Research Article

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Eco-design influence on the life cycle assessment of frozen cauliflower gnocchi: a comprehensive cradle-to-grave analysis

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Abstract

BACKGROUND: Nowadays, when discussing agri-food products, it is important to talk about sustainable production methods. Environmental sustainability has become a production issue, especially when it comes to the design of a product, service, or process. Using frozen fresh cauliflower gnocchi marketed in different packaging and in different global areas as a case study, we aim to highlight the importance of the impact of product eco-design on the entire life cycle.

RESULTS: The environmental impact of cauliflower gnocchi was assessed based on the life cycle assessment methodology. With the cradle-to-gate approach, the most influential factors are the cultivation, distribution, and packaging phases. Considering the cradle-to-grave approach, home storage has proven to be the most influential factor for a quarter of the entire life cycle of cauliflower gnocchi. The eco-design of packaging has demonstrated how, by analysing only the packaging, it is possible to achieve significant reductions in impact (−47%), but when compared with the entire life cycle these actions have no significant responsibility (approximately 10%). If, however, the field of action is broadened and eco-design solutions are sought to reduce the impact deriving from the conservation phase, the consumer has the ability, through their decisions, to reduce the impact relating to conservation as much as possible or to double the impact of the product life cycle.

CONCLUSION: Overall, to promote prosperity while protecting the environment, according to Agenda 2030, the agri-food system must analyse the supply chains without neglecting any step involved in the life cycle of the product. The eco-design must go beyond the usual factors analysed and shall include downstream activities to aim for more sustainable products, including consumer behaviours, following the cradle-to-grave approach.

Supporting information may be found in the online version of this article.

Keywords: domestic storage; sustainability; LCA; packaging; cauliflower; food preservation

INTRODUCTION

In recent years, agri-food companies are increasingly looking for solutions to limit their products' environmental responsibilities avoiding additional costs and making their systems both environmentally and economically sustainable,[1] and also adopting integrated solutions such as 'life cycle thinking' and 'life cycle management' methods.[2] To reach this goal, the life cycle assessment (LCA) represents the most reliable solution to determine the environmental sustainability level of a product, or a process as followed in the ISO standards 14040[3] and 14044.[4] The LCA approach has been widely used to investigate many aspects of food production, from the environmental impacts of a single stage within a food supply chain (i.e. farming,[5-7] packaging,[8] transportation[9] and waste management[10]) up to the entire food supply chain.[11]

To make sustainable food products, it is necessary to apply an LCA technique that helps the design and development of food products in all the life cycle phases. The process of considering environmental aspects at all stages of the product development process, aiming for products that have the

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lowest possible environmental impact throughout the product's life cycle, is called eco-design.[12]

Considering the eco-design approach and its applicability in food systems, several studies focus attention on specific fields of the entire product life cycle. Yuan[13] drew attention to food packaging and demonstrated how eco-design can lead to choosing packaging that at the same moment effectively promotes the sales and commercial volume of the product and offers the market a more environmentally friendly solution. Casson *et al.*[14] approached a product eco-design level, in this case packaging for red meat, going beyond the conventional eco-design approach and including in the analysis the effects that the choice of one packaging over another can have on food waste. Favi *et al.*[15] considered an eco-design approach of a cooking appliance in conditions of real use, demonstrating how the use of particular ingredients can lead to a reduction in cooking time and, consequently, in energy consumption. The results of the study led to the identification of the use phase as the one with the most impact along the entire life cycle of the product. The application of eco-design to reduce energy consumption could lead to an important environmental benefit.

The performance of environmentally sustainable food products in decreasing the environmental effects of food production and consumption systems may be directly influenced by the consumer. Nowadays, consumers still do not actively contribute to the food industry's environmental sustainability, mostly as a result of the public's lack of awareness of environmental sustainability issues, as in Notarnicola *et al.*[16] Moreover, in food-related LCA studies, the use phase could result in weakness in terms of completeness and representativeness, even if the boundary systems declared are 'from cradle to grave'. The consideration of the use phase yields diverse results. This phase encompasses activities such as cooking or food preparation, as demonstrated in studies by Recchia *et al.*[17] and Casson *et al.*[18] Additionally, factors like consumer transport and domestic consumption, as highlighted by Notarnicola *et al.*,[19] contribute to this variability, underscoring the wide range of assumptions made in these assessments; and Gruber *et al.*[20] studied the effects of shopping, storage, preparation, and disposal of food products as well as the disposal of the sales packaging.

To answer this need, this study aims to go beyond the conventional from cradle-to-grave LCA for eco-design, shifting to an analysis that includes consumer habits. First, a cradle-to-gate packaging eco-design LCA approach via a comparative analysis of three different product sizes was proposed; second, a complete analysis was conducted to demonstrate how consumers' habits should be included in agri-food LCA analysis.

MATERIAL AND METHODS

This study was carried out following the ISO standards 14040[3] and 14044[4] and following the product category rule (PCR) 'Pasta cooked, stuffed, or otherwise prepared; couscous product category classification: UN-CPC 2372. PCR 2011:07. Version 3.0. Valid until 2024-11-14'[21] and the General Program Instructions ver. 3.01[22] for the International EPD(R) System.

Goal and scope definition

The goal of this study is to analyse the environmental impact of the product, to compare different packaging solutions and market distribution (European and American), and to include the use phase, taking into account storage and cooking processes. The results aid the company in understanding and implementing eco-design scenarios at different life cycle stages of the product. It also paves the path for exploring eco-design in the use phase of the product.

Functional unit

To reach the goal of the study, the functional unit was defined as '1 kg of product' plus its packaging consumed. The product analysed is obtained from a few ingredients (Table 1) and represents a low-calorie food (Table 2). From a technological point of view, cauliflower gnocchi is a precooked and frozen product, requiring a very short preparation process time before eating.

System boundary

The system boundary, presented in Fig. 1, shows all the processes involved in the life cycle of the product. A cradle-to-grave approach was followed, including in the study the following items:

- agricultural and pre-production activities;
- gnocchi production phase;
- distribution;
- consumer habits.

DATA INVENTORY

A real industrial case study was considered, and the data were collected at Zini Prodotti Alimentari Ltd based in Milan (Lombardy, Italy), specialized in the production of frozen fresh pasta and gnocchi. The data refer to the year 2019 and compare the American and European marketing scenarios, which include different types of packaging, distribution, waste scenarios, and resources used for energy supply.

For both the European and American scenarios, consumer habits were included based on the recommendations on the product label. Moreover, the study aims to analyse different eco-design strategies that can be implemented in the life cycle from the company and consumer sides.

Table 1. Recipe characterization of cauliflower gnocchi

Ingredients	Fraction (%)
Durum wheat semolina	<50%
Cauliflower	>50%
Salt	<1%

Table 2. Nutritional characterization of cauliflower gnocchi

Nutritional factor	Quantity per 1 kg of product
Energy (kcal)	1600
Fats (g)	9
Carbohydrates (g)	320
Dietary fibre (g)	35
Proteins (g)	58

Even though the case study refers to a real industrial application, it could represent a limitation due to the product analysed being a niche product. Limitations to the LCA study are also represented by the limited possibility of repressing primary data relating to the production of raw materials. To overcome this problem, the data relating to these phases have been carefully studied in order to reflect the requirements of the reference standard and not use a data proxy for modelling this case study.

The following sections will propose an in-depth explanation of the different factors analysed and processes modelled within this study. A clear view of the factors analysed and selected from the databases and the network of processes created are reported in Supporting Information Data S1 for every single scenario proposed in the study.

Life cycle inventory analysis

Durum wheat semolina

The durum wheat semolina was obtained from wheat milled in northern Italy. According to the PCR 'Pasta cooked, stuffed, or otherwise prepared; couscous product category classification: UN-CPC 2372. PCR 2011:07. Version 3.0. Valid until 2024-11-14',[22] 500 km was assumed as the average distance from the farm to the mill. Regarding the transformation of wheat into semolina, selected secondary data

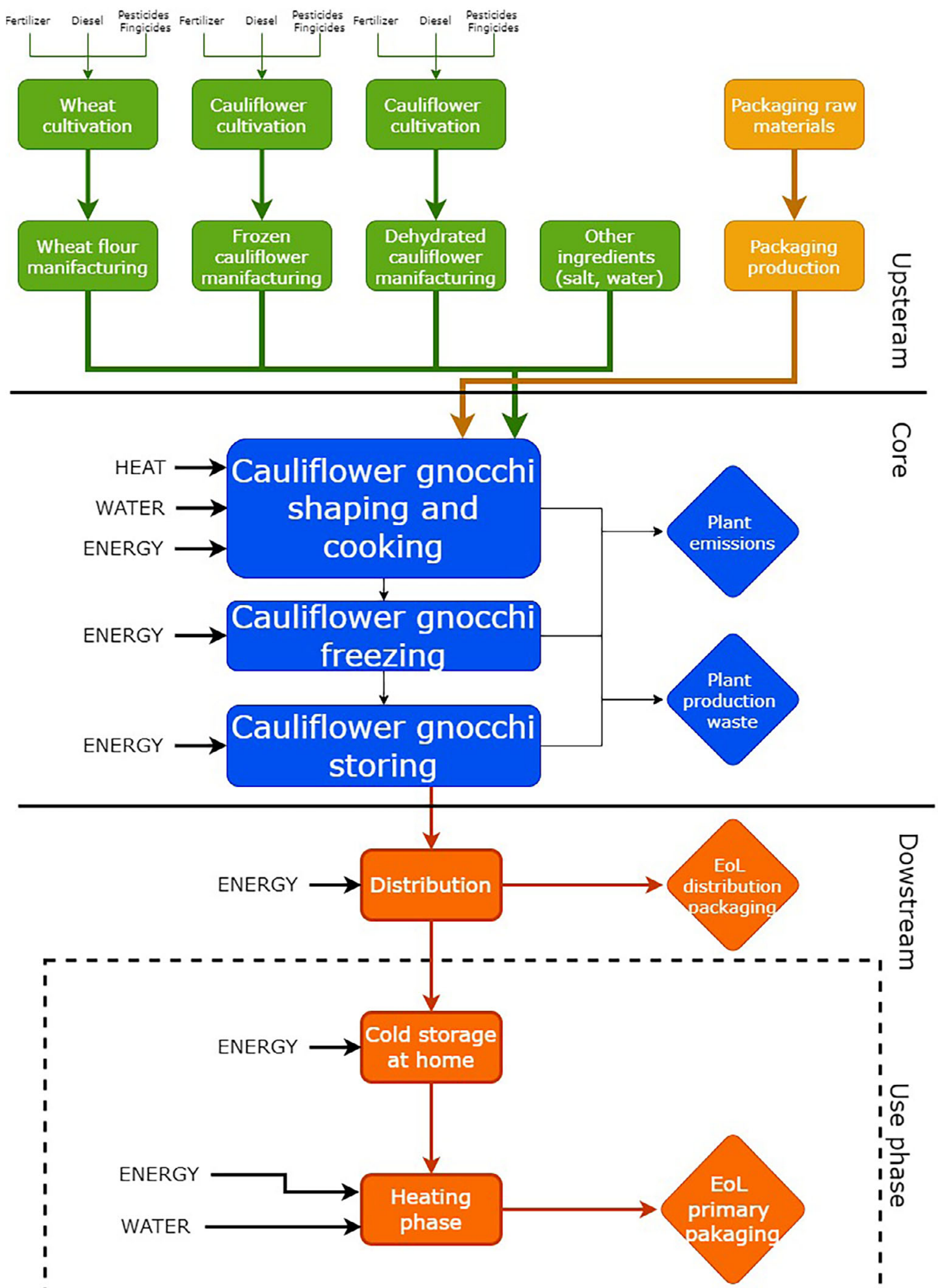

Figure 1. System boundaries and processes involved in the life cycle of cauliflower gnocchi.

have been used and the Agri-footprint 5.0 database was used to obtain the 1 kg of wheat semolina dataset. Distance from the mill to the gnocchi production plant was quantified as 463 km.

Cauliflower cultivation and transformation

The agricultural activity models of cauliflower production were selected from the Agri-footprint 5.0 database, whereas transformation activity has been modelled. Cauliflowers were produced in three different regions of Europe: Spain, the Netherlands, and France. According to the Agri-footprint 5.0 database, secondary data were selected for this production activity. Distance from the Spanish cultivation zone to the transformation one was quantified as 1604 km, whereas it was 500 km for the French and Dutch scenarios. The frozen cauliflower ingredient is obtained from cauliflowers that come from Spain and France. On the other hand, dried cauliflower is obtained starting from the product grown in Holland. Details regarding the transformation from raw material to intermediate product are proposed in the following sections.

Frozen cauliflower production

Regarding this process, no reasonable quality life cycle inventory data have been identified; therefore, the freezing energy was calculated by applying the following criteria. According to Abhay *et al.*,[23] fresh cauliflowers, after separation of the edible (66%) and inedible (44%) fractions, were washed, cut, and frozen. According to the European Commission Guidance Document,[24] the total amount of water necessary to wash an average vegetable was quantified as 3 m^3 per tonne of raw product, whereas energy consumption was calculated using Eqn (1) and the physical characteristics reported in Table 3:

$$\Delta H = uM[cp_l(T_{in} - T_{inc}) + L + cp_s(T_{inc} - T_{fin})] \quad (1)$$

Moisture content u was assumed equal to 100% (the real moisture content is 92%)[24] and allowed to not underestimate the enthalpy value results of the equation (402.16 kJ kg^{-1}). The epsilon factor $\varepsilon = 3$, electrical efficiency $E_{eff} = 0.9$, and the mechanical efficiency $M_{eff} = 0.7$ were defined to quantify the energy consumption of the machinery used to freeze the cauliflower from an initial temperature of 15 °C to the final temperature of −18 °C:

$$W = \frac{\Delta H}{\varepsilon} \quad (2)$$

$$\text{Energy consumption} = \frac{W}{E_{eff} + M_{eff}} \quad (3)$$

Using Eqns (2) and (3), the energy consumption to freeze 1 kg of cauliflower was quantified as 212.78 kJ kg^{-1} (0.059 kWh kg^{-1}).

Table 3. Cauliflower physical characteristic

Mass M (kg)	1
Moisture u (%)	100
Freezing temperature T_{inc} (°C)	−0.8
Specific heat over freezing cp_l (kJ kg^{-1} $°C^{-1}$)	4.02
Specific heat under freezing cp_s (kJ kg^{-1} $°C^{-1}$)	1.84
Latent fusion heat L (kJ kg^{-1})	307
Initial temperature T_{in} (°C)	15
Final temperature T_{fin} (°C)	−18

According to Knudsen *et al.*,[25] who identified 0.083 kWh of the electricity consumption necessary to freeze 1.4 kg of oranges, the result obtained can be defined as reliable. Distance from the transformation site to the gnocchi production plant was quantified as 172 km.

Dehydrated cauliflower powder

The dehydration process was modelled according to the European Commission Guidance Document,[24] implying the use of forced hot-air dehydrators. A lack of data on this process in the database implied a searching activity in the literature. Few studies analysed this process from an energetic point of view, but without referring to the cauliflower dehydration process. Therefore, based on a literature analysis, the following calculation was made.

The dehydrated cauliflower powder is obtained by the following operations. The whole cauliflower is washed and cut and the edible part of the cauliflower, which is at room temperature (15 °C), is transferred to a heating plant where it is heated to over 100 °C. During this process, the temperature variation ΔT_w until it reaches 100 °C is 85 °C. Under these specific conditions, water, with a specific heat capacity cp_w of 4.185 kJ kg^{-1} °C, undergoes a phase change from liquid to gas, with a heat of vaporization h_{vap} of 2257 kJ kg^{-1}.

Subsequently, as reported in table 4, the vapour in the heating system is not kept at 100 °C but at a higher temperature (e.g. 150 °C). This results in an increase in its temperature ΔT_{vap} of about 50 °C. The specific heat capacity of water vapour cp_{vap} is 1.996 kJ kg^{-1} °C.

$$\text{Heat} = \Delta T_w \times cp_w + h_{vap} + \Delta T_{vap} \times cp_{vap} \quad (4)$$

Eqn (4) quantified 4545.875 kJ kg^{-1} (1.26 kWh kg^{-1}) as the heat necessary to evaporate 1 kg of water contained in the cauliflower matrix. According to Tippayawong *et al.*,[26] an efficiency of the dehydrating system of 0.3 was set and heat consumption equal to 9091.75 kJ kg^{-1} (2.52 kWh kg^{-1}) was obtained. According to Beigi,[27] the heat source was divided into 98% gas burners and 2% heat based on electricity consumption. The results obtained can be assumed as reliable if compared with literature, in fact, Giovenzana *et al.*[28] analysed a chestnuts heat pump dryer that used low-temperature forced dry air to produce high-quality products, quantifying heat consumption equal to 8.84 MJ kg^{-1}. Finally, the distance from the transformation site to the gnocchi production plant was quantified as 576 km.

Salt and water production

According to the recipe, salt and water datasets were selected as secondary data. Regarding salt transportation, 1474 km was considered (99% road and 1% ship). Details related to the datasets selected are given in Supporting Information Data S1.

Table 4. Water physical characteristic

Water thermal variation ΔT_w (°C)	85
Specific heat cp_w (kJ kg^{-1} $°C^{-1}$)	4.185
Heat of vaporization h_{vap} (kJ kg^{-1})	2257
Specific heat water vapour cp_{vap} (kJ kg^{-1} $°C^{-1}$)	1.996
Vapour thermal variation ΔT_{vap} (°C)	50

Packaging alternatives

According to the goal and scope of the study, as reported in Table 5, the different markets imply the use of different primary packaging. The EU primary packaging was a biodegradable and mono material product that is used in two sizes: the 400 g packaging, which weighs 9.04 g, and the 1 kg bag, which weighs 16 g. Secondary packaging (corrugated board box) weighed 260 g for the 400 g selling unit, whereas the one for the 1 kg selling unit weighed 320 g; extensible film was also considered (216 g of polyethylene (PE) film per pallet). The tertiary packaging is characterized by a 25 kg flat EUR pallet. Details related to the datasets selected are given in Supporting Information Data S1.

In the US market, the primary packaging is multilayer packaging (low density PE–polyethylene terephthalate) with an overall weight of 9.1 g. A corrugated board box of 120 g was used as secondary packaging. A weight of 216 g of PE film per pallet was considered, whereas the tertiary packaging was characterized by 15 kg of polypropylene per pallet. Details related to the datasets selected are given in Supporting Information Data S1.

Cauliflower gnocchi production

The gnocchi production line is characterized by an automated production line equipped with a turbo-cooker that can mix and cook the gnocchi dough at the same time, avoiding the presence of two types of machinery. The gnocchi produced is then frozen, packaged, and stored in freeze cells waiting to be shipped.

Direct measurements were carried out, and mass allocation criteria were carried out to evaluate the energy, gas, water, and auxiliary materials consumption for 1 kg of cauliflower gnocchi. The total production of frozen fresh pasta products, the gnocchi production, and cauliflower gnocchi production were taken into consideration to allocate the environmental impacts of production to the product analysed. According to mass allocation criteria, two allocation factors have been used: (i) an allocation factor with respect to all plant production, equal to 2.1%; and (ii) an allocation factor of cauliflower gnocchi with respect to the gnocchi production line, equal to 3.7%.

According to production volumes of the year 2019, allocated input and output quantities of water, gas, electricity, waste, and detergents used were quantified and are reported in Table 6.

Regarding electricity consumption, the dataset related to the Italian energy country mix was adjusted to be representative of the temporal sampling time in accordance with the residual country mix reported by the Association of Issuing Bodies.[29] Gas consumption was quantified; and in accordance with a heat coefficient of 0.039 GJ/smc (data coming from gas supplier), the heat necessary to produce 1 kg of cauliflower gnocchi was quantified as 1.665 MJ. Site emissions, detergents, and refrigerant liquid leaks were also accounted for in the system studied and modelled in the core process. A food loss of 5.4% was accounted for in the production process, but no waste treatment was modelled instead of transportation activity due to the feed use. Details related to the datasets selected are given in Supporting Information Data S1.

Transportation

Once the product is packaged, it is ready to be shipped to the EU and the USA. For both markets, the distances between the

Table 5. Packaging alternatives for the different markets analysed

	Primary packaging			Secondary packaging			Tertiary packaging		
Market	Material	Capacity (g)	Weight (g)	Material	Selling units per box *n*	Weight (g)	Material	Selling units per pallet *n*	Weight (kg)
EU	Polyester-complexed starch biopolymer	400	9.04	Corrugated board box	6	260	Polyethylene film Wood pallet	600	0.216 25
		1000	16			320	Polyethylene film Wood pallet	650	0.216 25
USA	Low-density polyethylene + polyethylene terephthalate	286	9.1			120	Polyethylene film Polypropylene pallet	650	0.216 15

Table 6. Gnocchi production input

Factor	Amount	Unit	Allocated quantity per CGP	Unit	Allocated quantity per 1 kg of CG	Unit
Water input	69 843.0	m^3	1 464.82	m^3	5.30	dm^3
Water evaporated	21 980.2	m^3	439.60	m^3	1.59	dm^3
Water discharged	33 772.0	m^3	675.44	m^3	2.44	dm^3
Gas	558 039.0	smc	454 308.09	MJ $year^{-1}$	1.65	MJ
Electricity	5999.5	MWh	124.94	MWh	0.45	kWh
Production waste	717 460.0	kg	15 066.66	kg	0.05	kg

Abbreviations: CG, cauliflower gnocchi; CGP, cauliflower gnocchi production.

production site and an average retailer were obtained through interviews with the company and using the Eco TransIT World platform, distances were characterized and are reported in Table 7. For both transports (road and sea), freezing energy consumption was considered. According to the PCR,[22] the rate of food loss during distribution (due to breakage of the product, and failure to return it to the manufacturer) was assumed to be 1%.

The product delivered in the market is then purchased by the consumer and stored at home.

Domestic storage

The final product must be frozen for storage. The International EPD® System[21] provides the guidelines for modelling the energy consumption related to storage in a refrigerator and in a freezer. According to the International EPD System,[22] Cappelletti *et al.*,[30] and the data available from a screening of the two markets, an average refrigerator with an annual energy consumption of 218 kWh (class E) was considered. The capacity of the refrigerator is about 311 L, and the recommended loading percentage is about 75% of the capacity. Considering the fact that the refrigerator is loaded and unloaded continuously and assuming that the capacity in litres is equal to kilograms, the average load of the refrigerator was calculated to be 117 kg. By dividing the energy consumption of the refrigerator by the capacity, the energy consumption was quantified as 1.8 kWh kg^{-1} $year^{-1}$. Considering the shelf life of the product analysed (18 months), the estimated energy consumption per 1 kg of the product was quantified as 2.5 kWh (storing the product for half of its shelf life, i.e. 9 months). To identify an impact that represents the European scenario, the Ecoinvent dataset relating to the European energy mix (Electricity {Europe without Switzerland} | market group for electricity) was selected. As regards the American energy mix, the 'Electricity {US} market group for electricity' dataset was selected. Further details related to the datasets selected are given in Supporting Information Data S1.

Domestic preparation process

Regarding the preparation phase, the suggestions provided by the company on the product packaging were used. The impacts related to the cooking phase for 1 kg of the product were estimated according to the International EPD System.[21]

Table 7. Distances and type of transport

Destination	Average distance (km)	Transport	Road (km)	Sea (km)
USA	9000	Road and sea	300	8700
Europe	535	Road	535	

Domestic preparation methodologies consist of (i) boiling water or (ii) a cooking pan. In the case of the 'boiling water' process, 10 L was considered; 0.18 kWh per litre of water was necessary to get the water boil, whereas the cooking phase required only 0.05 kWh per minute of cooking. Considering that the cauliflower gnocchi required only 90 s, the total energy consumption was quantified as 1.875 kWh.

Differently for the pan, the water used was less at 0.25 L (0.10 L per 400 g of product), and 0.05 kWh per minute of cooking was required to heat the gnocchi products. The products are ready in just 180 s; therefore, the energy consumption was quantified as 0.15 kWh. To identify an impact that represents the European scenario, the Ecoinvent dataset relating to the European energy mix (Electricity {Europe without Switzerland} | market group for electricity) was selected. As regards the American energy mix, the 'Electricity {US} market group for electricity' dataset was selected. Details related to the datasets selected are given in Supporting Information Data S1.

End-of-life processes of any wasted part of the product at the domestic level (domestic food losses)

As specified in the 'Pasta cooked, stuffed or otherwise prepared; couscous' PCR developed by the International EPD System,[22] default pasta loss rates at the consumer can be assumed as 2%. The product loss at home is assumed to be 50% trashed (25% incinerated and 25% landfilled), 25% composted, and 25% methanized.

Packaging end-of-life

End-of-life scenarios for packaging after consumption have been created in compliance with the Plastics Europe report for plastics, and for paper products according to the COMIECO 'Raccolta, riciclo e recupero di carta e cartone' report.[31] The waste management share for Europe is given in Table 8.

Data referring to the plastics and paper waste management system in the USA were obtained from the US Environmental Protection Agency.[32] Details about these waste management systems are reported in Table 9.

For all the processes involved in the end-of-life scenario, the cut-off allocation procedure was followed; further details related to the datasets selected for the end-of-life modelling are given in Supporting Information Data S1.

Life cycle impact assessment

According to the PCR for cooked pasta,[21] EPD (2018), and CML-IA baseline v.3.5 methods, the following impact categories were proposed:

- global warming potential (GWP);[33]
- acidification potential (AP);[34-36]
- eutrophication potential (EP);[36,37]
- formation potential tropospheric ozone (FPTO);[38,39]
- abiotic depletion potential – elements (ADP-E);[36]
- abiotic depletion potential – fossil fuels (ADP-FF);[36]

Table 8. Waste management system in Europe

Product	Landfill	Recycling	Incineration
Plastic	20.4	40.8	38.8
Paper	7.2	85.6	7.2

Table 9. Waste management system in the USA

Product	Landfill	Recycling	Incineration
Plastic	20.4	68.2	38.8
Paper	75.6	8.7	15.7

- water scarcity potential (WSP).[40]

Simapro version 9.1 (PR Sustainability, Amersfoort, Netherlands), Ecoinvent 3.6 (cut-off allocation), and Agri-footprint 5.0 database were used to assess the environmental impacts of the product under study.

Strengths, weaknesses, opportunities, and threats analysis

We present a strengths, weaknesses, opportunities, and threats (SWOT) analysis regarding the potential implementation of the prototype for ultrasonic remuage in the Champenoise method for the sparkling wine sector. SWOT is a well-known method to evaluate new potential solutions. Several studies have attempted to use SWOT to analyse the implementation of solutions in the agri-food sector related to (i) procedures in Sarter *et al.*,[41] (ii) environmental impact aspects in Baudino *et al.*[42] and Casson *et al.*,[43] and (iii) technological innovation for automated systems in Giovenzana *et al.*,[44] and Pampuri *et al.*[45] Internal characteristics known as strengths and weaknesses provide the items a competitive edge or disadvantage. Threats and opportunities, on the other hand, are outside forces that might help or impede the creation of a product.

RESULTS

In order to understand how the different factors involved in the life cycle of the gnocchi product can influence the environmental footprint of the product, an evaluation of the impact of frozen fresh cauliflower was conducted. The LCA analysis allows one to focus the attention on two eco-design scenarios:

(1) packaging eco-design scenario;
(2) use phase eco-design scenario.

Regarding the packaging eco-design a comparative analysis of three different product sizes (cradle-to-gate assessment) was done and the details are reported in the Cradle-to-gate impact assessment and packaging eco-design section. The Cradle-to-grave impact assessment and use phase eco-design section, on the other hand, refers to the cradle-to-grave assessment and the responsibilities of consumers is highlighted proposing use phase eco-design analysis.

First, the LCA study, despite comparisons of company decisions already implemented at the product marketing level, made it possible to identify the most sustainable packaging solution, demonstrating how the first level of eco-design concerns companies and their possibility of redesigning the packaging that they intend to place on the market.

Second, the same study with a broader approach analyses the consequences of the use phase and their effect on the entire life cycle of the product, representing the second eco-design hotspot, where educating consumers becomes obligatory.

Finally, a SWOT analysis was performed to highlight better mitigation strategies.

Cradle-to-gate impact assessment and packaging eco-design

Figure 2 shows at the same time the comparison among the different packaging solutions and, for every single product, the environmental hotspots for each impact category proposed.

Owing to the consumption of cauliflower and wheat flour, agricultural activities are the main hotspot for GWP (from 32% to 36% of the impact), AP (from 61% to 74% of the impact), and EP (from 86% to 81% of the impact) because of the use of fertilizers and agricultural machinery. According to Recchia *et al.*,[17] agricultural activities represent hotspots also in WSP (from 90% to 92% of the impact) due to the large amount of water used for irrigation.

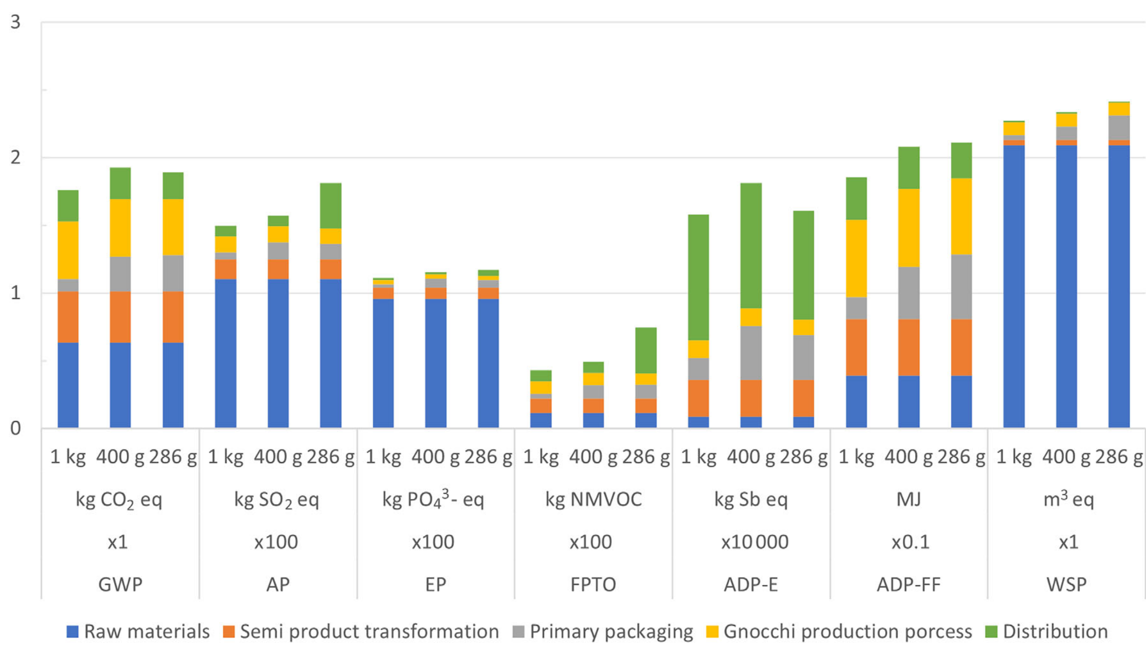

Figure 2. Environmental impact assessment and hotspot identification of different product size cauliflower gnocchi in a cradle-to-gate system. GWP, global warming potential; CO_2 eq, carbon dioxide equivalents; AP, acidification potential; SO_2 eq, sulfur dioxide equivalents; EP, eutrophication potential; PO_4^{3-} eq, phosphate equivalents; FPTO, formation potential tropospheric ozone; NMVOC, non-methane volatile organic compounds; ADP-E abiotic depletion potential – elements; Sb eq, antimony equivalents; ADO-FF, abiotic depletion potential – fossil fuels; WSP, water scarcity potential; EoL, end of life.

The second overall hotspot is represented by the distribution phase; the channels studied report an average environmental impact responsibility of about 17% among impact categories, neglecting the different destinations of the products analysed; while focusing on the different destinations, higher responsibilities are reached by European market product (59% for 1 kg size) in ADP-E. Different results are reported in AP, EP, and FTPO impact categories, where the US scenario represents the worst case in terms of environmental impact due to transportation.

The semi-product transformation of raw agricultural products into semi-finished products represents the third hotspot in the life cycle analysed. In fact, semi-product transformation activities are one of the main things responsible in GWP (from 19% to 21% of the impact), in FPTO (from 14% to 25% of the impact), in ADP-E (from 15% to 17% of the impact), and in ADP-FF (from 20% to 22% of the impact) due to the heat used in processing plants to dehydrate cauliflower into cauliflower powder and the energy consumption to freeze the cauliflower.

The environmental impact related to cauliflower gnocchi production is not representing one of the main hotspots; the average responsibility of this factor is around 12%. The main responsibility of this phase is derived from the use of fossil resources to obtain the final product, such as natural gas and electricity consumption. Higher percentages are recorded in GWP (from 20% to 22% of the impact), in FPTO (from 10% to 17% of the impact), and ADP-FF (from 25% to 28% of the impact). The centralization of the cooking procedure and the freezing activity to obtain the frozen product require high energy demands, both in terms of heat and in terms of electricity consumption.

Packaging represents an average responsibility among impact categories and products of about 10%. Even if the responsibilities are lower with respect to other factors, higher impacts are recorded in FPTO (from 9% to 21% of the impact), in ADP-E (from 10% to 22% of the impact), and in ADP-FF (from 9% to 23% of the impact). A trend can be highlighted: the packaging with higher capacity (1 kg) is much better with respect to the other, and the plastic one represents the worst choice in most of the impact categories. A focus on this trend is proposed in Table 10, where the only impact related to the production and waste management of the different packaging solution is proposed.

From Fig. 2 and Table 10, the environmental impact assessment comparison among the three types of products analysed can be examined. A few differences among the products were highlighted, mostly related to the packaging and distribution channels. Moreover, comparing the three products, the 1 kg size reported the best environmental performance in all the impact categories, whereas the 400 g and the 286 g sizes showed different behaviours depending on the impact category analysed.

From the eco-design approach, the company has adopted a change in packaging solution by introducing packaging with a reduced environmental impact on the European market compared with the solution in the US market. The comparison between the 1 kg package and the 400 g package can highlight an indirect correlation between the environmental impacts and the volumetric capacity of the package (the greater the volume, the lower the relative environmental impact). In the ADP-E impact category, the increase in material for the 400 g package exceeds the environmental impacts related to the increase in material for the 286 g package by approximately 20% due to the production of biobased polymers, guaranteeing the package from 1 kg the best environmental performance.

By analysing the effects of a transition from a plastic packaging solution (286 g) to a compostable packaging solution in a larger format (400 g and 1 kg), it is possible to see how, by analysing only the impacts relating to packaging, there is a substantial reduction in the environmental impact, going from an average −47% with the 400 g solution to −62% with the 1 kg solution.

The eco-design approach should not stop here, and a broader vision should be included by analysing the effect of the choice of packaging on the entire life cycle. In fact, from Fig. 2 it is possible to demonstrate how the choice of one packaging compared with another can mean quite significant reductions in impact.

Even in this case, the focus on alternative packaging solutions may represent the most significant aspect of a product's life cycle. In fact, no effects derived from consumer behaviours have been reported in the results so far. To respond to this lack, the following section aims to analyse the effect of consumer behaviour on the life cycle of the product by introducing one of the key aspects in the analysis of the environmental impact assessment of food products.

Table 10. Primary packaging solution comparison (all the formats are referring to 1 kg of product)

		Primary packaging for			Percentage reduction from (%)	
Impact category	Unit	US market (286 g)	EU market (400 g)	EU market (1 kg)	286 g pack to 400 g	286 g pack to 1 kg
GWP	kg CO_2 eq	3.62×10^{-1}	2.92×10^{-1}	1.07×10^{-1}	−60.37	−71.83
AP	kg SO_2 eq	1.07×10^{-3}	1.19×10^{-3}	4.76×10^{-4}	−45.48	−61.25
EP	kg PO_4^{3-} eq	8.03×10^{-4}	8.28×10^{-4}	2.83×10^{-4}	−40.02	−57.37
FPTO	kg NMVOC	1.17×10^{-3}	1.24×10^{-3}	4.73×10^{-4}	−51.77	−65.72
ADP-E	kg Sb eq	1.13×10^{-6}	1.31×10^{-6}	5.59×10^{-7}	−23.97	−45.96
ADP-FF	MJ	4.56	3.64	1.51	−63.22	−73.86
WSP	m^3 eq	1.70×10^{-1}	1.60×10^{-1}	6.64×10^{-2}	−48.81	−63.61

Abbreviations: GWP, global warming potential; CO_2 eq, carbon dioxide equivalents; AP, acidification potential; SO_2 eq, sulfur dioxide equivalents; EP, eutrophication potential; PO_4^{3-} eq, phosphate equivalents; FPTO, formation potential tropospheric ozone; NMVOC, non-methane volatile organic compounds; ADP-E abiotic depletion potential – elements; Sb eq, antimony equivalents; ADO-FF, abiotic depletion potential – fossil fuels; WSP, water scarcity potential.

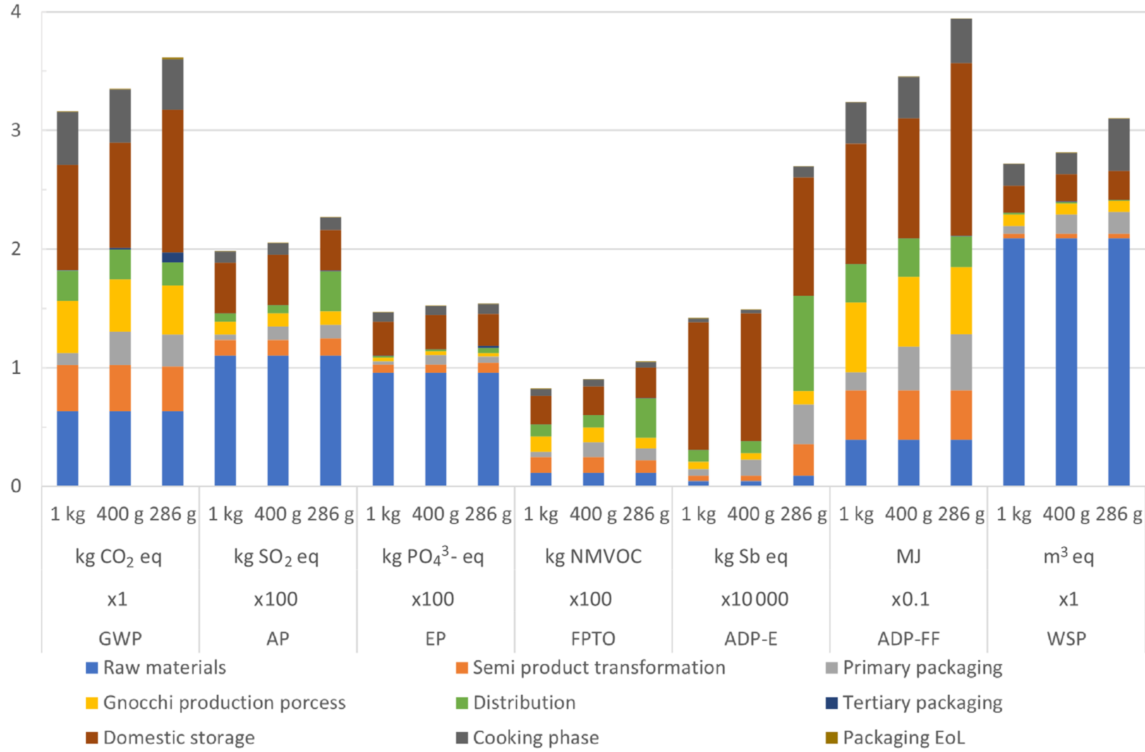

Figure 3. Environmental impact assessment and hotspot identification of different product size cauliflower gnocchi in a cradle-to-grave system. GWP, global warming potential; CO_2 eq, carbon dioxide equivalents; AP, acidification potential; SO_2 eq, sulfur dioxide equivalents; EP, eutrophication potential; PO_4^{3-} eq, phosphate equivalents; FPTO, formation potential tropospheric ozone; NMVOC, non-methane volatile organic compounds; ADP-E abiotic depletion potential – elements; Sb eq, antimony equivalents; ADO-FF, abiotic depletion potential – fossil fuels; WSP, water scarcity potential.

Cradle-to-grave impact assessment and use phase eco-design

During the use phase, consumer behaviour and related effects are fundamental to assess the environmental impact of the entire product life cycle, especially if referring to a 'long shelf-life' and 'short preparation time' product.

Analysing with a 9-month storing period, Fig. 3 reports the environmental impact assessment related to consumers' activities in which the storing phase represents the main hotspot with an average impact responsibility of about 28% among impact categories. The hotspot 'domestic storage' is highly dependent on the electricity consumption of the fridge (2.5 kWh).

Owing to the different energy country mix, the storage activity in the USA reports higher impacts in GWP, EP, FPTO, ADP-FF, and WSP, whereas higher impacts are reported in the EU scenario in the other impact categories. These results depend on the higher hard coal usage for energy production in the USA.

Analysing Fig. 3 and the magnitude of the different factors that can affect the system in a cradle-to-grave view, the impacts deriving from the domestic storage affects from 0.8 to 1.2 kg of CO_2 equivalents, which is a quarter of the entire cauliflower gnocchi life cycle.

Considering the weight of this activity and the large contribution to the overall environmental impact is fundamental to identify and analyse mitigation actions that can be performed in order to reduce the environmental profile of the product analysed to identify an environmental break-even point.

From the cradle-to-gate point of view, mitigation strategies can be identified in different phases of the life cycle of the product, but a very limited number of them could be really improved that would lead to a more sustainable product. Agricultural activities, semi-product transformation, and the gnocchi production process involve phases that could be modified, as indicated by Venturi *et al.*,[46] whereas packaging solutions (even if not representing the highest hotspot) could be improved by using different materials and by involving different capacities. This activity could lead to an overall reduction of environmental impacts among impact categories of about 11%.

Considering the whole life cycle, the highest hotspot is not represented by the packaging but by consumer habits, and in particular by the domestic storage, which is highly influenced by several factors, mainly the electricity country mix and the storage period.

From an eco-design approach, the origin of the grid electricity (electricity country mix) is not dependent on the consumer choices, which leads to one of the main controllable factors in the use phase; that is, the storage period of the product.

Aiming to understand the effect of this factor on the whole life cycle, Fig. 4 proposes a clear representation of the impact of the storage period of the cauliflower gnocchi in the two markets, from zero storage time to the end of the shelf life. From Fig. 4, it is clear that the impacts are directly proportional to the storage period, meaning that a lower storage period would result in lower impacts.

By analysing the starting point of the proposed trend, it is possible to identify that the US gnocchi product is better than the EU mainly because of the lower impacts of packaging. An increasing trend can be seen for both the market as the storage time increases. From month zero to month 18 (end of shelf life), different increases of impacts can be recorded. At the end of the shelf life, the impacts of the US gnocchi product are almost doubled, moving from 2.4 to 4.8 kg of CO_2 equivalents due to the impact of the electricity country mix factor.

Consumers should be more aware about their responsibilities of storing the products for a long period, which could lead to higher energy consumption in the freezer and thus aiming to a more sustainable consumption of frozen fresh cauliflower gnocchi.

Depending on the month of consumption, the two products may be better or worse than each other. Compared with the behaviour of consumer storage activities, the shorter the product conservation time, the lower the impact associated with the life cycle of the gnocchi. In the event that the product was consumed within the first month and a half, the most sustainable product would be the gnocchi marketed in the USA, whereas from the first month and a half up to the 18th month of shelf life the gnocchi marketed in the EU would be the most convenient product, thanks to the energy mix.

This result demonstrates how decisions taken by the company in placing packaging solutions and products on the market that can be defined as more sustainable can be the subject of revisiting the benefits in the face of activities that do not depend on the producer but on the consumer. As can be seen in Fig. 2 and Table 10, the most sustainable solution from the company's point of view should be the 1 kg format; but if we analyse Fig. 4, this decision leads to other reflections: depending on the moment of consumption of the product, the environmental impact may vary. If the consumer is aware of reducing the overall environmental impact of food products, the definition of a domestic eco-design approach at household level is mandatory to promote mitigation actions and reduce the overall impact. In fact, Fig. 4 shows how a change in domestic choice, linked only to the conservation period, could significantly reduce, or increase, the environmental impact of the product's life cycle.

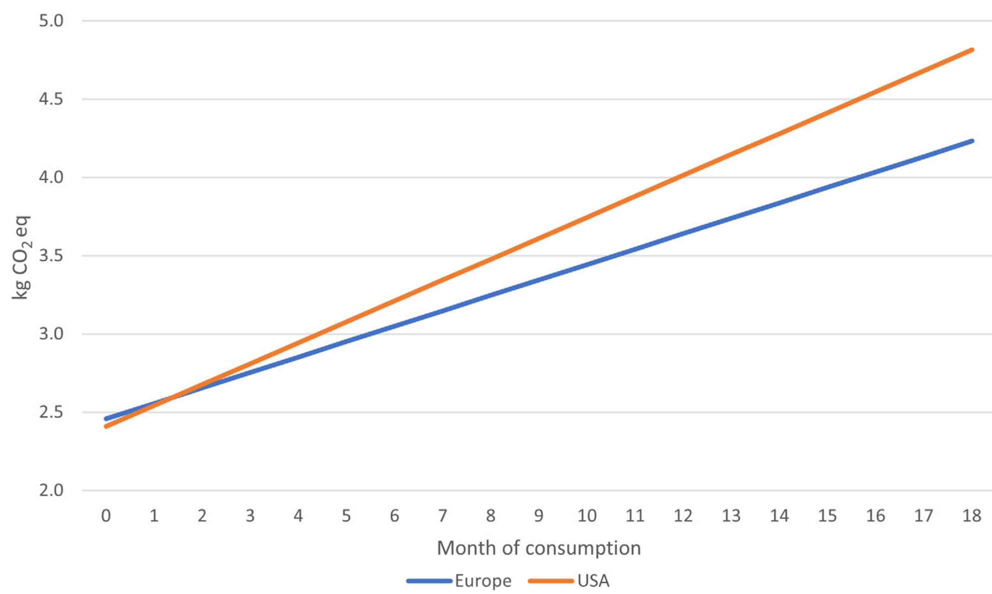

Figure 4. Sensitivity analysis between US and European cauliflower gnocchi within the shelf-life cycle time.

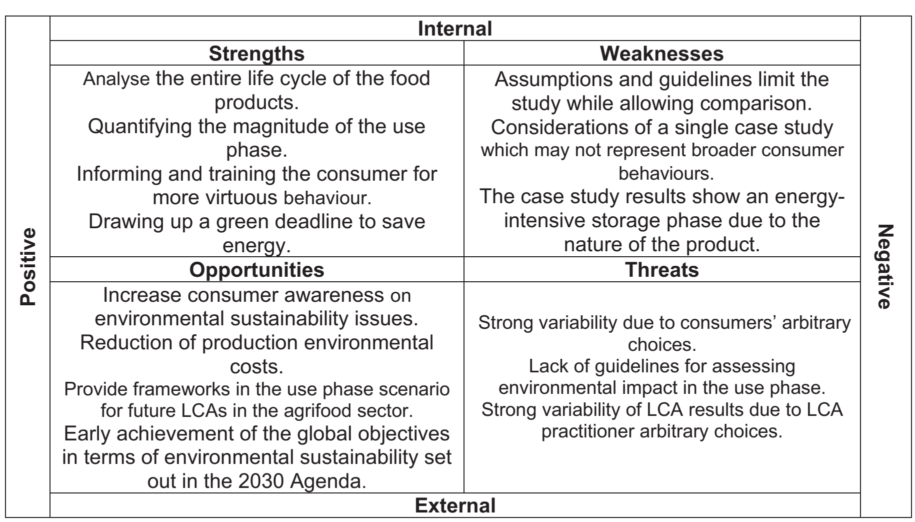

Figure 5. Strengths, weaknesses, opportunities, and threats in considering the use phase in the agri-food life cycle assessment (LCA) studies.

Looking at the LCA studies available in the literature of Notarnicola *et al.*[19] and Gruber *et al.*,[20] consumer behaviour is generally not analysed, even if the application is from the cradle to the grave. In order to better analyse the results of use-phase eco-design research in terms of real applications in the agri-food sector, a SWOT analysis is proposed (Fig. 5).

Use-phase eco-design research outputs have strengths, including promoting environmentally conscious approaches, educating consumers on more sustainable storage, and disseminating information. Weaknesses include overreliance on case studies, which may not represent broader consumer behaviours.

Opportunities lie in increasing consumer awareness on environmental sustainability issues, reducing production environmental costs and trying to provide frameworks in the use phase scenario for future LCAs in the agrifood sector. However, LCA studies that include the use phase in the scope face threats that could lead to high variability in methodology, giving incomparable and unreliable LCA results. Balancing tradition and innovation is key to mitigating these threats, while new sustainability challenges and opportunities emerge.

CONCLUSION

When evaluating the environmental performance of 1 kg of cauliflower gnocchi and its packaging for two different markets, in three distinct sizes and formats, an in-depth study on the environmental impacts was conducted. Different activities along the entire product life cycle were analysed and included in the analysis using the eco-design approach. This study has identified some activities that could be the subject of mitigation strategies by the company, whereas others require awareness-raising intervention on the part of consumers.

With regard to the production of packaging, three different packaging solutions were examined (plastic and biobased in two different formats). The comparison of packaging alone highlighted a reduction in environmental impacts of 62% by switching from the plastic packaging to bio-based packaging, whereas the analysis of the entire life cycle of the product highlighted an overall reduction in impacts of 11% between the different impact categories, mainly because of lower impacts in production and disposal of bio-based packaging.

The results of the analysis highlighted other factors of greater importance. Domestic storage significantly affects the environmental impact of the product examined, representing the most critical and variable phase of the life cycle. Considering, for example, a shelf life of 9 months (half the commercial life of the product), this activity represents a quarter of the overall impact of the product's life cycle. However, if the product is stored until the expiry date (i.e. 18 months), the environmental impact of 1 kg of gnocchi doubles.

Research in the field of eco-design must also involve different stakeholders, promoting environmental awareness and the adoption of sustainable practices. This educational approach aims to disseminate information in the agri-food sector. Although this study is based on a specific case, use-phase eco-design also includes other parameters, like the availability of efficient appliances in food preparation, optimal water consumption, and food waste disposal, that can help companies fully understand the most influential factors throughout the supply chain.

In conclusion, finding the balance between tradition and innovation will be fundamental to face future challenges and maximize the impact of research on eco-design. Future studies dedicated to food eco-design should not be limited to factory doors but should also include the use phase. Only in this way will it be possible to adopt a broader approach to life cycle thinking, going beyond conventional methodologies.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study will be openly available after publication article.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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