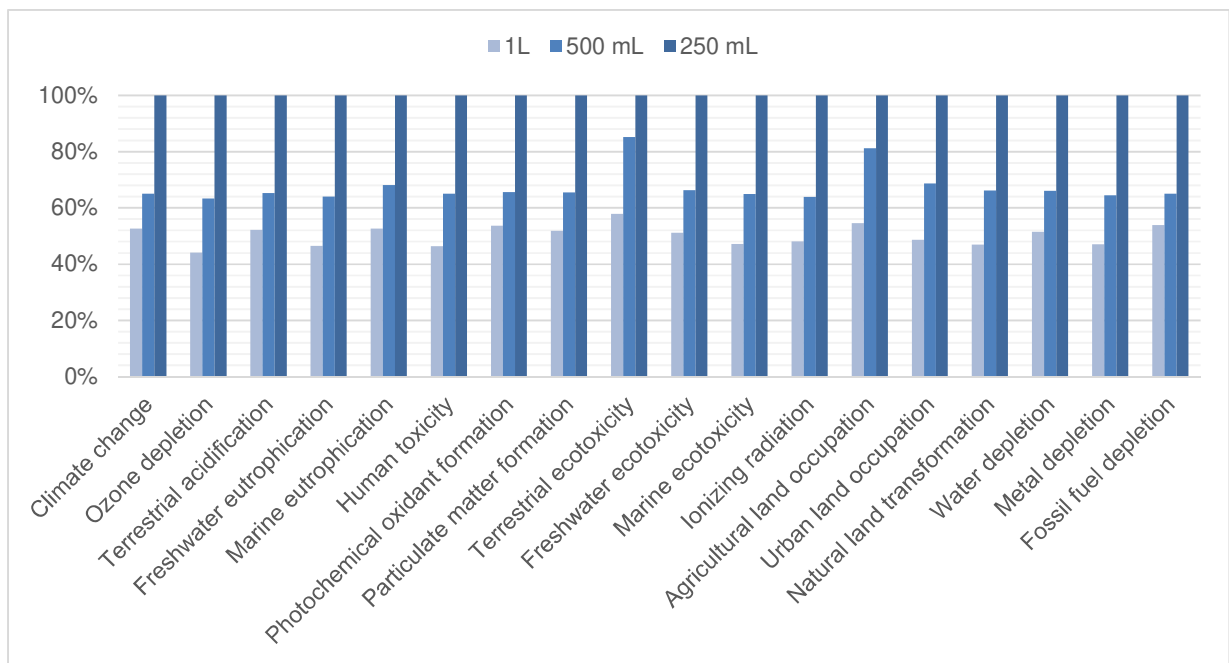
748

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*



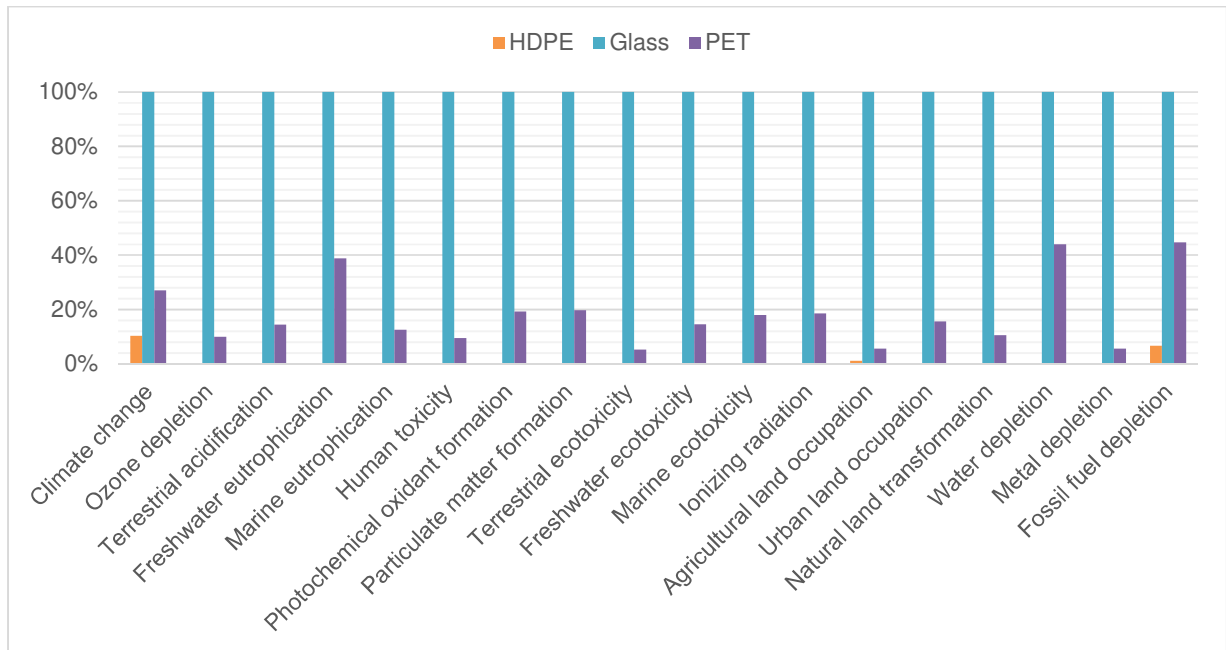
752

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)*