



Addressing environmental and economic impacts in the sustainable production profile of organic canned pickled mussels

Eduardo Entrena-Barbero^{*}, Gumersindo Feijoo, Sara González-García, María Teresa Moreira

CRETUS, Department of Chemical Engineering, School of Engineering, Universidade de Compostela, 15782, Santiago de Compostela, Spain

ARTICLE INFO

Keywords:

Food security
Seafood products
Life cycle assessment
Product environmental footprint
Monetary valuation
Green policies

1. Introduction

The global human population reached 8 billion people in November 2022 and is expected to continue growing to 9.7 billion by 2050 (United Nations, 2022). This upward trend will imply a 70% increase in demand for food (King et al., 2017), thus hindering the achievement of food security. The concept of food security relates to ensuring availability and access to a sufficient amount of food that can be used to meet the nutritional needs, as well as to maintain an active and healthy lifestyle over time (Mc Carthy et al., 2018).

Food security entails an arduous task, with a notable impact on human welfare, which is interrelated with many other aspects (FAO, IFAD, UNICEF, WFP, WHO, 2020). Among them, a term with greater social presence is food safety, which refers to the challenge of feeding the population in optimal sanitary conditions to prevent food-borne diseases (Manning and Soon, 2016) and food sovereignty, which refers to the capacity of a country to produce the food its population needs and the will to do so (Jarosz, 2014). Although, in environmental terms, ensuring food security is inversely related to accelerating Climate Change (CC), as it may pose a risk to its four dimensions: food availability (quantity and quality of food), food accessibility (access to nutritious and adequate food), food utilization (food to meet all socio-physiological needs) and food stability (permanence of food availability, accessibility and utilization over time) (Firdaus et al., 2019).

Hence, to reverse this trend, it is not enough to increase the productivity of food systems to meet population demand, but to make them

capable of withstanding adverse situations caused by the secondary effects of CC through adaptation and mitigation measures (Loboguerrero et al., 2019). Furthermore, beyond greenhouse gas (GHG) emissions, food production systems are also related to other important burdens depending on the environment in which they are developed, for example, land use change for land-based aquaculture facilities or eutrophying discharges to water for fisheries (Henriksson et al., 2021).

At EU level, several policies have emerged to lay the foundations for a roadmap in global food security. In 2013, the European Commission launched an initiative: the Product Environmental Footprint (PEF). This aims to create a common framework for estimating and communicating the potential environmental impacts associated with products (goods or services) based on Life Cycle Assessment (LCA) methodology, thus establishing a single market for green products that promotes sustainable production and consumption (European Commission, 2013). In addition, there are also a number of specific guidelines tailored by sector and product group: PEF Category Rules (European Commission, 2018a). According to the food sector, these include some beverages: water, wine and beer, as well as some foods such as dairy products or pasta, while others are still under development (e.g., fish). Notwithstanding, although the assessment and communication of environmental impacts of food products is becoming more common practice, the same is not true when the focus of the study is broadened to include the indirect effects caused by them, such as the indirect economic effects of mitigating them. In fact, the lack of monetary resources is one of the crucial issues in pushing forward climate action policies, even though it has been estimated that avoiding the side effects of CC would only accounts for around 0.18% of the global gross domestic product in 2050 (Fujimori

^{*} Corresponding author.

E-mail address: eduardo.entrena.barbero@usc.es (E. Entrena-Barbero).

<https://doi.org/10.1016/j.cesys.2023.100152>

Received 13 July 2023; Received in revised form 6 November 2023; Accepted 6 November 2023

Available online 9 November 2023

2666-7894/© 2023 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Nomenclature			
AC	Acidification	LCA	Life cycle assessment
ASC	Aquaculture Stewardship Council	LCI	Life cycle inventory
CC	Climate change	LCIA	Life cycle impact assessment
CF	Carbon footprint	LU	Land use
CFF	Circular footprint formula	MEU	Marine eutrophication
EC	Freshwater ecotoxicity	MVM	Monetary valuation method
EF	Environmental footprint	nOCPM	Non-organic canned pickled mussels
EU	European Union	OCPM	Organic canned pickled mussels
EVOO	Extra virgin olive oil	ODP	Ozone depletion
FEU	Freshwater eutrophication	PEF	Product environmental footprint
FU	Functional unit	PM	Particulate matter
GHG	Greenhouse gas	RUF	Fossils resource use
HTC	Human toxicity, cancer	RUM	Minerals and metals resource use
HTN	Human toxicity, non-cancer	SB	System boundaries
IC	Impact category	SM	Supplementary material
IR	Ionizing radiation	SS	Subsystem
		WU	Water use

et al., 2019).

Consequently, it is also important to take into consideration not only the environmental impacts produced on the food system, but also the indirect economic impacts of mitigating them, since these in turn lead to food poverty (Drewnowski, 2022). Moreover, foods with high nutritional value must be accompanied by low environmental impact to promote more sustainable diets (Lacour et al., 2018). Then, to win the battle against food insecurity, society must be fed according to environmentally friendly, healthy and affordable diets (FAO, IFAD, UNICEF, WFP, WHO, 2022).

One type of food that meets the three singularities mentioned above is seafood (i.e., fish, crustaceans and mollusks). Seafood has proven to be a better choice of protein source than other animal-based alternatives (e.g., beef, chicken, or pork) for the purpose of following low-carbon footprint (CF) dietary patterns (Entrena-Barbero et al., 2022). Despite this, there are important differences depending on the type of fish and its production method, being preferable from a nutritional and environmental point of view small pelagic and salmonid species caught in the natural environment and farmed bivalve mollusks, such as mussels and oysters (Bianchi et al., 2022). Moreover, the nutritional profile of these products provides innumerable benefits for human health, such as improved cardiovascular and neurocognitive functions, as well as prevention against some types of cancer (Liu and Ralston, 2021). Likewise, in the Southern Hemisphere, the main concern is to ensure food security, although measures to address this major issue should be coupled with measures that focus on sustainability (Belton et al., 2020).

Among the different ways in which seafood products can be consumed, canned seafood products stand out as a long-lasting option with all the nutritional benefits of fresh products (Nurliza et al., 2021). In the production levels of canned seafood, Spain ranks first and second in a European and global context, respectively (Lamarca España, 2021). In addition, this country is not only the fourth in the world in terms of seafood imports, but it also happens to be an important producer (FAO, 2022). In fact, Spain was the first aquaculture producer in the EU in 2017 in massive quantity, playing a key role in the production of mussels (European Parliament, 2023). By region, Galicia (northwest Spain) stands out as the main mussel producer (97% of the national share), contributing more than 255,000 tons and reporting more than 110 million euros in sales in 2021. Of all this production, almost 40% was destined for seafood cookers and canning factories (APROMAR, 2022).

On the basis of ensuring products that are sustainable while guaranteeing food safety, it was decided to select one product for evaluation: Organic Canned Pickled Mussels (OCPM). These organic mussels are harvested in the deep, clear waters of the Galician Firths on Spain's

northwest Atlantic coast, having particularity of avoiding resources of fossil and virgin origin, thus promoting recycled resources. They are also handcrafted with a traditional pickled sauce made from several organic certified ingredients.

The reason for this is that mussels are a nutritious and accessible food, as they are usually cheaper than fresh alternatives and have a longer period of consumption because they are less perishable, apart from the socio-economic importance of this type of product in Spain in terms of employment and profit. In addition, the organic aquaculture scenario is expected to perform better than standard methods from an environmental point of view. Therefore, it was decided to carry out different procedures to evaluate this product from (i) environmental, (ii) economic and (iii) social perspectives:

- i) The main environmental impacts of the OCPM were analyzed using the PEF methodology (European Commission, 2013). Moreover, in order to compare different production models (i.e., organic and non-organic procedures), several scenarios were proposed: a non-organic alternative (i.e., conventional farming), as well as two improved scenarios that would meet EU requirements by 2030 (in terms of recycling rate and electricity grid mix, respectively), to study potential improvements in the near future.
- ii) To assess the economic dimension, the estimated environmental impacts were converted into monetary terms, taking into account the implications for achieving food security. For this purpose, data from the literature were used, applying a holistic approach to represent the monetary impacts through an easy-to-understand single value.
- iii) The social aspects of the evaluated product were discussed in order to identify factors that would affect its ability to be incorporated into a sustainable production process.

2. Literature review

In this section, a bibliographical review has been conducted considering other studies available in the literature related to LCA applied to mussel production systems, highlighting the novelty of the present manuscript to be the first to evaluate the environmental profile of the manufacture of canned organic mussels in the region of Galicia.

In a global context, in Algeria, two long-line mussel farming management scenarios were comparatively evaluated by means of an LCA: (i) the independent management of each farm and (ii) the grouping of all farms in a single aquaculture management area, with significant

reductions in terms of energy and GHG emissions for the latter scenario (Lourguioui et al., 2017). Another long-line production system using a cradle-to-gate approach for the production of fresh mussels was evaluated in Italy. Here, a sensitivity analysis showed a significant reduction in environmental impacts through the use of an electric motor for the vessel to avoid fuel consumption, as well as the use of hemp textile yarn for the mussel seedling structures instead of plastic (Tamburini et al., 2020).

Other mussel production systems have also been addressed, such as the bouchot culture (mussels grown on wood pillars) in France, whose study focused on the beneficial effects on climate change and eutrophication through carbon sequestration by mussel shell, and N and P export in mussel flesh, respectively (Aubin et al., 2018). Moreover, a Swedish case study of mussel cultivation in nets assessed the potential for using the shell as an organic fertilizer, lime and eutrophication reducer on agricultural land (Spångberg et al., 2013). In Scotland, the CF of suspended mussels and intertidal oysters was addressed using a cradle-to-gate approach and it was reported that mussels had up to 10 times lower CF than oysters, while electricity and fuel used for cultivation and harvesting were the main sources of GHG emissions (Fry, 2012). Another CF study was carried out on fresh mussels transported from Norway to Paris (France). On this occasion, despite the lack of external feed required for the mussels, their GHG emissions were similar to those reported for salmon aquaculture due to their low edible yield, as the indicator was expressed in terms of kg of edible seafood at the wholesaler (Ziegler et al., 2013).

At the Spanish level, given the importance of the mussel aquaculture sector in the Autonomous Community of Galicia, this region has been on several occasions a subject of study through LCA methodology. Among the papers available, a comparison of the processing and consumption of both fresh and canned mussels (Iribarren et al., 2010b), as well as between valorization strategies of two mussel by-products: shell and organic remains to produce calcium carbonate and pâté, respectively (Iribarren et al., 2010c), have been carried out. Moreover, canned and frozen mussels has been also compared from a sectorial perspective, doing a differentiation between four different sub-sectors: culture, dispatch centers, canning factories and cooking plants (Iribarren et al., 2010d). In addition, for the specific case of a product packaged in a three-can format (i.e., a case containing three cans), an LCA has been addressed in terms of CF, having identified that the production process of the cans to contain the mussels as the main hotspot (Iribarren et al., 2010a). Finally, LCA has been jointly applied along with the Data Envelopment Analysis to set efficiency targets for mussel rafts based on their environmental impacts associated (Lozano et al., 2009).

Consequently, two main conclusions can be drawn from the review of the available literature. Firstly, at a global level, no LCA assessment about an eco-certified mussel product has been identified and, therefore, the environmental implications that this can entail remain unaddressed. Secondly, the same is true for the case studies carried out in Galicia, which also date back to more than a decade ago, and during this time there has been a change both on the part of producers, who are opting for more environmentally friendly production models (Yang and Liu, 2021), and on the part of consumers, who are demanding products with some kind of eco-certification (Li et al., 2020). Thus, the current study comes to fill this gap in the literature by presenting a recent LCA study on the production of organic canned mussels in a Galician context.

3. Methodology

The methodology followed can be divided into three main stages: environmental analysis (Section 3.1), combining environmental and economic aspects (Section 3.2), and discussion about the social aspects (Section 3.3).

3.1. Environmental analysis

For the analysis of the product under study, an environmental LCA was performed. For this purpose, two international standards that establish the principles and framework as well as the requirements and guidelines of this environmental management tool (ISO, 2006a, 2006b) were taken into consideration. The procedure was divided into 4 steps: (I) goal and scope definition, (II) inventory analysis, (III) impact assessment and (IV) interpretation of results.

3.1.1. Step I: goal and scope definition

The goal of this LCA study was to estimate the potential environmental impacts associated with a specific seafood product: OCPM. For this purpose, an attributional LCA was applied and 1 can of OCPM was considered as Functional Unit (FU). This product has a 115 g net weight format and is composed of mussels (*Mytilus galloprovincialis*) from organic aquaculture (85 g) and pickle (30 g). The pickle is composed of extra virgin olive oil (EVOO) (18.18 g), apple cider vinegar (11.73 g), onion and garlic powders (30 mg each one), and sweet paprika (30 mg), all meet the requirements of organic farming. The mussels together with their marinade are contained in an aluminum can (18 g) and in an individual 9 g carton box. In addition, the secondary packaging corresponding to each can for marketing and distribution was included, consisting of shrink-wrap and corrugated cardboard.

Several different scenarios were also proposed to make a comparison between them. On the one hand, canned pickled mussels were evaluated considering a standard aquaculture method, i.e., non-Organic Canned Pickled Mussels (nOCPM). On the other hand, two additional improved scenarios were evaluated in which the recycling rates and the Spanish electricity grid mix were updated according to the EU requirements for 2030 (European Commission, 2022; European Parliament, 2017). Therefore, up to 4 scenarios can be distinguished: (i) organic aquaculture, (ii) standard aquaculture, (iii) improved recycling rates (iv) and improved electricity mix.

The System Boundaries (SB) were defined considering a “cradle-to-gate” approach of the life cycle of a can of OCPM, i.e., from the mussel aquaculture until the product leaves the factory gate having been processed and packaged (see Fig. 1).

Thus, according to Fig. 1, the system under study can be further divided into four subsystems (SSs): SS1 – mussels aquaculture, SS2 – pickle production, SS3 – processing treatment and SS4 – packaging materials. Each of these is described in more detail below.

3.1.1.1. SS1. Mussels aquaculture. All activities necessary to produce mussels from the Galician estuary were considered. The mussels are cultivated on hanging ropes attached to rafts, which are wooden platforms with a series of floats. In addition, these structures are in a fixed position, as they are anchored to the seabed. The mussel cultivation process is carried out following extensive marine aquaculture practices (i.e., without control or addition of feed). First, the mussel hatchlings are harvested under natural conditions, such as from rocks near coastal areas where these larvae have attached themselves. Later, they are strung out and wrapped in a fine net, usually made of cotton, which is removed a few days after the mussels have attached to the hanging ropes. Once the mussels reach about 5 cm in length when the pre-fattening stage is over (4–6 months), it is necessary to relocate them at the rate of 2–4 final ropes per pre-fattening rope. Finally, once the mussels reach the desired commercial size, which is around 8–10 cm, they are extracted from the ropes, which reach an average weight of 40 kg of mussels after approximately 6–8 months of fattening stage. Likewise, a number of auxiliary vessels are required to service the rafts. Consequently, this SS comprises the rafts (SS1.1) and auxiliary vessels (SS1.2), having considered the main material and energy flows related to the construction, maintenance and operation of both. Specifically for rafts, the following flows were considered: concrete, iron, steel,

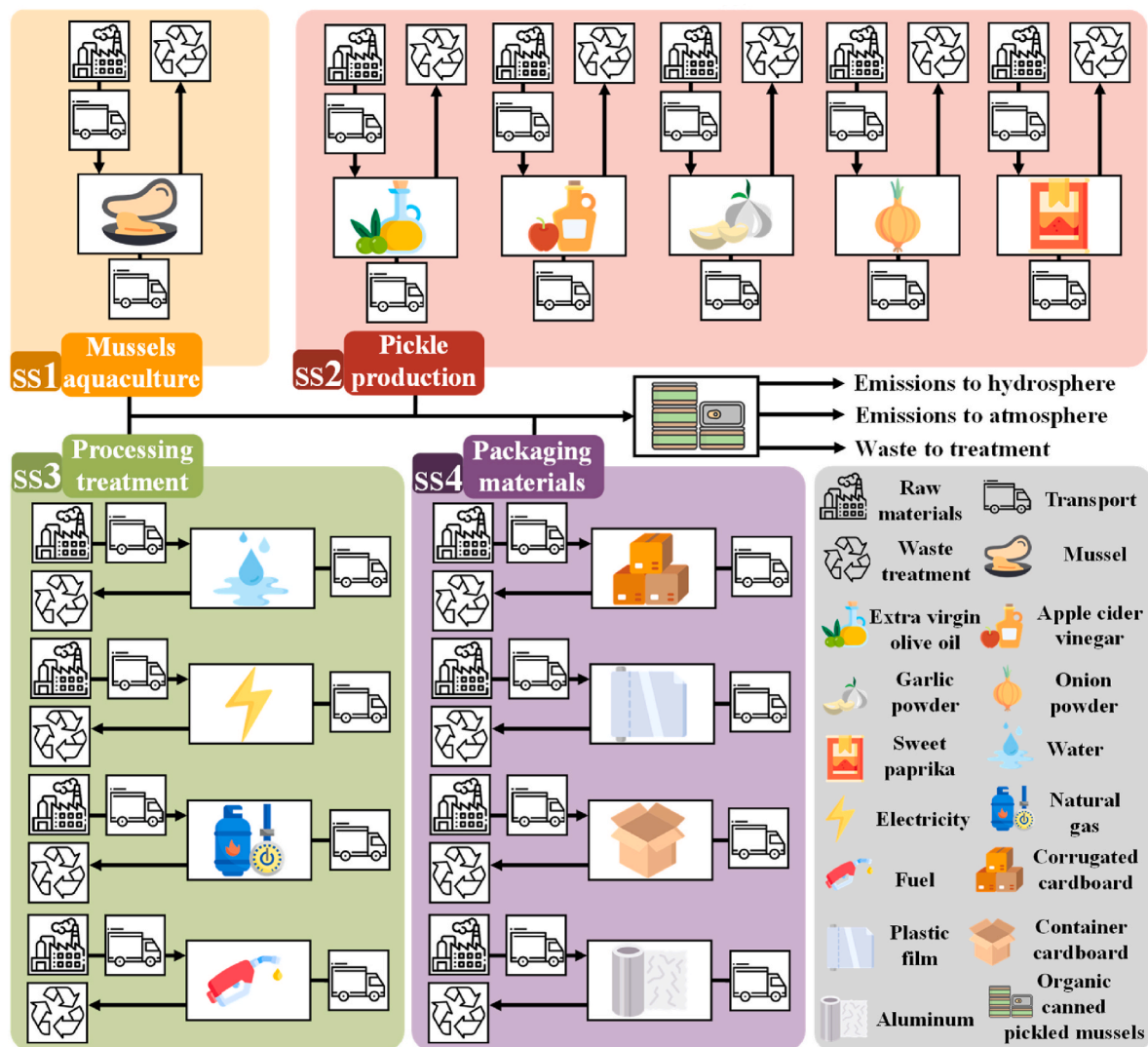


Fig. 1. System boundaries of the organic canned pickled mussels, detailed according to 4 subsystems.

electricity, different types of plastics, among others. The materials consumed during the maintenance and operation of the vessels were boat paint, diesel, lubricating oil, antifouling, etc. Organic mussel aquaculture has two main features that distinguish it from the standard alternative. One is the use of organic cotton for the nets. On the other hand, the use of an organic wood preservative for the rafts, which is necessary to make them impermeable to the marine environment in which they are located and to prevent them from rotting, while in standard mussels aquaculture are used other non-environmentally friendly alternatives derived from fossil resources such as tar oil.

3.1.1.2. SS2. Pickle production. The pickle is composed of EVOO, apple cider vinegar, onion powder, garlic powder and sweet paprika powder. This SS includes the production of all the elements necessary to formulate the pickle for the mussels, except for industrial processing into powder for onion, garlic, and sweet paprika. As an additional feature for the OCPM, all pickle ingredients come from organic farming in accordance with EU Regulation 2018/848 (European Commission, 2018b). In addition, transportation of all these ingredients is included, which once they arrive at the factory are mixed in 250 L capacity tanks.

3.1.1.3. SS3. Processing treatment. The captured mussels are boiled in an external company, although the impacts of this action were included in the product profile. Once the mussels are cooked, they are stored in

the factory until further processing. The cans previously washed are filled according to the following proportions: 85 g of cooked mussels and 30 g of pickle. Finally, the cans are sealed and sterilized in an autoclave before final washing.

3.1.1.4. SS4. Packaging materials. At this stage, 18 g of aluminum are necessary for the manufacture of cans, apart from the secondary packaging consisting of a 9 g cardboard box. Subsequently, ten units of product (i.e., aluminum cans with the cardboard box) are coated with approximately 1 g of plastic film and each five of these packages (i.e., 50 units of product) are placed in 160 g corrugated cardboard boxes for distribution and marketing. Transportation of the packaging materials to the factory was considered within the SB.

For a more detailed information, the SB of each SS can be consulted in Figure SM1 in the Supplementary Material (SM).

3.1.2. Step II: inventory analysis

3.1.2.1. Data collection. As in any LCA, data collection is a critical step since the quality of the assessment is directly determined by the inventory data. Therefore, to ensure data quality and reduce uncertainty, most of the information used was primary data. The data related to SS1 came from average values of a survey carried out by *Mejilloneros de San amaro*, a Galician organization of mussel farmers. This survey collected

data from 42 vessels serving 153 rafts with standard (i.e., non-organic) production in one year during the period 2018–2019, not being able to provide it in the SM for confidentiality reasons. Among the most significant data collected in this survey are all the characteristics of shape, size and materials of the raft, as well as all the relevant consumptions of the auxiliary vessels (boat paint, lubricating oil, diesel, etc.). The use of this data collection strategy makes it possible to establish the main differences between standard and organic production. This is because according to primary data, each auxiliary vessel serves on average 5 ecological rafts, while the number of auxiliary vessels dedicated to mussel aquaculture in Galicia is 1,286 for a total of 3,387 rafts (Xunta de Galicia, 2020), corresponding to 1 vessel for 2.7 rafts. Therefore, it can be concluded that the production of organic mussels will have a lower energy and material intensity and the impacts derived from the auxiliary vessel will be lower than in standard production.

The information on energy and material consumption in the canning plant was primary, provided directly by the company. In this regard, it is worth noting the high level of detail achieved, since the origin of most of the consumables has been provided. However, the consumption of natural gas, electricity and water were assigned to the organic line of mussels. This was because it is not possible to determine exactly to what extent the consumption of the factory corresponds to one production line or another. Thus, the information provided was used for 2,400,000 units produced in 2019 in the entire plant, of which 145,725 units belong to the organic mussel line (i.e., 6.1% of the generic consumption of the plant). The inputs related to the cooking of mussels had to be collected from the literature, since this operation is carried out by and external plant, estimating the amount of fuel and electricity needed to cook one ton of mussels at around 69.8 kg and 2.6 kWh, respectively (Iribarren et al., 2010b).

3.1.2.2. Burden allocation strategy and life cycle inventory. In this study, since mussel aquaculture is a mono-functional product system, it was not required to allocate burdens among mussels and different co-products. Consequently, it was only necessary to establish allocation factors to determine the edible weight of mussels. In this regard, according to the primary data provided by the company, only 15% of the total weight of the mussels caught in SS1 was considered as the edible portion. The Life Cycle Inventory (LCI) by FU is shown in Table SM1, appearing collected the main differences between the organic and standard procedures for the mussel aquaculture (i.e., OCPM and nOCPM, respectively).

3.1.2.3. Modelling processes and assumptions. To establish the LCI processes, the Ecoinvent v3.8 database (Moreno Ruiz et al., 2021) was used, which can be consulted in more detail in Table SM2. However, with the aim of detailing the process as precisely as possible, it was necessary to model some processes or life cycle stages under some assumptions:

Infrastructure of rafts and auxiliary vessels: for the estimation of the amount of infrastructure required, the average weights of the main materials composing the rafts (concrete, iron, wood, steel, etc.) were selected for the 143 rafts surveyed. The same procedure was followed according to the auxiliary vessels, considering an average weight of 67 tons for the 42 vessels composing the fleet, wood being the main material of the boat hulls. According to the primary information provided by the fishermen, the average lifespan of the rafts was 30 years, while for the auxiliary vessels it was 50 years.

Fishing vessel operations: There are certain flows consumed during the fishing vessel operations which produce emissions. However, due to the failure to monitor them, they had to be estimated and modelled through secondary data. For this, the procedure carried out by Ceballos-Santos et al. (2023) was followed, which considered the environmental implications related to diesel burning, as well as air emissions related to the consumption of lubricating oil. According to the production of antifouling, its modelling was possible thanks to information on

their average chemical composition. This is shown in Table SM3, assuming that two thirds of the protective layer covering the hulls of ships will be discharged at sea (Hospido and Tyedmers, 2005).

Processing treatment: For emissions related to natural gas and fuel oil consumed during processing treatment, the emission factors for CO₂, CH₄ and N₂O from the Intergovernmental Panel on Climate Change (IPCC, 2006) are used, while for the other gases, the emissions factors were those reported in EMEP/EEA (2019).

Pickle production: To model the ingredients that make up the organic pickle, distributed by external companies, it was necessary to make some assumptions. In the case of garlic, onion and sweet paprika, they are supplied in powder form and were not taken into account due to the lack of data from industrial processes. Instead, fresh weights from non-organic production processes were taken into account through the Ecoinvent database (Moreno Ruiz et al., 2021). In addition, since garlic cultivation was not available, it was assumed to have similar contributions as onion. As for the liquid components, apple cider vinegar was assumed to have a similar contribution to that of the acetic acid production process. Similarly, two references were considered to construct the corresponding LCI of the organic extra virgin olive oil: Laso et al. (2017) and Maffia et al. (2020) (see Table SM4).

Electricity: Energy consumption was modelled by differentiating the different sources that make up the mix of the Spanish electricity grid. For this purpose, information was taken at the national level considering a two-year average (2018 and 2019) from the Association of Issuing Bodies (AIB, 2020), as it is the group in charge of providing reliable disclosure information on the origin of electricity supplied to consumers in the EU, which is shown in Table SM5.

End-of-life: The Circular Footprint Formula (CFF) was used for the modelling of the end-of-life phase of the following flows: steel, aluminum, cardboard, PET, HDPE, PP, LDPE, which are mainly related to the primary and secondary packaging. The reason for the selection of these flows is that they are the ones for which data was available, as they were collected in Table SM6, while for the rest of the flows it was the one included by default in the waste treatment of the Ecoinvent database (Moreno Ruiz et al., 2021). The CFF, the description of the parameters that compose it, as well as their respective values are available in Annex C of “Suggestions for updating the Product Environmental Footprint (PEF) method” (Zampori and Pant, 2019). This formula is promoted for the PEF methodology to include the entire life cycle of the material used: the virgin and recycled fractions used during its manufacture, the percentage of the material that will be recycled once used, as well as the waste management of the non-recycled part: energy recovery or final disposal. According to the energy recovery rates by incineration and landfill, average values of 17.75% and 82.25%, respectively, were taken into account for the particular case of Spain during the period 2018–2019 (Eurostat, 2020). The modelling processes per material, apart from their respective recycling processes, are shown in Table SM7–SM19 in the SM.

Improved scenarios: Other scenarios were hypothetically analyzed considering that the objectives expected by the EU to transform the food system towards a more sustainable production model by 2030 would have been achieved: (i) “improved recycling rates” and (ii) “improved electricity mix”. Regarding the former, the waste ratios of the main product packaging materials under assessment (i.e., aluminum and cardboard) were updated taking into account the European circular economy targets for the percentage of these materials to be recycled by 2030 (see Table SM9 and SM11): 60% and 85% for aluminum and cardboard, respectively (European Parliament, 2017). According to the second improvement scenario, the expected Spanish electricity mix was modelled taking into account the European Commission REPowerEU plan, which seeks to reach 45% of the total energy produced by renewable sources by 2030 (European Commission, 2022). In this sense, given the lack of data on future expectations, it was considered that renewables (i.e., renewables (unspecified), solar, wind, hydro and biomass) would increase proportionally to their consumption demand

for the period 2018–2019 until their combined contribution reaches the European target (see [Table SM5](#)). Lastly, the main features of all scenarios appear collected in [Table SM27](#).

3.1.3. Step III: impact assessment

The Life Cycle Impact Assessment (LCIA) was performed according to the 16 midpoint Impact Categories (ICs) of the PEF method ([European Commission, 2013](#)): CC, ozone depletion (ODP), ionizing radiation (IR), photochemical ozone formation (POF), particulate matter (PM), non-cancer and cancer human toxicity (HTN and HTC, respectively), acidification (AC), freshwater, marine and terrestrial eutrophication (FEU, MEU and TEU, respectively), freshwater ecotoxicity (EC), land use (LU), water use (WU), fossils and minerals and metals resource use (RUF and RUM, respectively). For this, the software tool SimaPro v9.5 was used and the Environmental Footprint (EF) 3.0 method ([European Commission, 2021](#)) was selected.

3.1.4. Step IV: interpretation of results

To identify the main hotspots, a distinction was made between the different SSs that make up the production process, as well as the flows considered in each of them. In addition, a comparison was carried out between the baseline scenario (i.e., OCPM) and the three additional scenarios proposed in this study: standard mussel aquaculture (nOCPM), improved recycling rates and improved electricity mix.

3.2. Combining environmental and economic aspects

For the monetarization of the environmental impacts, [Amadei et al. \(2021\)](#) was taken as reference. In this work, a literature review is carried out on LCA valuation procedures in monetary terms. In addition, the authors identify those that are compatible with the PEF method, adapting the monetary valuation coefficients to the 2019 European inflation rate. Consequently, for this study, since it coincides with the year of production of the OCPM, no modification was necessary. Therefore, the average values of the different Monetary Valuation Methods (MVM) were used (see [Table SM25](#) in the SM), multiplying by the results obtained in the environmental performance to obtain the monetary values corresponding to each IC.

Once the environmental and economic analyses were performed, the results of both associated to the satisfaction of the annual consumer demand in the context of Spain were represented in a dot plot to make an easy and direct comparison of all scenarios. For this, it is necessary to integrate the results of each analysis into single values. As for the environmental assessment, an aggregation of all midpoint ICs was performed after a normalization and weighting processes using the corresponding characterization factors included in the EF 3.0 method ([European Commission, 2021](#)). The endpoint results are expressed in terms of micropoints (i.e., μPt), which representing one millionth of the annual environmental burden divided by the share of an average European citizen. In parallel, the sum of the economic impacts was done after considering all the MVMs. Furthermore, information regarding the consumption patterns of Spaniards for 2019 was used: 300 g of canned mussels per capita ([MAPA, 2019](#)). Finally, a fifth scenario was added, in which all the improvement actions previously proposed by the other scenarios were applied.

3.3. Social aspects

After analyzing the environmental and economic aspects related to canned pickled mussels, a discussion of the third pillar of sustainability (i.e., society) was conducted from a double approach. Firstly, from the point of view of consumers, analyzing the consumption patterns of canned seafood in the case of Spain, as well as the associated financial contributions. Secondly, with respect to the perspective of producers, evaluating the different types of practices in terms of social responsibility, respect for nature and traditional know-how which are not

represented in the two certifications currently held by the product under assessment: (i) protected designation of origin and (ii) organic one.

4. Results and discussion

The results obtained are shown and discussed below, appearing divided as follows: environmental assessment ([Section 4.1](#)), combination of environmental and monetary aspects ([Section 4.2](#)), and social implications of the mussels aquaculture sector ([Section 4.3](#)).

4.1. Environmental assessment

The specific values of each IC (in their corresponding units) per SS for the organic aquaculture scenario can be found in [Table SM20](#). In light of them and with the purpose of identifying the main hotspots, the relative contribution of each SS was analyzed per IC (see [Fig. 2](#)). With respect to SS1, it constitutes about a quarter of the total environmental contributions related to most ICs. However, a different trend occurs with respect to human toxicity (i.e., HTN and HTC), where it does not exceed 12%. Likewise, mussel aquaculture doubles its average contribution in terms of AC and FEU, reporting 32.9% and 38.8%, respectively. Finally, this SS has one of its maximum rates for IR, representing more than half of the total impact. Pickle production shows generally low contribution values, which could be associated with the fact that it represents only around a quarter of the product in mass terms, having the lowest impact on several ICs. In contrast, SS2 is the main contributor in several ICs: TEU and RUM, with the impact on the latter being particularly notable, with more than 75%. Processing treatment (i.e., SS3) involves less than one tenth of the total impact in 6 ICs: IR, HTN, HTC, FEU, LU and RUM, even having a negative contribution in the case of WU. This is due to the fact that a large amount of effluent is discharged during processing, as the mussels are cleaned upon arrival at the plant to remove mainly sand, algae and other organisms that may have adhered to them in their growing periods in a marine environment. In addition, if we take a closer look at the flows that could have caused this negative value for SS3, fuel oil and waste are identified (see [Table SM23](#)). On the other hand, these are not the only flows with negative WU values, as also the diesel consumed for mussel aquaculture or the one necessary for transport of the pickle sauce or packaging materials (see [Table SM21](#), SM22 and SM24). Thus, it can be concluded that a value lower than 0 for this IC is associated with the consumption of energy flows (diesel, fuel oil, etc.) or waste management. The reasons for this could be related to the use of a database to model these flows (Ecoinvent), which results in negative values for certain LCA issues, such as avoided products or system expansion. Therefore, this IC needs special attention for a more appropriate estimation. To this end, studies on the estimation of the water footprint should be carried out, even if this is not the main motivation for the study conducted. However, it is the main hotspot when it comes to CC, ODP and RUF. The last stage of the production process related to packaging materials has the highest overall impact. In fact, SS4 has the highest contribution in up to 7 out of the 16 ICs (i.e., PM, HTN, HTC, FEU, MEU, EC and LU).

Once the ICs were analyzed according to each SS, an additional analysis was performed by differentiating the relative contribution of material and energy flows in [Fig. 3](#). For more detailed information, the values of the different flows for each SS are shown in [Table SM21-SM24](#) in the SM.

In relation to mussel aquaculture, the hotspot in almost all the ICs evaluated is the electricity needed to develop the maintenance works of the infrastructure. In fact, apart from being the main contributor to practically all the ICs, its contribution exceeds 80% in 5 of them: CC, IR, FEU, WU and RUF. Moreover, it is another energy input (i.e., diesel), which is also an important source of impacts with more than 40% for POF, PM, MEU and TEU. It is worth noting that, contrary to many LCA studies applied to seafood products, diesel is not the main hotspot ([Avadí et al., 2020](#)). The low diesel consumption of the auxiliary vessels is due

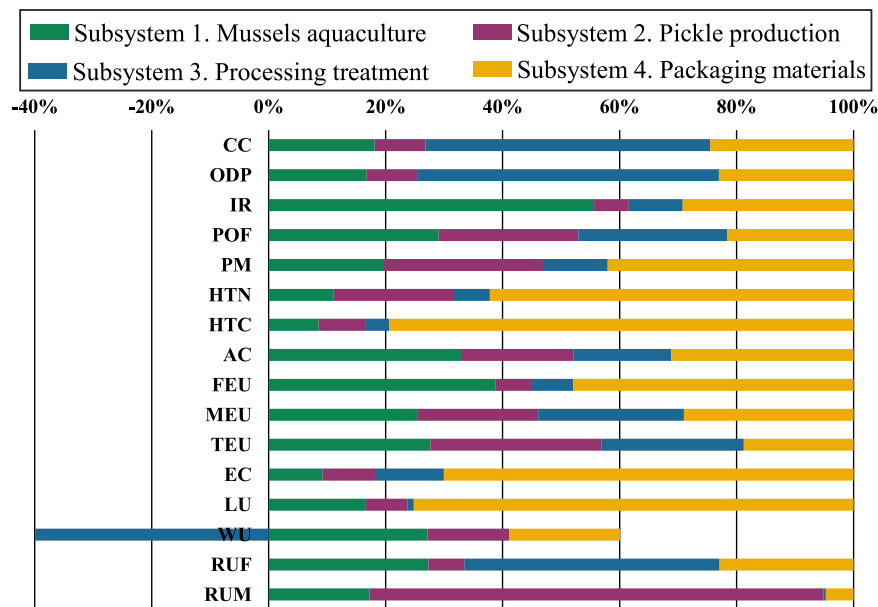


Fig. 2. Relative contributions of each subsystem for the organic mussel aquaculture per impact category: Climate change (CC), ozone depletion (ODP), ionizing radiation (IR), photochemical ozone formation (POF), particulate matter (PM), human toxicity, non-cancer and cancer (HTN and HTC, respectively), acidification (AC), freshwater and marine eutrophication (FEU and MEU, respectively), freshwater ecotoxicity (EC), land use (LU), water use (WU), fossils and minerals and metals resource use (RUF and RUM, respectively).

to the short distance of the rafts from the coast, as well as the fact that only two trips per year are necessary to harvest the mussels (once the pre-fattening phase is over and when they reach commercial size), apart from the trips necessary for maintenance purposes. According to LU, concrete and organic cotton have the greatest impact, with contributions of approximately 39% and 33%, respectively. Likewise, the impact of antifouling consumption stands out, reporting more than 70% in the case of RUM. As for the production of pickles, the main ingredient of this liquid: EVOO, is in turn the one that has the greatest impact on most of the ICs. However, there are some exceptions, such as ODP, WU and RUF, in which apple cider vinegar represents more than half of the total impact. Furthermore, sweet paprika has an impact of around 60% for HTN and LU. During the processing treatment, natural gas consumption generates high relative environmental impacts according to 8 ICs. The other two energy inputs: electricity and fuel oil, are supposed to be the hotspots in relation to two ICs: IR and FEU, as well as PM and HTC, respectively. On the other hand, waste processing treatment produces significant impacts related to HTN, WU and EC. Lastly, in SS4, aluminum is the packaging material with by far the highest environmental impact, except for cardboard in terms of LU, as well as its recycling for MEU and WU.

In global terms, the main hotspots identified were energy flows (i.e., diesel, electricity and natural gas) to ICs related to ecosystem damage and resource depletion such as CC, DOP, IR, AC, RUF, among others, and to a lesser extent the EVOO required for pickle, while aluminum production for packaging materials has the greatest impact on human health (i.e., PM, HTN and HTC) and cardboard in terms of LU.

After having analyzed the environmental impacts related to one can of organic pickled mussels, this product was compared with three other scenarios. Then, the ICs obtained were compared on a percentage basis in Fig. 4. Likewise, the specific values of the additional scenarios appear collected in Table SM26 in the SM.

As expected, the worst performing scenario is the standard aquaculture, which reaches the maximum values in all ICs. However, there is an exception about LU, since the two proposed improvement actions (i.e., improved recycling rates and improved electricity mix) obtain slightly higher values. This may be due to the need to use larger land

areas for new recycling plants or extensions of existing ones. The same applies for increasing the share of renewable energy produced, as the largest increases have been assumed for wind and solar energy, exceeding 17% and 11%, respectively (see Table SM5 in the SM). In relation to organic aquaculture, a general slight reduction is obtained in comparison with the standard aquaculture scenario. The same is true when the recycling rates are improved, as both scenarios report very similar values. This trend occurs in all ICs, except for the approximately 10% reduction that is achieved for EC, which could be due to the large weight of packaging materials (i.e., SS4) in this IC (see Fig. 2). Conversely, improving the Spanish electricity mix, although it performs worse in some ICs (e.g., POF, PM, MEU or TEU), it is the most promising alternative as it achieves the highest reduction percentages in a larger number of ICs, being especially notable for WU (with more than 50%) and IR. This latter reduction of more than 20% is justified by the drastic minimization of nuclear energy (see Table SM5 in the SM).

Finally, the results in Fig. 4 are influenced by the modelling of the main characteristics considered for each scenario in Table SM27. Therefore, in this sense, proper modeling of the characteristics is essential to obtain plausible results. Both standard and ecological aquaculture are the main scenarios considered in this study and the ones which require more assumptions to be taken into account based on their main differences: (i) proportion of auxiliary vessels used to serve the rafts, (ii) organic cotton for the nets, (iii) use of organic wood preservative for the rafts and (iv) organic ingredients for the pickling sauce. In this sense, three of the four particularities of organic mussel aquaculture have been fully addressed, while for the organic ingredients for pickling, some modeling gaps have been identified, as in the case of garlic, onion and sweet paprika, which could not be considered organic due to the lack of data. However, in the case of EVOO (main ingredient of pickling), it has been modelled according to its organic production. Therefore, on the one hand, onion, garlic and sweet paprika in powder format represent only about 0.08% of the total weight and the contribution of pickle production and these ingredients to the overall results is almost negligible (see Figs. 2 and 3). Accordingly, the addition of organic or non-organic production of these ingredients would be almost imperceptible when evaluating a can of pickled mussels. On the other hand, from the

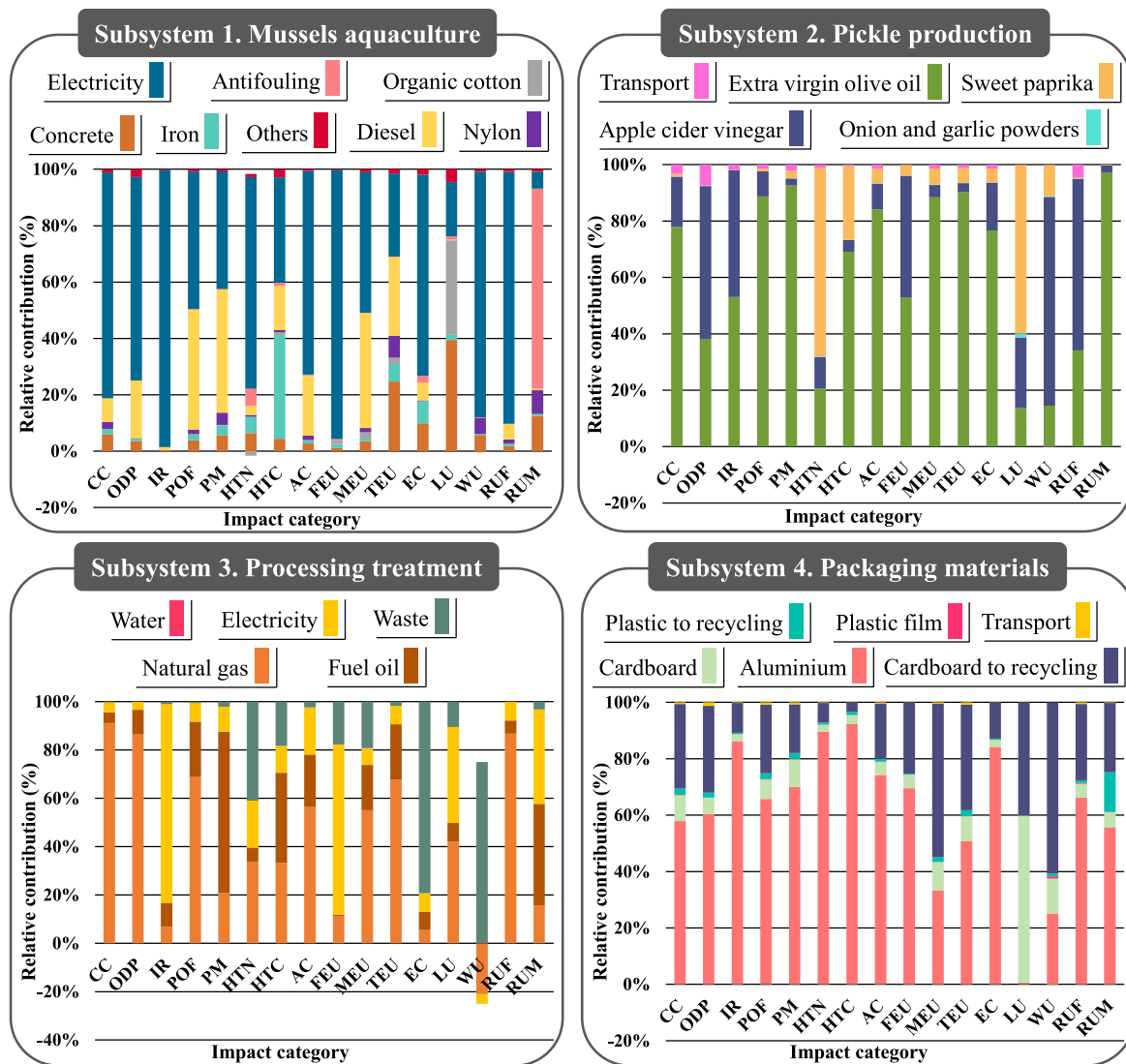


Fig. 3. Relative contributions of flows in each subsystem for the organic aquaculture scenario per impact category: Climate change (CC), ozone depletion (ODP), ionizing radiation (IR), photochemical ozone formation (POF), particulate matter (PM), human toxicity, non-cancer and cancer (HTN and HTC, respectively), acidification (AC), freshwater and marine eutrophication (FEU and MEU, respectively), freshwater ecotoxicity (EC), land use (LU), water use (WU), fossils and minerals and metals resource use (RUF and RUM, respectively).

point of view of the comparison between organic and non-organic production models, the drying process would have the same effect in both processes. Consequently, it can be said that the results are sufficiently representative for the purpose of comparison with the other improved scenarios proposed in this study.

4.2. Combination of environmental and monetary aspects

Taking into consideration the per capita demand of canned mussels in Spain in 2019: 300 g (MAPA, 2019) as well as the amount of food analyzed in this study (85 g), it was obtained that around three and a half cans would be necessary to satisfy the requirement of a consumer. Therefore, the environmental and economic impacts associated to meet such an annual demand for every scenario are shown in Fig. 5, having also compared them on a percentage basis.

Looking at Fig. 5 and considering both relative environmental and economic impacts, the following figures were obtained: 97.0%, 96.5%, 92.3%, 91.8%, for the organic aquaculture, improved recycling rates, improved electricity mix and for the application of all improvement actions, respectively, in comparison to the standard aquaculture

scenario. Therefore, opting for purchasing OCPM instead of nOCPM implies reducing both the environmental and economic impacts around 3%. Moreover, improving the recycling rates and the electricity grid mix to the 2030 European targets would increase this reduction by 0.5% and 4.7%, respectively. Consequently, through the combination of all the improvement actions, a maximum reduction of 8.2% can be achieved. The previous percentage would mean that each Spaniard could reduce by up to 10 μ Pt and 0.1 euros their annual environmental and economic contributions, respectively, related to the consumption of canned mussels.

Thus, the results obtained are arguably not very promising. The reason behind this is that the proposed improvement actions were only based on future projections by the EU on recycling and renewable energy, apart from an environmentally friendly method of mussel cultivation. Therefore, other actions relative to the seafood sector focused on more advanced techniques of the circular economy concept could have achieved more favorable values. For instance, commissioning a bio-refinery to obtain a series of value-added products, such as pediocin, lactic acid or crude protein from the cooking water of bivalves, thus offsetting the environmental and economic burdens associated with the

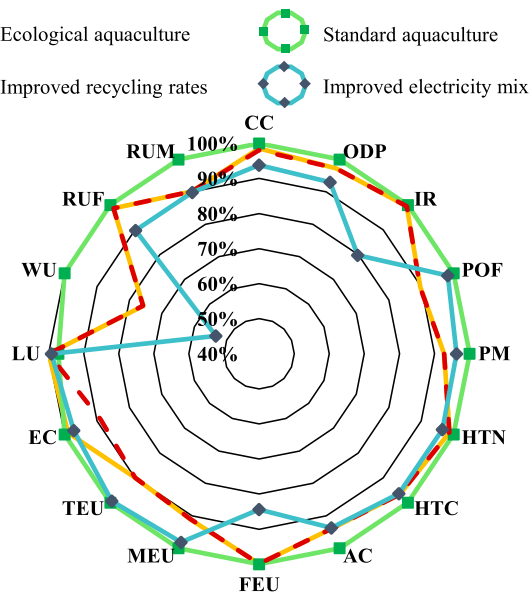


Fig. 4. Percentage comparison among the scenarios of the canned pickled mussels per impact category: Climate change (CC), ozone depletion (ODP), ionizing radiation (IR), photochemical ozone formation (POF), particulate matter (PM), human toxicity, non-cancer and cancer (HTN and HTC, respectively), acidification (AC), freshwater and marine eutrophication (FEU and MEU, respectively), freshwater ecotoxicity (EC), land use (LU), water use (WU), fossils and minerals and metals resource use (RUF and RUM, respectively).

treatment of these wastewater streams (Arias et al., 2022), as well as the development of biomaterials for packaging from fish discards, thereby reducing the consumption of resources and raw materials (Ruiz-Salmón et al., 2020). Likewise, regarding one of the differentiating characteristics of organic mussel aquaculture, which was the use of an organic preservative in substitution to tar oil for the maintenance of the wooden rafts, nowadays, the structures of the rafts are being composed of other materials, such as ultra-high performance concrete, which are proving to have a better environmental performance thanks to longer lifetimes, as well as the absence of having to carry out maintenance tasks (Caruso

et al., 2022).

However, it is important to consider that the main objective of this study was to propose a procedure to visualize the differences between the environmental and economic contributions of choosing one or the other option in meeting consumption patterns. Furthermore, for obtaining only one value for each of the environmental and economic dimensions, it has been necessary to make a series of assumptions.

First, for the aggregation of all the environmental impacts in a unique value, it was unavoidable to carry out a process of weighting. This turns out to be an optional element of the LCIA (i.e., step 3 of the LCA), and despite the fact they consist of using numerical factors based on value judgements without a scientific basis, these can be employed depending on the target and scope of the study (ISO, 2006a, 2006b). Second, up to eight types of MVMs can be distinguished for the 16 ICs of the PEF method relative to 2019 (see Table SM25): damage cost (cost derived from changes in natural capital), abatement cost (cost which mitigates, avoids, reduces, control, restores or replace the damage), budget constraint (willingness to pay for an additional quality-adjusted life year, i.e., a life year lived at full well-being), averting behavior (cost which prevents or offsets the change in availability of a good), contingent valuation (willingness to pay or accept compensation for a specified change in the availability of a good), market price (willingness to pay in an existing market for a good), mixed approaches and other approaches, i.e., the consideration of two (or more) or none of the approaches mentioned above, respectively. Consequently, since for none of these MVMs is available for all ICs, it has been necessary to make an approximation considering an average single value of all those available in the literature, even though for some ICs were up to 5 MVMs, while for others only one (e.g., CC and AC, respectively). However, this has also meant that there is a large disparity in the final data obtained due to the high values for the standard deviation, therefore, this shortcoming should be addressed in future iterations of the methodology by proposing more monetary characterization values so that each MVM can cover all the ICs of the EF method. Likewise, some of these MVMs have proven to have better applicability for the LCA methodology, while others have certain limitations (Amadei et al., 2021). Finally, It was necessary to assume that the total national demand for canned mussels in Spain could be supplied thanks to the product under study, without considering alternative products exported, levels of manufacturing or other consumption patterns related to gastronomic preferences or

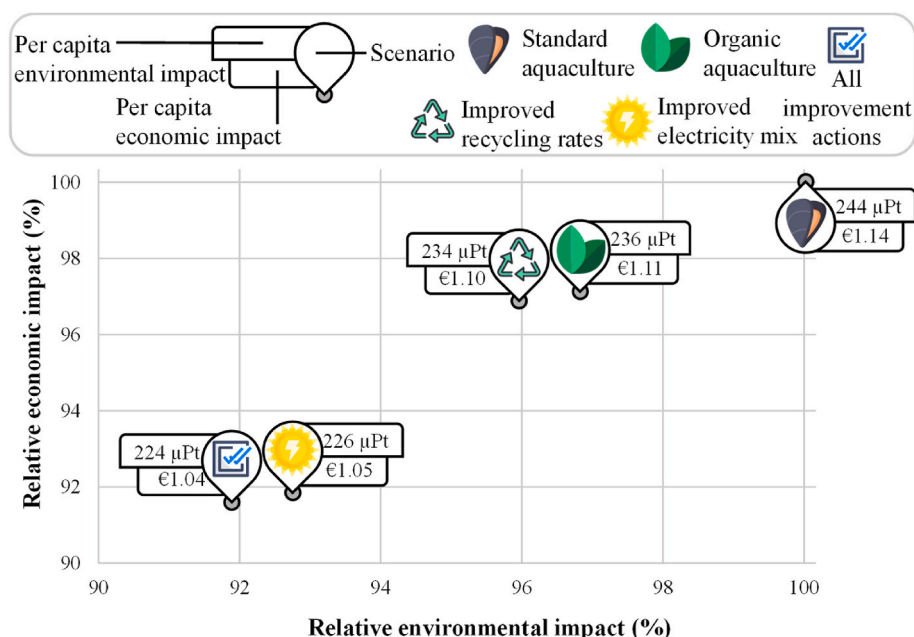


Fig. 5. Comparison among scenarios of the canned pickled mussels through their relative environmental and economic impacts.

economic availability (Cai and Leung, 2022).

4.3. Social implications of the aquaculture of mussels

The social implications of the aquaculture of mussels have been analyzed from a dual perspective: (i) from a consumer point of view relative to the Spanish market, and (ii) from a producer perspective with respect to different kinds of certifications.

To study consumption trends in the Spanish market, in Fig. 6 shows per capita consumption and total expenditure for the main canned seafood products since 2001. From this figure it can be seen that consumption per consumer has not stopped growing since the 21st century. This means that total annual expenditure per household has almost doubled (from around 1,000 euros in the period 2001–2006 to 2,000 euros in the period 2017–2021), which has a direct impact on the increased environmental impact of the production of this type of food. Moreover, the maximum per capita consumption was recorded in 2020 (4.85 kg) driven by the covid-19 pandemic, being particularly noticeable during the two first weeks of home confinement, when the purchase of canned seafood products increased by more than 40% (MAPA, 2021a, 2020). Some reasons behind this unstoppable growth would be that thanks to investments in innovation, this sector has been able to adapt to the preferences of a new generation of younger consumers who demand an added value in the products they buy in terms of health, pleasure and convenience, such as those certifications which guarantees the origin of food, as well social and environmental responsibilities (Alimarket, 2021). By species, undoubtedly tuna is the most important in the Spanish market, contributing more than half of the total consumption of canned seafood products. After this, mussels and sardines occupy the second and third position, respectively, followed by squid and octopus, as well as mackerel, with 3.2% of the annual per capita consumption during 2001–2021. In terms of expenditure, tuna is once again the first species by far, although now it is salmon that occupies the second position, while mussels are the third species with a contribution close to 6%. The second position of salmon in monetary terms is explained, on

the one hand, by its higher price compared to other canned seafood products (MAPA, MERCASA, 2022), and on the other hand, by its growing global demand due to the emergence of a more sporty consumer profile, being therefore canned salmon a ready-to-eat option that is healthy and rich in protein (Future Market Insights, 2022).

Concerning the seafood product evaluated in this paper, this has a couple of certifications: (i) the protected designation of origin “Mexillón de Galicia”, which is subject to a series of rules which ensure that its quality and characteristics are due to primarily or exclusively natural and human factors in the geographical environment in which it is located (Mexillón de Galicia, 2022), and (ii) organic certification for the ingredients that make up the pickle: EVOO, apple cider vinegar, onion, garlic and sweet paprika powders, in line with the EU Regulation 2018/848 (European Commission, 2018b).

Likewise, one of the priorities of the company that produces OCPM is social responsibility and respect for nature, through the rational and sustainable use of marine resources, processed according to traditional methods. In this way, the company ensures that mussel farming is carried out using small vessels belonging to local coastal communities, with highly selective methods. However, these additional measures taken by the producer are not reflected in any type of certification, which means that the product lacks added value for the consumer. Moreover, a study analysing consumer behaviour concluded that social responsibility is a more important factor than environmental responsibility (Plank and Teichmann, 2018).

To reverse this issue, the international organisation Aquaculture Stewardship Council (ASC) proposes a set of standards applied to the specific case of the aquaculture of bivalve species for its transformation towards environmental sustainability and social responsibility. The ASC certification and labelling programme evaluates seven principles: (1) obey the law and comply with all applicable legal requirements and regulations where farming operations is located, (2) avoid, remedy or mitigate significant adverse effects on habitats, biodiversity, and ecological processes, (3) avoid adverse effects on the health and genetic diversity of wild populations, (4) manage disease and pests in an

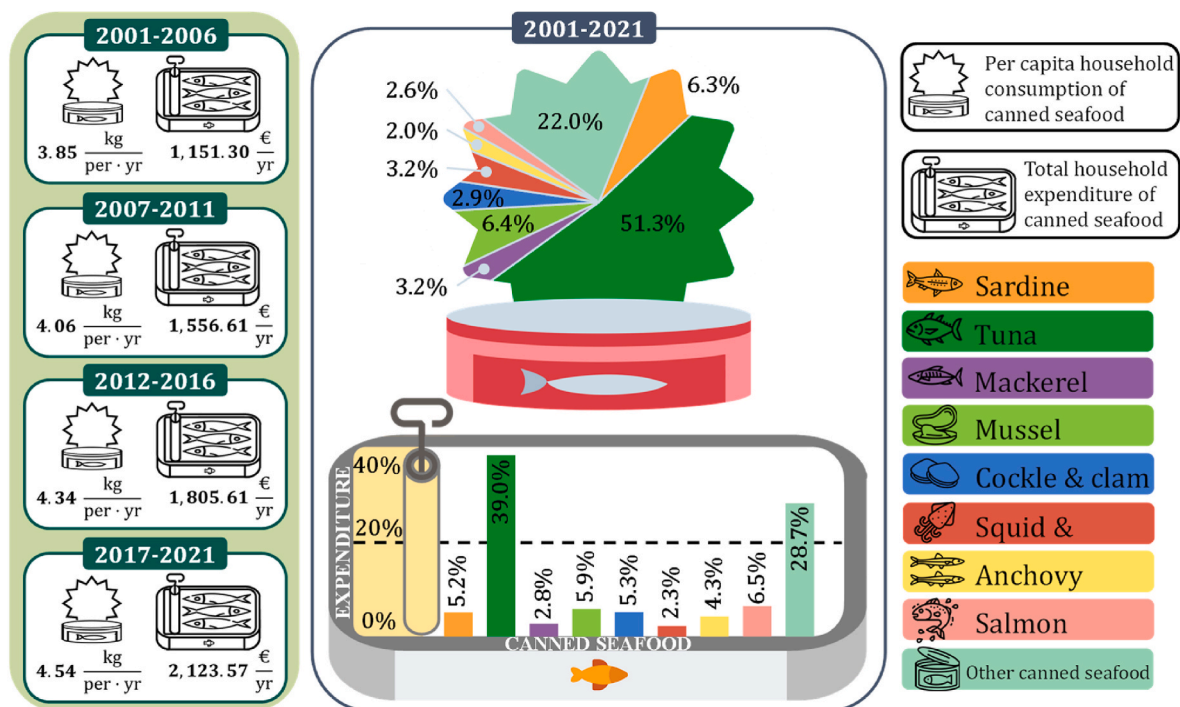


Fig. 6. Per capita household consumption and total household expenditure of canned seafood products in Spain. The total amount of both is shown on average values divided by different periods (2001–2006, 2007–2011, 2012–2016 and 2017–2021), and the relative weight by species appears for the period 2001–2021 (MAPA, 2021b).

environmentally responsible manner, (5) use resource efficiently, (6) be a good neighbour and conscientious coastal citizen and (7) develop and operate farms in a socially and culturally responsible manner, being these in turn composed of a number of criteria and indicators (ASC, 2019).

In this study it has been decided to discuss only the social implications of the evaluated product, both because of the lack of available data and because the objective has been focused more on applying a methodology to quantify the monetization of environmental impacts. Notwithstanding, there are currently other methodologies to evaluate the social issues, such as the methodological sheet proposed by the United Nations Environment Program, with up to six stakeholder categories to be evaluated through social indicators (Life Cycle Initiative, 2021), or the Job Creation Potential, which is an indicator that reflects the number of potential direct and indirect jobs that a process or product can generate in a region during a given period (Pillain et al., 2019). Some of these procedures are usually to be conducted along with an LCA and an economic evaluation method to conduct a life cycle sustainability assessment. Consequently, their applications are highly encouraged in order to evaluate the social dimension of sustainability in a more appropriate way.

Last but not least, despite the environmental LCA carried out goes a step further by broadening the focus to take monetary impacts into consideration, this work overlooks the assessment of the positive impacts on the three pillars of the sustainability. In environmental terms, a series of ecosystem services are related to the mussel farming, such as potential of carbon sequestration and bioremediation, regulation of nutrients and carbon cycling or provision of habitats for other organisms (Feng et al., 2023; Sea et al., 2022; van der Schatte Olivier et al., 2020). In terms of socio-economic issues related to the vertical aquaculture of bivalve mollusks (in which the production of mussels would be integrated) represented a net value added of more than 110 million euros, making it possible to consolidate more than 5,600 direct jobs in 2021 (MAPA, 2021c). Regarding the mussels sector in Galicia, this is mainly made up of local people who are family members of the owner, as well as fishermen who work on the rafts during the closed season. In addition, this economic activity has a positive influence on the canning industry, which is based in the surrounding coastal areas (European Commission, 2021). Nevertheless, small size of enterprises plays in turn a negative role due to the lack of investment in innovation of a production process which is highly dependent on external environmental conditions such as the spread of diseases, algal blooms, lack of spat, predation and low earnings (Avdelas et al., 2021).

5. Conclusions

The LCA study conducted shows that the main ICs related to the production of canned mussels are CC, RUF and EC. Furthermore, its application has allowed identifying the contribution of each stage in the production process of OCPM, as well as the hotspots in terms of inputs: electricity, EVOO, natural gas, as well as aluminum for mussel aquaculture, pickle production, processing treatment and packaging materials, respectively. Moreover, the transformation from standard mussel aquaculture to an organic alternative has not brought major environmental benefits. Similarly, improving the recycling rates of the main packaging materials of this seafood product (i.e., aluminum and cardboard) has not significantly reduced the environmental impact either. On the contrary, upgrading the Spanish electricity mix has proven to be the most promising alternative. However, it is necessary to consider the greater difficulty of increasing energy production from renewable sources compared to the recycling rates of aluminum and cardboard. Therefore, the relatively low improvement rates can be justified for three main reasons: (i) although the proposed improvement scenarios have focused on the main hotspots detected during the OCPM production system, some of its SS, such as pickle production, have been neglected, (ii) due to the large number of ICs analyzed, achieving an

overall improvement may be an arduous task, since an improvement in one of them may be masked by a worsening in another, and (iii) the proposed improvement actions do not represent major technological advances compared to others being implemented.

The proposed methodology for integrating environmental and economic impacts related to the manufacture of canned pickled mussels has allowed a clear and direct comparison of the different production model scenarios evaluated. It follows that if the annual demand of the Spanish population were to be supplied through OCPM, this would not result in significant reductions in the environmental and economic impacts produced compared to a non-organic alternative. Conversely, if the EU targets for 2030 had been met, they would have resulted in a considerable improvement in the environmental and economic performance of OCPM, in particular regarding the transformation of the electricity mix. This novel procedure followed can be replicated to be applied to other food products. However, to do so, it is first necessary to review some aspects such as the way in aggregating into single values or to have in the literature a greater availability of methods for monetary valuation of environmental ICs. Also, to develop future iterations of the procedure, it is crucial to consider the social dimension on all those socioeconomic strengths related to the evaluated product in terms of employment or business creation to have a holistic view of sustainability.

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

The authors are unable or have chosen not to specify which data has been used.

Acknowledgements

This research was funded by the EAPA_576/2018 NEPTUNUS project, supported by Interreg Atlantic Area. The authors belong to the Galician Competitive Research Groups (GRC) ED431C-2021/37, co-funded by Xunta de Galicia and FEDER (EU). E.E.B is funded by Xunta de Galicia PhD Grant (ED481A-2021/164).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cesys.2023.100152>.

References

- AIB, 2020. Association of issuing bodies - guaranteeing the origin of European energy. European Residual Mix for the period 2018-2019. <https://www.aib-net.org/> [WWW Document].
- Alimarket, 2021. Informe 2021 del sector de conservas y semiconservas de pescado y marisco en España.
- Amadei, A.M., De Laurentiis, V., Sala, S., 2021. A review of monetary valuation in life cycle assessment: state of the art and future needs. *J. Clean. Prod.* 329, 129668 <https://doi.org/10.1016/j.jclepro.2021.129668>.
- APROMAR, 2022. Spanish Aquaculture Business Association. Report on the Executive Summary of the Year "Aquaculture in Spain 2022".
- Arias, A., Barreiro, D., Feijoo, G., Moreira, M.T., 2022. Waste biorefinery towards a sustainable biotechnological production of pediocin: synergy between process simulation and environmental assessment. *Environ. Technol. Innov.* 26, 102306 <https://doi.org/10.1016/j.eti.2022.102306>.
- ASC, 2019. Aquaculture Stewardship Council Bivalve Standard, Version 1.1.
- Aubin, J., Fontaine, C., Callier, M., Roque d'orcastel, E., 2018. Blue mussel (*Mytilus edulis*) bouchot culture in Mont-St Michel Bay: potential mitigation effects on climate change and eutrophication. *Int. J. Life Cycle Assess.* 23, 1030–1041. <https://doi.org/10.1007/s11367-017-1403-y>.
- Avadi, A., Vázquez-Rowe, I., Symeonidis, A., Moreno-Ruiz, E., 2020. First series of seafood datasets inecoinvent: setting the pace for future development. *Int. J. Life Cycle Assess.* 25, 1333–1342. <https://doi.org/10.1007/s11367-019-01659-x>.

- Avdelas, L., Avdic-Mravljic, E., Borges Marques, A.C., Cano, S., Capelle, J.J., Carvalho, N., Cozzolino, M., Dennis, J., Ellis, T., Fernández Polanco, J.M., Guillen, J., Lasner, T., Le Bihan, V., Llorente, I., Mol, A., Nicheva, S., Nielsen, R., van Oostenbrugge, H., Villasante, S., Visnic, S., Zhelev, K., Asche, F., 2021. The decline of mussel aquaculture in the European Union: causes, economic impacts and opportunities. *Rev. Aquacult.* 13, 91–118. <https://doi.org/10.1111/raq.12465>.
- Belton, B., Reardon, T., Zilberman, D., 2020. Sustainable commoditization of seafood. *Nat. Sustain.* 3, 677–684. <https://doi.org/10.1038/s41893-020-0540-7>.
- Bianchi, M., Hallström, E., Parker, R.W.R., Mifflin, K., Tyedmers, P., Ziegler, F., 2022. Assessing seafood nutritional diversity together with climate impacts informs more comprehensive dietary advice. *Commun. Earth Environ.* 3 <https://doi.org/10.1038/s43247-022-00516-4>.
- Cai, J., Leung, P.S., 2022. Unlocking the potential of aquatic foods in global food security and nutrition: a missing piece under the lens of seafood liking index. *Global Food Secur.* 33, 100641 <https://doi.org/10.1016/j.gfs.2022.100641>.
- Caruso, M.C., Pascale, C., Camacho, E., Ferrara, L., 2022. Comparative environmental and social life cycle assessments of off-shore aquaculture rafts made in ultra-high performance concrete (UHPC). *Int. J. Life Cycle Assess.* 27, 281–300. <https://doi.org/10.1007/s11367-021-02017-6>.
- Ceballos-Santos, S., Laso, J., Ulloa, L., Ruiz Salmón, I., Margallo, M., Aldaco, R., 2023. Environmental performance of Cantabrian (Northern Spain) pelagic fisheries: assessment of purse seine and minor art fleets under a life cycle approach. *Sci. Total Environ.* 855 <https://doi.org/10.1016/j.scitotenv.2022.158884>.
- Drewnowski, A., 2022. Food insecurity has economic root causes. *Nat. Food* 3, 555–556. <https://doi.org/10.1038/s43016-022-00577-w>.
- EMEP/EEA, 2019. EMEP/EEA air pollutant emission inventory guidebook (EMEP CORINAIR emission inventory guidebook) 2019: technical guidance to prepare national emission inventories, pp. 1–36. EEA Report 13/2019.
- Entrena-Barbero, E., Feijoo, G., González-García, S., Moreira, M.T., 2022. Blue carbon accounting as metrics to be taken into account towards the target of GHG emissions mitigation in fisheries. *Sci. Total Environ.* 847 <https://doi.org/10.1016/j.scitotenv.2022.157558>.
- España, Lamarca, 2021. El sector de las conservas en España: marisco y pescado enlatados como forma de crecimiento en la pandemia.
- European Commission, 2013. Communication from the commission to the European parliament and the Council. Building the single market for green products. Facilitating better information on the environmental performance of products and organisations.
- European Commission, 2018a. Product Environmental Footprint Category Rules Guidance, version 6.3.
- European Commission, 2018b. Regulation (EU) 2018/848 on Organic Production and Labelling of Organic Products and Repealing Council Regulation (EC) No 834/2007. Off. J. Eur. Union.
- European Commission, 2021. Commission Recommendation (EU) 2021/2279 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations. Official Journal of the European Union.
- European Commission, 2022. REPowerEU Plan - Communication from the Commission to the European Parliament, vol. 21. the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions.
- European Parliament, 2017. Circular Economy Package. Four legislative proposals on waste.
- European Parliament, 2023. Aquaculture Production in the European Union. Fact Sheets on the European Union.
- Eurostat, 2020. Municipal Waste by Waste Management Operations.
- FAO, 2022. The state of world fisheries and aquaculture. Towards blue transformation. Rome, Italy. <https://doi.org/10.4060/cc0463en>.
- FAO, IFAD, UNICEF, WFP, WHO, 2020. The State of Food Security and Nutrition in the World. Transforming Food Systems for Affordable Healthy Diets, the State of Food Security and Nutrition in the World 2020. Transforming Food Systems for Affordable Healthy Diets. <https://doi.org/10.4060/ca9692en>.
- FAO, IFAD, UNICEF, WFP, WHO, 2022. The State of Food Security and Nutrition in the World 2022. Repurposing Food and Agricultural Policies to Make Healthy Diets More Affordable. <https://doi.org/10.4060/cc0640en>.
- Feng, J.-C., Sun, L., Yan, J., 2023. Carbon sequestration via shellfish farming: a potential negative emissions technology. *Renew. Sustain. Energy Rev.* 171, 113018 <https://doi.org/10.1016/j.rser.2022.113018>.
- Firdaus, R.B.R., Senevi Gunaratne, M., Rahmat, S.R., Kamsi, N.S., 2019. Does climate change only affect food availability? What else matters? *Cogent Food Agric.* 5 <https://doi.org/10.1080/23311932.2019.1707607>.
- Fry, J.M., 2012. Carbon Footprint of Scottish Suspended Mussels and Intertidal Roysters. Scottish Aquaculture Research Forum.
- Fujimori, S., Hasegawa, T., Krey, V., Riahi, K., Bertram, C., Bodirsky, B.L., Bosetti, V., Callen, J., Després, J., Doelman, J., Drouet, L., Emmerling, J., Frank, S., Fricko, O., Havlik, P., Humpenöder, F., Koopman, J.F.L., van Meijl, H., Ochi, Y., Popp, A., Schmitz, A., Takahashi, K., van Vuuren, D., 2019. A multi-model assessment of food security implications of climate change mitigation. *Nat. Sustain.* 2, 386–396. <https://doi.org/10.1038/s41893-019-0286-2>.
- Future Market Insights, 2022. Global Canned Seafood Market Analysis 2022–2032.
- de Galicia, Xunta, 2020. Rexistro de Buques Pesqueiros da Comunidade Autónoma de Galicia [WWW Document]. Xunta Galicia. Cons. do Mar.
- de Galicia, Mexillón, 2022. Normas Xerais de Certificación para Produtores e Operadores.
- Henriksson, P.J.G., Troell, M., Banks, L.K., Belton, B., Beveridge, M.C.M., Klinger, D.H., Pelletier, N., Phillips, M.J., Tran, N., 2021. Interventions for improving the productivity and environmental performance of global aquaculture for future food security. *One Earth* 4, 1220–1232.
- Hospido, A., Tyedmers, P., 2005. Life cycle environmental impacts of Spanish tuna fisheries. *Fish. Res.* 76, 174–186. <https://doi.org/10.1016/j.fishres.2005.05.016>.
- IPCC, 2006. Guidelines for national greenhouse gas inventories chapter 2: stationary combustion. Intergovernmental Panel on Climate Change.
- Iribarren, D., Hospido, A., Moreira, M.T., Feijoo, G., 2010a. Carbon footprint of canned mussels from a business-to-consumer approach. A starting point for mussel processors and policy makers. *Environ. Sci. Pol.* 13, 509–521. <https://doi.org/10.1016/j.envsci.2010.05.003>.
- Iribarren, D., Moreira, M.T., Feijoo, G., 2010b. Life Cycle Assessment of fresh and canned mussel processing and consumption in Galicia (NW Spain). *Resour. Conserv. Recycl.* 55, 106–117. <https://doi.org/10.1016/j.resconrec.2010.08.001>.
- Iribarren, D., Moreira, M.T., Feijoo, G., 2010c. Implementing by-product management into the life cycle assessment of the mussel sector. *Resour. Conserv. Recycl.* 54, 1219–1230. <https://doi.org/10.1016/j.resconrec.2010.03.017>.
- Iribarren, D., Moreira, M.T., Feijoo, G., 2010d. Revisiting the life cycle assessment of mussels from a sectorial perspective. *J. Clean. Prod.* 18, 101–111. <https://doi.org/10.1016/j.jclepro.2009.10.009>.
- ISO, 2006a. ISO 14040:2006 - Environmental Management - Life Cycle Assessment - Principles and Framework.
- ISO, 2006b. ISO 14044:2006 - Environmental Management - Life Cycle Assessment - Requirements and Guidelines.
- Jarosz, L., 2014. Comparing food security and food sovereignty discourses. *Dialogues Hum. Geogr.* 4, 168–181. <https://doi.org/10.1177/2043820614537161>.
- King, T., Cole, M., Farber, J.M., Eisenbrand, G., Zabarar, D., Fox, E.M., Hill, J.P., 2017. Food safety for food security: relationship between global megatrends and developments in food safety. *Trends Food Sci. Technol.* 68, 160–175. <https://doi.org/10.1016/j.tifs.2017.08.014>.
- Lacour, C., Seconda, L., Allès, B., Hercberg, S., Langevin, B., Pointereau, P., Lairon, D., Baudry, J., Kesse-Guyot, E., 2018. Environmental impacts of plant-based diets: how does organic food consumption contribute to environmental sustainability? *Front. Nutr.* 5, 8.
- Laso, J., Margallo, M., Fullana, P., Bala, A., Gazulla, C., Irabien, A., Aldaco, R., 2017. Introducing life cycle thinking to define best available techniques for products: application to the anchovy canning industry. *J. Clean. Prod.* 155, 139–150. <https://doi.org/10.1016/j.jclepro.2016.08.040>.
- Li, H., Inzamam, U.H., Hira, N., Gadah, A., Wedad, A., Ahsan, N., Javaria, H., 2020. How environmental awareness relates to green purchase intentions can affect brand evangelism? Altruism and environmental consciousness as mediators. *Rev. Argent. Clin. Psicol.* 29, 811–825. <https://doi.org/10.24205/03276716.2020.1079>.
- Liu, C., Ralston, N.V.C., 2021. Chapter Seven - seafood and health: what you need to know? In: Toldrá, F. (Ed.), *Advances in Food and Nutrition Research*. Academic Press, pp. 275–318. <https://doi.org/10.1016/bs.afnr.2021.04.001>.
- Loboguerrero, A.M., Campbell, B.M., Cooper, P.J.M., Hansen, J.W., Rosenstock, T., Wollenberg, E., 2019. Food and earth systems: priorities for climate change adaptation and mitigation for agriculture and food systems. *Sustain. Times* 11. <https://doi.org/10.3390/su11051372>.
- Lourguioi, H., Brigolin, D., Boulahdid, M., Pastres, R., 2017. A perspective for reducing environmental impacts of mussel culture in Algeria. *Int. J. Life Cycle Assess.* 22, 1266–1277. <https://doi.org/10.1007/s11367-017-1261-7>.
- Lozano, S., Iribarren, D., Moreira, M.T., Feijoo, G., 2009. The link between operational efficiency and environmental impacts. A joint application of Life Cycle Assessment and Data Envelopment Analysis. *Sci. Total Environ.* 407, 1744–1754. <https://doi.org/10.1016/j.scitotenv.2008.10.062>.
- Maffia, A., Pergola, M., Palese, A.M., Celano, G., 2020. Environmental impact assessment of organic vs. Integrated olive-oil systems in Mediterranean context. *Agronomy* 10, 1–21. <https://doi.org/10.3390/agronomy10030416>.
- Manning, L., Soon, J.M., 2016. Food safety, food fraud, and food defense: a fast evolving literature. *J. Food Sci.* 81, R823–R834. <https://doi.org/10.1111/1750-3841.13256>.
- MAPA, 2019. Informe del consumo alimentario en España 2019.
- MAPA, 2020. Informe del Consumo Alimentario en España 2019. Efecto del Estado de Alarma. Datos preliminares 2020.
- MAPA, 2021a. Informe del Consumo de Alimentación en España 2020.
- MAPA, 2021b. Panel de consumo alimentario. Datos de consumo desde 2001 a 2021 (mes a mes y acumulados) [WWW Document]. URL: <https://www.mapa.gob.es/es/alimentacion/temas/consumo-tendencias/panel-de-consumo-alimentario/>.
- MAPA, 2021c. Encuesta Económica de Acuicultura. Informe Principales Resultados.
- MAPA, MERCASA, 2022. Observatorio de Precios de los Alimentos. Observatorio de la Cadena Alimentaria. Precios Semanales.
- Mc Carthy, U., Uysal, I., Badia-Melis, R., Mercier, S., O'Donnell, C., Ktenioudaki, A., 2018. Global food security – issues, challenges and technological solutions. *Trends Food Sci. Technol.* 77, 11–20. <https://doi.org/10.1016/j.tifs.2018.05.002>.
- Moreno Ruiz, E., Fitzgerald, D., Symeonidis, A., Ioannidou, D., Müller, J., Valsasina, L., Vadenbo, C., Minas, N., Sonderegger, T., Dellenbach, D., 2021. Documentation of Changes Implemented in the Ecoinvent Database V3, vol. 8.
- Nurliza, Suharyani, A., Nugraha, A., 2021. The product features, functions, and benefits of seafood products for competitive repositioning. *Agraris* 7, 1–110. <https://doi.org/10.18196/agraris.v7i1.10571>.
- Plank, A., Teichmann, K., 2018. A facts panel on corporate social and environmental behavior: decreasing information asymmetries between producers and consumers through product labeling. *J. Clean. Prod.* 177, 868–877. <https://doi.org/10.1016/j.jclepro.2017.12.195>.
- Ruiz-Salmón, I., Margallo, M., Laso, J., Villanueva-Rey, P., Mariño, D., Quinteiro, P., Dias, A.C., Nunes, M.L., Marques, A., Feijoo, G., Moreira, M.T., Loubet, P., Sonnemann, G., Morse, A., Cooney, R., Clifford, E., Rowan, N., Méndez-Paz, D.,

- Iglesias-Parga, X., Anglada, C., Martin, J.C., Irabien, Á., Aldaco, R., 2020. Addressing challenges and opportunities of the European seafood sector under a circular economy framework. *Curr. Opin. Environ. Sci. Heal.* 13, 101–106. <https://doi.org/10.1016/j.coesh.2020.01.004>.
- van der Schatte Olivier, A., Jones, L., Vay, L. Le, Christie, M., Wilson, J., Malham, S.K., 2020. A global review of the ecosystem services provided by bivalve aquaculture. *Rev. Aquacult.* 12, 3–25. <https://doi.org/10.1111/raq.12301>.
- Sea, M.A., Hillman, J.R., Thrush, S.F., 2022. The influence of mussel restoration on coastal carbon cycling. *Global Change Biol.* 28, 5269–5282. <https://doi.org/10.1111/gcb.16287>.
- Spångberg, J., Jönsson, H., Tidåker, P., 2013. Bringing nutrients from sea to land e mussels as fertiliser from a life cycle perspective. *J. Clean. Prod.* 51, 234–244. <https://doi.org/10.1016/j.jclepro.2013.01.011>.
- Tamburini, E., Turolla, E., Fano, E.A., Castaldelli, G., 2020. Sustainability of Mussel (*Mytilus galloprovincialis*) farming in the Po River delta, northern Italy, based on a life cycle assessment approach. *Sustain. Times* 12. <https://doi.org/10.3390/su12093814>.
- United Nations, 2022. *World Population Prospects 2022: Summary of Results*. Department of Economic and Social Affairs. Population Division. UN DESA/POP/2022/TR/NO. 3.
- Yang, G., Liu, B., 2021. Research on the impact of managers' green environmental awareness and strategic intelligence on corporate green product innovation strategic performance. *Ann. Oper. Res.* <https://doi.org/10.1007/s10479-021-04243-5>.
- Zampori, L., Pant, R., 2019. Suggestions for Updating the Product Environmental Footprint (PEF) Method. Publications Office of the European Union. <https://doi.org/10.2760/424613>.
- Ziegler, F., Winther, U., Hognes, E.S., Emanuelsson, A., Sund, V., Ellingsen, H., 2013. The carbon footprint of Norwegian seafood products on the global seafood market. *J. Ind. Ecol.* 17, 103–116.