Environmental performance of mixed animal and plant protein sources for designing new fermented foods

Juliette Huguet, Christophe Chassard, René Lavigne, Françoise Irlinger, Isabelle Souchon, Stephan Marette, Anne Saint-Eve, Caroline Pénicaud

Cleaner Environmental Systems 9 (2023) 100115

Contents lists available at ScienceDirect

Cleaner Environmental Systems

journal homepage: www.journals.elsevier.com/cleaner-environmental-systems

Environmental performance of mixed animal and plant protein sources for designing new fermented foods

Juliette Huguet [a], Christophe Chassard [b], René Lavigne [b], Françoise Irlinger [a], Isabelle Souchon [c], Stephan Marette [d], Anne Saint-Eve [a], Caroline Pénicaud [a,*]

[a] Université Paris-Saclay, INRAE, AgroParisTech, UMR SayFood, 91120, Palaiseau, France
[b] Université Clermont Auvergne, INRAE, Vetagro Sup, UMRF, 15000, Aurillac, France
[c] Avignon Université, INRAE, UMR SQPOV, 84000, Avignon, France
[d] Université Paris-Saclay, INRAE, AgroParisTech, Paris-Saclay Applied Economics, 91120, Palaiseau, France

ARTICLE INFO

Keywords:
Life cycle assessment (LCA)
Fermentation
Sustainable diets
Sustainable proteins
Legumes
Dairy products

ABSTRACT

In the food industry, there is currently a great deal of interest in the development of plant-based alternatives to dairy products. However, little is known about the ways in which differences in formulation and/or processing affect the potential environmental benefits of such products. In this study, we investigated the environmental performance of four new fermented products created using different mixtures of plant- (pea) and animal- (cow milk) derived protein sources and prepared using a cheese-technology process (Camembert production). Life cycle assessments (LCAs) were performed that included all steps from the agricultural production of ingredients to the generation of the final ready-to-eat product. The goals were to identify the hotspots of this production system and to compare the different products to each other as well as to other common fermented or legume-based products (Camembert, tofu, hummus). The LCA results revealed that the two main hotspots for the mixed products were milk production (when used) and the ripening stage. All four products were similar with respect to the environmental impacts related to processing. Instead, with regard to the impacts of agricultural production, the products made with a higher proportion of pea protein were superior, providing clear evidence of the potential environmental benefit of pea-milk fermented foods. Overall, though, the mixed products did not present any environmental benefit compared to Camembert, hummus, and tofu due to the complex and energy-intensive nature of the manufacturing process. It is therefore critical that these processing steps be simplified and optimized in order to realize the environmental potential of such pea-based products.

1. Introduction

Modern food systems are facing numerous challenges related to the environment and human health, including mitigating climate change; protecting and enhancing biodiversity; reducing natural resource depletion; improving soil, air, and water quality; and preventing nutritional deficiencies and obesity. In Europe, it has been estimated that food production accounts for 20–30% of all environmental impacts (Tukker et al., 2006), and worldwide, it is responsible for a third of global greenhouse gas (GHG) emissions (Vermeulen et al., 2012). In particular, animal products have been singled out as having a particularly high environmental impact (Weidema et al., 2008). Reduced consumption of such products has also been recommended by recent health guidelines, which advocate for balanced diets that are adapted to the needs of consumers, have an appropriate caloric intake, and are composed of a variety of plant-based foods—with preference given to unsaturated fats over saturated fats—and with few animal-based foods, added sugars, refined grains, and highly processed foods (Willett et al., 2019). All of these concerns are compounded by the fact that the global population is predicted to increase to 10 billion by 2050, which will intensify the impacts of food production and consumption on both the environment and human health.

In addressing these challenges, one potential strategy may be the increased production and consumption of legumes, which have many potential benefits with regard to sustainability (Cusworth et al., 2021). A major one is the ability of legumes to fix nitrogen, which can help to decrease the use of mineral fertilization, thus reducing the GHG emissions associated with fertilizer production and application. In addition,

* Corresponding author.
E-mail address: caroline.penicaud@inrae.fr (C. Pénicaud).

https://doi.org/10.1016/j.cesys.2023.100115
Received 26 September 2022; Received in revised form 6 April 2023; Accepted 7 April 2023
Available online 8 April 2023

legumes release high-quality organic matter in soil, facilitate the circulation of soil nutrients, and improve soil water-holding capacity (Stagnari et al., 2017). Another advantage is that legumes are rich in protein and contain certain amino acids (notably lysine) that are otherwise difficult to source in plant-based diets (Willett et al., 2019). This makes legumes an interesting alternative to protein sources derived from animals.

One of the most popular types of animal products is cheese, particularly in Europe, where 39% of milk is used for cheese production (Eurostat, 2019). It is thus not surprising that plant-based alternatives to cheese have received considerable scientific attention in recent years (Grossmann and McClements, 2021). These alternative products contain three main types of ingredients: proteins, fats, and polysaccharides, predominantly from starches. The proteins used in plant-based cheese alternatives are mainly derived from pea, soy, lupin, potato, nuts, and corn, each of which is characterized by different physicochemical and functional properties with respect to emulsification, gelation, water-holding capacity, and flavor precursor properties. The choice of fat also plays an important role in determining the structure, texture, sensory quality, and nutritional profile of products, and common plant-derived options include avocado, rapeseed oil, cocoa, coconut, corn, palm, vegetable, safflower, sesame, soybean, or sunflower oils. Starches, mainly from tapioca, potato, or corn, are used in plant-based cheeses because of their ability to form a gel upon cooling, which traps fluids and other ingredients within the hydrocolloid networks. In their recent review, Grossmann and McClements (2021) hypothesize that the use of ingredients with lower environmental impacts than animal milk will most likely lead to the creation of more-sustainable alternatives to real cheeses, but the authors also underline that we currently lack the data to draw firm conclusions on the environmental benefits of plant-based alternatives to cheese.

To fill this gap, we investigated the environmental performance of new fermented products created using different combinations of plant and animal protein sources. The fermented products were manufactured using the cheese-technology process used to make Camembert, a very popular French cheese. Indeed, it has been suggested that the use of processing operations similar to those used to commercially manufacture regular cheeses represents a good opportunity to repurpose and add value to existing equipment and manufacturing facilities (Grossmann and McClements, 2021).

Here, environmental performance was evaluated using life cycle assessment (LCA) of all steps from agricultural production to the creation of the ready-to-eat product. Data were collected on-site during manufacturing, constituting a valuable resource for efforts to understand the environmental impacts of plant-based cheese alternatives. LCA is a standard method that enables quantification of the environmental impacts of a product, process, or service over its whole life cycle (ISO 14040:2006). LCA has been widely applied to the agrifood sector, and the number of food products that have been analyzed by LCA is constantly increasing (Cucurachi et al., 2019). One of the main outcomes of LCA is the identification of the major environmental impacts, the so-called hotspots, of a production process, which for food products is often the agricultural stage (Roy et al., 2009). LCA can also be used to compare different modes of production, such as, for example, scenarios of strawberry production that use different types of packaging (Matar et al., 2021). Finally, LCA can also enable comparisons between the environmental impacts of different products, as was recently performed for a variety of cheeses (Cortesi et al., 2022b).

The objectives of this study were thus (i) to identify the environmental hotspots of the production process of new fermented products based on mixtures of animal and plant protein sources and suggest ways to reduce them; (ii) to compare the environmental performance of different mixes; (iii) to compare the environmental performance of the studied products with that of Camembert, which uses the same manufacturing technology as the new products; and finally, (iv) to compare the environmental performance of our products with two other plant-based products, hummus and tofu.

This paper provides a unique analysis of the environmental impacts of plant-based alternatives to cheese, and makes a much-needed contribution to our understanding of the potential benefits and drawbacks of plant-based substitutes for dairy products. In particular, this information could be used to guide decision-making regarding further product developments by members of the food industry, policy makers, and consumers.

2. Materials & methods

2.1. Manufacturing process of the new fermented products

The new fermented products were all created using a cheese-making process (Camembert production) with pilot equipment that mimicked semi-artisanal production at the facility of a technology platform in Aurillac, France. The chosen plant protein source was the yellow pea (*Pisum sativum*), a legume commonly cultivated in northern Europe, including France, that is particularly rich in protein, fiber, and minerals (González et al., 2011). The fat source was rapeseed oil, chosen for its abundant omega-3 fatty acids. The products did not contain polysaccharides; gelation was instead ensured by the use of agar-agar and glucono-delta-lactone (GDL). Four products were created using different ratios of plant-based and animal-based (cow milk) protein in the mix. Details of the processing steps of the new fermented products are presented in the associated data paper and summarized in Fig. 1.

Briefly, the pea suspension and the reconstituted milk were prepared separately, each in a sterile bioreactor. The pea suspension was composed of pea protein isolate, tap water, salt, and rapeseed oil. We chose to work with protein isolate because it is a standardized raw material that could simplify product development. Furthermore, this kind of ingredient is often used in plant-based alternative foods, but its environmental performance has not been well documented in the literature. The reconstituted milk was composed of skimmed milk, tap water, salt, and rapeseed oil. The pea suspension and milk were then stored and transported to the mixing site (85 km away), where they were mixed with each other in different ratios: 100% pea, 75% pea (w/w), 50% pea (w/w), and 25% pea (w/w). The processing of the mixes involved the addition of agar-agar and GDL for texturing, and of lactic ferments and yeast cultures for fermentation. The mixes were then molded, yeasted (development of yeast on the surface of the products), and dried. Finally, the products were unmolded and ripened for 14 days.

2.2. LCA methodology

2.2.1. Goal and scope

The objective of the LCA was (i) to identify the environmental hotspots associated with the production of four new fermented products based on a mixture of animal and plant protein sources and suggest ways to reduce them; (ii) to compare the relative environmental performance of the different mixtures; (iii) to compare the environmental performance of these products with that of Camembert, the cheese produced with the same manufacturing technology; and finally (iv) to compare the environmental performance of our products with two other plant-based products: hummus and tofu.

An attributional approach was used to carry out the LCAs. The functional unit chosen to describe the systems was 1 kg of the final product. The studied system included all steps from the agricultural production of ingredients to the final ready-to-eat product.

2.2.2. Life cycle inventories

The data related to the novel fermented products were collected during the experiment in Aurillac (France), either through direct measurement during the experiment or from information provided by Greencell, the laboratory that manufactured the pea and milk suspensions. Simplified process flows are presented in Fig. 1 and details are

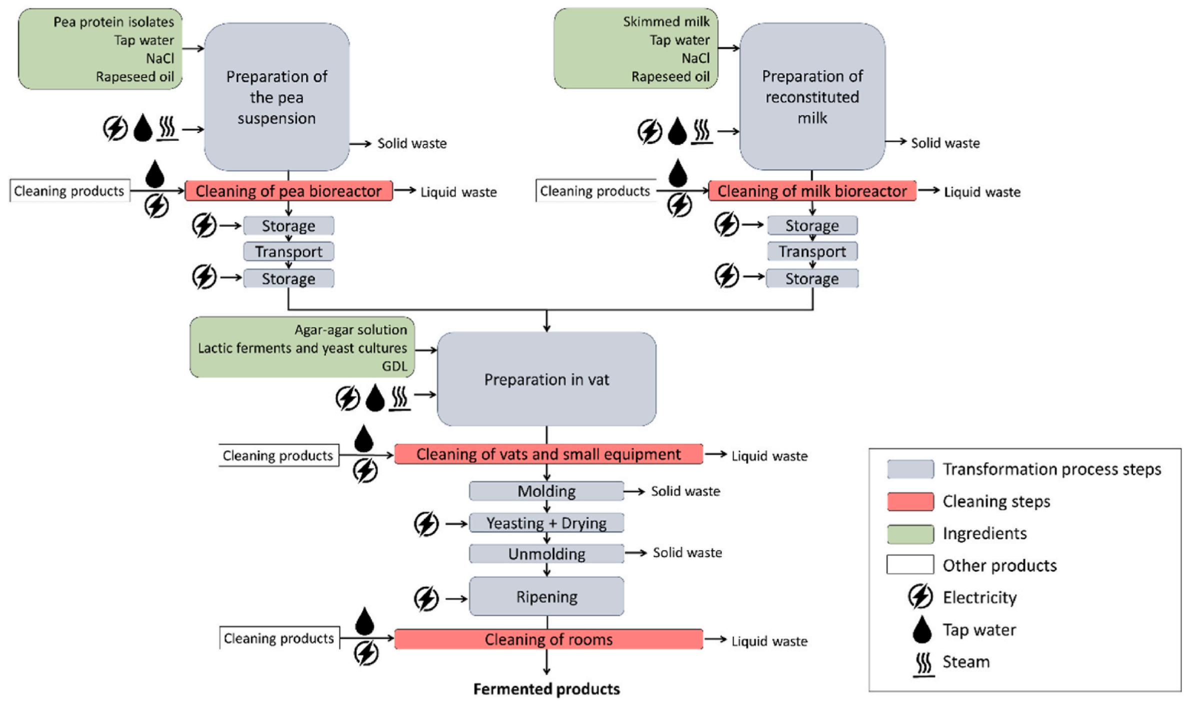

Fig. 1. Summary of the process flowchart for the production of the fermented products.

available in the associated data paper. The main flows evaluated in the study were the mass flows of ingredients, water, and steam necessary and the electricity consumed. The equipment, materials, and infrastructure used were also considered, as well as the cleaning of equipment and facilities, including the cleaning products, water, and electricity consumed together with the liquid waste generated.

The LCI of hummus, presented in Supplementary Table 1, was estimated from data collected from industry websites. The ingredients used were chickpeas, sesame seeds, lemon, oil, and salt. The recipe consisted of the cleaning, peeling, cooking, and milling of chickpeas; the preparation of tahini and lemon juice; the mixing of ingredients; cooling; and the cleaning of equipment. The main flows considered were the mass flows of ingredients and water, as well as electricity consumption. We took into account the use/consumption of equipment and materials, as well as the cleaning of equipment, including the consumption of cleaning products, water, and electricity, and the generation of liquid waste.

The LCI of tofu, presented in Supplementary Table 2, was reconstructed from the study of Mejia et al. (2018). Those authors did not describe the process steps but provided the amounts of ingredients (soybeans), energy (electricity and natural gas), and tap water necessary to produce tofu.

The LCI data for Camembert were obtained from the data paper of Cortesi et al. (2022a). The main ingredient used was cow milk. The processing stages included the transport of milk from the farm to the cheese-making facility, milk pumping, storage, preparation in vat, and ripening for 17 days. The process considered was artisanal, similar to the one described in this study for the production of the new fermented products. We assessed the use of all equipment and materials as well as the cleaning of equipment, including the cleaning products, water, and electricity consumed and the liquid waste generated. The main flows considered were the mass flows of ingredients and water and the consumption of electricity.

2.2.3. Impact assessment method

The LCAs of the different products were performed using SimaPro 9.1.0.11 software and the "EF 3.0 Method (adapted) V1.00/EF 3.0 normalization and weighting set" (Fazio et al., 2018). To facilitate comparisons, the measured flows of the inventories were converted into the amounts necessary for 1 kg of final product for each product. All midpoint impact categories available in this method were calculated: Climate change, Ozone depletion, Ionizing radiation, Photochemical ozone formation, Particulate matter, Human toxicity (non-cancer), Human toxicity (cancer), Acidification, Eutrophication (freshwater), Eutrophication (marine), Eutrophication (terrestrial), Ecotoxicity (freshwater), Land use, Water use, Resource use (fossils), and Resource use (mineral and metals). However, the indicators related to toxicity (human toxicity and ecotoxicity) are not discussed in this paper due to their lack of robustness (Sala et al., 2018). Raw LCA results for the four new fermented products are available in the file "LCIA_fermented_-products" of the dataset associated to the paper (https://doi.org/10.57745/X4QWKZ). These data are also deeply described in the data paper associated with the present study. Raw LCA results for the production of hummus and tofu are available in Supplementary Tables 3 and 4, respectively. Raw LCA results regarding Camembert are available in the file "data_PDOcheeses_LCIA" of the dataset (https://doi.org/10.15454/JQLIOX) presented in the data paper (Cortesi et al., 2022a).

3. Results & discussion

3.1. Environmental impacts of new fermented products

Figs. 2 and 3 present the contributions of different production steps to the environmental impacts of the 25% and 100% pea products, respectively. The impact categories are listed in the left-most column, with the other columns depicting the relative contributions of the different production steps. The process steps presented here correspond to those presented in Fig. 1 with the exception of *jug sterilization*, which was used for the transport and storage of the pea suspension and the preparation of reconstituted milk; the specific role of this step will be detailed below. All impacts related to the agricultural production of ingredients are included in *pea suspension production* and *reconstituted milk production*, respectively.

3.1.1. 25% pea product

For the product made using 25% pea suspension and 75%

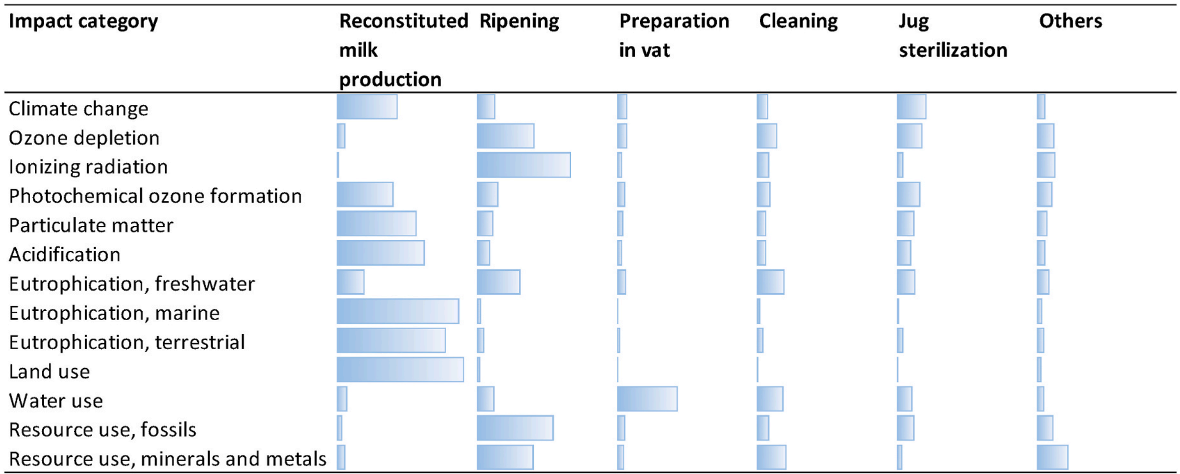

Fig. 2. Contribution analysis of 1 kg of the product made using 25% pea suspension and 75% reconstituted milk. Impacts were calculated using the EF3.0 method. For each impact category (horizontal rows), the relative contributions of the different production steps are shown.

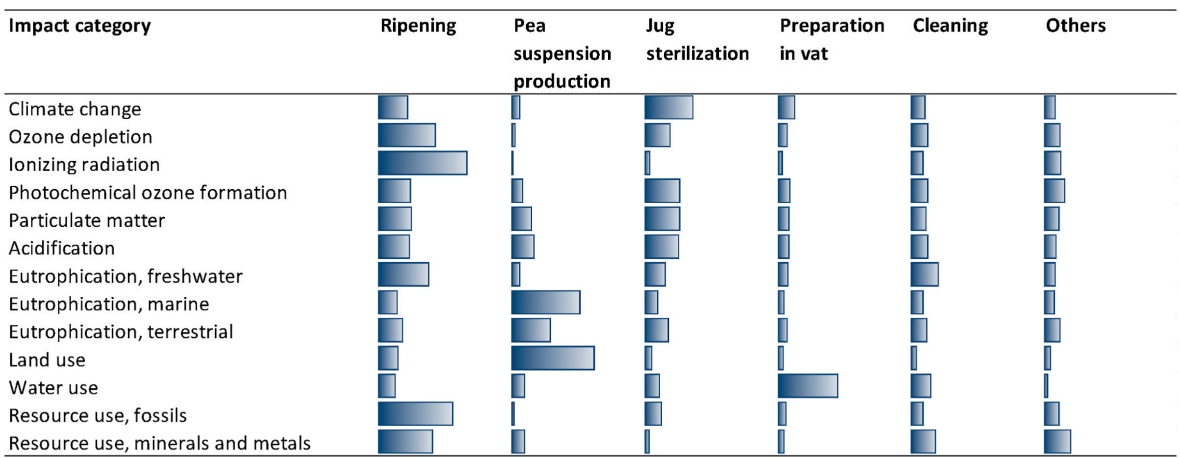

Fig. 3. Contribution analysis of 1 kg of the product made of 100% pea suspension. Impacts were calculated using the EF3.0 method. For each impact category (rows), the relative contributions of the different production steps are shown.

reconstituted cow milk (Fig. 2), the two hotspots of the manufacturing process were the production of reconstituted milk and the ripening stage. This is very similar to LCA results on cheeses, which showed that milk production and ripening were the main hotspots of cheese production systems (Cortesi et al., 2022b).

The production of reconstituted milk was responsible for 41–93% of the total impact of this product for 7 of the 13 environmental indicators (Fig. 2): land use (93%), eutrophication of marine (89%) and terrestrial (79%) environments, acidification (64%), particulate matter (58%), climate change (44%), and photochemical ozone formation (41%). These findings were not particularly surprising given that this step comprises all processes involved in the agricultural production of milk, including the rearing of cattle and the production of fodder and crops for their feed. These activities require large parcels of land, especially for feed production, as was demonstrated for Italian dairy farms (Lovarelli et al., 2019). Indeed, milk production was by far the main factor responsible for land use (96%), with the remaining 4% mostly associated with rapeseed cultivation. The impact on eutrophication can be explained by the agricultural practice of frequently spreading manure, slurry, or chemical fertilizers that contain high levels of nitrogen and phosphorus, resulting in an accumulation of nutrients in terrestrial environments. When agricultural nitrates leach into fresh and marine waters, it can lead to eutrophication in these habitats as well (Le Moal et al., 2019). Acidification occurs when molecules such as sulfur dioxide (from the combustion of fuel for equipment), nitrogen oxides (from fertilizer spreading), or ammonia (from manure storage and spreading) are emitted into the air and are oxidized or hydrolyzed, producing nitric and sulfuric acids that then fall back to the surface in the form of acid rain, snow, or fog. The same phenomenon can occur in soils and subsequently leach into water. The effect of milk production on climate change is largely due to the production of methane by livestock (enteric fermentation and fermentation of manure) and the generation of nitrous oxide (manure storage and fertilizer spreading) and carbon dioxide (farm equipment, e.g. fuel for tractors) (Dollé et al., 2011), which intensify the greenhouse effect. In addition to producing greenhouse gases, the combustion of tractor fuel also generates particulate matter. Finally, the impact of milk production on photochemical ozone formation is the result of reactions between primary agricultural pollutants such as nitrogen oxides or methane and energy provided by solar ultraviolet radiation. Overall, the process of producing reconstituted milk was responsible for at least 40% of the environmental impact of more than half of the impact categories (7 out of 13). Indeed, for many of the indicators, the process of obtaining this one ingredient was almost as detrimental to the environment as the entirety of the transformation process. Given the reasons for the environmental impacts, it is not possible for food producers to reduce them directly; the solutions can only be found at farm-level. However, farming practices can be influenced by the expectations of food producers (Meynard et al., 2017), and our result confirms the importance of dialogue between farmers and food producers in working toward a reduction in the environmental impacts of food products.

The ripening phase was responsible for 31–68% of the total impact of the 25% pea product for 5 of 13 indicators (Fig. 2): ionizing radiation (68%), fossil resource use (56%), ozone depletion (42%), mineral and metal resource use (41%), and freshwater eutrophication (31%). In the Camembert production process, ripening is carried out in a refining cellar, which requires a considerable amount of electricity to maintain a constant temperature and humidity. In France, electricity mainly comes from nuclear power plants and is thus dependent on the extraction of uranium, a fossil resource. Uranium mining generates nitrogen oxides, which can contribute to eutrophication when the water required for uranium mining is returned to lakes and rivers (Poinssot et al., 2014). The impact on ionizing radiation is likewise related to the routine releases of radioactive material associated with nuclear power production, in activities ranging from mining to fuel reprocessing (Frischknecht et al., 2000), as well as the generation of radioactive waste. The high impact on mineral and metal resource use reflects two main factors: the transport of electricity is dependent on metals such as copper and the construction and maintenance of nuclear plants requires substantial mineral and metal resources.

Of the 13 indicators, only one was largely unaffected by reconstituted milk production and ripening: water use (Fig. 2). This impact category was instead mainly affected by preparation in vats (44%), due to the large amount of water needed to produce lactic ferments. However, as explained in the original source of the data (Pénicaud et al., 2018), this high water consumption was specific to the production system used in this study (in which cooling water was not in a recirculating loop) and was not necessarily representative of all systems for producing lactic ferments. Logically, water use was also affected by cleaning (19%), a step which also had an impact on mineral and fossil resource use (22% of the impact on this category) and freshwater eutrophication (20% of the impact on this category), mainly due to the use of cleaning products. Cleaning products are partly composed of mineral-derived substances, and industrial wastewater discharges are rich in nitrates, ammonium, phosphorus and organic matter; these are only incompletely treated in wastewater treatment plants and can then contribute to freshwater eutrophication.

The other processing steps made no substantial contributions to the environmental impacts of this product, with the exception of the sterilization of the jugs used for storage and transport of the pea suspension and reconstituted milk. This step had notable effects on climate change (22%), ozone depletion (19%), and photochemical ozone formation (17%) (Fig. 2), mainly due to the fuel needed for the production of steam (although the averaged data used for modeling do not permit precise identification of the causes; Althaus et al., 2007). However, in the process modeled here, the autoclave used for sterilization was over-sized and, as for the water use in lactic ferment production, probably not truly representative of a real production process.

3.1.2. 100% pea product

For the product made with 100% pea suspension, ripening was the main hotspot (Fig. 3); this step made major contributions to ionizing radiation (68%), fossil resource use (57%), mineral and metal resource use (42%), ozone depletion (44%), and freshwater eutrophication (39%). As explained above, such impacts are due to the electricity consumption of ripening.

Ripening also had considerable impacts on photochemical ozone formation (25%), particulate matter (26%), and acidification (25%). These three indicators were similarly affected by jug sterilization (26–27% for each indicator), which also had a notable effect on climate change (37%). Here again, it was mainly due to the impact of energy use: electricity for ripening and fuel combustion for the production of steam for jug sterilization.

As for the 25% pea product, water use was mainly affected by the vat preparation step (46%), due to the large amounts of water used in the production of lactic ferments, and to a lesser extent by equipment cleaning (15%).

For the 100% pea product (Fig. 3), preparation of the pea suspension made considerable contributions to the impacts on land use (64%) and the eutrophication of marine (53%) and terrestrial (30%) environments. These could be traced to the production of both rapeseed oil and peas, but mostly the former: of the impacts attributable to preparation of the pea suspension, rapeseed oil was responsible for 68% of marine eutrophication, 95% of terrestrial eutrophication, and 46% of land use. These results made sense given that, as explained above, cultivation requires large parcels of lands and the agricultural use of chemical fertilizers causes an accumulation of nutrients and nutrient leaching in terrestrial, freshwater, and marine environments, leading to eutrophication. The use of such fertilizers is much more needed in the cultivation of non-leguminous crops such as rapeseed compared to that of legumes like peas.

However, for the 10 other indicators, preparation of the pea suspension contributed to less than 20% of the impacts. For the 100% pea product, then, the manufacturing process was responsible for considerably more environmental impact than the agricultural stage. Similar results have been reported for other highly processed plant-based foods: in the cases of a vegetable milk alternative made from lentil proteins and some extruded-vegetable meat alternatives consisting of protein combined with amaranth or buckwheat flour, the processing stage was responsible for up to 75% of environmental impacts (Detzel et al., 2021). In the production of plant-based alternatives to cheese, two main processing methods are used (Grossmann and McClements, 2021): fractionation and tissue disruption. With the former, fractionated ingredients from raw plant-based products are solubilized in water and blended with oil to create a plant-based emulsion, while with the latter, the intact plant-based raw material is soaked and broken down to obtain a colloidal dispersion. The products in this study were created using fractionation, since we used pea protein isolate as our raw material. It has been shown that the fractionation of ingredients can have a very high environmental impact (Lie-Piang et al., 2021), which here was equal to or larger than that associated with the cultivation of ingredients. To further investigate this, we compared the environmental impacts of winter pea and of pea protein using data from LCA databases (Agribalyse 3.0 and Ecoinvent 3.6, respectively). This comparison (Fig. S1) revealed that the environmental impacts of winter pea were lower than those of pea protein for 7 of 13 indicators, with, for instance, a 35% lower impact on climate change. However, the opposite pattern was found for the other indicators, with winter pea having twice the impact on freshwater eutrophication as pea protein, for example. This comparison must be treated with caution, though, as the data for these two ingredients come from different databases which do not necessarily use the same system boundaries, allocations, and assumptions. If this trend is true, it suggests that one means of improving the production process for the 100% pea product could be to work directly with peas instead of pea protein isolates.

3.2. Comparison of the four new fermented products

After identifying the environmental hotspots of the 25% and 100% pea products—reconstituted milk production and ripening—we wanted to determine how changes in the raw materials might influence the environmental performance of these products. Fig. 4 presents a comparison of the relative environmental impacts of all four new fermented products, made with 25%, 50%, 75%, and 100% pea, respectively. For each impact category, the effect of the 25% pea product is used as the baseline (i.e., normalized at 100%), and the impacts of the other products are expressed relative to those of the 25% pea product.

The four products had similar effects (<5% variation) on five indicators: ozone depletion, ionizing radiation, water use, and depletion of fossil and mineral/metal resources. Indeed, these categories were

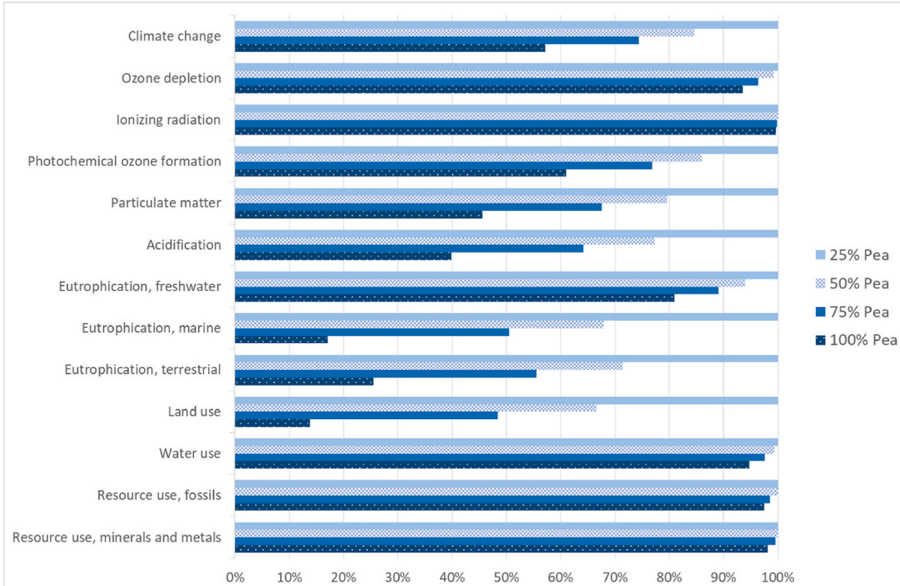

Fig. 4. Comparison of the environmental impacts of 1 kg of each of four new fermented products, made using 25%, 50%, 75%, and 100% pea suspension, respectively. Impacts were calculated using the EF3.0 method. For each indicator, the impact of the 25% pea product is normalized at 100%, and the impacts of the other products are expressed relative to those of the 25% pea product.

largely affected by the ripening, vat processing, and cleaning stages, which were identical for all four products. A change in raw material would therefore not bring any benefit for these indicators.

For 7 of 13 indicators (climate change, photochemical ozone formation, particulate matter, acidification, eutrophication of marine and terrestrial environments, land use), the higher the pea protein content, the lower the impact. For example, the use of 100% pea protein reduced impacts by 43% for climate change, 39% for photochemical ozone formation, 54% for particulate matter, 60% for acidification, 83% for marine eutrophication, 74% for terrestrial eutrophication, and 86% for land use compared to the 25% pea product. These impact categories were the main ones affected by reconstituted milk production, and the decrease in environmental impacts observed with the increase in pea content was almost linear. This result clearly demonstrates that, for these specific environmental impacts, substituting pea protein for milk in these products leads to a marked improvement in their environmental footprint. This mirrors previous findings for plant-based milk substitutes, in which the impact on climate change was found to be 67% and 42% less for almond and soy milk compared to dairy milk, respectively (Clune et al., 2017), and 83% less for lentil milk (Detzel et al., 2021). Similarly, oat-based yogurts were associated with a 31% decrease in carbon footprint compared to milk yogurts (Mogensen et al., 2020).

For freshwater eutrophication, the same trend was observed: an increase in pea content was associated with lower impacts. However, the reduction in this case was less marked, with a maximum reduction of 20%. This is likely due to the fact that, as described above, freshwater eutrophication was linked not only with reconstituted milk preparation but also with ripening and cleaning. These latter two steps were similar for all products, which would explain why the effect of a change in raw materials was more muted for this indicator.

This comparison provides clear evidence of the potential environmental benefits of novel fermented foods that are based on a mixture of pea protein and dairy milk. However, in a companion study (Saint-Eve et al., 2021) to the present work, we investigated consumers' acceptance of the three mixed products (25%, 50%, and 75% pea). We found that the more pea there was in a product, the less it was appreciated by consumers and the less willing they were to pay for it. These products thus represent a case in which environmental benefit and consumer preference are not aligned with each other, and demonstrate the need to find a balance—to obtain environmentally friendly products that are also appreciated by consumers. If consumers remain resistant to plant-based cheese alternatives, another potential strategy for mitigating the environmental impacts of food could be to develop legume-based feed products for livestock, which can also lead to a significant decrease in the environmental impacts of animal-based products (Cusworth et al., 2021).

3.3. Comparison of the fermented products with camembert

As a change in raw material appeared to have considerable effects on certain aspects of the environmental performance of these products, we wanted to directly compare the environmental impacts of the fermented products (specifically the ones containing 25% and 100% pea protein) with those of Camembert cheese. All three products use a similar manufacturing process since production of the cheese alternatives was based on soft cheese manufacturing technology. However, the raw material used for Camembert is 100% cow milk. Fig. 5 presents a comparison between these three products.

As discussed in the previous section, certain indicators were unaffected by a change in raw material between the fermented products (ozone depletion, ionizing radiation, water use, and depletion of fossil and mineral/metal resources). Surprisingly, for these indicators the environmental impacts were significantly lower for Camembert than for the fermented products: ~60% lower for ozone depletion, ~50% for ionizing radiation, ~40% for water use, ~45% for depletion of fossil resources, and ~40% for the depletion of mineral and metal resources. Since the impacts of the fermented products on these indicators were mainly due to the manufacturing process, it can be hypothesized that the production process for the fermented products generates considerably more environmental impacts than that of Camembert. As the same technology was used for the pea protein–containing products and for Camembert, the discrepancy must derive from the preparation of the ingredients: the preparation of pea protein suspension and milk from powders instead of the direct use of milk. These results are accompanied by certain caveats, however: the pea-product inventories took into account more details of production, while the Camembert inventory did not consider the use of equipment or infrastructure, and included many steps that were performed manually (thus consuming less energy than

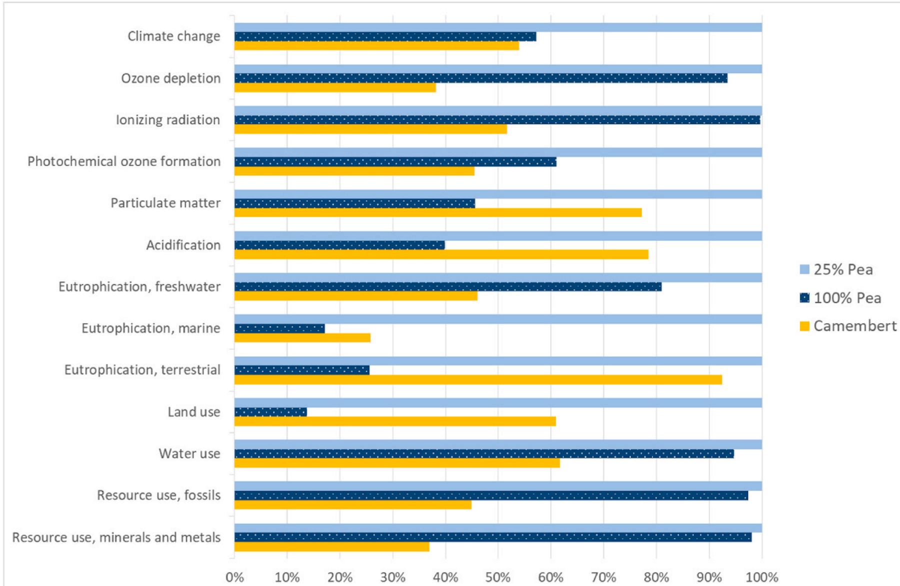

Fig. 5. Comparison of the environmental impacts of 1 kg of the 25% or 100% pea products with 1 kg of Camembert. Impacts were calculated using the EF3.0 method. For each impact category, the 25% pea product is normalized at 100%, and the impacts of the other products are expressed relative to those of the 25% pea product.

for the pea products). These difference in the data should be kept in mind when drawing conclusions.

Among the indicators linked to the use of raw materials, only particulate matter, acidification, eutrophication of marine and terrestrial environments, and land use were less affected by the pea products than by Camembert, and only for the 100% pea product. A switch from Camembert to the 100% pea product reduced impacts by 41% for particulate matter, 49% for acidification, 34% for marine eutrophication, 72% for terrestrial eutrophication, and 77% for land use. Surprisingly, though, switching from Camembert to the 25% pea product increased impacts by 23% for particulate matter, 22% for acidification, 74% for marine eutrophication, 8% for terrestrial eutrophication, and 39% for land use. To investigate this further, we directly compared the impacts of the raw materials—reconstituted milk + pea suspension *versus* cow milk—and found that the raw materials of the 25% pea product actually had a ~50% lower impact on these indicators (data not shown). This means that the increased impacts of the manufacturing process totally canceled out, and even outweighed, the benefits of the change in raw material.

The same conclusion can be drawn for the final three indicators: climate change, photochemical ozone formation, and freshwater eutrophication. For these indicators, the impacts of Camembert were lower than those of the fermented products, particularly for the one made with 25% pea. Here again, the increased impacts due to the manufacturing of the fermented products outweighed the benefits obtained by the change in raw material.

A few caveats should be kept in mind in the interpretation of these results. The attributional LCA performed in this study only takes into account environmental impacts directly related to the system, and not indirect and/or avoided effects. For instance, it does not consider the reduced need for mineral fertilization of the crops that follow pea, nor other benefits of pea such as the release of high-quality organic matter in the soil and the promotion of soil nutrient circulation and water retention (Stagnari et al., 2017). In addition, if adopted by consumers, these mixed products could help in reducing the environmental impacts of livestock, which affect land use, eutrophication, acidification, and climate change. However our attributional LCA does not capture these effects. Future work could consider the use of a consequential LCA approach to go further in these comparisons, but this is beyond the scope of the current study.

3.4. Comparison of the 100% pea fermented product with hummus and tofu

It is clear from our results that any environmental benefit that might be realized from substituting milk with pea protein would depend on the processing steps linked to manufacturing: it is entirely possible for the benefit of a change in raw material to be outweighed by the increased environmental impact of processing. To more thoroughly evaluate the role of processing in the environmental performance of pea-milk alternatives to animal products, we compared the environmental impact of our products with those of other legume-based products processed with different technologies. Specifically, we compared LCA data of the 100% pea product with those of hummus and tofu. The results of this analysis are presented in Fig. 6. For each impact category, the product with the largest impact is normalized at 100%, and the other products are expressed relative to that one.

Compared to the 100% pea product, the production of tofu appeared to have little environmental impact: its contribution to the different impact categories never exceeded 25% of the impact of the 100% pea product. The process of making tofu therefore seems to be much less harmful to the environment than that of our fermented pea-milk product. These results may be explained, at least in part, by the fact that our fermented product contains oil, while tofu does not. However, it is also possible that at least part of this discrepancy may be due to differences in data quality: the inventory data for tofu come from the literature (Mejia et al., 2018) but many details were not included, which limits our ability to directly compare these results with those of the current study.

Again compared to the 100% pea product, the production of hummus had a larger impact (40–75% greater) on marine and terrestrial eutrophication and land use. This is likely due to the fact that, in addition to the cultivation of legumes (in this case chickpeas), hummus requires twice as much rapeseed oil as our 100% pea product. Both the cultivation of legumes and that of rapeseed require land, to which phytosanitary treatments are applied that are detrimental to the quality of aquatic and terrestrial environments. The 10 other impact categories, however, were less affected by the production of hummus: its contribution represented between 1 and 90% of the impact of the 100% pea product.

Even if the production of hummus seems to have a greater impact than that of tofu—because it requires the cultivation of rapeseed in addition to a legume—these two products remain less globally harmful

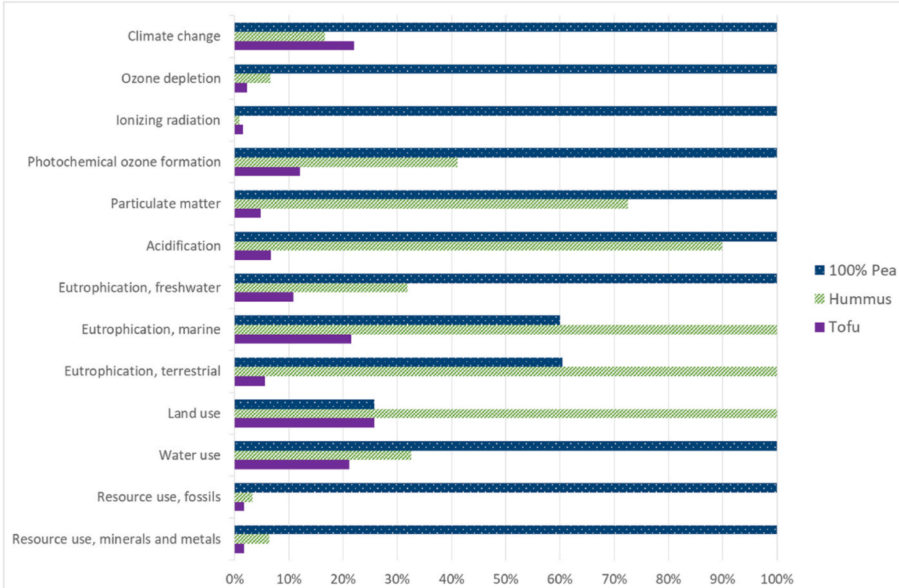

Fig. 6. Comparison of the environmental impacts of 1 kg of the 100% pea product, hummus, and tofu. Impacts were calculated using the EF3.0 method. For each impact category, the product with the largest impact is normalized at 100%, and the other products are expressed relative to that one.

to the environment than our fermented product. The processing of hummus and tofu is relatively simple, since the legumes undergo few processing steps. In addition, the hummus and tofu examined here are not fermented, unlike the pea-milk products, and thus avoid the additional time and electricity consumption associated with ripening. It is therefore logical that the environmental impacts linked to the production of hummus and tofu are lower than those of the fermented mixed products.

Furthermore, tofu and hummus are produced on automated process lines that have been optimized to produce large quantities very quickly. In contrast, the mixed products studied here were produced on a pilot scale in experimental facilities that are not suitable for mass production. This could be another reason for their lower environmental performance, but this aspect could be improved with future work on process optimization.

3.5. Sensitivity analysis to the choice of functional unit: using a protein-based functional unit

In LCAs of food products, the choice of functional unit is a key decision that can have major implications for the results. Here, we studied products that are intended as alternatives to cheese, a food that is rich in protein. In such cases, a protein-based functional unit has been suggested as the most appropriate way to compare products (Sonesson et al., 2017). More recently, though, McLaren et al. (2021) concluded that a nutritional functional unit should be reserved for cases in which nutrient deficiency is an issue, which is generally not the case for protein in France. However, a comparison of multiple functional units can provide a useful overview of the links between nutrition and environmental impacts (Cortesi 2022). Therefore, to complement our mass-based analysis in which the functional unit was 1 kg of final product, we re-analyzed the pea-milk fermented products, Camembert, hummus, and tofu using a functional unit of 1 kg of protein. The protein content of each product is shown in Table 1. The protein contents of the pea-milk mixes were calculated from Saint-Eve et al. (2021), based on the initial protein content of the mix and the water loss during ripening. The protein contents of Camembert, hummus, and tofu were obtained from the Ciqual database (French food composition table, https://ciqual.anses.fr/#).

Fig. 7 presents a comparison of the environmental impacts of 1 kg of product (a) or protein (b) obtained from the 25% and 100% pea products, Camembert, hummus, and tofu.

The results obtained in this analysis were largely similar to those presented in the sections above. The 25% and 100% pea products had very similar impacts on five categories: ozone depletion, ionizing radiation, water use, and depletion of fossil and mineral/metal resources. For the other categories, the pea protein content was inversely correlated with the magnitude of the impact. The impacts of Camembert were generally lower than those of the pea products, with the exceptions of acidification, terrestrial eutrophication, and land use (but only compared to the 100% pea product). The emission of particulate matter, which was higher for Camembert than 100% pea product with a mass-based functional unit (Fig. 7a), became lower for Camembert than for pea products with a protein-based functional unit (Fig. 7b). The production of hummus generated less impact than the pea products, with the exceptions of marine and terrestrial eutrophication and land use (again, only compared to the 100% pea product). Only the acidification became slightly more important for hummus than pea products when changing the mass-based functional unit (Fig. 7a) into a protein-based functional unit (Fig. 7b). Tofu was the product with the lowest impacts overall.

The overall degree of similarity between the two analyses can easily be explained by the protein content of the products (Table 1). The two pea products had very similar protein contents (~110 g/kg), and thus the choice of a mass-based or a protein-based functional unit would lead to similar conclusions. Camembert and tofu had higher protein contents (203 and 147 g/kg, respectively) than the pea-based products. Given that a protein-based functional unit favors the products richest in

Table 1
Protein content of the products compared in this study.

Product	25% Pea	50% Pea	75% Pea	100% Pea	Camembert	Hummus	Tofu
Protein content (g/kg)	112	113	114	106	203	82	147

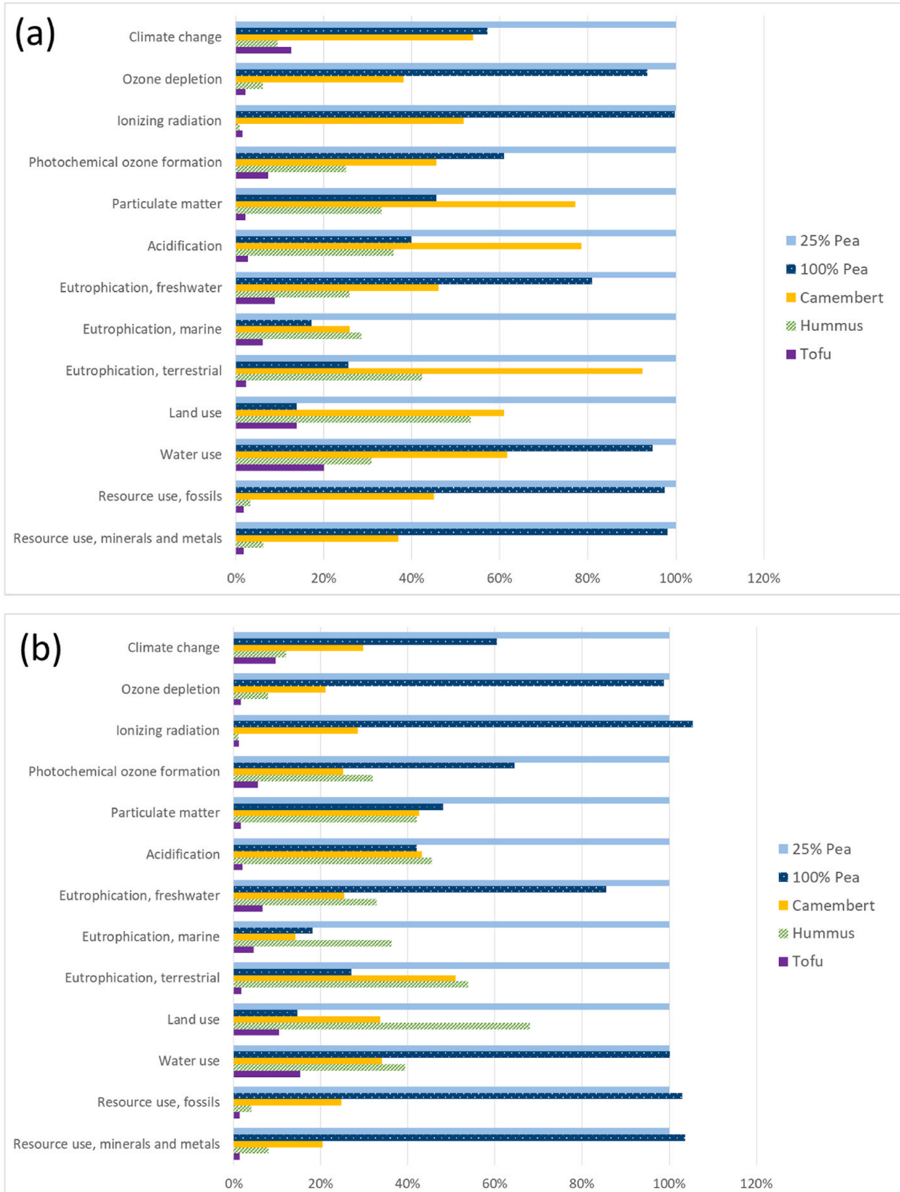

Fig. 7. Comparison of the environmental impacts of 1 kg of product (a) or protein (b) obtained from the 25% and 100% pea products, Camembert, hummus, and tofu. Impacts were calculated using the EF3.0 method. For each impact category, the 25% pea product is normalized at 100%, and the impacts of the other products are expressed relative to those of the 25% pea product.

protein (McLaren et al., 2021), the use of a protein-based functional unit only reinforces the conclusions presented above. The only product for which different results might have been obtained is hummus, since it contains less protein (82 g/kg) than the pea-based products. However, the magnitude of the difference between hummus and the pea-based products was not sufficient to change the comparison between these products, except for the acidification indicator.

3.6. Improvement analysis

One of the main takeaways from the results presented above is that the energy consumption of the manufacturing process plays a pivotal role in determining the environmental impacts of a product, and may even negate any environmental benefits of a change in raw materials. For the products studied here, the energy used was mainly electricity, specifically modeled as the French electricity mix, which is dominated by nuclear power (~78%) and, to a much lesser extent, hydropower (~10%) (data from year 2016 used in Ecoinvent database, International Energy Agency, 2017). As discussed above, this explains the high impact of the mixed products on ionizing radiation, an indicator that is strongly associated with nuclear power. In order to assess the extent to which the composition of the electricity mix might influence the results, we re-calculated the environmental impacts of the pea products using a Danish electricity mix, which is mainly composed of renewables (~60%, mostly wind) and coal (~29%) (data from year 2016 used in Ecoinvent database, Danish Energy Agency, 2018). A comparison between the 25% and 100% pea products evaluated using French and Danish electricity mixes are presented in Fig. 8.

Among the five indicators previously identified as being mainly affected by electricity, the three that are most associated with nuclear power—ionizing radiation, fossil resource use, and ozone depletion—were effectively mitigated by using the Danish electricity mix. However, the use of water, minerals, and metals was slightly increased in this scenario, probably due to the use of coal in the Danish electricity mix.

Impacts on all other indicators were increased by the use of the

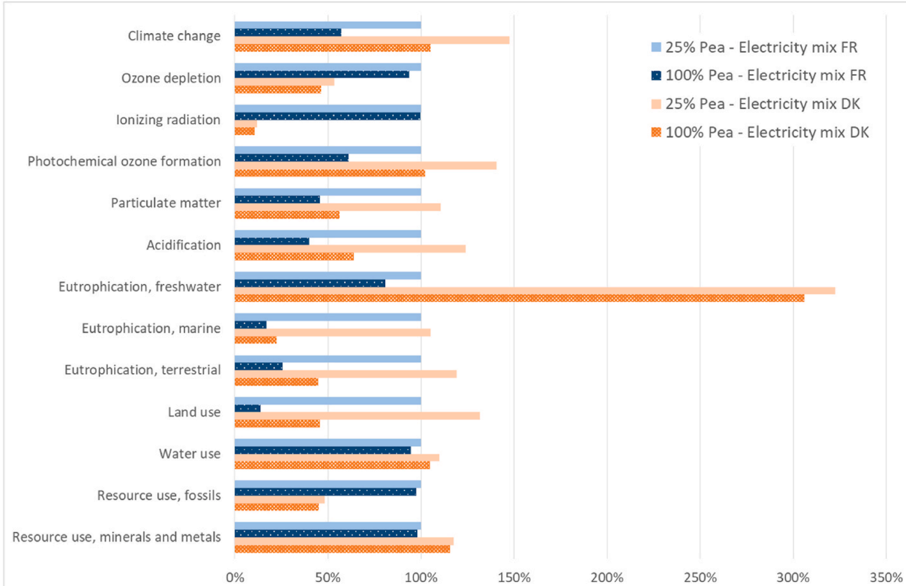

Fig. 8. Comparison between the environmental impacts of the 25% and 100% pea products computed using French and Danish electricity mixes. Impacts were calculated using the EF3.0 method. For each impact category, the 25% pea product with the French electricity mix serves as the baseline (normalized at 100%), and the other products are expressed relative to that one.

Danish electricity mix: very slightly for some (e.g., ~5% for marine eutrophication) but quite strongly for others (e.g., 30%–50% increases for land use and climate change, respectively, and 300% for freshwater eutrophication). This represents the fact that nuclear power has a very low impact on these indicators, while renewable energies have more deleterious effects. Testing alternative hypothetical renewable energy sources could be an option to deepen this improvement analysis.

Despite these differences, the pattern of relative impacts between the 25% and 100% pea products was not altered by the change in electricity mix. Although the results were highly sensitive to the electricity mix in terms of absolute values, changing from one mix to another did not modify our conclusions regarding the comparisons between the two products. However, if a similar study were conducted with products coming from different countries, the composition of the electricity mix would become a parameter of utmost importance. Together with the results presented above, this analysis confirms that optimization of the production process, especially regarding electricity consumption, would be necessary to improve the environmental performance of these products.

4. Conclusion

This study describes the environmental impacts of novel food products made with pea protein—used alone or mixed with reconstituted milk—which were created using a process similar to cheese-making. For this, we collected data on all aspects of production, starting from the agricultural production of ingredients and ending with the final ready-to-eat product. Life cycle assessments revealed that the two environmental hotspots in the creation of these products were milk production (when used) and the ripening stage. The use of pea protein instead of cow milk was associated with certain benefits to environmental indicators that were sensitive to the raw materials used. For other indicators, though, the pea-based products had substantial environmental impacts due to the energy- (and water-) intensive nature of their manufacturing process. For this reason, the pea protein–containing products were found to be more detrimental to the environment than Camembert, hummus, or tofu. The assumption that is frequently found in the literature—that substituting dairy milk with pea can reduce the environmental impact of products—must therefore be qualified, as we demonstrate that the processing of a product can generate significant environmental impacts, ones that can even outweigh the benefits of changing the raw material.

However, these comparisons are constrained by several limitations. First, the LCAs of the pea-based products were conducted using specific data measured during their production, while those of Camembert, hummus, and tofu were performed on the basis of literature data. Second, for the pea-based products, this study analyzed a pilot production process conducted in experimental facilities, which had not yet undergone process optimization; this was not necessarily the case for the Camembert, hummus, and tofu. One way of improving the environmental performance of the pea-based product could thus be to simplify and optimize its manufacturing process. This could be done at two levels: first by using raw pea instead of pea isolate and second by systematically optimizing all production steps. This study highlights how the process of designing new food products should include a thorough assessment of the environmental performance of the system, which can provide guidance on developments and avoid increasing the environmental impact of food.

From a methodological point of view, our use of an attributional LCA approach provided a picture of the environmental impacts of the studied system, but was not able to account for any indirect and/or avoided effects due to the production of these new products. Further work in this area could consider the use of a consequential LCA approach, which would be able to assess broader effects in the agricultural stage (e.g., benefits of pea cultivation for other cropping systems, avoidance of impacts due to milk production).

This work contributes to the broader discussion on the transition toward more sustainable diets, in which plant proteins have a prominent place. This study demonstrates that pea-milk products are not necessarily more eco-friendly than animal products, especially when they are highly processed. However, we show here that the agricultural phase is not necessarily the most impactful stage, and that the sustainability of food must be assessed and communicated to the consumer using reliable data on the entire perimeter from farm to fork.

CRediT authorship contribution statement

Juliette Huguet: Investigation, Formal analysis, Methodology, Writing - original draft. **Christophe Chassard:** Conceptualization, Investigation, Methodology, Writing - review & editing. **René Lavigne:** Investigation, Methodology, Writing - review & editing. **Françoise Irlinger:** Conceptualization, Investigation, Methodology, Writing - review & editing. **Isabelle Souchon:** Conceptualization, Investigation, Methodology, Writing - review & editing. **Stephan Marette:** Conceptualization, Funding acquisition, Methodology, Writing - review & editing. **Anne Saint-Eve:** Conceptualization, Methodology, Writing - review & editing. **Caroline Pénicaud:** Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are shared in a dataset and a datapaper

Acknowledgments

We thank our research colleagues from UMRF (Céline Delbes) and UMR SayFood (David Forest, Anne-Sophie Sarthou) for providing technical support during this study. We also thank Lindsay Higgins from English Services for Scientists for the English revision of the paper. We conducted this research as part of the project DIETPLUS ANR-17-CE21-0003, which was funded by the French National Research Agency (ANR).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2023.100115.

References

Althaus, H.-J., Chudacoff, M., Hischier, R., Jungbluth, N., Osses, M., Primas, A., 2007. Life Cycle Inventories of Chemicals. Final Report Ecoinvent Data v2.0 No. 8 EMPA, Swiss Centre for Life Cycle Inventories (Dübendorf, CH).

Clune, S., Crossin, E., Verghese, K., 2017. Systematic review of greenhouse gas emissions for different fresh food categories. J. Clean. Prod. 140, 766–783. https://doi.org/10.1016/j.jclepro.2016.04.082.

Cortesi, A., 2022. Environmental Quality of Food: How to Assess it in Order to Integrate it with Other Quality Dimensions in Product Design? PhD Thesis. Université Paris-Saclay, Palaiseau, France.

Cortesi, A., Dijoux, L., Bris, G.Y.-L., Pénicaud, C., 2022a. Data related to the life cycle assessment of 44 artisanally produced French protected designation of origin (PDO) cheeses. Data Brief 43, 108403. https://doi.org/10.1016/j.dib.2022.108403.

Cortesi, A., Dijoux, L., Yannou-Le Bris, G., Pénicaud, C., 2022b. Explaining the differences between the environmental impacts of 44 French artisanal cheeses. Sustainability 14, 9484. https://doi.org/10.3390/su14159484.

Cucurachi, S., Scherer, L., Guinée, J., Tukker, A., 2019. Life cycle assessment of food systems. One Earth 1, 292–297. https://doi.org/10.1016/j.oneear.2019.10.014.

Cusworth, G., Garnett, T., Lorimer, J., 2021. Legume dreams: the contested futures of sustainable plant-based food systems in Europe. Global Environ. Change 69, 102321. https://doi.org/10.1016/j.gloenvcha.2021.102321.

Danish Energy Agency, 2018. Energy Statistics 2016. Danish Energy Agency, Denmark.

Dollé, J.-B., Agabriel, J., Peyraud, J.-L., Faverdin, P., Manneville, V., Raison, C., Gac, A., Le Gall, A., 2011. Greenhouse gases in cattle breeding: evaluation and mitigation strategies. Inra Prod. Anim. 24, 415–431.

Detzel, A., Krüger, M., Busch, M., Blanco-Gutiérrez, I., Varela, C., Manners, R., Bez, J., Zannini, E., 2021. Life cycle assessment of animal-based foods and plant-based protein-rich alternatives: an environmental perspective. J Sci Food Agric jsfa 11417. https://doi.org/10.1002/jsfa.11417.

Eurostat, 2019. Milk and milk product statistics. URL. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Milk_and_milk_product_statistics#Milk_products, 1.24.22.

Fazio, S., Biganzioli, F., De Laurentiis, V., Zampori, L., Sala, S., Diaconu, E., 2018. Supporting Information to the Characterisation Factors of Recommended EF Life Cycle Impact Assessment Methods, Version 2, from ILCD to EF 3.0 (No. PUBSY No. JRC11482). EUR 29600 EN. European Commission, Ispra.

Frischknecht, R., Braunschweig, A., Hofstetter, P., Suter, P., 2000. Human health damages due to ionising radiation in life cycle impact assessment. Environ. Impact Assess. Rev. 20, 159–189. https://doi.org/10.1016/S0195-9255(99)00042-6.

González, A.D., Frostell, B., Carlsson-Kanyama, A., 2011. Protein efficiency per unit energy and per unit greenhouse gas emissions: potential contribution of diet choices to climate change mitigation. Food Pol. 36, 562–570. https://doi.org/10.1016/j.foodpol.2011.07.003.

Grossmann, L., McClements, D.J., 2021. The science of plant-based foods: approaches to create nutritious and sustainable plant-based cheese analogs. Trends Food Sci. Technol. 118, 207–229. https://doi.org/10.1016/j.tifs.2021.10.004.

International Energy Agency, 2017. Energy Policies of IEA Countries France 2016 Review. OECD/IEA, France.

ISO 14040:2006, 2006. Environmental Management - Life Cycle Assessment - Principles and Framework, second ed. International Organization for Standardization, Geneva, Switzerland.

Le Moal, M., Gascuel-Odoux, C., Ménesguen, A., Souchon, Y., Étrillard, C., Levain, A., Moatar, F., Pannard, A., Souchu, P., Lefebvre, A., Pinay, G., 2019. Eutrophication: a new wine in an old bottle? Sci. Total Environ. 651, 1–11. https://doi.org/10.1016/j.scitotenv.2018.09.139.

Lie-Piang, A., Braconi, N., Boom, R.M., van der Padt, A., 2021. Less refined ingredients have lower environmental impact – a life cycle assessment of protein-rich ingredients from oil- and starch-bearing crops. J. Clean. Prod. 292, 126046 https://doi.org/10.1016/j.jclepro.2021.126046.

Lovarelli, D., Bava, L., Zucali, M., D'Imporzano, G., Adani, F., Tamburini, A., Sandrucci, A., 2019. Improvements to dairy farms for environmental sustainability in Grana Padano and Parmigiano Reggiano production systems. Ital. J. Anim. Sci. 18, 1035–1048. https://doi.org/10.1080/1828051X.2019.1611389.

McLaren, S., Berardy, A., Henderson, A., Holden, N., Huppertz, T., Jolliet, O., De Camillis, C., Renouf, M., Rugani, B., Saarinen, M., van der Pols, J., Vázquez-Rowe, I., Antón Vallejo, A., Bianchi, M., Chaudhary, A., Chen, C., CooremanAlgoed, M., Dong, H., Grant, T., Green, A., Hallström, E., Hoang, H.M., Leip, A., Lynch, J., McAuliffe, G., Ridoutt, B., Saget, S., Scherer, L., Tuomisto, H., Tyedmers, P., van Zanten, H., 2021. Integration of Environment and Nutrition in Life Cycle Assessment of Food Items: Opportunities and Challenges. FAO, Rome, Italy. https://doi.org/10.4060/cb8054en.

Matar, C., Salou, T., Hélias, A., Pénicaud, C., Gaucel, S., Gontard, N., Guilbert, S., Guillard, V., 2021. Benefit of modified atmosphere packaging on the overall environmental impact of packed strawberries. Postharvest Biol. Technol. 177, 111521 https://doi.org/10.1016/j.postharvbio.2021.111521.

Mejia, A., Harwatt, H., Jaceldo-Siegl, K., Sranacharoenpong, K., Soret, S., Sabaté, J., 2018. Greenhouse gas emissions generated by tofu production: a case study. J. Hunger Environ. Nutr. 13, 131–142. https://doi.org/10.1080/19320248.2017.1315323.

Meynard, J.-M., Jeuffroy, M.-H., Le Bail, M., Lefèvre, A., Magrini, M.-B., Michon, C., 2017. Designing coupled innovations for the sustainability transition of agrifood systems. Agric. Syst. 157, 330–339. https://doi.org/10.1016/j.agsy.2016.08.002.

Mogensen, L., Heusale, H., Sinkko, T., Poutanen, K., Sözer, N., Hermansen, J.E., Knudsen, M.T., 2020. Potential to reduce GHG emissions and land use by substituting animal-based proteins by foods containing oat protein concentrate. J. Clean. Prod. 274, 122914 https://doi.org/10.1016/j.jclepro.2020.122914.

Pénicaud, C., Monclus, V., Perret, B., Passot, S., Fonseca, F., 2018. Life cycle assessment of the production of stabilized lactic acid bacteria for the environmentally-friendly preservation of living cells. J. Clean. Prod. 184, 847–858. https://doi.org/10.1016/j.jclepro.2018.02.191.

Poinssot, Ch, Bourg, S., Ouvrier, N., Combernoux, N., Rostaing, C., Vargas-Gonzalez, M., Bruno, J., 2014. Assessment of the environmental footprint of nuclear energy systems. Comparison between closed and open fuel cycles. Energy 69, 199–211. https://doi.org/10.1016/j.energy.2014.02.069.

Roy, P., Nei, D., Orikasa, T., Xu, Q.Y., Okadome, H., Nakamura, N., Shiina, T., 2009. A review of life cycle assessment (LCA) on some food products. J. Food Eng. 90, 1–10.

Saint-Eve, A., Irlinger, F., Pénicaud, C., Souchon, I., Marette, S., 2021. Consumer preferences for new fermented food products that mix animal and plant protein sources. Food Qual. Prefer. 90, 104117 https://doi.org/10.1016/j.foodqual.2020.104117.

Sala, S., Cerutti, A.K., Pant, R., 2018. Development of a Weighting Approach for the Environmental Footprint (No. EUR 28562). Publications Office of the European Unio, Luxembourg.

Sonesson, U., Davis, J., Flysjö, A., Gustavsson, J., Witthöft, C., 2017. Protein quality as functional unit – a methodological framework for inclusion in life cycle assessment of food. J. Clean. Prod. 140, 470–478. https://doi.org/10.1016/j.jclepro.2016.06.115.

Stagnari, F., Maggio, A., Galieni, A., Pisante, M., 2017. Multiple benefits of legumes for agriculture sustainability: an overview. Chem. Biol. Technol. Agric. 4, 2. https://doi.org/10.1186/s40538-016-0085-1.

Tukker, A., Huppes, G., Guinée, J., Heijungs, R., de Koning, A., van Oers, L., Suh, S., Geerken, T., Van Holderbeke, M., Jansen, B., Nielsen, P., 2006. In: Environmental Impact of Products (EIPRO). Analysis of the Life Cycle Environmental Impacts Related to the Final Consumption of the EU-25., Technical. European Commission, Joint Research Center.

Vermeulen, S.J., Campbell, B.M., Ingram, J.S.I., 2012. Climate change and food systems. Annu. Rev. Environ. Resour. 37, 195–222. https://doi.org/10.1146/annurev-environ-020411-130608.

Weidema, B.P., Wesnaes, M., Hermansen, J., Kristensen, T., Halberg, N., Communities, E., 2008. Environmental Improvement Potentials of Meat and Dairy Products (IMPRO). European Commission. Joint Research Center.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.