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Carbon and Water Footprint Assessment of a Pea Snack

Josemi G. Penalver [1,2], Maria Jose Beriain [1,2], Paloma Vírseda [1,2] and Maite M. Aldaya [1,3,*]

[1] Institute for Sustainability & Food Chain Innovation (IS-FOOD), Public University of Navarra (UPNA), Jerónimo de Ayanz Building, Arrosadia Campus, 31006 Pamplona, Spain; josemiguel.gonzalez@unavarra.es (J.G.P.); mjberiain@unavarra.es (M.J.B.); virseda@unavarra.es (P.V.)
[2] Agronomy, Biotechnology and Food Department, Public University of Navarra (UPNA), Arrosadia Campus, 31006 Pamplona, Spain
[3] Science Department, Public University of Navarra (UPNA), Arrosadia Campus, 31006 Pamplona, Spain
* Correspondence: maite.aldaya@unavarra.es

Abstract

The agri-food sector in Navarra, Spain, is exploring alternative protein sources like pea protein due to concerns regarding the environmental impacts and allergenic properties of traditional options like soy. This study aimed to evaluate a pea-based snack using carbon footprint and water footprint methodologies to assess the environmental performance of pea extrusion. The carbon footprint of the pea snacks was found to be 0.12 kg of CO_2e per 100 g of packaged product. The water footprint was 174 L per 100 g of packaged product, with the blue water footprint accounting for the largest share (52%), followed by green (47%) and grey (1%) water footprints. Strategies such as minimizing ingredient loss and switching to renewable electricity could potentially reduce greenhouse gas emissions by 17% and green water consumption by 3%. Regarding alternative protein matrices, pea extrusion utilized 225 L of water per 150 g of extrudate, primarily as green water, demonstrating a lower dependence on blue and grey water compared to soy-based alternatives, suggesting its suitability for blue water-scarce regions. The carbon and water footprint assessments highlight the potential of pea protein as a regionally suitable, low-impact alternative to soy in terms of both carbon and water use.

Keywords: carbon footprint; water footprint; pea-based product; pea protein; environmental sustainability

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1. Introduction

The growing need to transition toward more sustainable and health-conscious food systems has placed increasing pressure on the agri-food sector to develop innovative solutions. In this context, the agri-food industry in Navarra, Spain, plays a strategic role due to its economic relevance and potential to lead sustainable transformation [1]. In the Chartered Community of Navarra, water is predominantly allocated to agriculture (51%), followed by the livestock sector (21%) and industry (16%). Smaller amounts go toward forestry (10%), human consumption (2%), and tourism (less than 1%) [2]. This heavy reliance on water resources places immense pressure on local ecosystems, especially as global demand for food continues to rise. Moreover, food production systems worldwide are responsible for approximately 30% of anthropogenic greenhouse gas emissions, with animal protein production identified as one of the most environmentally impactful activities [3]. This has prompted research into innovative approaches, such as the application of circular economy principles to the agri-food sector. These principles aim to minimize resource waste while

developing high-value food ingredients and products [4]. One area of particular interest is the development of plant-based products that minimize environmental impacts while meeting evolving consumer expectations.

Soy has traditionally been a key protein source in plant-based food formulations due to its high protein content, favourable amino acid profile, and functional versatility [5]. However, despite these advantages, soy production is associated with several environmental concerns, including deforestation, particularly in the Amazon, loss of biodiversity, and increased greenhouse gas emissions [6]. Furthermore, soy is one of the most common food allergens [7], limiting its use for sensitive populations. In Navarra, soy-based vegan products have been previously developed [8,9], yet alternative proteins are gaining attention. Pea protein, in particular, has emerged as a promising alternative. Its cultivation is well-established in the region of Navarra, and it offers several advantages, including a neutral taste profile [10], the absence of major allergens [11], and desirable functional properties [12]. Focusing on Navarra's crop production, this study examines the opportunities for local crops, such as peas, to reduce environmental impacts while fostering regional resilience and supporting traditional agriculture. Local protein sources will be compared to facilitate decisions on which crop should be backed and how its effective development can be ensured.

Despite increasing interest in sustainable food innovation, there is still a lack of data on the environmental performance of alternative pea-based protein products. To ensure that new developments align with sustainability goals, robust environmental assessments are essential, particularly in identifying the life cycle stages with the highest environmental burden. This study aims to contribute to the sustainability of the agri-food production system in Navarra by evaluating a pea-based product prototype, specifically, a pea-based snack with rice and curry sauce, developed under the ALISSEC project. This project, led by the Agrifood Cluster of Navarra (NAGRIFOOD), was part of the ALPES IV challenge ("Personalized and Sustainable Food") under the S3 Strategy, funded by the Government of Navarra during the 2021–2024 period.

The environmental assessment focused on two widely recognized indicators: carbon footprint (CF) and water footprint (WF). These methodologies enabled the identification of life cycle stages with the highest greenhouse gas emissions and water consumption, facilitating the development of a targeted improvement plan. In doing so, this research not only supports environmentally responsible decision-making in product development but also adds market value through measurable sustainability benefits. The integration of carbon and water footprint assessments into product innovation represents a critical step in aligning regional food production with global environmental objectives.

2. Materials and Methods

2.1. Definition of Boundaries

The production and processing of the product were carried out across several locations in the region of Navarra, Spain, reflecting a decentralized agri-food value chain. The product manufacturing process begins with pea cultivation in Cirauqui, followed by the milling process at Caparroso, which includes shelling, grinding, and separation to produce pea concentrate. The concentrate is then sent to Tudela for wet extrusion, involving mixing, extrusion, and packaging to form snacks. Finally, preparation and cooking take place in Esquiroz, including conditioning, the cooking of rice, the preparation of sauce, assembly, and the packaging of the final product. A description of the process, inputs, and outputs can be found in Figure 1.

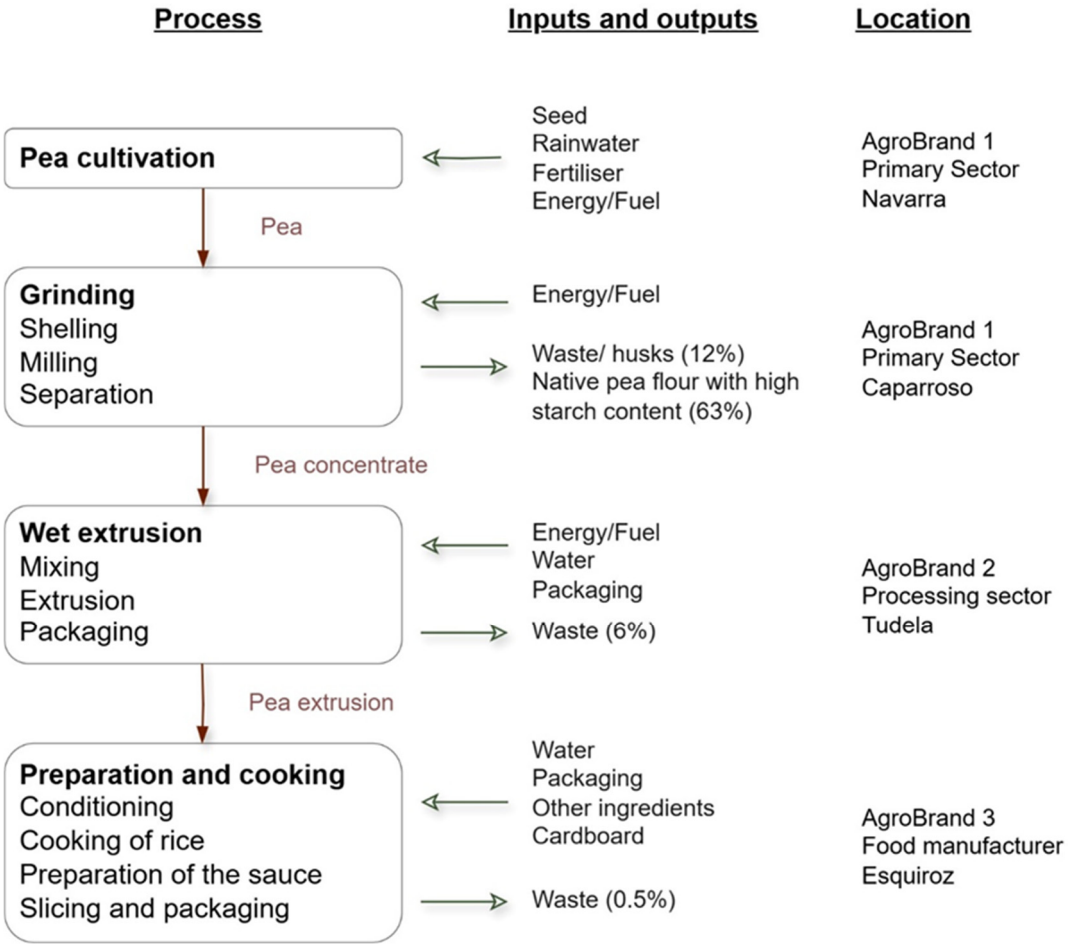


Figure 1. Flow chart of the curry sauce and pea snacks, including the main process, upstream (inputs) and downstream (outputs) processes, and the production site for each stage.

The present product is categorized as a snack, being a prepared meal that offers a vegetable-based analogue to a traditional chicken and rice with curry sauce dish. The carbon footprint and water footprint of pea snacks for the 2020/2021 period were analysed from cradle to factory gate (i.e., from the production of raw materials to the assembly and packaging of the product). The functional unit of the study is the production of 100 g of pea snacks with rice and curry. When first-hand data were unavailable, the scientific literature and reputable institutional sources were utilized to complete the calculations. The contributions of concrete, steel, and vehicle construction have been excluded, as their impact on the water footprint is considered minimal, according to Jefferies et al. [13].

2.2. Data Sources

The activity data were provided by members of the project consortium. These data were sourced from consumption invoices, vehicle mileage logs, and questionnaires completed by farmers. The used crop was dry peas, grown in Cirauqui, Navarra, Spain. The sowing took place on 29 November 2020, and the harvest was completed on 4 July 2021. Information on the cultivation process was obtained by direct survey of the farmers. The specific information on the cultivation requirements can be found in Supplementary Text S1. Climatic data for estimating the water requirements of crops during the 2020/2021 agricultural year were obtained from the MeteoNavarra database [14]. The data were collected from the meteorological stations closest to the crop locations. The electricity consumption used came from the mix of the contracted marketing company: EDP CLIENTES S.A.U., Oviedo, Spain.

Relevant data can be found in the Supplementary Material: Supplementary Table S1 provides conversion factor sources for the different energy sources used during the snacks' production. Supplementary Tables S2 and S3 include information on ingredients, origins, and factors used in the calculation of the carbon and water footprint. Supplementary Table S4 details packaging materials, origins, factor sources, and their role in footprint calculations.

2.3. Carbon Footprint Methodology

The carbon footprint refers to the total greenhouse gas (GHG) emissions, either directly or indirectly, caused by an individual, organization, event, or product. The main GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). However, CO_2 is the GHG with the greatest impact on global warming, and therefore GHG emissions are typically measured in terms of this gas. The metric ton of CO_2 equivalent (t CO_2e) is the universal unit of measurement used to calculate the atmospheric warming potential or global warming potential (GWP) of each of these GHGs, expressed relative to the GWP of one unit of CO_2 [15].

The calculation of GHG emissions was carried out following the methodology outlined by MITECO [15] and other international standards, including the GHG Protocol [16], ISO 14067 [17], and IPCC [18]. First, an inventory was compiled to account for all emissions generated during each phase of the production process. The carbon footprint was calculated by multiplying the activity data that generates an emission (quantity) by the emission factor of the activity, which is typically expressed in tons of CO_2e per unit of activity.

$$\text{GHG emissions} = \text{Quantity} \times \text{Emission factor} \quad (1)$$

Emission factors related to the carbon footprint corresponding to each greenhouse gas-emitting activity were extracted from MITECO [15], ADEME [19], and other internationally recognized sources.

2.4. Water Footprint Methodology

The water footprint of a product is defined as the total volume of freshwater used, both directly and indirectly, for its production [20]. The estimation considers water consumption and pollution across different stages of the production chain. The water footprint is divided into three components: green, blue, and grey.

The blue water footprint refers to the volume of surface and groundwater consumed during the production of a good or service. Consumption encompasses the volume of freshwater used and subsequently evaporated or incorporated into the product. It also includes water extracted from one catchment area and returned to another or to the sea, as well as water withdrawn but not returned to the original catchment area.

The green water footprint represents the volume of rainwater consumed during production processes. This is particularly relevant for agricultural and forestry products, where it accounts for the evapotranspiration of precipitation (from fields and plantations) and water incorporated into harvested crops or wood.

The grey water footprint is defined as the volume of freshwater required to assimilate the pollutant load, considering natural background concentrations and existing water quality standards. It is calculated as the volume of water needed to dilute contaminants to maintain the water quality above agreed standards.

The green, blue, and grey water footprint components were calculated using the methodology outlined in the *Water Footprint Assessment Manual* by Hoekstra et al. [20].

Operational (direct) and supply chain (indirect) water footprints were differentiated within the analysis.

For estimating green and blue water evapotranspiration during crop growth, the CROPWAT model, developed by the Food and Agriculture Organization of the United Nations [21] and based on the methodology described by Allen et al. [22], was used. Crop evapotranspiration estimated in millimetres was converted to cubic metres per hectare by applying a factor of 10. The green component of the water footprint for a crop (WF_{green}, m^3/t) was calculated by dividing the green water use of the crop (WU_{green}, m^3/ha) by the crop yield (Y, t/ha). The blue component (WF_{blue}, m^3/t) was calculated similarly:

$$WF_{green} = \frac{WU_{green}}{Y} \quad (2)$$

$$WF_{blue} = \frac{WU_{blue}}{Y} \quad (3)$$

The grey water footprint (WF_{grey}, m^3/year) associated with nitrogen (N) was calculated by dividing the nitrogen load (NL, kg/year) by the difference between the maximum allowable concentration (C_{max}, mg/L) and the natural background concentration (C_{nat}, mg/L):

$$WF_{grey} = \frac{NL}{C_{max} - C_{nat}} \quad (4)$$

The diffuse nitrogen load to freshwater (NL) was estimated for each crop using a soil nitrogen balance method, as described by the Spanish Ministry of Agriculture, Fisheries, and Food [23] and Aldaya et al. [24]. Six nitrogen inputs were considered: mineral fertilization, the application of manure, other organic fertilizers, seeds, atmospheric deposition, and biological nitrogen fixation. Outputs included nitrogen removed via crop harvest, the removal of crop residues (e.g., straw or plant material), annual growth of woody crops (e.g., wood and roots), the burning of crop residues, volatilization from fertilization, and gaseous soil losses.

The natural background concentration was determined based on water in its natural state, free from anthropogenic alterations. According to Royal Decree 817/2015 [25], the threshold for a good to very good status was used as the reference for the river Ega (R-T17, a highly influential river in the Mediterranean environment). For environmental quality standards, a distinction was made between surface and groundwater. In accordance with the European Nitrates Directive [26], a value of 37.5 mg NO_3/L was applied for groundwater, while for surface water, the maximum allowable concentration was established by Royal Decree 47/2022 [27] as the threshold between good and moderate status.

Runoff data were obtained using the SIMPA model [28], which evaluates water resources under natural conditions. The percentages of surface and groundwater runoff for the agricultural areas studied were extracted. Runoff values were validated using flow rate data from monitoring stations operated by the Ebro River Basin Authority [29].

The grey water footprint and estimated water contamination levels were cross-checked with water quality reports from monitoring stations maintained by the Government of Navarra. For food industry processes, wastewater treatment is managed by the Mancomunidad of Pamplona Region and the Mancomunidad of La Ribera.

3. Results

3.1. Carbon Footprint of Pea Snacks with Rice and Curry Sauce

The carbon footprint of the pea snacks with rice and curry sauce was 0.12 kg of CO_2e per 100 g of packaged product.

The primary sources of emissions were attributed to the ingredients, accounting for 75% of the total emissions (Figure 2). Greenhouse gas emissions generated by natural gas ranked second, representing 11% of total emissions. Indirect emissions related to electricity use contributed 8%, while emissions associated with the production of packaging accounted for 7% of the product's total emissions (0.0079 kg CO_2e/100 g).

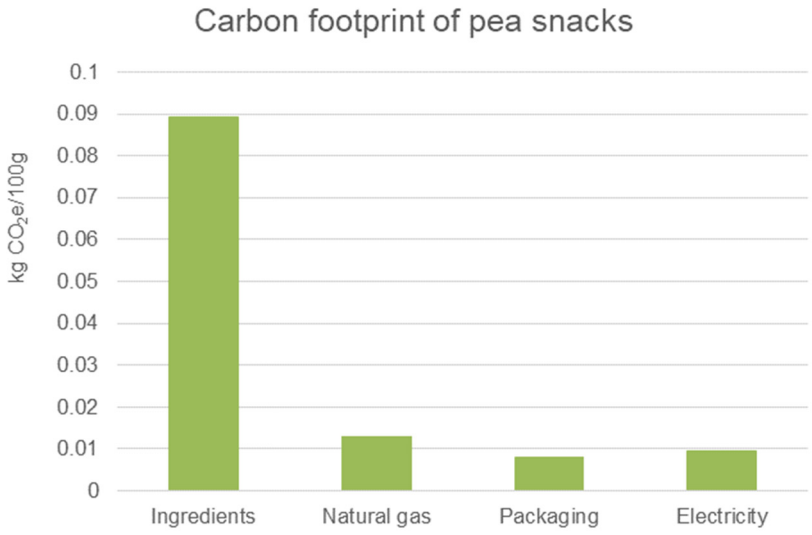


Figure 2. Flow chart of the curry sauce and pea snacks and the production site for each stage.

The carbon footprint analysis of the ingredients in the pea snack identified rice as the primary emitter of greenhouse gases, accounting for 53% of the total emissions associated with the ingredients. The second-largest contributor to the carbon footprint was the extruded pea, at 18%, highlighting waste management (crop residues are incorporated back into the soil) and fertilizer use as the main emission sources of the pea cultivation phase; this ingredient is followed by sunflower oil (10%) and curry (7%). Specific results per ingredient can be found in Figure 3. The detailed information regarding ingredients, origins, and factors utilized in the calculation of the carbon footprint is available in Supplementary Table S3.

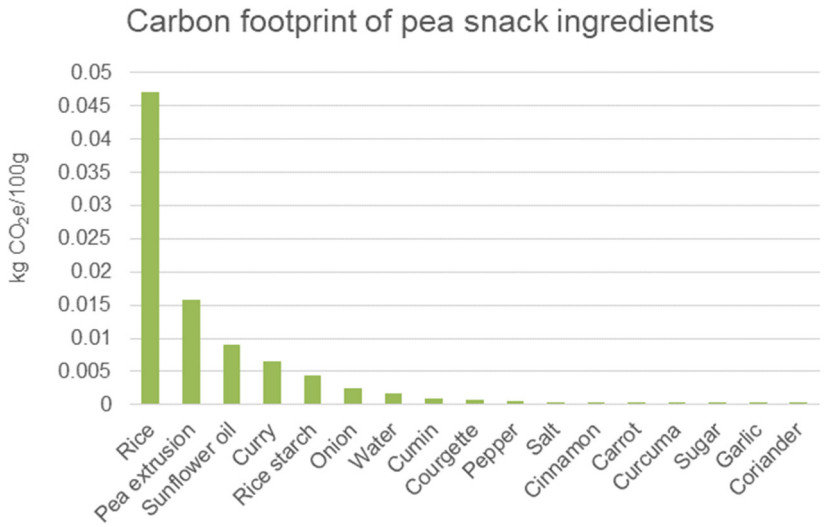


Figure 3. Carbon footprint of pea snack ingredients (kg CO_2e per 100 g of packaged product).

3.2. Water Footprint of Pea Snacks with Rice and Curry Sauce

The water footprint of the pea snack was 174 L of water per 100 g of packaged product, with the blue water footprint representing the largest share (52%), followed by the green

water footprint (47%) and the grey water footprint (1%) (Figure 4). Similar to the carbon footprint, the primary water consumer was the ingredients, accounting for 98% of the total water use. A distant second was the packaging, with 2% of the total water usage.

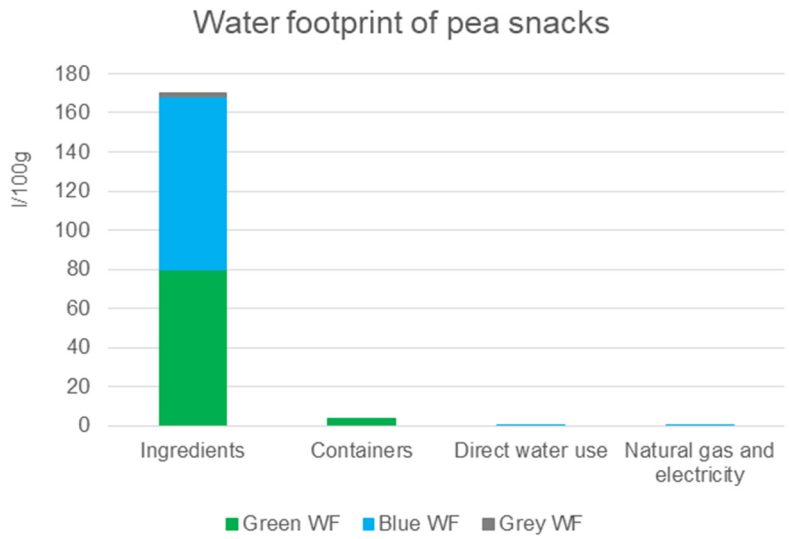


Figure 4. Green water footprint (green WF), blue water footprint (blue WF), and grey water footprint (grey WF) of pea snacks (l of water per 100 g of packaged product).

Among the ingredients of the pea snack, rice again emerged as the primary water consumer, accounting for 54% of the total water usage associated with the ingredients. It was followed by the extruded pea (28%) and sunflower oil (13%). Regarding the pea production analysed in Navarra, the water footprint is composed almost entirely of green water (150 L/100 g). Regarding nitrogen-related impacts, due to the high efficiency of nitrogen's application in the pea cultivation system, the resulting grey water footprint is practically negligible according to the nitrogen balance assessment. Specific results per ingredient can be found in Figure 5. The detailed information regarding ingredients, origins, and factors utilized in the calculation of the water footprint is available in Supplementary Table S2.

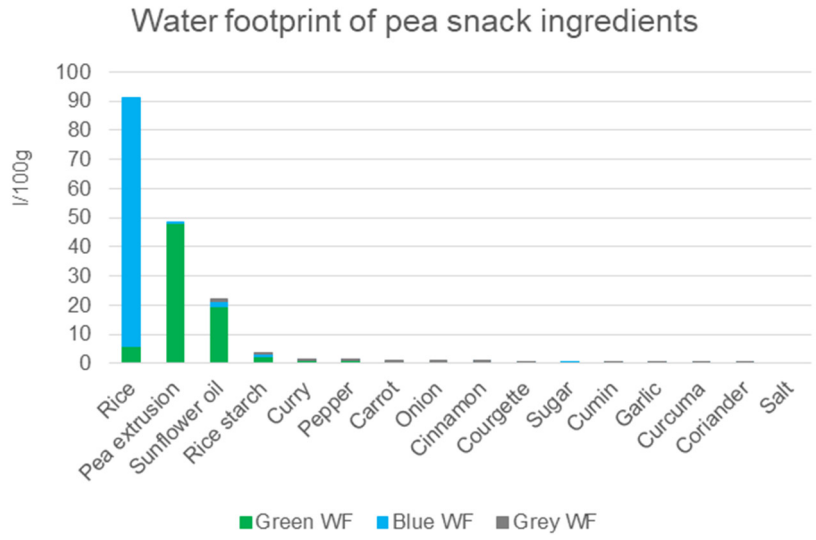


Figure 5. Green water footprint (green WF), blue water footprint (blue WF), and grey water footprint (grey WF) of pea snack ingredients (l of water per 100 g of packaged product).

3.3. Result Comparison with Previous Studies

In the literature there is a wide variation in the reported carbon footprints of different patties types; however, the product under evaluation (the pea snack with rice and curry sauce) follows a manufacturing process that includes conditioning, cooking of rice, preparation and addition of sauce, trimming, and packaging adapted to the product. This product is highly complex, and to ensure a more reliable comparison with other products in the literature, we will use impact data from the vegetable protein base, calling it pea extrusion, as a comparative raw material, similar to that used for plant-based, hybrid, or meat patties. An amount of 150 g of product will be used as a reference unit. Due to data collection limitations and to ensure comparability with other studies, the impact of raw materials' transport was not considered, and packaging was excluded from product comparisons wherever possible.

The pea extruded product developed exhibits the lowest carbon footprint, following patties made from soybean flour, beans, and rice, as well as a mixed patty (50% beef and 50% plant-based—soybean, beans, and rice) produced in Navarra (Table 1). Although the carbon footprint is relatively low, there is still room for improvement.

Table 1. Comparison of the results of this study with the carbon footprint of previous studies. It does not include the carbon footprint of transport.

Product	kg CO_2e/Product	Source	Other
Beef	7.2	Tang et al. (2024) [30]	UK, approximation without transport or packaging
	6.6	Saget et al. (2021) [31]	Brazil, packaging and transport included
	4.5	Saget et al. (2021) [31]	Ireland, packaging and transport included
	2.09	Domínguez-Lacueva (2022) [8]	PGI Veal from Navarra, Without raw material transportation. Kg CO_2e/150 g
Mixed	-	Chaudhary & Tremorin (2020) [32]	Reduces ~33% of CF
	1.09	Domínguez-Lacueva (2022) [8]	Navarra, Without raw material transportation. Kg CO_2e/150 g
Plant-based	0.56	Tang et al. (2024) [30]	UK, approximation without transport or packaging, 5:4:1 mixture ratio of soy protein isolate, vital wheat gluten, and corn starch.
	0.16	Domínguez-Lacueva (2022) [8]	Navarra. Soybean, bean, rice flour. Without raw material transportation. Kg CO_2e/150 g
Pea snack [1]	0.14	Current research	Pea flour. Without raw material transportation. Kg CO_2e/150 g

[1] Pea extrudate after wet extrusion without curry sauce and rice.

In terms of water footprint, the pea snacks developed show the highest water footprint of the plant based products, due to the cultivation requirements of pea in Navarra. Following are the plant-based soy patties, both those made from soy alone (Canada and China origin) and those made from soy flour (USA origin), beans, and rice (Spain origin). The differences found between the vegan plant-based analogues of Table 2 are specifically marked by the production systems used in their country of origin and the agro-climatic conditions of these countries.

Table 2. Comparison of the results of this study with the water footprint of previous studies (L/150 g of product).

Product	L/150 g of Product	Source	Other
Beef	4027	Mekonnen & Hoekstra (2012) [33]	Spain
	2617	Casado et al. (2008) [34]	Spain
	3871	Domínguez-Lacueva (2022) [8]	PGI, Veal from Navarra
Mixed	-	Chaudhary & Tremorin (2020) [32]	Reduces ~33% of WF
	2075	Domínguez-Lacueva (2022) [8]	Navarra
Plant-based	158	Ercin et al. (2012) [35]	Soybeans
	184	Domínguez-Lacueva (2022) [8]	Navarra. Soybean, bean, rice flour
	225	Current research	Pea flour [1]

[1] Pea extrudate after wet extrusion without curry sauce and rice.

It is worth noting that the pea extrudate has a blue and grey water footprint close to 0%, as the green water footprint accounts for almost 100%. In contrast, the plant-based soy patties exhibit a higher blue and grey water footprint: 18% and 7% (33 and 13 L/150 g), respectively, for the patty made from soy flour, beans, and rice; and 4% and 26% (7 and 42 L/150 g), respectively, for the soy-based patty.

These results suggest that the cultivation techniques described in the methodology and their geographical location are quite good at avoiding GHG emissions compared to the soybean production considered in the literature. Furthermore, although the product's total water footprint is higher than its vegan counterparts, it is worth noting that its blue and grey water footprint is lower, due to the production systems considered in the countries of origin of this raw material.

The water quality criteria outlined in the 2023 Surface Water Quality Network report, published by the Government of Navarra, indicates that the Tierra Estella area, located in the Ega river basin, has a very good water quality assessment, with no risk of nitrate overconcentration. While this may not be a concern in this case, it is an important factor to consider for future comparisons between pea and soybean production in Navarra, to ensure efficient water use based on geographical location. In regions facing drought risks (blue water vulnerability) or high nitrate concentrations in natural water bodies (grey water vulnerability), such as in the Ebro basin in Southern Navarra [24], choosing crops that rely primarily on green water, like peas, can help protect vulnerable water resources, even if the overall water footprint is higher.

4. Discussion

4.1. Recommendations for Improvement

Once the carbon and water footprint of the pea snacks has been calculated, the activities that emit the most greenhouse gases and use more water have been analysed, and potential alternatives have been examined, the following proposed measures are presented as recommendations to reduce these emissions and water uses:

- Reduction of waste: Strategies are proposed to minimize waste throughout the entire flow chart of the curry sauce and pea snacks product. The development of waste tracking and control programs could be considered to identify areas where continuous improvements in production efficiency can be made.
- Use of renewable electricity: It is recommended to contract renewable electricity services, as this type of energy emits almost no GHGs. At the time of the study, only 25% of the energy used in the food manufacturing phase was self-generated by solar panels. The remaining energy depended on external sources

To estimate the reductions, this improvement plan assumes that the activity level (consumption) will remain at the same level as in the base year of 2021. Therefore, the reductions will be the result of efficiency improvements.

The proposed measures to reduce waste throughout the value chain of the snacks, as well as the implementation of renewable electric energy in both the extrusion and production processes, could decrease the carbon footprint of the snacks by 17%, reducing emissions to 0.10 kg of CO_2e per 100 g of product instead of the original 0.12 kg of CO_2e (Table 3).

Table 3. Percentage reduction of greenhouse gas (GHG) emissions projected for each year compared to the previous year according to the different emission sources.

Proposed Measure	GHG Emissions 2021 (kg CO_2e/100 g of Products)	GHG Emissions After Measures' Implementation (kg CO_2e/100 g of Product)	Reduced GHG Emissions (kg CO_2e)	Snack's Carbon Footprint 2021	Snack's Carbon Footprint After Implementation of Measures	Carbon Footprint Reduction (%)
Reduction of waste	0.01	0	0.01	0.12	0.10	17
Renewable electricity service contracting	0.01	0	0.01			

In terms of the water footprint, these same measures would result in a 3% reduction in the consumption of green water (Table 4).

Table 4. Percentage reduction in water use planned for each year compared to the previous year according to the different emission sources.

Proposed Measure	Water Use 2021 (L/100 g of Products)	Water Use After Implementation of Measures (L/100 g of Products)	Reduced Water Use (L)	Snack's Water Footprint 2021	Snack's Water Footprint After Implementation of Measures	Water Footprint Reduction (%)
Reduction of waste	5	0	5	174	169	3
Renewable electricity service contracting	0	0	0			

4.2. Implications of the Study

As evidenced by the numerous articles previously discussed on the environmental evaluation of meat analogue products, the search for sustainable food products has gained considerable momentum. Plant-based products have emerged as a diverse range of alternatives with reduced environmental impacts. While animal-based foods offer essential nutrients, their production often comes at a high environmental cost. In contrast, hybrid (combining animal and plant proteins) and fully plant-based food products offer a promising path forward [36]. These products are primarily made from legumes, which are already a key component of traditional Spanish cuisine [37], and aim to reduce overall meat consumption while maintaining taste and consumer acceptance [36].

Parallel to the lines of research focused on developing new plant-based products and studying their environmental interactions, the Spanish government provides support through the newly approved "Law on the Prevention of Food Losses and Food Waste." This law mandates food chain agents to minimize productive losses during food production and seeks to promote the re-integration of agri-food waste and by-products into the food chain. Recent studies have already explored ways to apply this new law within Navarre's agri-food sector by revaluing agricultural by-products [38,39]. This publication contributes by demonstrating the benefits of applying these policies, specifically in waste reduction during the production chain of food products. Future studies should aim to further achieve the reduction of food and ingredient waste in industrial stages.

In the short term, no subsidies have been identified to support practices that enhance a product's environmental responsibility. However, it is noteworthy that such measures also increase the economic profitability of the process by minimizing raw material costs [40]. Thus, at this point of supply chain improvement, the interplay between policy and private business interests becomes intertwined.

4.3. Limitations of the Study

Although this study's scope is limited to the local production of ingredients, the main limitation has been data availability regarding the origin and transportation of raw ingredients produced outside the Navarrese region. This impact was excluded from the analysis due to the high uncertainty derived from the lack of information on the origin of the ingredients and how transportation is carried out.

It should be noted that our study focuses on plant protein sources, and we compare two crops: pea and soybean. Traditionally, pea cultivation has been one of Spain's strengths in the European context [41]. In contrast, soybeans are commonly produced abroad. The data indicates that Spain imports, on average, nearly 6 million metric tons of soybean and soybean products annually, with most originating from Argentina, followed by other American countries like Brazil or the United States [42]. Given this information, previous studies by Domínguez-Lacueva [8] estimated the greenhouse gas emissions impact that such transoceanic ingredient transportation could entail. They determined that the impact on the final plant-based product is minimal (less than 0.01 kg CO_2e per 150 g of product). Regarding the water footprint, it is generally not significantly affected by the transport phase, except when biofuels are involved in the process, which is not common [20]. Considering this, we believe our study's results are not significantly compromised by the absence of raw material transportation data.

Data on the recharge of fluorinated gases in pea storage chambers is also unavailable. While this could significantly influence the carbon footprint, we can assume the impact assigned to peas would be highly diluted due to the large diversity and quantity of agricultural products typically stored in the respective facilities (company data).

Regarding fertilizer production. The present study solely considered the downstream effects of fertilizers' application, such as nitrogen migration. To approximate the magnitude of this data gap on our study's results, we estimated the carbon and water footprints of a similar nitrogen–phosphorus–potassium (NPK) fertilizer (15-15-15, meaning 15% N, 15% P_2O_5, 15% K_2O) from 2011 [43]. According to the carbon footprint factor of this fertilizer and the water use associated with the energy consumed for its production (assuming the energy mix of the Navarra-based companies studied), we determined the following: For the water footprint, the impact is minimal and negligible (less than 0.000001 L per kg of pea). For the carbon footprint, the impact per kilogram of pea could increase by approximately 0.07 kg CO_2e. However, this value becomes even more diluted considering the ingredient proportions of the studied snack, adding only 0.0062 kg CO_2e to the total carbon footprint. This leads one to conclude that the findings of the present article remain reliable.

5. Conclusions

The results emphasize the potential of pea protein as a sustainable alternative to soy-based vegan products in Navarra. While soy is widely used in the type of product analysed, pea protein offers several key advantages that make it a viable option for the region's food production. These advantages include its ability to be locally cultivated, revaluing traditional agricultural culture. Additionally, pea protein does not pose a risk of triggering common allergens, as with soy, making it an appealing choice for a broader range of consumers.

The environmental assessment also suggests that removing crop residues from the field or minimizing the use of fertilizers can significantly contribute to lowering the greenhouse gas emissions associated with pea production, although the final impact on the developed snack would hardly be noticeable. Moreover, while the green water footprint of pea-based extrusion is higher than that of soy-based alternatives, it is important to note that pea cultivation relies less on blue and grey water, making it a preferable choice in areas that face water scarcity or contamination risks. In particular, regions with limited access to freshwater resources can benefit from using peas as a primary crop rather than soy, as it can help conserve valuable water resources.

Regarding the developed product, it has been determined that the carbon footprint of the pea snacks is 0.12 kg of CO_2e per 100 g of packaged product, while the water footprint reaches 174 L of water per 100 g of packaged product. The blue water footprint represents the largest share (52%), followed by the green water footprint (47%) and the grey water footprint (1%). To further reduce the environmental impact of similar pea-based products, several strategic measures have been proposed. These include minimizing ingredient losses throughout the entire value chain (from production to consumption), as well as transitioning to renewable electricity sources for manufacturing processes. By implementing these strategies, it is estimated that greenhouse gas emissions could be reduced by 17%, while green water consumption could decrease by 3%. Actions such as conducting environmental impact assessments for production processes, along with the proposed impact reduction strategies, can contribute to global efforts to mitigate climate change, conserve natural resources, and promote food security.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su17135913/s1. The following supporting information can be found in the Supplementary Material section, annexed at the end of the chapter. Supplementary Text S1: Data on plot and farming systems. Supplementary Table S1: Conversion factors for the different energy sources used during the snack production. Supplementary Table S2: Ingredients, origins, and factors used in the calculation of the water footprint. Supplementary Table S3: Ingredients, origins, and factor sources used in the calculation of the carbon footprint. Supplementary Table S4: Packaging

materials, origins, factor sources and parts of the packaging used in the calculation of the carbon and water footprint. References [44–51] are cited in the supplementary materials.

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Abbreviations

ALISSEC project	Design of Healthy and Sustainable Food and Ingredients from the Circular Economy
CF	Carbon Footprint
C_{max}	Maximum Allowable Concentration
C_{nat}	Natural Background Concentration
CO_2e	CO_2 Equivalents
GWP	Global Warming Potential
GHG	Greenhouse Gas
Kc	Crop Coefficient
NL	Diffuse Nitrogen Load to Freshwater
PGI	Protected Geographical Indication
SDG	Sustainable Development Goals
WF	Water Footprint
WU	Water Use
Y	Crop Yield

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