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Full length article

The carbon footprint of the mussel food chain in Spain

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ABSTRACT

The global food system is a major contributor to greenhouse gas emissions (GHG), and there is increasing interest in identifying sustainable protein alternatives. Mussels are often promoted as an environmentally friendly source of seafood. However, comprehensive assessments of its carbon footprint, which consider the entire food chain, remain limited. This study estimates the carbon footprint of the mussel food chain in Spain, focusing on its product forms—fresh, frozen, and canned— by reconstructing the mussel supply chain, integrating national production and trade data, and modelling its logistics across international, national, and intraprovincial transport. The relationship between fresh, frozen and processed mussel allows to articulate a consumption approach taking into consideration the interconnections between industrial processing, global supply chains and mussel production. Total GHG emissions reached 287.8 $GgCO_2eq.yr^{-1}$, with the main contributions from aquaculture production (45 %), industrial processing (43 %), and transport (12 %). Emissions linked to domestic consumption are 190.1 $GgCO_2eq.yr^{-1}$, representing 6.3 $kgCO_2eq.kg^{-1}$ edible mussel meat, with pickled mussels representing the most impactful product (8.5 $kgCO_2eq.kg^{-1}$ edible mussel meat), followed by mussels in brine (6.7 $kgCO_2eq.kg^{-1}$ edible mussel meat), fresh mussels (4.1 $kgCO_2eq.kg^{-1}$ edible mussel meat), and frozen mussels (3.6 $kgCO_2eq.kg^{-1}$ edible mussel meat). Although Galicia accounts for 99 % of domestic mussel production, only 25 % of available fresh mussels are destined for direct domestic consumption. The remainder feeds industrial processing or is exported, revealing a structure highly dependent on international trade and interprovincial transport. Our findings show that processing and transport are key contributors, and that the most consumed forms present the highest carbon footprints. We highlight the need to promote more sustainable consumption patterns, enhance local consumption of lower-impact forms, and reconfigure industrial and trade strategies to reduce environmental impacts while maintaining the sector's economic viability.

1. Introduction

The global food system is now recognized as a major contributor to climate change, accounting for 21–37 % of net greenhouse gas emissions, hereafter GHG, (IPCC, 2020). Livestock production is responsible for the largest share, contributing approximately 14 % of total emissions (Springmann et al., 2016; 2018). Given the key role of animal protein in driving these emissions, a variety of solutions have been proposed, including dietary shifts away from animal-based foods or replacing them with alternative protein sources that produce lower emissions (Free et al., 2022; Westhoek et al., 2011; Willet et al., 2019.

In this context, food from fisheries and aquaculture could be an alternative (Costello et al., 2020). The level of fishery delocalization, international agreements and divergent policies regarding fishery effort investment requires international agreements to fulfill a sustainable future, something currently not happening (Ye and Gutierrez, 2017). In this sense, the 2030 Agenda for Sustainable Development has set a target of ending overfishing and restoring depleted fish stocks (UN, 2015) since one-third-of the 400 fish stocks monitored by the FAO are over-fished (FAO, 2024).

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While global landings stabilized since the 1990s, aquaculture production doubled (FAO, 2022), shifting its environmental footprint to "farming" systems that rely on feed derived from agriculture and fisheries, thus displacing rather than reducing overall impacts (Asche, 2008; Naylor and Burke, 2005). Nevertheless, it seems to have a net reduction regarding direct emissions in aquaculture due to the absence of direct land-use changes and the reduced methane emissions from the aquatic animals' digestive systems (Gephart et al., 2021). Its potential environmental reduction, health contribution and social acceptance pushes forward its expansion (Clark et al., 2019; Godfray et al., 2010), but it has been criticized for being incapable of feeding the global demand (Sumaila et al., 2022). Therefore, rather than focusing on ecological outcomes regarding sustainable supply diets or vice versa, it is mandatory to focus on the coupled system production–exchange-consumption to promote social-ecological and health diets (Golden et al., 2021; Parodi et al., 2018).

Among aquaculture systems, bivalve farming has been particularly highlighted for its potential net ecological effects, including the potential for emission reductions (Barrett et al., 2022; Jones et al., 2022; Lee et al., 2020; Ray et al., 2019, The Nature Conservancy, 2021; Theuerkauf et al., 2019). There are some positive ecological functions relevant to the health and resilience of marine environments as nutrient cycling, biodeposition or water clarification (Petersen et al. 2016; Rose et al. 2021). Bivalve mariculture is discussed as a sustainable source of nutrient-rich protein production (Parodi et al. 2018; Willer and Aldridge 2020; Troell et al., 2023). Mussel farming in particular is considered a sustainable activity, since in addition to providing essential and healthy nutrients for humans such as vitamins, minerals and proteins (Alonso et al., 2021; Carboni et al., 2019; Koodathil et al., 2025), it contributes positively to the conservation of marine environment and to socioeconomic development of coastal communities (Matarazzo Suplicy, 2020; Rodríguez-Rodríguez and Bande Ramudo, 2017; Shumway et al., 2003). As filter feeders, mussels contribute to nutrient cycling, reduce coastal erosion, promote biodiversity, and help regulate aquatic ecosystems (Carboni et al., 2019; FAO, 2022, 2024, Zieritz et al., 2022). However, throughout all stages of their life cycle, from extraction to production, distribution, consumption and waste management, mussel production can also have significant environmental impacts such as ecosystem degradation (eutrophication, oxygen depletion, affectation of benthic communities), energy consumption and other effects (Cranford et al. 2007; Danovaro et al. 2004, Mascorda Cabre et al., 2021; Vélez-Henao et al., 2021).

Life cycle assessments of mussel production in various countries have identified common critical stages (Bohnes and Laurent, 2019; Vélez-Henao et al., 2021). These include fuel consumption and vessel manufacturing during harvesting (Aubin and Fontaine, 2014; Joël 2018; Frösell, 2019; Winther et al., 2009; Meyhoff-Fry, 2012; Tamburini et al., 2020), and the manufacture of capital goods such as boats and farming structures, particularly noted in Sweden, Scotland, Italy, and the Mediterranean (Frösell, 2019; Meyhoff-Fry, 2012; Tamburini et al., 2020; Lourguioui et al., 2017). In Spain, France, Algeria, and New Zealand, significant energy use has been reported for farm operations, purification plants, and water pumping or cleaning (Iribarren, 2010; Iribarren et al., 2010a–c, 2011; Lozano et al., 2010; Aubin and Fontaine, 2014; Joël 2018; Lourguioui et al., 2017; Thinkstep-anz, 2021). For processed and canned products, impacts are particularly associated with packaging, transport, oil production, and cooking, as seen in Spain and New Zealand (Iribarren et al., 2011; Warmerdam et al., 2021; Thinkstep-anz, 2021). Global warming potential is the most frequently studied impact category (Langdal et al., 2025)

Between 2012 and 2022, the main mussel culture producing countries were China (927.7–715 kt); Chile (429.3–211.3 kt), Spain (283.8–162 kt), Thailand (127.9–34 kt), New Zealand (101.7–76.8 kt), Italy (64.2–50.3 kt) and France (77.1–48.8 kt). In the context of the EU27, fresh mussel production varied between 545.1 and 430.2 kt during the same period. Of this total, from 87 % to 94 % came from aquaculture whereas the extractive fisheries contribution progressively decreased over time from 10.5 to 6 % (FAO, 2025). In fact, European production began to decline in 1999, when it reached a peak of 743.4 kt. and since then the trend has been downward except for the period 2014–2018, something also identified worldwide (Avdelas et al., 2021; Pérez Agúndez et al., 2025).

Spain stands out as the main mussel culture producer in the EU, with 192.2 kt in 2022, representing almost half of total production (47 %). It is followed by France, (71.2 kt, 17 %); Italy (60.5 kt, 14.8 %); the Netherlands (29.6 kt, 7.2 %); Ireland (19.8 kt, 4.8 %) Greece (10.7 kt, 2.6 %) and Germany (8.6 kt, 2.1 %) (FAO, 2025). Spain was the world's leading mussel producer from the 1960s to the 1980s, until China took over. During 2010–2020 period, Spain was the third largest producer worldwide, after China and Chile. Studying Spain's trajectory as a major producer and trading country (FAO, 2022) provides a useful case study of the functioning of the global food system.

Within Spain, 98 % of mussel production (*Mytilus galloprovincialis)* is concentrated in Galicia, specially in Pontevedra (72 %, Arousa estuary) and A Coruña (26 %, Sada estuary) (Figueras and Cáceres, 2007). The remaining 2 % is produced along the Mediterranean coast, primarily in Catalonia, the Valencian Community, Andalusia and the Balearic Islands (MAPA, 2022). Introduced in 1940, mussel aquaculture in Galicia developed into a globally relevant activity based on the use of floating rafts made of wooden frameworks from which mussel ropes are suspended (Labarta and Corbacho, 2002; Labarta and Fernández- Reiriz, 2019; OESA, 2017).

The process includes spat collection, transfer to rafts, stringing to cultivation ropes, thinning to avoid detachment and encourage fattening, harvesting and sorting, and finally purification—a filtering process that eliminates intestinal contents and reduces contamination from bacteria. Notably, the purification phase involves considerable energy consumption and represents the stage with the greatest environmental impact in the production process (Iribarren et al., 2010a).

Despite the growing body of research on the environmental impacts of mussel aquaculture, a significant knowledge gap remains regarding the full carbon footprint of the entire food chain, including all product forms. This information is essential for guiding more sustainable practices in mussel farming and processing, and for promoting consumption patterns aligned with dietary sustainability goals.

This contribution aims to estimate for the first time the carbon footprint of the mussel farming food supply chain in Spain, with special attention to consumption in its various forms (fresh, frozen, and canned), taking 2017 as a reference year. To this end, the main factors contributing to GHG emissions throughout the mussel food chain in Spain have been identified, considering emissions associated with production, processing, transport, import, and export. The analysis also incorporates emissions from the different mussel commercial formats, produced in Spain and/or imported for use by the processing industry. This analysis will help understand the importance of adopting sustainable practices in the sector to mitigate the environmental impact, as well as identify areas for improvement throughout the food chain. With this approach we try to reconstruct and understand the mussel food system as part of the development and implementation of a sustainable and healthy diet in Spain.

2. Materials and methods

2.1. Scope of the study

The analysis uses 2017 as the reference year because it was the most recent year with complete data available at the time of the study. The analysis follows a cradle-to-household gate perspective that covers all processes from mussel cultivation to the point of domestic consumption, including transport, industrial processing, and trade flows (Fig. 1). The system boundaries therefore encompass:

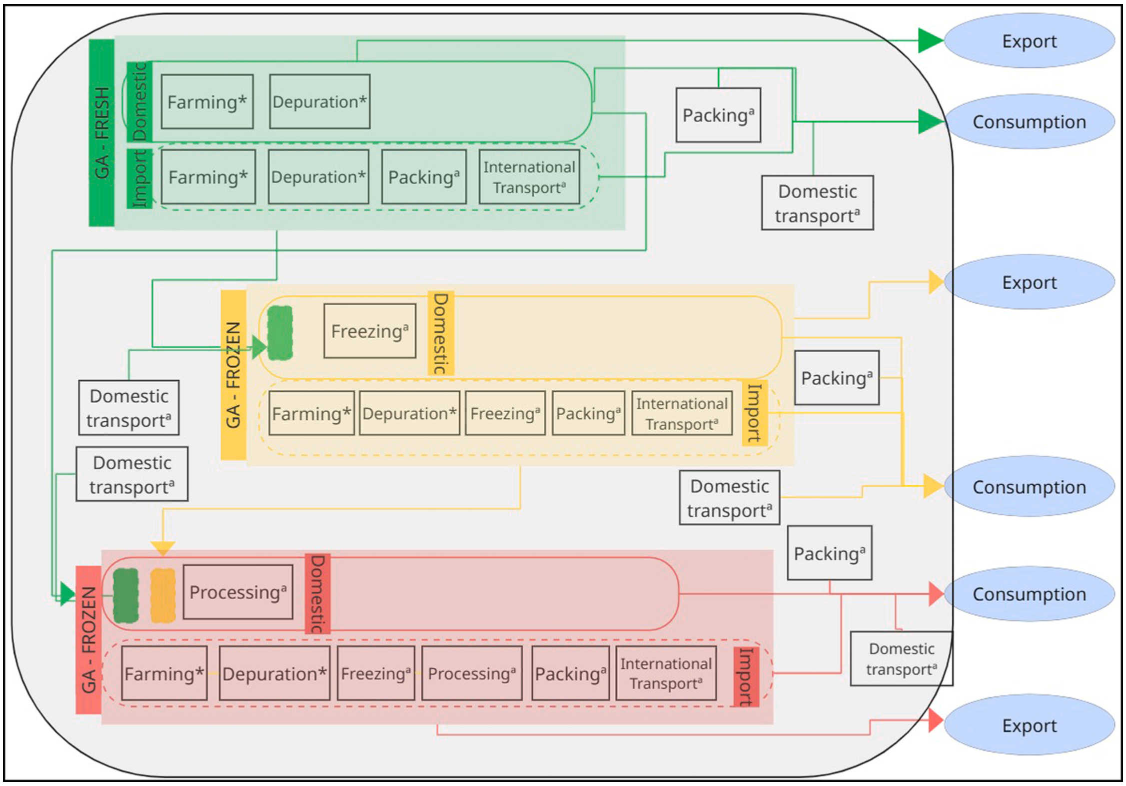

Fig. 1. Diagram of the mussel production and processing system analyzed. The system boundary, denoted by the grey-shaded area, includes all processes contributing to the gross availability G_A of mussels in each product form: fresh, frozen, and processed. Box colors denote product type: grey boxes correspond to products (fresh, frozen, processed), and white boxes to processes. Products acting as raw materials for subsequent stages are represented by grey rectangles (e.g., fresh mussels used for frozen and processed G_A, and frozen mussels used for processed G_A). Symbols: * values retrieved from literature review; [a] values reconstructed based on combined factors.

(i) Production, including mussel farming, depuration, and primary packaging;
(ii) Processing, comprising shelling, cleaning, freezing, cooking, and canning;
(iii) Transport, at international, national, and intraprovincial levels; and
(iv) Trade and distribution, including exports and domestic recirculation among provinces up to retail and household delivery.

End-of-life stages such as consumer waste treatment, recycling, or landfill disposal of packaging are excluded, as these processes contribute marginally to total emissions and are poorly documented in available data. This boundary definition expands the conventional cradle-to-gate approach commonly applied to aquaculture LCA (Vélez-Henao et al., 2021) by integrating the consumption (Avadí et al., 2015; Bohnes and Laurent, 2019) and trade dimensions of the mussel food chain (Molina-Besch et al., 2019).

Moreover, several post-farming processes in aquaculture have been shown to generate significant environmental impacts (Gephart et al., 2021; Seves et al., 2016). In the following sections, we adopt a combined approach using Material Flow Analysis and Life Cycle Assessment as the main methodological framework of the article (Barkhausen et al., 2023; Han et al., 2022).

Mussel production includes the mussel farming itself, the depuration process and the packaging. The industrial processing includes shelling, cleaning, sorting and freezing for frozen mussels, and for processed products it includes cooking and canning. To compare results among fresh, frozen, brine, and pickled mussels, the Functional Unit (FU) is defined as one kg of mussel meat. This unit was chosen because it is the common element across all presentations.

2.2. Reconstruction of mussel food chains

To reconstruct the mussel food chains, we defined gross availability G_A as the total quantity of mussels available within the Spanish system boundary during the reference year. It was calculated as the sum of domestic production and imports, minus food losses and waste occurring before final consumption, and adjusted for stocks when applicable. This indicator represents the mass of mussels entering the domestic supply chain, either for direct consumption, industrial processing, or export. The estimation followed FAO guidelines and approaches used in previous national food flow analyses (e.g., Billen et al., 2012; Aragão et al., 2022; Aragão et al., 2021; Guillen et al., 2019; Saralegui-Díez et al., 2023). Data on production and mussel trade were obtained from national databases (MAPAMA, 2017) and disaggregated to the provincial level based on regional studies (OESA, 2017) and expert input. International commerce flows were extracted from Datacomex (DataComex, 2017) and production data for the processing industry were from the Annual Industrial Products Survey (INE, 2017). Apparent consumption was calculated by estimating the remaining amount of G_A once exports and industrial use are detracted, and it was spatialised computed using population data on a provincial level (Cerrillo et al., 2023; Saralegui-Díez et al., 2023). Provincial G_A surpluses and deficits were balanced through an estimated recirculation flow between provinces. All numerical datasets used for reconstructing production, import, export, and consumption flows—together with the corresponding conversion factors—are provided in the Online Supplementary Material, hereafter OSM, (A1.2-A1.3, A2.1-A2.2 and Tables SM1–SM3), allowing full reproducibility of the supply-chain reconstruction.

2.3. Modelling the logistics of the mussel transport chain

The logistics model reconstructed international, national, and intraprovincial transport routes, along with distribution pathways to households and out-of-home establishments, to ensure comprehensive accounting of all transport-related emissions (Saralegui-Díez et al., 2023). Routes were identified using trade and logistics network data, with distances calculated through shortest-path algorithms and adjusted according to modal shares. This multimodal approach aligns with recent recommendations for robust food supply chain analysis. Additional details on network assumptions, transport modes, routing methods and results are provided in the OSM.

2.4. The mussel carbon footprint

The carbon footprint was estimated as total GHG emissions in CO_2eq following the ReCiPe (H) 2016 v.1.04 methodology (Huijbregts et al., 2016). The calculation used an approximation to the 100-year global warming potential (GWP-100), which accounts for climate system feedback in accordance with the latest available IPCC report (IPCC, 2021).

Emission factors (EFs) for mussel production, processing, packaging, and transport were derived primarily from peer-reviewed literature and harmonized to the functional unit of one kg of meat, applying conversion factors for different product forms (Table SM1, OSM). Mussel production was considered to include growth, depuration, cleaning and preparation for fresh use, consistent with the scope used in previous LCA studies. Processing encompassed shelling, freezing, canning, cooking and mixing as part of the manufacturing stage. Weighted average distances were calculated for each stage of the supply chain to estimate transport-related emissions. Allocation criteria for processing by-products and the transport emission factors are detailed in tables SM2-SM5, OSM).

To ensure methodological consistency, all emission factors were cross-checked and, when available, updated using the most recent databases (Ecoinvent, 2019; MITECO, 2022). Values from earlier references (e.g., Iribarren, 2010) were only retained where no newer, system-compatible data existed. Reported values represent mean estimates, and the propagated uncertainty of emission factors (±15–25 %) is presented in the SM (Section SM4). For clarity, chain-specific totals (fresh, frozen, brine, pickled) are not additive. Upstream burdens of batches used as industrial inputs are carried exclusively by their downstream subchain, in line with our no-double-counting rule (see SM A2.4, Table SM6). Minor discrepancies (<0.5 %) arise from rounding. A stepwise description of the CF calculation, including emission factors, intermediate values, and conversion equations, is presented in the SM (Section SM2). This ensures the reproducibility of all estimates reported in the main text.

Carbon sequestration associated with mussels shells was not considered, as it is not an intended outcome of current waste management practices. Potential sequestration occurs only when shells are buried in landfills, and in Spain only about 35 % of total waste ends up in landfills (INE, 2022). Furthermore, there is no consensus regarding the inclusion of shell carbon sequestration within the mussel carbon cycle, as discussed in OSM.

3. Results

3.1. Mussel gross availability and its destinations

This section focuses on quantifying the G_A of mussels in Spain and how this supply is distributed across its main destinations, that is, domestic consumption, processing into frozen and canned products, and exports.

In 2017, the G_A of fresh mussels amounted to 276 kt, of which 270 kt corresponded to domestic production and 6 kt to imported fresh mussels (Fig. 2). The domestic industry produced 15.4 kt of frozen mussels, while 0.9 kt of the same product was imported, resulting in a G_A of frozen mussels of 16.3 kt. For canned mussels, the domestic industry produced 25 kt and imported 12 kt, resulting in a G_A of 37 kt.

Losses and waste in the supply chain were relatively low: 1.9 kt for fresh mussels (primarily from domestic production), and approximately 0.2 kt for both frozen and canned mussels.

Geographically, Galicia accounted for 99 % of fresh mussel production (264.5 kt) in 2017, with 72 % produced in the province of Pontevedra (194 kt) and 26 % in A Coruña (71.8 kt). Other Autonomous

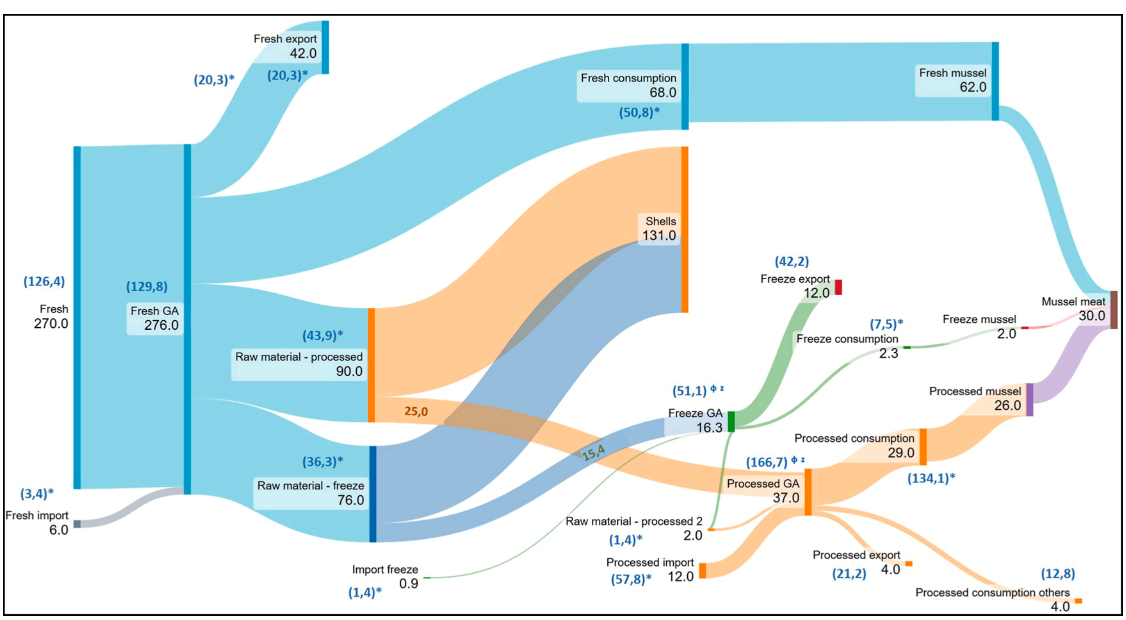

Fig. 2. Sankey diagram representing biomass fluxes and CO_{2eq} emissions (numbers in blue and in parentheses, $GgCO_2eq.yr^{-1}$). Using the gross availability (G_A) of fresh mussels, biomass fluxes and emissions are detailed for the three product subsystems: fresh, frozen and canned, including export. For ease reading, FLW is not represented. All values of weight are expressed in thousands of tonnes (kt). [z] Includes industrial processing; [ɸ]Includes emissions from raw materials; *Includes transport.

Communities contributed marginally (6.1 kt, 1 %). Fresh imports (6.4 kt) were mainly destined for Tarragona (Catalonia) (2.1 kt), Valencia (2.0 kt), and Pontevedra (1.2 kt). The main countries of origin were Italy (37 %), Greece (23 %), France (19 %), and Portugal (14 %) (SM-A2.1).

Mussel fresh exports (42 kt) were mainly shipped from Pontevedra (33.3 kt; 80 %) and Girona (Catalonia) (7.1 kt; 18 %). The most important importing countries were France and Italy, which represented 57 % and 39 % of the total fresh export respectively (SM-A2.1).

The G_A of fresh mussel is distributed as follows. Processing industries accounted for 166 kt (60 %) of fresh mussels for frozen and canned food (76 and 90 kt respectively), 68 kt (25 %) for fresh consumption and 42 kt (15 %) for fresh export. The raw mussel material used by the industry comes from fresh production, representing 99 %.

The frozen mussel processing industry produced 15.4 kt, 98 % of which was concentrated in Galicia (Figure A2 SM). The remaining 2 % was processed in Tarragona and Barcelona (Catalonia) and Valencia (0.3 kt). Frozen mussel imports amounted to 0.9 kt, 77 % coming from New Zealand (0.7 kt). In Spain, Pontevedra (0.3 kt; 37 %) and Las Palmas (Canary Islands) (0.2 kt; 27 %) stand out as the largest importing provinces of this product.

Exports represented 72 % of the total G_A (12 kt), while only 2.3 kt (16 %) is destined for frozen consumption and 2 kt (12 %) for the production of canned mussels. Pontevedra produced 94 % of the total frozen export (11 kt), France and Italy were the main importing countries (Figure A3 SM).

The canning industry produced 25 kt, and 12 kt that were imported. The largest production was concentrated in A Coruña and Pontevedra, reaching 98 % (Figure A2 SM). Two percent (0.4 kt) of production was recorded in the provinces of Tarragona, Valencia and Málaga (Andalusia). Of this production, 90 % was used to produce pickled mussels and 10 % to produce mussels in brine. The importing provinces were, once again, the major producing provinces of Pontevedra (7.8 kt) and A Coruña (3.4 kt), which together accounted for 93 %. The majority of these canned products originated from Chile. Exports were concentrated in Pontevedra (2.2 kt; 55 %), Gipuzkoa (Basque Country) (0.9 kt; 26 %) and A Coruña (0.4 kt; 8 %).

3.2. Emissions from the mussel supply chain

This section likely covers all emissions across every stage (production, processing, transport, trade and consumption), providing a full life cycle perspective.

The entire mussel supply chain emitted 287.8 $GgCO_2eq.yr^{-1}$, with contributions from fresh mussel production (44 % of total emissions; 126.4 $GgCO_2eq.yr^{-1}$), industrial processing (43 %; 123 $GgCO_2eq.yr^{-1}$), and transport (13 %; 34.9 $GgCO_2eq.yr^{-1}$) being the main components (Fig. 3). Only 1 % of emissions (3.5 Gg CO_2eq) are due to imported fresh mussel production in Spain. Processing emissions associated with the Spanish industrial sector account for 22 % (63.7 $GgCO_2eq.yr^{-1}$), while processing in third countries accounts for 21 % (59.3 $GgCO_2eq.yr^{-1}$). Among the processing industry's emissions, 76 % are due to the production of pickled mussels (48.2 $GgCO_2eq.yr^{-1}$). This product also accounts for 90 % of the emissions from imported processed products (53.4 $GgCO_2eq.yr^{-1}$). Of the emissions associated with transport, 58 % are related to fresh mussels (20.2 $GgCO_2eq.yr^{-1}$), followed by emissions from pickled mussels (35 %; 12.3 Gg CO_2eq), while the rest (7 %) is related with brine mussels (2.4 $GgCO_2eq.yr^{-1}$). Due to the small volume of fresh mussel imports compared to mussels produced in Spain, 99 % of their transport emissions are associated with domestic transport.

Within the overall emissions, 66 % (190.1 $GgCO_2eq.yr^{-1}$) are associated with mussels ultimately consumed by the Spanish population, and 29 % (83.8 $GgCO_2eq.yr^{-1}$) are associated with exports. Similarly, 5 % (13.9 $GgCO_2eq.yr^{-1}$ of emissions are linked to processed products that are ultimately not intended for human consumption or export (i.e. animal feed) (Fig. 3).

The fresh mussel supply chain accounts for 71.1 $GgCO_2eq.yr^{-1}$ emitted, of which 70 % (49.6 $GgCO_2eq.yr^{-1}$) are due to aquaculture production itself (including the depuration process essential for marketing). They do not include emissions related to fresh mussel production destined for the industry (considered below), so they refer to fresh mussels as a product directly consumed or exported, whether they come from imports or domestic production. Transport accounts for 27 % of emissions (19.3 $GgCO_2eq.yr^{-1}$): 14 % is due to recirculation transport (9.9 $GgCO_2eq.yr^{-1}$), 9 % to its final distribution (6.7 $GgCO_2eq.yr^{-1}$), and 4 % to international and national transport combined (2.7 $GgCO_2eq.yr^{-1}$). The remaining 3 % of fresh mussel emissions are related to imported

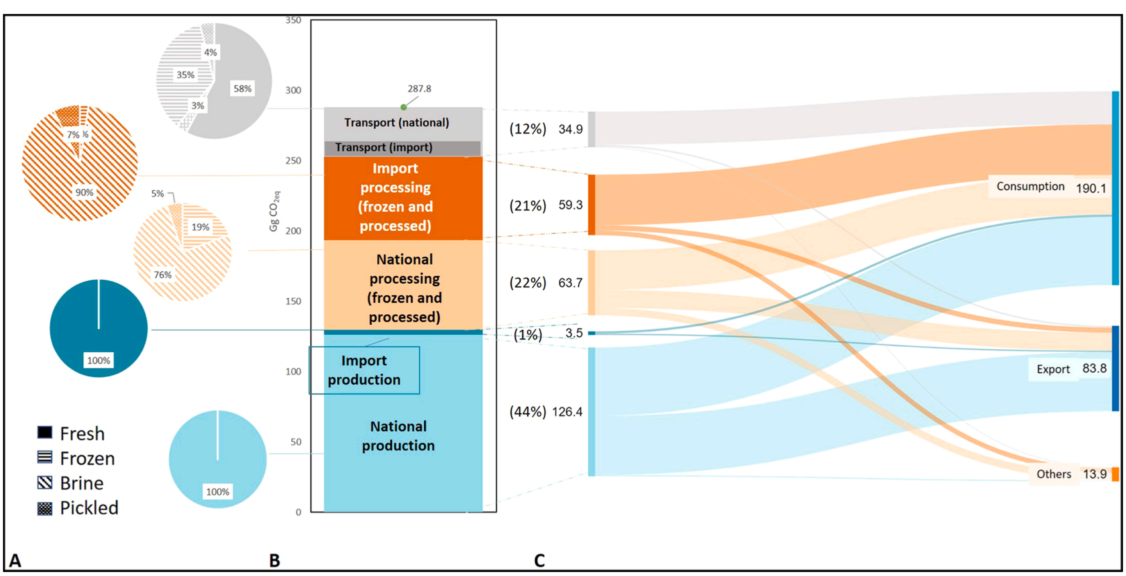

Fig. 3. Total emissions from the Spanish mussel supply chain. A: Contribution of each subchain to emissions by stage (for canned products, a distinction is made between pickled and brine); B: Emissions breakdown by production, processing and transport stages; C: Emission destinations (domestic consumption, processing, and exports). Production burdens of batches used as industrial inputs are allocated exclusively to their downstream subchain (frozen or canned) and excluded from the fresh chain; therefore, totals by stage sum without overlaps across subchains. International transport to final foreign destinations is not included in the export flow. Subchain totals are reported for comparison and should not be summed to obtain the system total.

products (2.2 $GgCO_2eq.yr^{-1}$).

Of the total emissions associated with fresh mussels, 71 % (50.8 $GgCO_2eq.yr^{-1}$) correspond to domestic consumption, while 29 % (20.3 $GgCO_2eq.yr^{-1}$) are associated with exports abroad. Although the largest amount of emissions corresponds to the production of the mussels domestically consumed in Spain (30.3 $GgCO_2eq.yr^{-1}$), it's important to recognize that the transport of imported fresh mussels from abroad, domestic transport, recirculation transport, and final distribution associated with domestic consumption account for 26 % of the fresh mussel supply chain`s emissions (18.8 $GgCO_2eq.yr^{-1}$). A similar amount of mussel production emissions was also associated with exports, with 19.3 $GgCO_2eq.yr^{-1}$ (27 % of the fresh mussel supply chain emissions).

In the case of the frozen mussel food chain, emissions amount to 49.7 $GgCO_2eq.yr^{-1}$ and 71 % correspond to emissions associated with the production of fresh mussels used as raw material in the industry (35.1 $GgCO_2eq.yr^{-1}$). Emissions associated with the freezing process of fresh mussels are also notable, reaching 23 % (11.3 $GgCO_2eq.yr^{-1}$). Meanwhile, processing associated with import and transport accounts for 3 % (1.3 $GgCO_2eq.yr^{-1}$) and 2 % (1.2 $GgCO_2eq.yr^{-1}$) of emissions.

Of the total emissions associated with frozen mussels, 85 % (42.2 $GgCO_2eq.yr^{-1}$) correspond to exported products, while 15 % (7.5 $GgCO_2eq.yr^{-1}$) are associated with national consumption.

Mussels in brine account for emissions of 13.7 $GgCO_2eq.yr^{-1}$: 32 % of emissions are due to imports (4.3 $GgCO_2eq.yr^{-1}$), 31 % to the production of fresh mussels used as raw material by the industry (4.1 $GgCO_2eq.yr^{-1}$), and 25 % of emissions are due to the transformation process of fresh and frozen mussels into mussels in brine (3.4 $GgCO_2eq.yr^{-1}$). Industrial transformation processes, regardless of whether they are carried out in the Spanish industry or abroad, account for 57 % of total emissions (7.7 $GgCO_2eq.yr^{-1}$), being the factor with the greatest weight in this chain. It is worth noting that the import flow associated with processed products is mainly due to ready-to-eat mussels in brine (4.4 $GgCO_2eq.yr^{-1}$), with only 0.1 $GgCO_2eq.yr^{-1}$ associated with the import of mussels produced and frozen abroad used as raw material in the production of mussels in brine. Transport accounts for 12 % of emissions. Of these, 0.7 $GgCO_2eq.yr^{-1}$ is due to the imported transport of raw materials and grouped processed products, while domestic transport, recirculation, and final distribution account for 1.2 $GgCO_2eq.yr^{-1}$.

Of the total emissions associated with mussels in brine, 55 % are due to consumption (10.9 $GgCO_2eq.yr^{-1}$), while 13 % are associated with exports. It's also worth noting that part of this product is used for other purposes (1.0 $GgCO_2eq.yr^{-1}$), primarily as animal feed in Spain.

The entire pickled mussel food chain accounts for the emission of 155.4 $GgCO_2eq.yr^{-1}$ of which 34 % are due to imported processed products (53.4 $GgCO_2eq.yr^{-1}$), 32 % to domestic industries (49.1 $GgCO_2eq.yr^{-1}$), and 24 % to the production of fresh mussels used as raw material (37.5 $GgCO_2eq.yr^{-1}$). Domestic industries generate emissions associated with both the production of canned mussels (48.2 $GgCO_2eq.yr^{-1}$) and the production of frozen mussels used as raw material for pickled mussels (0.9 $GgCO_2eq.yr^{-1}$). Foreign industries generate 0.2 $GgCO_2eq.yr^{-1}$ due to mussel production. Among all emissions, 10 % are due to transport (international transport to final distribution, 15.0 $GgCO_2eq.yr^{-1}$). The largest contribution in transport comes from domestic and recirculation transport (6.4 $GgCO_2eq.yr^{-1}$, 43 % of transport emissions), followed by import transport (5.9 $GgCO_2eq.yr^{-1}$, 40 %), and transport to distribution points and homes (2.5 $GgCO_2eq.yr^{-1}$, 16 %).

Emissions of pickled mussels consumption represent 79 % (123.2 $GgCO_2eq.yr^{-1}$), while 12 % (19.4 $GgCO_2eq.yr^{-1}$) are due to exports. We also observe the use of this product for other purposes, with 12.8 $GgCO_2eq.yr^{-1}$ (8.2 %).

The detailed data used to derive these aggregated results, including emission totals by subsystem and province, are available in Tables SM4–SM6 of the OSM. Minor discrepancies between subtotals and aggregated values (<0.5 %) are due to rounding differences in intermediate steps and do not affect the overall results or proportions among production, processing, and transport stages.

3.3. Emissions from mussel consumption in Spain

This section focuses on the share of emissions attributable to mussels consumed within Spain, regardless of whether they are produced domestically or imported. It isolates the emissions linked to domestic consumption rather than the global supply chain.

Total emissions from mussel meat consumption in Spain amount to 190.1 $GgCO_2eq.yr^{-1}$. Of these, 46 % are due to processing and transformation, 36 % to mussel production, and 17 % to transportation (Fig. 4). Expressed in relative terms, this means that for every kg of meat consumed, 6.3 $kgCO_2eq$ are emitted.

The value associated with processing amounts to 88.4 $GgCO_2eq.yr^{-1}$ (46 % of total emissions), which represents 2.9 $kgCO_2eq$.kg-1 edible mussel meat. Of these, the largest factor is associated with the processing phase of imported mussels with some degree of processing: 16 % of emissions from frozen mussels (1.2 $GgCO_2eq.yr^{-1}$), 37 % for pickled mussels (44.5 $GgCO_2eq.yr^{-1}$), and 36 % for brine mussels (3.8 $GgCO_2eq.yr^{-1}$). All processing products of international origin involve an amount of 1.6 $kgCO_2eq.kg^{-1}$ edible mussel meat, that is, 26 % of total emissions from the consumption of this product. The remaining 20 % of the processing emissions is associated with processing in Spanish industries, which accounts for 38.8 $GgCO_2eq.yr^{-1}$. This value is the result of industrial processing for the production of canned mussels (37.1 $GgCO_2eq.yr^{-1}$) of which 34.9 $GgCO_2eq.yr^{-1}$ are associated with pickled mussels and 2.2 $GgCO_2eq.yr^{-1}$ with the brine presentation, 29 % and 21 % of the emissions from their respective chains), and processing into frozen mussels (1.7 $GgCO_2eq.yr^{-1}$, 16 % of the emissions of the frozen mussel chain). All this implies that for every kg of mussel meat consumed in Spain, taking into account all its presentations, 1.3 $kgCO_2eq$.kg-1 are attributable to industrial processing in national territory, mainly due to canned presentations.

Secondly, production emissions stand out at 36 % and 69.3 $GgCO_2eq.yr^{-1}$, which means that for every kg of mussel meat consumed, regardless of the presentation, 2.3 $kgCO_2eq$.kg-1 are emitted. Of these emissions, only 32.1 $GgCO_2eq.yr^{-1}$ are associated with the consumption of fresh mussels, being mainly composed of emissions from national production (60 % of emissions, 30.3 $GgCO_2eq.yr^{-1}$), and a small contribution from imports (4 % of emissions, 1.8 $GgCO_2eq.yr^{-1}$). Thus, the largest contribution of these emissions is associated with the use of fresh mussels as raw material in the rest of the presentations, 37.2 $GgCO_2eq.yr^{-1}$, distributed between frozen mussels (4.5 $GgCO_2eq.yr^{-1}$ of national production and 0.1 $GgCO_2eq.yr^{-1}$ of imports), pickled mussels (29.1 $GgCO_2eq.yr^{-1}$ and 0.3 $GgCO_2eq.yr^{-1}$ of national production and imports respectively) and mussels in brine (3.1 $GgCO_2eq.yr^{-1}$ and 0.1 $GgCO_2eq.yr^{-1}$ of national production and imports respectively).

Transport accounts for 17 % of total emissions from consumption in this food chain (32.4 $GgCO_2eq.yr^{-1}$), which is equivalent to 1.1 $kgCO_2eq.kg^{-1}$ edible mussel meat. Within transport, recirculation accounts for 8 % of emissions (14.8 $GgCO_2eq.yr^{-1}$), the largest contribution within the transport category. This value is mainly due to the transport of fresh mussels for consumption (9.9 $GgCO_2eq.yr^{-1}$, which represents 19 % of the emissions for this presentation) and pickled mussels (3.9 $GgCO_2eq.yr^{-1}$). The second largest is the final distribution, which reaches 9.7 $GgCO_2eq.yr^{-1}$, which represents 29 % of the emissions associated with total transport and 5 % of total emissions. The key factors here are the distribution of fresh mussels (6.7 $GgCO_2eq.yr^{-1}$) and pickled mussels (2.5 $GgCO_2eq.yr^{-1}$). Finally, import transport accounts for 8 $GgCO_2eq.yr^{-1}$, mainly associated with canned mussels (4.6 $GgCO_2eq.yr^{-1}$ for pickled mussels and 0.5 $GgCO_2eq.yr^{-1}$ for mussels in brine) and the import of fresh mussels (2.6 $GgCO_2eq.yr^{-1}$).

Mussel consumption, as part of seafood products, has been identified as a dietary alternative to animal protein (Costello et al., 2020; Guillen et al., 2019; Golden et al., 2021; Parodi et al., 2018). This is due to its emission coefficient per tonne of product being below 1 $kgCO_2eq.kg^{-1}$ edible mussel meat in most studies (see supplementary material tables). When expressed per kg of meat, our results indicate that fresh mussels

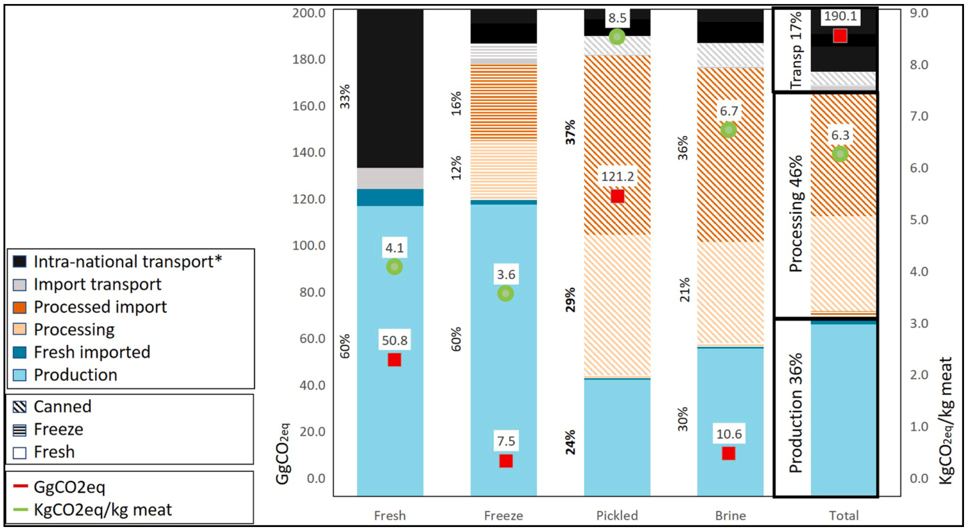

Fig. 4. Emissions associated with the consumption of mussels in their various forms. Relative contribution of each stage for each product (bars at 100 %), along with the net emissions of each consumption chain in Spain (left axis, red line) and the emissions relative to the functional unit (1 kg of mussel meat) for each product (right axis, green line). *: Intranational transport includes national transport, recirculation, final distribution, and distribution to households. The processing stage incorporates both the contribution of processing frozen mussels for consumption by the population and for use as raw material for the manufacture of canned products.

consumption yields a value of 4.1 kgCO_2eq.kg^{-1} edible mussel meat.

Emissions associated with the consumption of frozen mussels in Spain amount to 7.5 GgCO_2eq.yr^{-1}, of which 60 % are derived from the production of fresh mussels (4.5 GgCO_2eq.yr^{-1}). The fact that this product is processed requires a contribution to the emissions associated with manufacturing, both in Spain (0.9 GgCO_2eq.yr^{-1}, 12 % of emissions for this type of product) and abroad (16 % of emissions, 1.2 GgCO_2eq.yr^{-1}). Furthermore, the overall transport required for consumption in Spain accounts for 11 % of the emissions in this chain (0.8 GgCO_2eq.yr^{-1} and 0.4 kgCO_2eq.kg^{-1} edible frozen mussel meat). All this means that consuming one kg of frozen mussel meat requires 3.6 kg CO_2eq.

Regarding canned products, it should be noted that mussels in brine and pickled mussels emit 32.3 GgCO_2eq.yr^{-1} as a result of the production of the fresh mussels required for their manufacture, i.e., used as raw material. This represents 2 kgCO_2eq.kg^{-1} edible mussel meat used as an input for the canning industry. However, within canned mussels, the largest share is associated with industrial processing, where the industrial production of mussels in brine in Spain accounts for 2.5 kgCO_2eq.kg^{-1} edible mussel meat for pickled and 1.4 kgCO_2eq.kg^{-1} edible mussel meat in brine. Furthermore, the significant import component associated with canned products means that the value of imported processing is the most significant for these products, with 3.1 kgCO_2eq.kg^{-1} edible mussel meat for pickled and 2.4 kgCO_2eq.kg^{-1} edible mussel meat in brine. Considering all the contributions associated with canned products, it is observed that for each kg of pickled mussel meat consumed, 8.5 kgCO_2eq are emitted, and in the case of brine, the value is 6.7 kg CO_2eq.

4. Discussion

4.1. Productive concentration, global trade integration and the decoupling of domestic production/manufacturing and consumption

In 2017, Spanish domestic production accounted for most of its G_A (270 kt out of 276 kt) with minimal imports (6 kt). From this supply, 25 kt of mussels without shells were processed into domestic canned mussels and 15.4 kt into domestic frozen mussels. In addition, Spain imported 12 kt of canned mussels and 0.9 kt of frozen mussels. These organization identifies three outcomes of the mussel food chain in Spain: 1) a large share of fresh production is directed to processing, with 166 kt (60 % of fresh mussel production) used to produce 76 kt of frozen and 90 kt of canned products; 2) exports play an important role, with 42 kt (15 %) of fresh availability, 12 kt of frozen (72 % of total frozen mussel production), and 4 kt of canned mussels commercialized through these channels; and 3) domestic demand, especially for canned mussels, depends on imports, as national industry production covers 25 kt while imports add 12 kt. Notably, only 25 % (68 kt) of fresh mussels available are directed toward domestic consumption in Spain. Current configuration of this food chain reveals that the main source of mussel protein is the pickled presentation (65 %, 4.6 kt), followed by fresh (23 %, 1.6 kt), brined (7 %, 0.5 kt), and frozen (5 %, 0.4 kt), resulting in a total of 7.1 kt of protein (OSM, section A2.5).

Territorially, the mussel sector in Spain (production, processing, and international trade hubs) is concentrated in the northwest of Spain, with Galicia leading in production (99 %), processing (98 %), and international trade (62 % of imports and 82 % of exports). This fact invites reflection on its climate change vulnerability (Fuentes-Santos et al., 2021; Padin et al. 2024; Soliño and Figueras, 2025), as well as its historical dynamics of innovation (Labarta and Fernández- Reiriz, 2019). This positions the region as a key player in the global mussel trade network, exporting products in all three forms (particularly fresh and frozen mussels). Nevertheless, it is significant the import flow of canned mussels, with Galician provinces as primary entry points, alongside others such as Madrid, Málaga, Valencia, and Barcelona, which serve as gateways for products from third countries, mainly Chile (11.9 kt). Accordingly, notable import flows also reach provinces that neither produce nor process mussels industrially, but instead supply their populations with processed products from abroad, rather than from Galicia's domestic production. New Zealand is identified as the main exporter of frozen mussels to Spain (0.7 kt), with shipments primarily entering through Valencia, A Coruña, and Barcelona. It should be noted that this imported mussel corresponds to different species than the one produced in Spain.

The high level of mussel production and import concentration in Galicia has two important implications. First of all, extensive interprovincial recirculation is required to meet the domestic mussel consumption. Eighty four percent of fresh mussels, 89 % of canned mussels, and 73 % of frozen mussels are recirculated and consumed in non-producing provinces, arriving mainly from Galician provinces and/or imported to the main gateway provinces and then recirculated. Secondly, only a small portion (3.2 kt, or 4 %) of the fresh and frozen mussels used in canning were recirculated from outside Galicia, as production and processing facilities are highly concentrated in the region. Therefore, we identified that the exporting role of Galicia as part of its integration into global value chains weakens the domestic supplying capacity of fresh and processed products, with consumption increasingly met through imports. These patterns of decoupled production and consumption is also recognized in other Spanish food chains as is the tomato or hake (Aragão et al., 2022; Saralegui-Díez et al., 2023), as well as in its whole food system (Guzmán Casado and González de Molina, 2015).

This international dependence is further deepened as a significant portion of domestic production is used as raw material for the frozen and canned mussel processing industry, with much of this output ultimately destined for export. Although national production could cover domestic demand for all three processed product forms (frozen, in brine, and pickled), there is still a notable market dependence on imports, particularly of canned mussels and, to a lesser extent, of frozen mussels. This reveals a strategic focus on expanding international trade as it is happening globally, rather than prioritizing environmental sustainability or meeting domestic demand (Gephart and Pace, 2015). Such an export-oriented approach, primarily aimed at maximizing economic returns, inevitably reduces the resilience of the mussel supply chain by making it highly dependent on international flows. This increases its vulnerability to external shocks, such as shifts in food policies of third countries, which may redirect exports in response to higher prices or rising demand elsewhere (Gephart et al. 2017; Grassia et al. 2022). In fact, richer countries are more likely to suffer from shocks coming from different sources, and they tend to import more calories, increasing its vulnerability (Grassia et al., 2022). At the same time, it reflects a missed opportunity to strengthen local consumption and enhance the value of the Spanish mussel industry.

4.2. The relation between emissions and the mussel supply chain

Mussel farming is generally regarded as a low-impact activity with minimal resource use compared to traditional livestock farming (Thinkstep-anz, 2021), it is noteworthy that our results estimate emissions comparable to those from industrial processing. The main reason is that our analysis includes three steps within the production phase—farming, purification, and packaging—following previous studies (Iribarren et al., 2010b,d,e; Lourguioui et al., 2017; Meyhoff-Fry, 2012). However, the latter two steps (purification, and packaging) account for most of the emissions attributed to production. In this sense, environmental impacts should be allocated by separating farming at sea from purification and packaging, but this was not possible due to the lack of disaggregated factors within the current bibliography.

Regarding the chain's emissions, three main aspects stand out: 1) emissions from mussel production in Spain are largely driven by industrial processing, which embodies 76.8 $GgCO_2eq.yr^{-1}$ out of the 126.4 $GgCO_2eq.yr^{-1}$ emitted by national mussel aquaculture; 2) industrial activities, both domestic and international, are the largest contributors, with 63.7 $GgCO_2eq.yr^{-1}$ from Spanish processing and 59.3 $GgCO_2eq.yr^{-1}$ from foreign industries; and 3) global trade flows account for a substantial share of the impact, as exports are responsible for 83.8 $GgCO_2eq.yr^{-1}$ (29 %), while imports embodied 59.8 $GgCO_2eq.yr^{-1}$ (21 %) of total emissions. Therefore, our results suggest that mussel emissions in Spain are mainly linked to processing demand and export flows rather than final domestic consumption.

4.3. Edible mussel meat sources and its relation with emissions

In terms of consumption, canned mussels are the primary source of mussel-derived meat in Spain, supplying 0.34 kg per person per year. Its import-dependent dynamic (see above) configures a high level of internationalization: 45 % of its consumption depends on third countries, primarily Chile. This indicates that Spain's main source of mussel protein is characterized by a high degree of internationalization and industrial processing, with implications for both the fragility of global food supply chains and the associated environmental impact (8.5 $kgCO_2eq.kg^{-1}$ edible mussel meat for pickled mussels and 6.7 $kgCO_2eq.kg^{-1}$ edible mussel meat for mussels in brine). This result contrasts with the fact that Spain is one of the principal producers in terms of mussel farming, and yet is highly dependent on foreign imports.

Fresh mussels, as the second highest source in the mussel chain, account for 41 % of total mussel meat consumption in Spain, and represent a significant protein source, with a comparatively lower carbon footprint (4.1 $kgCO_2eq.kg^{-1}$ edible mussel meat). However, the chain presents challenges related to their geographic concentration and the emissions linked to transportation. As fresh mussels are distributed nationwide, this results in substantial interprovincial recirculation, contributing with 9.9 $GgCO_2eq.yr^{-1}$, equivalent to 19.5 % of total consumption-related emissions in Spain. Notably, the transport of live fresh mussels adds the extra weight of the shells, reducing transport efficiency, although there may be opportunities to optimize logistics and improve aquaculture practices to mitigate the associated footprint.

Finally, frozen mussels are the least domestically consumed product form, and consequently they generate the lowest emissions per unit of edible meat (3.6 $kgCO_2eq.kg^{-1}$ edible mussel meat). This is due to the absence of shells during transport and less intensive industrial processing compared to canned products. The low level of domestic consumption may be attributed to the significant export volumes of frozen mussels, as previously noted.

Therefore, it is relevant to highlight that the products with the highest emissions per kg—canned mussels—are also the most widely consumed, while those with the lowest emissions—frozen mussels—are primarily directed toward export markets.

These patterns suggest that the product form and processing intensity are decisive determinants of supply-chain emissions, beyond differences in farming technology or regional energy mixes. The prominence of processing in the aggregate footprint reflects the energy demand of cooking, sterilization, canning and associated packaging workflows. These steps concentrate electricity and heat use, as well as materials with non-negligible embodied emissions (e.g., metals and plastics). By contrast, aquaculture operations, while continuous and involving depuration, pumping and cleaning, contribute a smaller share per kilogram of edible meat. Transport contributes a modest fraction overall, but its relative importance rises in export and interprovincial flows, where refrigerated logistics, partial loads and circuitous routing increase tonne-kilometres. These stage-specific mechanisms help to explain why mitigation leverage points are located downstream of farming: in energy performance of processing plants, packaging choices and logistics organization.

4.4. Mussel meat as a potential alternative to animal-based diets, but with room for maneuver

From a broader perspective, this research highlights both the challenges and opportunities involved in advancing toward more sustainable food production and consumption systems. This transition requires not only technological and systemic changes but also dietary shifts. It is emphasized in previous studies (Chai et al., 2019; González-García et al., 2018; Ivanova et al., 2020), which call for nutritionally adequate and culturally appropriate consumption patterns adapted to each region (Castañé and Antón, 2017). These shifts imply a necessary substitution of animal-based protein (particularly from livestock) with more sustainable alternatives (Baroni et al., 2014). To fully assess the potential of such dietary substitutions, it is essential to rely on robust, context-specific data on the GHG emissions associated with food products in Spain.

Within the current structure of the Spanish food system, mussel meat generates an average of 6.3 $kgCO_2eq.kg^{-1}$, a value significantly lower than that of most livestock products, such as beef (32.5 $kgCO_2eq.kg^{-1}$) and small ruminants (28 $kgCO_2eq.kg^{-1}$). It is comparable to pork (6.6 $kgCO_2eq.kg^{-1}$), but higher than chicken and hake (4.4 $kgCO_2eq.kg^{-1}$), milk (1.4–2.9 $kgCO_2eq.kg^{-1}$ depending on the type), and eggs (2.1

$kgCO_2eq.kg^{-1}$) (Aguilera et al., 2020; Aragão et al., 2022; Saralegui-Díez et al., 2023). Since bivalves are proposed as a key element to fulfil population demands for healthy products (Tan et al., 2019), the relation between commercial patterns, product presentations and emissions are important aspects to consider. When disaggregated by product form, fresh mussels (4.1 $kgCO_2eq.kg^{-1}$ edible mussel meat) and frozen mussels (3.6 $kgCO_2eq.kg^{-1}$ edible mussel meat) exhibit the lowest emissions among the products analyzed, whereas canned mussels—particularly pickled (8.5 $kgCO_2eq.kg^{-1}$ edible mussel meat) and in brine (6.7 $kgCO_2eq.kg^{-1}$ edible mussel meat)—surpass the emissions of pork, mainly due to processing and packaging. In general terms, bivalve culture is the second-lowest emitter among farmed aquaculture products, second only to seaweed cultivation (Gephart et al., 2021), but when it is processed, packaging and canning are emission hotspots that should be taken into consideration (Iribarren et al., 2010d; 2010e).

Although mussels are a rich source of protein and are considered a relatively sustainable food compared to other forms of animal protein, the results of this study reveal several areas of improvement. The high geographic concentration of mussel production, its predominant orientation toward industrial processing, and its dependence on imports for certain product forms raise critical concerns regarding food security, sustainability, and supply chain resilience.

4.5. Limitations

Firstly, for the calculation of provincial food consumption, the regional available data from the Food Consumption Panel statistics (MAPAMA, 2017a, 2017b) was taken into consideration and downsized provincially based on population data. This relative distribution was applied to the apparent consumption. We acknowledge that within autonomous communities there may be differences in per capita consumption, especially for a product of maritime origin, where coastal provinces may have a higher consumption than the rest of them. This could affect the estimated value of both the Weighted Average Supply Distance (WASD), since it is a coefficient weighted by biomass distribution, and the subsequent calculation of domestic transport emissions.

On the other hand, the reconstruction of emission factors for imported products may entail a certain degree of error, given the lack of detailed, product-specific factors in the literature based on the countries of origin. In this regard, it should be noted that the mussel supply chain has a high degree of production in Spain, for which factors are based on case studies. However, there is a relevant flow of processed products (32 %) originating from abroad, and these are based on reconstructed factors combining previous data. It is important to note that the reconstructed factors include a highly significant component related to product processing and packaging. These activities depend less on mussel production practices and more on the specific industrial sector. In this sense, it is relevant to emphasize that processing techniques are very similar between countries, with industrial processes being practically equivalent, and the materials used in canned packaging (e.g., metals) are largely sourced from China—a fact that is accounted for in the available factors from Ecoinvent. Consequently, we assume that the margin of error introduced is not significant.

4.6. Recommendation and strategies to optimize mussel chain towards a sustainable food system

As Guillen et al. (2019) argue, countries should be accountable for what they consume, not merely for what they produce. In this context, it is essential to propose integrated measures that address the nexus between optimal aquaculture production locations, efficient distribution systems, industrial reconversion and relocation, and the reconfiguration of international trade flows.

One strategy involves promoting greater local consumption of fresh mussels, the product with the second-lowest carbon footprint. However, this will only lead to significant emission reductions if transportation impacts (which account for 36 % of emissions in this category) are minimized through improved and shortened logistics chains. This shift requires prioritizing domestic consumption over industrial use or exports, increasing local availability to supply consumption.

This approach aligns with findings from Mustapa et al. (2025), which suggest that Spanish consumers perceive fresh, organic mussels as healthier, more environmentally friendly, and of higher quality than conventional alternatives, and are therefore more willing to pay for them, as is reflected in the case of Europe (Tunca et al., 2024). A shift in consumption patterns, supported by stronger alliances between producers and consumers and greater domestic commercialization of fresh and frozen mussels, could help rebalance the current market structure. Awareness and educational initiatives aimed at promoting sustainable seafood choices would also encourage higher consumption of lower-emission products. Increased demand for fresh and frozen mussels instead of canned ones, would reduce packaging requirements and lower the use of finite materials such as metals and plastics commonly employed in canning. Informing consumers about the carbon footprint of seafood can therefore empower more sustainable purchasing decisions.

In parallel, a key complementary strategy is industrial reconversion aimed at increasing the production of lower-emission product forms (particularly frozen mussels), while reducing the production of canned products. Moreover, reorienting commercial strategies toward domestic demand and shorter supply chains may reduce dependence on both imports and exports, mitigating the environmental costs associated with global commodity flows. This adjustment would involve adapting industrial operations to favor domestic markets while maintaining the economic viability of the sector.

This transition must be supported by shifts in consumption patterns, given that mussels in brine and pickled mussels currently represent the main sources of mussel-derived protein in Spain. Redirecting consumption from canned to frozen products would significantly reduce the carbon footprint of the supply chain, as canned mussels exhibit the highest emissions per kg of edible meat. Reducing emissions throughout the supply chain will also depend on the adoption of more efficient and sustainable practices in processing and packaging. Encouraging innovation in sustainable packaging materials and energy-efficient technologies can contribute to lowering the sector's overall carbon footprint.

It should be noted the increase in industrial efficiency aimed at emission reduction, specifically in canned packaging impacts (Metal Packaging Europe, 2022). As the scenario analysis's results underlines (OSM), a 23 % reduction in the packaging emission factor results in a decrease of 16 % for domestic processing and 2 % for the processing of imported products. This is reflected in a total reduction of the supply chain's emissions by 4 % compared to the current situation. The abrupt decrease in emissions from domestic processing for consumption (−22 %), as well as for processed imports used in export products (−10 %), is also noteworthy. On the other hand, if emissions associated with aquaculture are reduced by 10 %, a 5 % decrease in total emissions is produced. This is reflected in a 4 % reduction for the consumption share compared to its current equivalent, while exports show a 7 % decrease.

However, the substantial share of frozen mussel production allocated to export poses a challenge, as it limits the domestic industry's capacity to process and distribute these lower-emission products locally. Therefore, coordinated efforts are needed to support the transformation of production and processing chains, promote domestic consumption of fresh and frozen mussels, and reduce dependency on exports.

These measures must be implemented without compromising the sector's economic viability. Emphasizing the high quality of Spanish aquaculture products could serve as a strategic lever to catalyze the transition toward lower-emission and more sustainable food systems. This is especially relevant in the context of climate change, given the increasing vulnerability of mussel aquaculture in Spain (Avdelas et al., 2021; Des et al., 2020; Padin et al., 2024; Soliño and Figueras, 2025).

Ultimately, this study highlights the importance of adopting a comprehensive, end-to-end approach to the food supply chain (from production to consumption) in order to effectively address environmental challenges and advance toward more sustainable and resilient food systems. It also aligns with recommendations to include aquaculture in climate adaptation strategies and action plans among European countries (Blanchet et al., 2019).

5. Conclusions

This study provides a detailed analysis of the mussel production and consumption chain in Spain. The total carbon footprint by product form, encompassing all life-cycle stages (production, processing and transport), is dominated by pickled mussels (54 % of total emissions), followed by fresh mussels (25 %). When emissions are disaggregated by supply chain stage, fresh mussel production accounts for 45 % of total emissions, processing for 43 %, and transport for 12 %. These results highlight the importance of addressing not only the production phase, but also the energy and material demands associated with processing, storage, distribution, and consumption when evaluating the overall carbon footprint of seafood products.

In a broader context, these findings provide an empirical foundation for discussing how climate-oriented policies and industry initiatives could foster seafood systems that are both environmentally responsible and economically resilient. Scenarios emphasizing lower processing intensity, optimized logistics, and revitalized local consumption patterns appear particularly promising for mitigating the carbon footprint of seafood, ensuring that mussel production and consumption in Spain move toward greater environmental sustainability.

CRediT authorship contribution statement

Pablo Saralegui-Díez: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sebastián Villasante:** Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Andrés Ospina-Álvarez:** Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Montserrat Ramón:** Visualization, Validation, Methodology, Investigation, Formal analysis. **Joan Moranta:** Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108742.

Data availability

Data will be made available on request.

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