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Environmental assessment of a hot sauce: Involving stakeholders in the development of new food products

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ABSTRACT

Meeting the expectations of consumers when developing eco-friendly products is essential for an effective change towards sustainable consumption patterns. Interdisciplinary design approaches including both, consumers' insights, and environmental aspects, are crucial for this purpose, but have been rarely adopted in the food sector. The aim of this study was to assess the environmental impact of a new food product (hot sauce) eco-developed by involving consumers' and other stakeholders from early stages, and to analyze how the different steps contributed to the environmental performance of the product. Consumer-centered design (CCD) was applied for direct involvement of consumers through qualitative and quantitative research sensory methods. This was key for product identification and optimization, as it enabled excluding some ingredients and processes with negligible contribution to the sensory profile. Life cycle assessment (LCA) was conducted to identify hot-spots and evaluate the environmental performance of the different prototypes: two hot sauces based on discarded green chili and a baseline hot sauce based on red chili, included for comparison purposes. Secondary ingredients and packaging were identified as the main hotspots in the first prototype. Ingredients produced under more sustainable methods and alternative plastic packaging were proposed for improvement. The final product, not only resulted in a reduction on its environmental footprint respect to the baseline in all impact categories (57–91%), but showed a high level of consumers' acceptance. Despite the limitations of the approach, results showed that combined disciplines could be effective tools for developing more sustainable foods while meeting consumers' expectations.

1. Introduction

Consumers, through their food choice decisions, have a central role in the transition toward a more sustainable food system. Thus, for an effective change, it is essential to understand the demands and expectations of consumers when developing new products or services that seek to contribute to more sustainable consumption patterns (Sijtsema et al., 2020; Guiné et al., 2020). For these reasons, consumer-centered design (CCD) has drawn increasing interest. In general terms, it implies the direct involvement of consumers in the new product development (NPD) process, which allows obtaining their insights from the different stages through qualitative and/or quantitative sensory research methods, which includes: (i.) opportunity identification, (ii.) development, (iii.) optimization and (iv.) launch (van Kleef et al., 2005). The final aim of CCD is to achieve an optimal degree of fit between the new product and consumers' needs (Costa and Jongen, 2006; Horvat et al., 2019). Świąder and Marczewska (2021) reported that nearly 70% of the companies in the European Union apply sensory evaluation methods in NPD, resulting in favourable outcomes for the market performance of food products (Garcia-Martinez, 2014; Grunert et al., 2011). Likewise, several studies have emphasized the importance and benefits of including sustainability experts when designing and developing new food products to contextualize shared visions, policies, initiatives, and regulatory frameworks (Polonsky and Ottman, 1998; Torán-Pereg et al., 2023a).

Food is one of the three main consumption areas that contribute the most to the environmental impacts in the household context (European Environment Agency, 2023), and several studies have highlighted the need to change to more sustainable food consumption patterns (Reisch et al., 2013; Willett et al., 2019). Thus, when developing new products from a sustainable perspective, it is important to know which ingredient, technique, or process is the most convenient to apply from an

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environmental point of view. Life Cycle Assessment (LCA) has shown to be a useful environmental management tool for purposes such as eco-design, because it has been successfully used to objectively, quantitatively, and systematically analyze the environmental impact caused by a process or product during its entire life cycle (ISO 14040:2006).

LCA has been applied in the food sector in a variety of perspectives to assess the impact of raw materials (Poore and Nemecek, 2018), final products (Roy et al., 2009), technologies (Pardo and Zufía, 2012), packaging (Siracusa et al., 2014), consumers cooking practices (Frankowska et al., 2020; Cortesi et al., 2023) or even diets (Hallström et al., 2015). Regarding food design and development of more sustainable products, recent works have stressed the need to incorporate the environmental aspect at an earlier stage of the innovation process in food industries, from the conceptualization or ideation phase (Thomas et al., 2021; Woodhouse et al., 2018). Interdisciplinary approaches including both, consumers' insights, and environmental issues from the beginning of the design process of a new food product is of crucial importance to meet consumers' expectations while not overlooking environmental implications (Sijtsema et al., 2020; Gonera et al., 2023). Eco-design processes integrating LCA methodology under a consumer-centered perspective have been successfully conducted in other production sectors, mostly related to household appliances (Dokter et al., 2023; Cor and Zwolinski, 2015) and electronical devices (Park and Tahara, 2008) where the use phase has a strong influence in the final impact of the product (Polizzi di Sorrentino et al., 2016). The importance of co-creation engaging consumers and other actors (e.g.: suppliers, processors) has been stressed, in order to achieve the environmental improvement of a product while ensuring product quality and consumer satisfaction. Despite this, the literature shows that few studies have adopted this combined approach (CCD and LCA) when developing new food products.

Thomas et al. (2021) presented a case study of a new product developed including spirulina and considered both consumers' and environmental data. However, their study underlined the need to adapt the methodology depending on the nature of the project, and the LCA results of the co-created products were not fully detailed. In the present research, the eco-development of a new food product was approached by involving consumers, but also other stakeholders such as food producers, processors, and environmental analysts at different steps. A hot sauce was designed and developed following environmental criteria, as a result of using CCD and LCA methodology. The aim of this study was to assess the environmental improvement of the resulting hot sauce and to explore if the different steps of the development process had positively contributed to the eco-design of the product. Therefore, the environmental performance of three sauce prototypes was compared: (i.) a prototype designed using the CCD perspective, considering consumers' and food stakeholders views about sustainability, (ii.) a second prototype developed considering the CCD perspective but improved by hot-spot identification using LCA methodology, and (iii.) a theoretical hot sauce prototype where the aforementioned methods were not applied, which was used as a baseline of the product environmental performance.

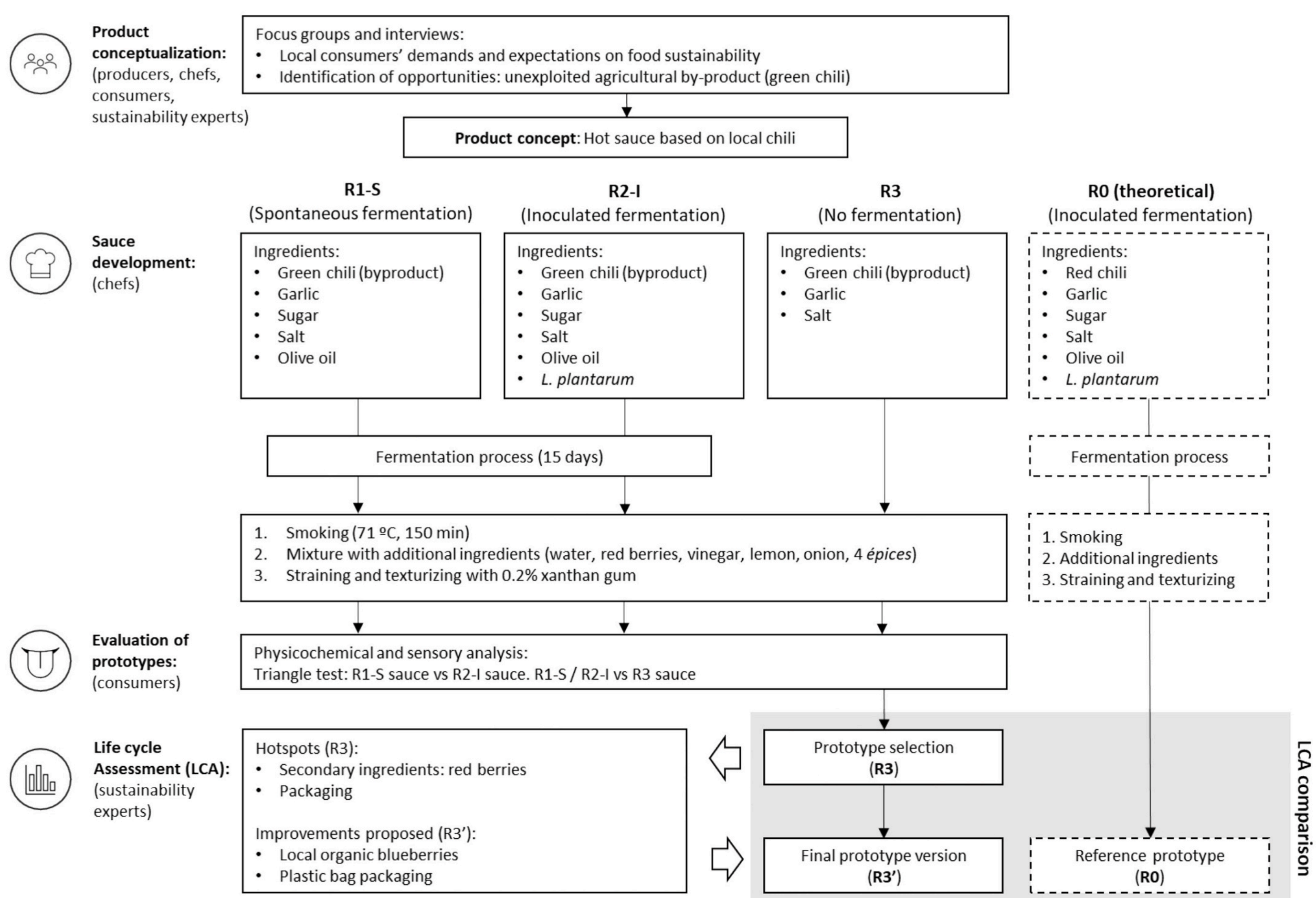

Fig. 1. Phases of product conceptualization and development combining consumer centered-design (CCD) and life cycle assessment (LCA) methodologies. R-0 represents a theoretical scenario where the same target product (locally produced hot sauce) is conceptualized and developed without the inputs of the stakeholders (for ideation), sensory panel (for prototype selection), and LCA (for eco-improvement).

2. Materials and methods

2.1. Product conceptualization and development

A new food product was designed and developed by combining CCD and LCA methodologies, following the stages shown in Fig. 1 and detailed below.

(i) Product conceptualization: The first step concerned the identification of local consumers' demands and expectations with regard to food sustainability. Previous results pointed out significant differences when compared to other European regions. Local consumers showed a wider vision of sustainability, highlighting concepts like "minimizing waste", "low footprint", "local sources", and "reduced packaging" for more than 50% of respondents to the conducted survey (Torán-Pereg et al., 2023b). Aiming at identifying opportunities to improve the regional food system in terms of sustainability, stakeholders of the food value chain, (including producers, suppliers, chefs, consumers, and sustainability experts) participated in a qualitative research activity. The results showed that "food waste" was one of the main challenges to address in the local food system context, and specific solutions were proposed, including policies for supporting circular economy, packaging reduction, and training of producers (Torán-Pereg et al., 2023a). Challenges like "demand for resources", "greenhouse gas emissions" and "lack of consumer awareness" were also highlighted, and solutions related with local production were often proposed for all of them (e.g. short supply chains). The outcome of this exchange with local stakeholders, followed by a series of interviews with local producers and chefs, resulted in the identification of an unexploited raw material as the base ingredient for the case study: the green chili from Espelette, characterized by its hot flavour. Market-oriented products such as spicy food and hot sauces are becoming increasingly popular in western food habits due to different factors, such as increasing trade, travelling or migration (Szűcs et al., 2018; Chironi et al., 2021). Even if Espelette region is a major producer of hot chilis, the lack of a reference local hot sauce that could respond to this trend was identified. A hot sauce based on discarded green chilis from Espelette was proposed as the target product, trying to capture from the conceptualization stage of the new food product design, the local consumers demands and expectations for sustainable food products, stressing aspects like waste minimization, low footprint, and local production. Since the agricultural product chosen as the base ingredient is currently discarded, the product is conceptualized as an opportunity to revalorise a local resource, with a low environmental impact expected.

(ii.) Sauce development: Three sauce prototypes (R1-S, R2-I, R3) were developed by chefs at Basque Culinary Center using green chili as the main ingredient, as a result of applying 3 different procedures for the product processing: spontaneous fermentation (R1-S), inoculated fermentation with lactic acid bacteria (*L.plantarum*) (R2-I), and no fermentation (R3). The three prototypes shared the same base ingredients (green chili, garlic, salt), with some differences in additional ingredients (e.g.: sugar, olive oil) linked to the fermentation process involved. Final processing steps involved smoking during 150 min, mixing with additional ingredients (water, red berries, vinegar, onion, lemon, 4 *épices*) and texturizing with xanthan gum (Fig. 2).

(iii.) Evaluation of prototypes: Physicochemical and sensory evaluations were carried out to detect similarities and differences among the three sauce prototypes. The results showed significant differences among prototypes in their physicochemical and microbiological parameters, but no significant differences were perceived by consumers when compared in the sensory panel (Torán-Pereg et al., 2023c). Consequently, prototype R-3 was selected for continuing the food development process, since it required less resources (time and ingredients) than the other prototypes.

(iv.) Environmental assessment: In the last stage of the development process, the environmental impacts of R-3 were analysed through LCA, identifying hotspots, and considering potential alternatives to improve the environmental performance of the final prototype (R-3′). The results of both prototypes were also compared with a reference prototype (R-0) that represents a theoretical scenario where the same target product (locally produced hot sauce) is conceptualized and developed without the inputs from the stakeholders (for ideation), sensory panel (for prototype selection), and LCA (for eco-improvement). We assumed that prototype R-0 uses red chili as the main base ingredient, since it is the most intuitive option for development of the target product (hot sauce) in the local context. Red chili is very present in local agriculture and gastronomy, and it has the right properties to develop a hot sauce equivalent to the most popular ones currently in the market. We assumed inoculated fermentation for the theoretical R-0 prototype (similar to R-2I) as it is a typical step involved for processing of similar hot pepper-based sauces (e.g.: Tabasco® sauce).

2.2. System description

The main ingredient of the developed hot sauces (R-3 and R-3′) was the discarded green chili (*Capsicum annuum*) grown in Espelette, derived from the production of Piment d'Espelette AOP. The cultivation area is limited to the department of the Pyrénées-Atlantiques (France). Currently, there are 299 ha cultivated by 207 producers (Syndicat du piment d'Espelette AOP, 2023). The case study involves the largest chili producer in the area, which manages a 12-ha farm, representing 4% of the total. For fruit production, seeds from the previous campaign are selected and sown in a mixture of green compost and peat. Then, they are grown under controlled greenhouse conditions at 18 °C for two weeks until reaching the seedling stage. When the first functional leaf emerges, each plant is replanted in a plant tray. Meanwhile, fields are ploughed and fertilized. Planting in fields is carried out from May to mid-July, combining manual and mechanical weeding. Organic fertilizers, green compost, and organic pesticides are used. Manual harvesting begins in August and ends on 1st December. The chilis that meet the quality standards are marketed in whole-fresh in a rope or dried in powder form. Those green chilis that have not matured sufficiently (do not have 80% of their surface of red colour) are not harvested but left in the plant and discarded as crop residues to the soil. These green chilis were used as the base ingredient to develop the different recipes used in the present research, except for the reference scenario (R0) which is based on red chili.

Once transported to the manufacturing centre, green chilis are processed together with other secondary ingredients and packaged. More details on the processing phase are shown in the section "2.3.4.3. Processing unitary operations". The recipe of the reference scenario (R-0) was modelled excluding the outputs obtained through the development of the R-3′ prototype. The main differences were: (i.) using red chili instead of green chili; (ii.) including a fermentation process traditionally used in other hot chili sauces (e.g.: Tabasco® sauce); which involves the addition of sugar, starter, and olive oil to boost the process; (iii.) using frozen red berries conventionally grown instead of local organic blueberries; and (iv.) using glass bottles as packaging.

2.3. Life cycle assessment

2.3.1. Goal and scope definition

The present study followed the principles described in the international standards ISO 14040 (ISOInternational organization for

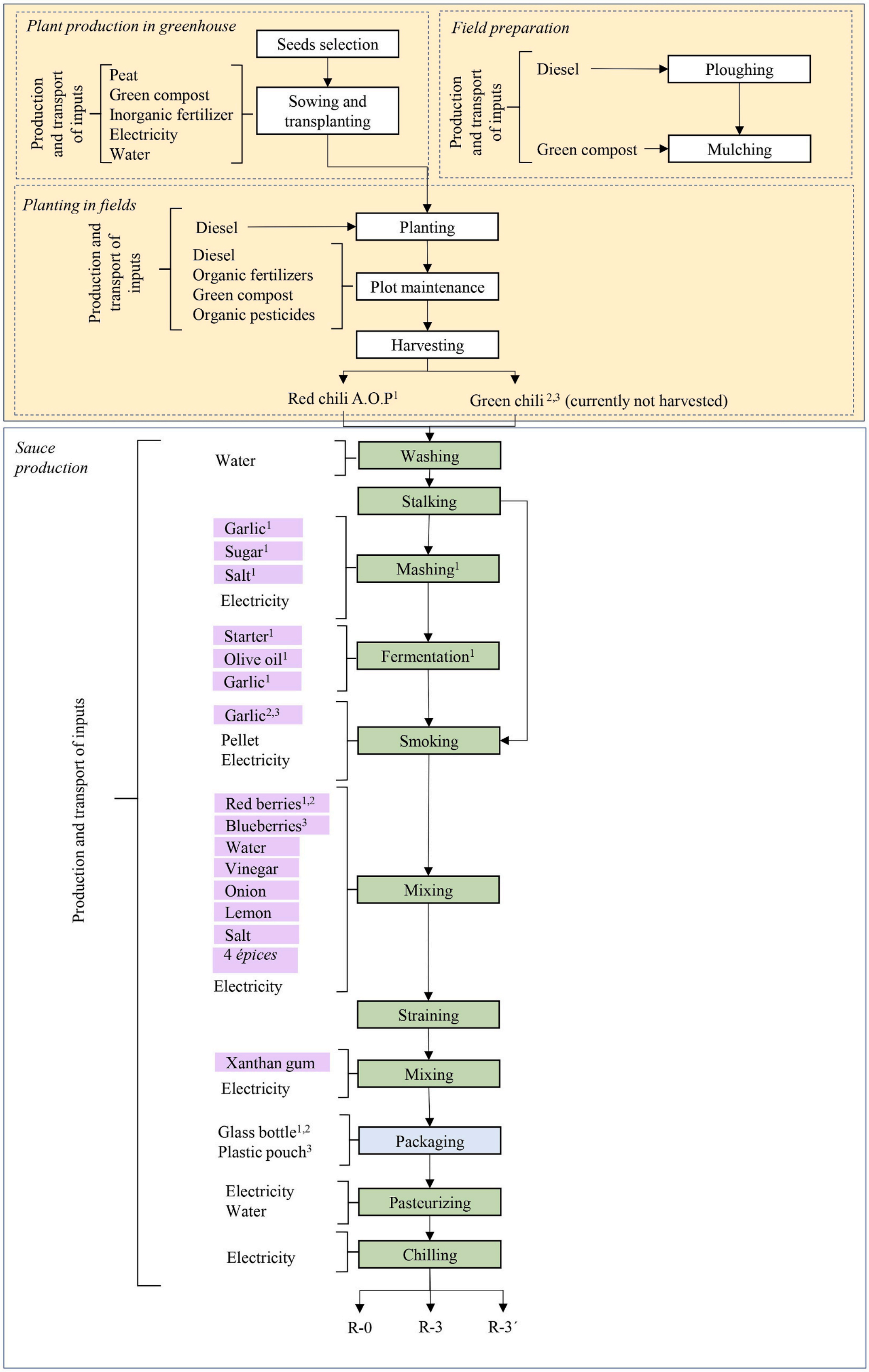

Fig. 2. System boundaries of the case study. Studied subsystems are highlighted in colours: chili production (yellow), secondary ingredients (purple), process (green), packaging (light blue). Numbers: (1) exclusively for R-0, (2) exclusively for R-3, (3) exclusively for R-3'. Note: R-0: reference prototype sauce based on red chili. R-3: Prototype sauce based on green chili (byproduct) and optimized processing (no fermentation). R-3': Final prototype sauce based on green chili with improvements in secondary ingredients (local blueberries) and packaging (plastic pouch). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

standardization 140, 2006) for conducting LCAs. The case study concerns the comparison of three hot sauces in which the chili produced in Espelette is the main ingredient. The prototype R-3 is the result of CCD (stakeholders for product conceptualization, and consumers' sensory panel for prototype selection), and the prototype R-3′ represents the result from combining CCD and LCA methodologies (LCA is used for eco-improvement of the selected prototype through hot-spot identification). The R-0 is a theoretical reference system to which the outputs of the CCD-LCA methodologies were not considered.

The goal of the study was to evaluate environmental impact among the three products considering the different unit operations involved in the production of the sauce. The scope of the study included the cultivation and transport of all the ingredients, as well as the processing in a kitchen context and the packaging material of the product ready for distribution ("*cradle-to-gate*" scope).

2.3.2. *Functional unit*

The functional unit (FU) is one bottle of 150 g of hot sauce at packaging stage gate.

2.3.3. *System boundaries and assumptions*

The system boundaries of this study were considered from the production of the ingredients to the final packaged product ready for distribution. The three aforementioned prototype sauces were compared. As shown in Fig. 2, the entire sauce elaboration process has been divided into four subsystems:

- Subsystem 1: chili production. The system boundaries include the production, transport, and use of energy (electricity and fuels), water, and cultivation inputs (peat, compost, fertilizers, pesticides), to whose emissions are accounted for. Economic allocation was applied to distribute the impacts between agricultural co-products. Green chili is a co-product of red chili production currently without commercial value; therefore, no environmental burdens were attributed to this raw material from the cultivation phase, only from transport phase. To explore the effect of potential future changes in their value, a sensitivity analysis of the economic allocation was conducted, exploring two additional scenarios where green chilis reach i) half, and ii) a similar market value to red chilis (Supplementary Material, Tables S5a,b,c. Figs. S1a,b,c).
- Subsystem 2: secondary ingredients. Including the entire life cycle of the supplementary ingredients used for sauce elaboration (garlic, sugar, salt, starter, olive oil, water, frozen red berries, organic blueberries, vinegar, onion, lemon, salt, 4 *épices*, xanthan gum).
- Subsystem 3: processing operations. Including the use of energy and resources for the processing of the ingredients to make the sauce (washing, smoking, squeezing, mixing, pasteurizing, and chilling). The fermentation process of R-0 did not require energy inputs because it is traditionally conducted at room temperature, and the mashing process was very brief, therefore it was not included in the analysis.
- Subsystem 4: packaging. For the R-0 and R-3 prototypes a glass bottle of 150 g of capacity was assumed, as it is the conventional packaging used in the product category. An alternative packaging was considered for the R-3′ prototype: a plastic pouch (nylon, PET, PP, and PE) of similar capacity.

2.3.4. *Inventory analysis and data collection*

Local data for cultivation of chilis (red and green) and blueberries were obtained through questionnaires completed by local producers in the study area. For the rest of the ingredients (garlic, lemon, onion, vinegar, salt, 4 *épices*), production data were taken from Agribalyse 3.1 database (Asselin-Balençon et al., 2022). Due to the lack of data on xanthan gum, guar gum was used as a proxy from the World Food LCA Database 3.5 (Nemecek et al., 2019).

Data concerning the sauce elaboration process (type and quantity of ingredients, energy, water consumption, and waste generation) was collected during the sauce-making process in the facilities of Basque Culinary Center. Inventory data of packaging materials and energy related consumptions were estimated from Ecoinvent 3.8 database.

2.3.4.1. *Cultivation of chilis.*

Inventory data for chili production is shown in Table 1. The extension of the studied field was 12 ha with a productivity of 8 ton/ha for red chili and 2 ton/ha for green chili (year 2021), for which a total of 250000 seedlings were used. For seedling and plant production, a blend of peat and green compost was used as a substrate (1:1) to which a synthetic fertilizer was added (1.6 kg/ton). Electricity was used for seedlings' growth, and water to irrigate the young plants.

In the field, green compost was used for soil maintenance and commercial organic fertilizers to stimulate plant growth. Nutrients derived from crop residues were also accounted for. Likewise, organic pesticides were used to avoid and eliminate insects and molds. Diesel was used for field work operations. The water for plant irrigation came from rainwater; thus, it was not included in the inventory. The fruits were harvested manually.

Estimation of direct and indirect emissions of N_2O to the atmosphere caused by the application of nitrogenous fertilizers and crop residues, as well as NO_3^- leaching to water were based on tier 1 calculations described in IPCCIntergovernmental panel on climate change (2019). Emissions of NH_3 were estimated based on models from the EMEP/EEA (2019). Estimation of phosphorus emissions to water derived from fertilizer application was based on the emission factors stated by Struijs et al. (2011). Emissions due to the use of pesticides were calculated based on the assumption that 100% of the applied pesticide was emitted to soil.

2.3.4.2. *Secondary ingredients.*

Inventory data for the sauce production is shown in Table 2. The main differences rely on the type of chili used (red vs green), and the type of red berries used (mixture of frozen red berries conventionally produced vs organic blueberries locally produced). Likewise, sugar, inoculum, and olive oil were used in the R-

Table 1
Inventory data for chili cultivation per FU (150 g of sauce). All input data is from primary sources.

Inputs	Amount[a]	Unit
Water	259.9	ml
Electricity	7.9	Wh
Seedlings	2	u
Green compost	78.7	g
Organic nitrogen fertilizer, as N	1.2	g
Organic phosphorous fertilizer, as P_2O_5	0.8	g
Organic potassium fertilizer, as K_2O	1.1	g
Azadirachtin ($C_{35}H_{44}O_{16}$) (Organic insecticide)	0.3	μl
$Cu(OH)_2$ (Organic fungicide)	0.01	g
Diesel	0.6	ml
Outputs	**Amount**	**Unit**
Red chili	65.4	g
Green chili (discarded as crop residue)	16.4	g
Emissions	**Amount**	**Unit**
Air		
Dinitrogen monoxide (N_2O)	0.05	g
Nitrogen monoxide (NO)	0.01	g
Nitrogen oxides (NO_x)	1.7E-02	g
Ammonia (NH_3)	0.4	g
Water		
Nitrate (NO_3-)	2.5	g
Phosphorus (P)	2.2E-0.5	g
Soil		
Copper (Cu)	0.01	g
Azadirachtin (Organic insecticide)	0.3	μl

[a] Productivity of 8ton/ha for red chili and 2 ton/ha for green chili (discarded).

Table 2
Inventory data of the ingredients (gross amount) used in R-0, R-3, and R-3′ per FU (150 g of sauce) and in percentage of the total mass of the product (%). All the data is from primary sources.

Ingredients	R-0		R-3		R-3′	
	g	%	g	%	g	%
Red chili	65.4	30.0	–	–	–	–
Green chili	–	–	66.6	30.8	66.6	30.8
Garlic	3.4	1.6	3.5	1.6	3.5	1.6
Sugar	3.4	1.5	–	–	–	–
Salt	3.9	1.8	3.9	1.8	3.9	1.8
Starter	0.1	0.0	–	–	–	–
Red berries	48.0	22.0	48.9	22.6	–	–
Blueberries	–	–	–	–	48.9	22.6
Purple onion	11.3	5.2	11.6	5.3	11.6	5.3
Water	41.1	18.8	41.9	19.4	41.9	19.4
Cider vinegar	5.1	2.3	5.3	2.4	5.3	2.4
Lemon (juice)	33.0	15.1	33.6	15.5	33.6	15.5
4 *épices*	0.8	0.3	0.8	0.3	0.8	0.3
Xanthan gum	0.3	0.1	0.3	0.1	0.3	0.1
Olive oil	2.7	1.2	–	–	–	–
Total	218.4	100.0	216.2	100.0	216.2	100.0

Note: R-0: reference prototype sauce based on red chili. R-3: Prototype sauce based on green chili (byproduct). R-3': Final prototype sauce based on green chili with improvements in secondary ingredients (local blueberries) and packaging (plastic pouch).

0 recipe for fermentation purposes but were not used in the R-3 and R-3′ prototypess. These variations resulted in slight differences in the ingredients percentage (%) of the different sauce prototypes.

2.3.4.3. Processing unitary operations. The processing unitary operations were similar for all prototypes. Chilis were washed in tap water in a 1:3 ratio and the peduncles were removed. In the case of R-0, a blending process was applied to chili, garlic, sugar, and salt to facilitate the mash fermentation process. In all the prototypes chilis were smoked together with peeled garlic in an electric smoker at 72 °C for 150 min and mixed with the rest of the ingredients (frozen red berries -R-0 and R-3- or organic blueberries -R-3'-, water, vinegar, onion, lemon juice, salt, 4 *épices*) with the aid of a kitchen robot. The mixture was strained manually. The solid part was discarded (~20%) and the liquid part was thickened with xanthan gum. The resulting sauces were packaged and pasteurized in a thermostatic bath at 77 °C for 1 min for product stabilization (Fellows, 2022; Smith and Stratton, 2006). Water use was assumed for 10 cycles. Finally, the packaged samples were cooled at 4 °C with a blast chiller (Table 3).

2.3.4.4. Packaging. The details on the packaging materials used is reported in Table 4. The glass packaging proposed for R-0 and R-3 was a glass bottle with aluminium cap, based on the one already used by producers from Espelette for this product category. The plastic

Table 3
Inventory of the processing in R-0, R-3, and R-3′ per FU (150 g of sauce). All the data is from primary sources.

Process	Amount	Unit
Washing		
Water	0.2	l
Smoking		
Electricity	14.6	Wh
Wood pellets	4.0	g
Squeezing		
Electricity	0.2	Wh
Mixing		
Electricity	4.0	Wh
Pasteurizing		
Electricity	17.4	Wh
Water	0.02	l
Chilling	13.5	Wh

Table 4
Packaging materials in R-0, R-3, and R-3'.

Packaging	Material	Amount per FU (g)
R-0 and R-3: Glass bottle	Glass	136
	Aluminum	5
R-3': Plastic pouch	Nylon (NY)	0.8
	Polyethylene terephthalate (PET)	0.8
	Polypropylene (PP)	4
	Polystyrene (PE)	3.5

Note: R-0: reference prototype sauce based on red chili. R-3: Prototype sauce based on green chili (byproduct). R-3': Final prototype sauce based on green chili with improvements in secondary ingredients (local blueberries) and packaging (plastic pouch).

packaging of R-3′ was proposed as an environmental improvement. It corresponded to a pouch of 150 ml of capacity, with dimensions of 10 x 17 × 6 cm based on an existent option for sauce packaging in the current market. Secondary packaging was not included in the study.

2.4. Impact assessment

For the quantification of the environmental impacts, the CML-IA baseline 3.07 midpoint method was applied (CMLDepartment of Industrial Ecology, 2016). The impact categories studied were global warming (GWP 100a), ozone layer depletion (OLD), acidification (ACD), eutrophication (EUT), and abiotic depletion (AD). The characterization factors of the main greenhouse gases for the selected method were: $CO_2 = 1$; $CH_4 = 28$; $N_2O = 265$. Given the relevance of N_2O emissions to ozone layer depletion and following recommendations from the scientific literature (Lane and Lant, 2012), an impact potential factor for this substance was also incorporated in the impact assessment (0.018 kg CFC-11e/kg N_2O). Likewise, the Cumulative Energy Demand (CED) method was used to quantify the primary energy required for product development. Data was analysed using SimaPro 9.5 software (PRé Sustainability, 2023).

3. Results and discussion

3.1. General overview

The environmental impacts of the three prototypes are shown in Table 5 and Fig. 3. The final prototype R-3' (FU = 150 g of packaged sauce) presented values of GWP = 0.11 kg CO2-eq., OLD = 4.33E-07 kg, CFC-11 eq., ACD = 6.47E-04 kg SO2 eq., EUT = 3.07E-04 kg PO43- eq., AD = 9.93E-07 kg Sb eq., CED = 1.88 MJ, reflecting an overall reduction in environmental impact across the different categories compared to the baseline sauce R-0 (from 57% to 91%). These reductions are linked to the improvements implemented through the eco-design process. Mainly, (i.) the use of green chili as the main ingredient of the sauce (input from CCD), (ii) the replacement of red berries (secondary ingredient) by organic blueberries (input from LCA), and (iii.) the use of plastic packaging instead of glass (input from both CCD and LCA). However, their contribution to environmental improvement differs substantially depending on the category analysed.

One of the main interests of the local stakeholders was to avoid food waste. Thus, the main change from the baseline (R-0) to the intermediate sauce prototype (R-3) was the use of green chilis derived from red chili production, which are currently discarded. In the presented system, green chilis were handled as co-products of red chili production, and their impact was allocated based on economic value. Because green chilis had no current market value, no burden was accounted for their production. Nevertheless, alternative scenarios for economic allocation were explored, and the use of green chilis was still significantly positive in terms of environmental performance in all of them (Table S5, Fig. S1). Therefore, the contribution of chilis decreased in all impact categories when comparing R-0 and R-3/R3', but this reduction was more

Table 5
Environmental impacts per FU (150 g) of the three prototypes (R-0, R-3, R-3′) in total and per subsystem. (Economic allocation: red chili = 100%, green chili = 0%).

Impact category	Subsystem	R-0	R-3	Diff % (R-3 - R0)	R-3′	Diff % (R-3' - R0)
GWP 100a (kg CO_2 eq.)	**Total**	**3.73E-01**	**3.41E-01**	**9**	**1.14E-01**	**69**
	Chilis	2.57E-02	1.21E-03	95	1.21E-03	95
	Secondary ingr.	7.14E-02	6.36E-02	11	5.73E-02	20
	Processing	2.52E-02	2.52E-02	0	2.52E-02	0
	Packaging	2.51E-01	2.51E-01	0	3.01E-02	88
OLD (kg CFC-11 eq.)	**Total**	**2.08E-06**	**7.90E-07**	**62**	**4.33E-07**	**79**
	Chilis	1.08E-06	1.02E-09	100	1.02E-09	100
	Secondary ingr.	7.28E-07	5.17E-07	29	3.55E-07	51
	Processing	6.14E-08	6.14E-08	0	6.14E-08	0
	Packaging	2.11E-07	2.11E-07	0	1.54E-08	93
ACD (kg SO_2 eq.)	**Total**	**3.09E-03**	**2.22E-03**	**28**	**6.47E-04**	**79**
	Chilis	7.32E-04	5.33E-06	99	5.33E-06	99
	Secondary ingr.	5.83E-04	4.43E-04	24	4.11E-04	29
	Processing	1.18E-04	1.18E-04	0	1.18E-04	0
	Packaging	1.66E-03	1.66E-03	0	1.12E-04	93
EUT (kg $PO4^{3-}$ eq.)	**Total**	**2.09E-03**	**1.19E-03**	**43**	**3.07E-04**	**85**
	Chilis	7.98E-04	1.38E-06	100	1.38E-06	100
	Secondary ingr.	4.28E-04	3.30E-04	23	1.77E-04	59
	Processing	1.03E-04	1.03E-04	0	1.03E-04	0
	Packaging	7.57E-04	7.57E-04	0	2.52E-05	97
AD (kg Sb eq.)	**Total**	**1.15E-05**	**1.13E-05**	**2**	**9.93E-07**	**91**
	Chilis	4.72E-08	1.78E-08	62	1.78E-08	62
	Secondary ingr.	1.41E-06	1.24E-06	12	8.75E-07	38
	Processing	7.67E-08	7.67E-08	0	7.67E-08	0
	Packaging	9.93E-06	9.93E-06	0	2.30E-08	100
CED (nrf) (MJ)	**Total**	**4.34**	**4.11**	**5**	**1.88**	**57**
	Chilis	1.42E-01	1.85E-02	87	1.85E-02	87
	Secondary ingr.	9.89E-01	8.73E-01	12	9.10E-01	8
	Processing	1.84E-01	1.84E-01	0	1.84E-01	0
	Packaging	3.03	3.03	0	7.63E-01	75

Note: R-0: reference prototype sauce based on red chili. R-3: Prototype sauce based on green chili (byproduct) and optimized processing (no fermentation). R-3': Final prototype sauce based on green chili with improvements in secondary ingredients (local blueberries) and packaging (plastic pouch). GWP 100a = global warming potential referred to 100 years, OLD = ozone layer depletion, ACD = acidification, EUT = eutrophication, AD = abiotic depletion, CED (non-renewable fossil) = cumulative energy demand.

pronounced in those in which the agricultural production has a higher relevance, such as OLD (−52%), EUT (−38%) and ACD (−24%), and to a less extent, GWP (−7%).

During the cultivation phase, plants do not consume all the nutrients (N-P-K) available from fertilizers, resulting in emissions and losses of different substances to the environment. Results of the present research showed that chili cultivation led to significant nitrous oxide (N_2O) emissions, which is one of the most damaging substances of the ozone layer (Ravishankara et al., 2009). In addition, fertilizer application led to ammonia (NH_3) emissions, which, together with other compounds resulting from fertilizers leaching, such as nitrate (NO_3^-) and phosphorus (P), and through atmospheric deposition, ultimately contributes to the acidification of soil and water surfaces (OECDOrganization for economic co-operation and development, 2013) and the eutrophication of the latest. Previous studies on chili production also pointed to fertilizers as relevant contributors to the impact in the aforementioned categories (Wang et al., 2018; Naderi et al., 2019; García-García and García-García, 2022).

Secondary ingredients of the sauce also had a relevant contribution to impacts related to the cultivation stage. Considering the results from sensory tests conducted in a previous study (Torán-Pereg et al., 2023b), some of the secondary ingredients used in R-0 for fermentation purposes (sugar, olive oil, and lactic acid bacteria), were excluded in R-3. Consequently, the impact of the secondary ingredients from this prototype slightly decreased if compared to R-0.

When applying a hotspot analysis to the LCA results of the R-3 prototype, the packaging was identified as the subsystem with the highest contribution to GWP (74%), ACD (70%), EUT (59%) and AD (89%). In the case of OLD, the secondary ingredients were the main contributors (70%) and remained the second main contributor in the rest of the impact categories. Therefore, a more sustainable version was proposed, resulting in the R-3′ prototype, in which different berries (organic blueberries instead of the mixture of conventional red berries), and an alternative packaging option (plastic pouch instead of a glass bottle) were used. These changes resulted in a significant decrease in the environmental impact of the prototype.

The changes associated with the berries selection showed that the principal variations did not only came from the change of the ingredient, but from their cultivation methods. The use of fertilizers in red berries (mainly in blueberry and blackberry production) was the main cause of OLD (N_2O emissions), ACD (NH_3 and NOx), and EUT (NH_3 and NO_3-) in the R-3 prototype. On the other hand, organic blueberries (proposed for R-3′), were produced with a very low input of fertilizers, and resulted in substantial impact reductions in these categories. The main impact of organic blueberry production comes from the petrol combustion of working machinery, contributing to some categories such as GWP or CED. Pérez et al. (2022) investigated the environmental performance of small-scale blueberry production in the Northern Spain region and reported that the use of fossil fuels for brush-cutting machinery significantly contributed to the environmental impact of the orchards. This issue especially affects organic crops, because the use of machinery for soil management is required due to restrictions on the use of chemical herbicides (Mohamad et al., 2014).

Carbon sequestration through biomass growth was also considered in the woody berries (blueberry, blackberry, and currant). Organic blueberry production resulted in a better balance between carbon inputs and outputs than conventional red berries production. These results were in line with the ones reported by Aguilera et al. (2014), who studied fruit tree orchards in the Mediterranean region of Spain. If carbon sequestration had been neglected in our study, the greenhouse gases (GHGs) balance would have been favourable for red berries managed under a conventional system and no reduction in GWP category would have been achieved.

The changes in packaging showed that the plastic pouch was more favourable than the glass bottle for different reasons. Glass manufacture requires a high amount of energy (mainly fossil fuels such as oil, natural

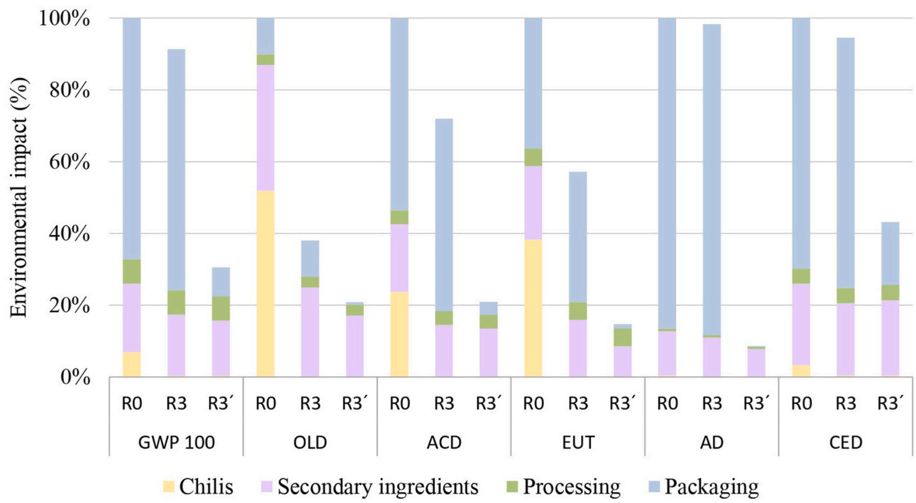

Fig. 3. Contribution analysis of the studied subsystems of the three prototypes (R-0, R-3, R-3′). (Economic allocation: red chili = 100%, green chili = 0%). **Note**: R-0: reference prototype sauce based on red chili. R-3: Prototype sauce based on green chili (byproduct) and optimized processing (no fermentation). R-3': Final prototype sauce based on green chili with improvements in secondary ingredients (local blueberries) and packaging (plastic pouch). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

gas, and coal resources), and its combustion results in significant emissions of GHGs (e.g., CO_2, CH_4), affecting the GWP. Besides, during glass production, sulphur dioxide (SO_2), nitrogen oxides (NOx), and ammonia (NH_3) are emitted, contributing to the acidification (ACD) of the environment. Glass produced entirely from virgin raw materials was assumed in our study. However, the high impact on the depletion of abiotic resources (AD) is explained by the extraction of metals and mine operations conducted to manufacture the aluminium cap. Different studies have stated the impacts of glass packaging, suggesting alternative options to decrease the impact such as the use of recycled glass, reusing bottles, lighter glass packaging, or using plastic alternatives (Humbert et al., 2009; Amienyo et al., 2014; Ferrara et al., 2021), being the last one among the most favourable options. Plastic pouches have been reported as sustainable packaging alternatives with relatively low environmental impact for several food products such as milk (Sun et al., 2021), ready-to-eat meals (Gulcimen et al., 2023) and sauces (IFEUInstitute für energie und unweltforschung, 2021). Recent studies have pointed out that the emptiability (ability of packaging to be emptied entirely), or food loss probability of the different packaging options could have a considerable influence on the environmental impact of the whole product (Conte et al., 2015; Molina-Besch et al., 2019). Wohner et al. (2020) showed that a glass bottle was more favourable option than a polypropylene bottle because the capacity to empty the content (ketchup) was more difficult in the latest. These researchers proved that the food waste that remained inside the packaging had a greater impact than the packaging itself, which resulted in higher costs for consumers.

The final version of the sauce, prototype R-3′, captured some environmental improvement strategies identified during the design and development process, but further optimization could be explored. The main hotspots of this version were the secondary ingredients (with contributions between 53% and 82%) and packaging (with contributions between 8% and 41%). Regarding OLD, blueberries, lemon, and the mix *4 épices* showed similar contributions. The latest, although used in very small amounts, gave the product a characteristic flavour note. The impact of the lemon juice on the flavour profile was lower and could be excluded from the formulation if only considering consumers' opinion, but it had an important role to decrease the pH of the product and ensure safety and an extended shelf life of the sauce. In terms of ACD and EUT a lower consumption of petrol in blueberry production could be possible by replacing conventional machinery with electrical ones (Pérez et al., 2022). Regarding packaging, energy from renewable sources and reduction of emissions during plastic transformation should be optimal to reduce impacts on CED and GWP.

Evaluating the environmental impact of the developed sauce in absolute terms was difficult due to the lack of LCA studies on this specific type of food. Andersson et al. (1998) reported that processing and packaging were the subsystems with the most significant environmental impacts in the life cycle of ketchup (farm to grave); however, the fertilizers and pesticide emissions of tomato cultivation were not considered, and the major impacts of foods often come from the farming stage (Poore and Nemecek, 2018). In terms of GWP, the processing stage reported by these researchers had higher emissions than the one shown in the present study (about 440 kg CO_2-eq/1000 kg ketchup), maybe because processes such as tomato concentration and sterilization (thermal and electric energy) required high energy; no concentration was used to make the sauce proposed in the present research, and pasteurization was the conservation method chosen for the product. Yang et al. (2020) studied the environmental performance (farm to gate) of monosodium glutamate, a well-known seasoning used in the food industry for flavour enhancement; the GWP reported was almost tenfold higher in emissions (6.26 t CO_2eq./t of MSG) than the one of the present processes, which mainly came from energy consumption during manufacture. Fantozzi et al. (2015) studied the carbon footprint (cradle to gate) of an olive oil-truffle sauce and identified a higher impact for this product (1.93 kg CO_2-eq./kg of sauce) than the one determined in the present research, being the cultivation of olive trees (fertilizer emissions) and packaging (glass) the main hotspots. Publicly available databases of carbon footprint for food products (e.g.: Concito (n.d), CarbonCloud (n.d)) estimate sauces in a range between 1.5 and 4.0 kg CO_2-eq/kg (including packaging), reporting a value of 1.82 kg CO_2-eq/kg for chili sauce (Concito, n.d). Using this data as reference, the baseline sauce prototype (R-0) showed a higher carbon footprint (2.49 kg CO_2-eq/kg) if compared with similar products, but the improved prototype (R-3') resulted in a substantial reduction of the impact (0.76 kg CO_2-eq/kg).

3.2. Limitations and assumptions of the study

It is important to highlight that the different approaches and assumptions made in the reviewed LCA studies of similar products make difficult the comparison with our results. Also, it must be noted that our study applies an attributional LCA approach aimed at analyzing the current status quo, in which green chilis hold no economic value.

However, if the product becomes successful in the market, green chilis could transform from being considered waste into valuable products, potentially changing the environmental load attributed to both, red and green chilis. To explore this effect, a sensitivity analysis of the economic allocation for green and red chilis has been included in the Supplementary Materials 5. According to the results, in the scenario where the green chilis are half the price of red chilis, the hot sauce (R-3′ product) would show a reduction of the environmental impact between 56 and 91% with regards to the baseline. In the scenario where both chilis reach a similar price, the decrease would still be substantial (38–91%), although moderate in some impact categories (OLD, ACD, EUT).

Consumers' acceptability of the final prototype (R-3′) was evaluated through home-use-test approach, involving sensory attributes and overall liking (Torán-Pereg et al., 2024). Results showed high acceptance for R-3' prototype (liking = 6.52 ± 1.93 in a 9-point scale). However, the consumer preferences regarding a prototype sauce based on red chilis (R-0) were not studied and could not be compared. A similar acceptability was assumed, and therefore no potential effect was captured in the assessment. While color is the main difference among them, sensory properties could also vary, affecting consumers response. Likewise, the potential influence of packaging design on food losses was not evaluated, because of being considered out of the system boundaries. Therefore, the interpretation of the impact reduction achieved through packaging in the present study should be considered tentative because it only assesses the material of the package, and no other implications in terms of potential food waste. Further research should explore consumers' opinion and the real use of the proposed final prototype to assess the impact of the "usability" of the sauce.

3.3. Implications for future research: barriers and opportunities

Beyond the comparison with similar products, the present study highlights the reduction achieved through the development of the product by using research methods from various disciplines for including consumers' views, revealing the potential of combining CCD and LCA methodologies. A similar approach was applied by Thomas et al. (2021) for a study case of spirulina-based food products, proposing a framework based on creating inventory modules and applying transversal analyses of developed prototypes through focus groups with consumers. Our research did not follow this systematic framework but presented several similarities in the approach and in the conclusions revealed. Subdividing the system in modules was key. It simplifies the analysis and interpretation, which helps to identify hotspots and eco-design options aligned with consumers' perceptions. When exploring different pre-concepts for a spirulina-based jam, Thomas et al., 2021 also identified ingredients as the key contributors to the environmental impact, highlighting the importance of the early stage of the innovation process, as it determines the characteristics of the future product.

In our study, implementing the environmental perspective from the beginning of the CCD approach conditioned the conception and early development of the product. This involved a substantial reduction (R-0 vs R-3) of some impact categories (OLD = 62%, ACD = 28%, EUT = 43%) attributed to the selection of the agricultural discard (green chili) and process optimization by consumers' evaluation of sauce prototypes. Likewise, CCD allowed to integrate consumers' insights (e.g.: local ingredients, organic production, eco-friendly packaging) when LCA pointed out the potential pathways for product improvement in aspects like secondary ingredients and packaging. This resulted in additional reductions (R-3 vs R-3') of other impact categories such as CC (60%), AD (89%) and CED (52%).

Among food groups, fruit and vegetables show one of the highest levels of loss globally (23%) (FAO, 2019). Estimates in Europe suggest over a third of total farm production of fruit and vegetables is lost due to cosmetic standards (Porter et al., 2018). Considering the rising concern about global food waste, the approach described in this study could be useful for similar contexts dealing with horticultural production. Food research can contribute to address food loss by developing upcycled foods (also called value-added surplus products (VASP)) which are based on ingredients usually discarded. Many different options for converting horticultural food surplus into VASP have been explored, including snacks, drinks, vegetable powder, fermented products, or like in this case, a sauce. Nevertheless, the main barrier for commercial feasibility of such novel foods is usually consumer acceptance, as they may perceive VASP of poor safety or quality (Bhatt et al., 2018; McCarthy et al., 2020).

Involving consumers in the design process (CCD) have shown to be an effective approach, allowing to consider their insights. To validate the acceptance of the final eco-designed sauce prototype (R-3′), a home-use-test was performed (involving a different consumers' group) in a real context of consumption (Torán-Pereg et al., 2024). A high acceptance of the product was reported for sensory attributes (5.77–6.40 in a 9-point scale). Moreover, overall liking increased significantly after communicating the product-making process (6.11 vs 6.52 respectively) which indicates the use of a byproduct was not a barrier in this case. However, results indicated a contradiction with regards to packaging, since glass was perceived by consumers as a lower footprint material vs plastic pouch. In this line, Thomas et al. (2021) also pointed out trade-offs between packaging preferences (glass) and the environmental impact of this material with respect to plastic alternatives. Similar studies have pointed out the consumers perception towards overestimating the sustainability of glass packaging (Groth et al., 2023). Consumers' perception may overestimate the influence of end-of-life stages (i.e.: recycling potential) on the impact of packaging, suggesting that an effort to communicate the environmental adequacy of plastic packaging should be emphasized during the market launch of eco-designed products, like the sauce developed in this study.

The importance of co-creation and prototyping during the early stages of sustainability-oriented innovation processes has been highlighted by recent studies (Dokter et al., 2023; Gonera et al., 2023). Despite this, there are few examples of co-creation of food products in the scientific literature (Sijtsema et al., 2020).Moreover, these iterative processes usually include the interaction of suppliers and manufacturers involved in the production, but the integration of consumers into the design process is rare (Gonera et al., 2023), which may lead to neglect aspects related to the final product acceptance (Park and Tahara, 2008). This can be of particular relevance when developing new food products, as consumers perceptions are influenced by many complex factors including intrinsic (e.g.: flavour, texture) and extrinsic properties (e.g.: labels, claims, packaging attributes). When analysing the consumers response to the hot sauce developed in this case study, the overall liking of different sensory parameters increased (from 6.11 to 6.52) after knowing about the product-making process characteristics (Torán-Pereg et al., 2024). While sensory properties prevalent as the major driver of acceptance in food products, extrinsic information related with sustainability claims have shown to be important, especially for some consumer segments (Bernard and Liu, 2017), and particularly in the case of VASP (Bhatt et al., 2018; McCarthy et al., 2020).

Consumers' engagement and participation in food production chains has been pointed out as a potential driver of behavioural change towards sustainable food consumption. For example, Puigdueta et al. (2021) applied a LCA approach to analyze the food patterns of citizens involved in urban agriculture activities, observing a low carbon footprint of their diets. In order to be effective, current challenges in the food system require the active participation of citizens in the design of policy interventions that are going to affect them. Depending on the scope, this can be done in different ways, such as living labs, citizen assemblies or participatory research groups, like the one that led to product conceptualization in this case study (Torán-Pereg et al., 2023a). Experiences of these community-based initiatives involving local stakeholders, help to close the gap between supply and consumption sides, promoting more sustainable production and consumption pathways, such as shorter supply chains, and potentially inducing behavioural changes (Doherty et al., 2023). Moreover, they can lead to innovative business models in the form of food hubs where participants can identify diverse opportunities for surplus agricultural products, from novel food concepts (i.e.: VASP) to specialized retailers for discarded vegetables (Hezarkhani et al., 2023).

4. Conclusions

Our work presents the potential benefits of designing and developing new products combining CCD and LCA methodologies through a specific case study. Integrating the interdisciplinary approach from the beginning involved the engagement and interaction with different actors of the food chain from the early stages of the design. This was crucial to identify opportunities and guide the whole development process without compromising the potential success of the product. As a result, the selection of a horticultural discard (green chili) as the main ingredient determined a substantial reduction of some impact categories like eutrophication (EUT = 43%) or ozone layer depletion (OLD = 62%), with regards to the baseline product. The CCD approach also allowed to consider consumers' insights (e.g.: local ingredients, eco-friendly packaging) when selecting the options for prototype improvement identified through LCA. Changes in secondary ingredients and packaging achieved reductions in energy-related categories such as global warming (60%), and cumulative energy demand (52%). The final product, not only resulted in an improvement on its environmental footprint respect to the baseline (57–91%), but showed a high level of consumers' acceptance. Despite the limitations of the approach described, results have shown that combining qualitative and quantitative research methods from various disciplines could be effective in developing new food products that seek to meet the demands of the food value chain agents while considering the environmental aspects. Further research in different product categories should be conducted to encourage the food industry to consider this cross-disciplinary approach useful and profitable to improve the food system from a sustainability standpoint.

CRediT authorship contribution statement

Paula Torán-Pereg: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Stéfani Novoa:** Writing – review & editing, Methodology, Conceptualization. **Laura Vázquez-Araújo:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Guillermo Pardo:** Writing – review & editing, Supervision, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare they have no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.144983.

Data availability

Data will be made available on request.

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