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# Embedding Life Cycle Assessment Criteria and Sustainability Indicators of the Fisheries and Dairy Sectors in the Framework of the Circular Economy in Galicia (NW Spain)

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# EMBEDDING LIFE CYCLE ASSESSMENT CRITERIA AND SUSTAINABILITY INDICATORS OF THE FISHERIES AND DAIRY SECTORS IN THE FRAMEWORK OF THE CIRCULAR ECONOMY IN GALICIA (NW SPAIN)


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**PhD PROGRAMME IN CHEMICAL AND ENVIRONMENTAL ENGINEERING**

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# List of articles

This PhD thesis is based on the following scientific manuscripts published in international peer-reviewed journals. Further details on scientific publications, journal metrics and copyrights can be found in **Appendix I**.

1. **Entrena-Barbero, E.**, Ceballos, S., Cortés, A., Esteve-Llorens, X., Moreira, M.T., Villanueva-Rey, P., Quiñoy, D., Almeida, C., Marques, A., Quinteiro, P., Dias, A.C., Laso, J., Margallo, M., Aldaco, R., Feijoo, G. (2023). Methodological guidelines for the calculation of a Water-Energy-Food nexus index for seafood products. Science of the Total Environment, 877, 162845. https://doi.org/10.1016/j.scitotenv.2023.162845
2. **Entrena-Barbero, E.**, Rebolledo-Leiva, R., Vásquez-Ibarra, L., Fernández, M., Feijoo, G., González-García, S., Moreira, M.T. (2023). Water-Energy-Food nexus index proposal as a sustainability criterion on dairy farms. Science of the Total Environment, 874, 162507. https://doi.org/10.1016/j.scitotenv.2023.162507
3. **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. Science of the Total Environment, 847, 157558. https://doi.org/10.1016/j.scitotenv.2022.157558
4. **Entrena-Barbero, E.**, Feijoo, G., González-García, S., Moreira, M.T. (2023). Addressing environmental and economic impacts in the sustainable production profile of organic canned pickled mussels. Cleaner Environmental Systems, 11, 100152. https://doi.org/10.1016/j.cesys.2023.100152
5. **Entrena-Barbero, E.**, Zepon Tarpani, R. R., Fernández M., Moreira, M.T., Gallego-Schmid, A. Integrating circularity as an essential pillar of dairy farms sustainability. Journal of Cleaner Production, 458, 142508. https://doi.org/10.1016/j.jclepro.2024.142508

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*A mi abuela Carmen, que nos dejó muy pronto.*

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# Acronyms

| | | | |
|---|---|---|---|
| **AC** | Acidification | **EU** | European Union |
| **AGACA** | Galician association of agri-food cooperatives | **EVOO** | Extra Virgin Olive Oil |
| **ASC** | Aquaculture Stewardship Council | **F** | Fodder |
| **AWARE** | Available Water Remaining | **FAO** | Food and Agriculture Organization |
| **C** | Circularity | **FEP** | Freshwater eutrophication |
| **$C_{AE}$** | Avoided emissions carbon flow | **FET** | Freshwater ecotoxicity |
| **$C_{BC}$** | Blue carbon flow | **FEU** | Freshwater eutrophication |
| **CC** | Climate Change | **FPCM** | Fat- and Protein- Corrected Milk |
| **CDFi** | Composite Dairy Farm index | **FPM** | Fine Particulate Matter |
| **CE** | Circular Economy | **FRS** | Fossil resource scarcity |
| **CF** | Carbon Footprint | **FU** | Functional Unit |
| **$C_{FC}$** | Fish catching carbon flow | **FUce** | Caloric- and Edible-based Functional Unit |
| **CFF** | Circular Footprint Formula | **GDA** | Guideline Dietary Amount |
| **$C_{FF}$** | Fishing footprint carbon flow | **GDP** | Gross Domestic Product |
| **$C_{FP}$** | Food processed carbon flow | **GHG** | Greenhouse Gas |
| **$C_{FW}$** | Food waste carbon flow | **G1** | Group 1 |
| **$C_{HM}$** | Human metabolism carbon flow | **G2** | Group 2 |
| **CI** | Caloric Intake | **G3** | Group 3 |
| **CISU** | Integration of circularity and sustainable indicators | **G4** | Group 4 |
| **CISUDASE** | Integration of circularity and sustainable indicators for the dairy sector | **GW** | Global Warming |
| **CO** | Carbon monoxide | **HSR** | Health Star Rating |
| **$CO_2$** | Carbon dioxide | **HTC** | Human toxicity, cancer |
| **$C_{PE}$** | Process emissions carbon flow | **HTN** | Human toxicity, non-cancer |
| **$C_{WT}$** | Waste treatment carbon flow | **IC** | Impact Category |
| **DEA** | Data Envelopment Analysis | **IR** | Ionizing radiation |
| **EF** | Energy Footprint<br>Environmental Footprint | **ISO** | International Organization for Standardization |
| **EFSI** | Environmental Footprint Single Index | **LCA** | Life Cycle Assessment |
| **EP** | Edible Portion | **LCC** | Life Cycle Costing |
| **eq** | Equivalent | **LCI** | Life Cycle Inventory |
| **CI** | Caloric Intake | **LCIA** | Life Cycle Impact Assessment |
| **EC** | Freshwater ecotoxicity | **LCSA** | Life Cycle Sustainability Assessment |

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# Acronyms

| | | | |
|---|---|---|---|
| **LCT** | Life Cycle Thinking | **PEF** | Product Environmental Footprint |
| **LNG** | Liquified Natural Gas | **PEFCR** | Product Environmental Footprint Category Rules |
| **LU** | Land Use | **POF** | Photochemical ozone formation |
| **MCDA** | Multi Criteria Decision Analysis | **PM** | Particulate Matter |
| **MCDM** | Multi Criteria Decision Making | **RI** | Reference Intakes |
| **MEP** | Marine eutrophication | **RSI** | Reference Seafood Intake |
| **MET** | Marine ecotoxicity | **RUF** | Fossil resource use |
| **MEU** | Marine eutrophication | **RUM** | Minerals and metals use |
| **MRS** | Mineral resource scarcity | **RV** | Recommended Value |
| **MRV** | Maximum Recommended Value | **S** | Sustainability |
| **MTL** | Multiple Traffic Lights | **SB** | System Boundaries |
| **MVM** | Monetary Valuation Method | **S-LCA** | Social Life Cycle Assessment |
| **MY** | Milk Yield | **SOD** | Stratospheric ozone depletion |
| **NAOS** | Nutrition, Physical Activity and Obesity Prevention | **SOx** | Sulfur oxides |
| **NE** | North-East | **SS** | Subsystem |
| **NF** | Nutritional Footprint | **TA** | Terrestrial acidification |
| **NL** | Nutrients to be limited | **tC** | Tons of carbon |
| **NMVOC** | Non-methane volatile organic compounds | **TET** | Terrestrial ecotoxicity |
| **nOCPM** | Non-organic Canned Pickled Mussels | **TEU** | Terrestrial eutrophication |
| **NOx** | Nitrogen oxides | **TSP** | Trisodium phosphate |
| **NP** | Nutrients to be promoted | **UNEP** | United Nations Environment Program |
| **NRF** | Nutrient Rich Food | **WC** | Water consumption |
| **NW** | Northwest | **WEF** | Water-Energy-Food |
| **OCPM** | Organic Canned Pickled Mussels | **WEFni** | Water-Energy-Food nexus index |
| **ODP** | Ozone depletion | **WF** | Water Footprint |
| **OFE** | Ozone formation | **WHO** | World Health Organization |
| **OFH** | Ozone formation, human health | **WS** | Warning Signs |
| **PC** | Protein Content | **WU** | Water use |
| **PCB** | Polychlorinated biphenyls | | |

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# Abstract

The food industry involves a diverse network of activities in the primary sector: agriculture, fishing or livestock farming, which constitute one of the main economic pillars of the EU. Spain stands out as the main producer of fruit, vegetables and olive oil, while Galicia, a coastal region in the Northwest of Spain, is one of the most important regions in the agri-food sector. In the marine sector, Galicia is a benchmark for quality and excellence, with the largest fishing fleet in Spain, as well as the aquaculture and canning industries, which are of particular importance. In the livestock sector, Spain is the seventh largest producer of milk in Europe, with Galicia being the main producing region.

Despite the importance of technification and intensification in ensuring food production and meeting society's demands, it should not be ignored the fact that food production systems have a significant impact on the environment. In this sense, greenhouse gas emissions from livestock farming and the overexploitation of fishing grounds are two of the main pressures on the dairy and fisheries and shellfish sectors, respectively. Actions to reduce the environmental impact of the food not only on producers, but also on consumers and how human choices in their diets may have an influence on its sustainable profile impacts. In this regard, the Life Cycle Assessment (LCA) turns out to be a helpful tool for the assessment of food products, identifying the main hotspots throughout the supply chain and allowing proposed improvements strategies. Likewise, it can also influence the decision-making process in the development of initiatives or policies.

In addition to analyzing the impact of the food industry, it is also important to promote the communication of the results obtained, for which labels play a fundamental role by creating direct communication channels between producers and consumers that help to inform and raise awareness. These include eco-labels, which provide recognizable, reputable symbols that guarantee a basic level of environmental friendliness, and nutritional labels, which provide information from a nutritional point of view. Notwithstanding, some aspects need to be improved with respect to the LCA methodology and eco-label criteria when analyzing and communicating food production systems impacts.

In this context, the main objective of this thesis is to contribute to a more sustainable model of food production and consumption by addressing a number of gaps identified in the LCA methodology related to the analysis stage of the impacts of food systems and their subsequent communication to stakeholders. To this end, three main actions been proposed and applied to a series of case studies constituted by the seafood and dairy sectors in the context of the Spanish region of Galicia: (i) To create new analytical perspectives that broaden the focus of the environmental studies in the food industry carried out so far, (ii) to develop methodological frameworks with the aim of

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proposing policies based on holistic approaches, and (iii) to propose composite indicators and eco-labels for improving the communication channels between stakeholders in the food industry. These actions have been proposed to be applied at different scales in a sample of case studies of the fishing and dairy industries mainly in the context of Galicia, as the main productive area of products associated with these sectors in Spain. The results obtained were analyzed to identify the strengths and weaknesses of the new methodologies proposed for analyzing and communicating the impact of food products, with the aim of finding out whether they can be extended to other regional contexts or economic sectors.

The specific methodological limitations which have been identified regarding the application of the LCA into the food industry have established the roadmap to be followed, since these have been addressed throughout the chapters of the thesis.

**Chapter 1** reviews the main socio-economic aspects linked to the food industry, highlighting the added value in monetary terms, as well as the jobs linked to this economic activity in the European Union (EU). In addition, it highlights the productive particularities of food production in the main Spanish regions, with special emphasis on the important role played at European level by the fisheries and dairy sectors in the region of Galicia. On the other hand, the main environmental impacts linked to food production are identified, highlighting the important source of greenhouse gas (GHG) emissions that livestock farming is, constituting an accelerator for climate change (CC) or the influence that overfishing has on key aspects such as ensuring biodiversity in the oceans. However, food consumption, and therefore food demand, also play a fundamental role in the impacts related to food systems, so changing consumers' eating patterns is crucial to align the food industry with sustainable development. In this situation, defining and promoting new patterns of food production and consumption is fundamental to reversing the current climate crisis and ushering in an era of sustainable development. This is when the so-called “sustainable” diets or eating habits come into play, which would be those that guarantee nutritional needs, the well-being and health of people, biodiversity and the integrity of natural systems, or that are committed to the culinary heritage of a given region and seasonal foods, among other aspects. Therefore, in order to link eating habits with sustainability, different food guides have been developed, some of them framed by the country, region or type of diet in which they apply. The role of food pyramids and how they have evolved in recent decades, integrating other aspects such as the regular practice of sport, has also been highlighted, thus becoming a practical guide to a healthy and sustainable lifestyle.

Different tools are now available to analyze and quantify the environmental impacts related to food production and consumption, among which the LCA is one of the most important. **Chapter 2** reviews this methodology, which can quantify the potential impacts associated with the production process of a certain system and stands out for considering Life Cycle Thinking (LCT). This means that it addresses a holistic perspective by integrating all the stages that make up the production chain, i.e., from the

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extraction of raw materials to the management of the end-of-life stage. LCA is also standardized at the international level. In the context of the food industry, LCA is of great interest, since it has been widely used at a practical level to analyze the impacts related to different food production systems and diets and has also been used as a tool in the decision-making process, influencing the development of initiatives and policies. However, given the complexity and diversity of food production systems, the LCA methodology also has a number of shortcomings, such as the lack of indicators that address positive impacts in terms of nutrient provision or ecosystem services, the definition of food function in mass or economic terms that ignore nutritional aspects, its lack of relationship with the concept of circular economy (CE), or its inability to address a holistic perspective of sustainability by integrating the social and economic dimensions. Similarly, food labels are highlighted as a means of communication and influence consumer eating habits. To this end, an overview of the main health and nutrition labels as well as LCT-based ecolabels is provided, reiterating the importance of creating simple means of communication between producers and consumers that address a more integrated perspective, bringing together different important aspects of food systems, such as sustainability and nutrition.

Based on the shortcomings of the LCA methodology when analyzing food systems previously identified, the objectives and roadmap of the thesis were established in **Chapter 3**. To this end, up to three different lines of action were proposed: (i) the creation of new analytical perspectives that broaden the focus of environmental studies carried out so far in the food industry, (ii) the development of methodological frameworks to propose policies based on holistic approaches, and (iii) the proposal of composite indicators and ecolabels to improve communication channels between actors in the food industry. All these actions aim to contribute to a more sustainable model of food production and consumption. Consequently, these actions have been conducted throughout the following chapters of the thesis, using different case studies of the fishing and dairy industry in the context of the Spanish region of Galicia.

In **Chapter 4**, methodological guidelines were proposed to reach a consensus on how to assess seafood products using a life cycle approach. On the other hand, the Water-Energy-Food (WEF) nexus concept was identified as a suitable approach to address a broader perspective of the environmental impacts of seafood production, while considering its positive contributions in terms of nutrition. Therefore, based on the above, a WEF nexus index (WEFni) was proposed to evaluate in a simple way, by means of a percentage, a series of seafood products of the European Atlantic area. In addition, the WEFni was presented in the form of an easy-to-read eco-label, creating a useful communication channel between stakeholders. However, to overcome certain identified gaps of the proposed methodology, a new Functional Unit (FU) was considered, which shows the environmental and nutritional performance of each seafood product in terms of its caloric and edible content. This methodological approach may represent a step forward in the studies conducted so far, which only consider the environment as an isolated compartment, thanks to the way it allows the integration of certain nutritional

concepts, although in future iterations it would be necessary to be more ambitious, integrating also other social or economic aspects to have a holistic perspective of sustainability.

Building on the WEF nexus approach, this was applied to the dairy sector in **Chapter 5**, also with the aim of obtaining a single indicator: the WEFni. On this occasion, a hundred Galician dairy farms were assessed using WEFni, taking into account a number of assumptions. Dairy nutritional footprints were not a criterion for farm differentiation, choosing to evaluate farms based on their ability to ensure food security through milk production, understood as the average productive capacity of the cows that make up the farm. In addition, although no label was designed to represent this, a series of improvement strategies were proposed for the dairy farms with the lowest scores, as a way of conducting a sensitivity analysis and improving their environmental and productive performance. These were based on fodders reformulation, feed additives to reduce GHG emissions, and an animal welfare program to reduce mastitis incidence. Once again, WEFni proved to be an easy-to-interpret and useful indicator to identify which farms were both the worst environmental and productive performers, as well as to see the extent of improvement through the proposed strategies. However, it turned out to be important to reach a consensus on this concept when defining which indicators to integrate, which is the most appropriate method for their normalization or weighting, apart from how to avoid masking the influence of individual flows.

Following with the objective of proposing holistic frameworks, the focus of the Carbon Footprint (CF) was broadened in **Chapter 6** through the analysis of a series of carbon flows associated with a given fish species. In this carbon cycle, an ecosystem service was considered in the form of blue carbon, understood as the negative carbon flow that accumulates on the seabed when fish die naturally, and a remineralization process takes place. For this purpose, an LCA was carried out together with additional information such as the natural and fishing mortality ratio or the carbon content of the fish specimen. From the results it was identified that the emissions from its capture and subsequent processing are not compensated by the service it provides as a carbon sink, so a series of measures were proposed. These were based on the implementation of technological improvements in the fishing fleet, the extension of the closed season and the modification of protein sources in the diet. Through their hypothetical applications was concluded that a combination of corrective measures is necessary to configure a carbon-neutral diet that includes the consumption of fresh fish.

To consider the different economic activities that make up the seafood industry, an aquaculture product was also evaluated: mussels. Moreover, it was evaluated in a processed format, since canned seafood plays an important role in ensuring global food security, due to its interesting nutritional profile and the fact that it is a non-perishable product. On the other hand, this approach also allows to quantify the impact of further activities in the food industry, such as processing or packaging. Therefore, a specific product was selected: organic canned pickled mussels (OCPM) in **Chapter 7**, due to the

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leading position of Galicia in the mussel aquaculture sector, to be assessed through different methodologies addressing the three pillars of sustainability: (i) an environmental study through an LCA following the Product Environmental Footprint (PEF) method, (ii) the estimation of the economic burdens derived from environmental impacts through a series of monetary value methods, and (iii) a social study focused on the evolution of consumption and consumer spending on this type of product in the Spanish context, as well as the analysis of the different certifications that the product has to be considered as ecological. In turn, its standard version (i.e., non-OCPM) was also evaluated, together with some improvement scenarios based on the recyclability rate of its packaging and the use of a more renewable energy mix. The results showed that the reduction of environmental and monetary impacts was not promising for the OCPM and the improved scenarios. However, the sustainable profile of the product could be improved or promoted with some additional certifications of the social pillar through the practices implemented in the producing company.

Lastly, the concept of sustainability was expanded through the consideration of circularity. Both are complex to address, so it has been common practice to consider them separately, both in policies and in their evaluation and monitoring. However, the relationship between them to achieve a more sustainable production and consumption system is undeniable. For this reason, a framework called CISU (CIrcularity and SUstainability indicators) has been addressed in **Chapter 8**, which brings together both perspectives to obtain a single value for the evaluation of production systems. In addition, 50 Galician dairy cows were selected as case studies to demonstrate the applicability of the proposed framework. To this end, a series of S and C indicators were proposed and integrated to obtain an easily interpretable indicator that would provide a means of communication between actors that vary as a percentage. The overall results of the sample assessed did not show promising results, although they highlighted the potential of the methodology conducted to implement the practices of the highest scoring farms to improve the sustainable and circular performance of the livestock cooperative as a whole. However, to exploit its potential at a multi-organizational level, the methodology should be updated to include other interesting aspects such as industrial symbiosis.

Ending with an analysis of the tendency in recent decades, significant progress has been made in quantifying the environmental impact of food production and consumption through standardized indicators and methodologies, and their subsequent communication through eco-labels. However, given the level of contamination of food systems, the current climate emergency and the complexity of ensuring food security on a global scale, it is recognized that the methodologies used to date need to be reconsidered and modified. Therefore, considering the LCA methodology as starting point, a series of modifications and methodological extensions have been proposed, such as the integration of social and economic perspectives of sustainability, the concept of CE, together with some other positive indicators in terms of ecosystem services or nutritional provision. Thus, based on the findings of the thesis (**Chapter 9**), it has become clear that it is essential to opt for more ambitious methodological procedures, which go beyond simple

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negative environmental indicators, when trying to solve current sustainability problems related to food production and consumption systems. Despite this, with the purpose of implementing ways of analyzing and communicating sustainable consumption patterns, the standardization of the proposed methodological procedures is of particular importance, so that they can be taken into account in the decision-making process after their integration into policies. Notwithstanding, the identification of the strengths and weaknesses of the novel methodological procedures, together with their application in real case studies, leaves the door open for their reproduction in other contexts and case studies in the form of improved iterations.

In the form of a take-home message, in this thesis a series of methodological frameworks have been developed focusing on the LCA methodology and applied to the dairy and seafood industries in a Galician and Spanish context, based on several shortcomings that have been identified. These have led to a notable advance in LCT when integrated with other key concepts in the food industry, such as the WEF nexus or the CE, from a purely environmental vision to a broader one that includes multiple aspects such as society, economy, ecosystem services or nutrition. Likewise, this conceptual change turns out to be an important contribution to the scientific literature for LCA practitioners. In addition, the composite indicators have also been approached from a certification point of view, proposing a label design that integrates the benefits of nutrition labels with eco-labels, while opting for an attractive and easy-to-understand design. In this way, it is possible to solve the problem that although the methodological procedure becomes more complicated in the analysis phase due to the integration of several concepts, this does not represent a disadvantage in terms of being applied by producers and understood by consumers, maintaining an aura of commitment to sustainability by all stakeholders in the food industry. From the outcomes, it can be said that this thesis represents a step forward in aligning the food industry with sustainable development. It is now time to pave the way for the harmonization of sustainable holistic food systems analysis methods based on a life cycle approach. Therefore, the reproducibility of the methodological procedures proposed through future iterations and refinements is of paramount importance. From here, the objective to be achieved will be the materialization in actions promoted by more holistic policies that lead to strategies towards a more sustainable food production and consumption system.

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# Resumo

A industria alimentaria engloba unha variada rede de actividades do sector primario: agricultura, pesca ou gandería, que constitúen un dos principais piares económicos da UE. España destaca como principal produtor de froitas, hortalizas e aceite de oliva, mentres que Galicia, rexión costeira do noroeste de España, é unha das rexións máis importantes no sector agro-alimentario. No sector mariño, Galicia é un referente de calidade e excelencia, coa maior frota pesqueira de España, así como as industrias acuícola e conserveira, de especial importancia. No sector gandeiro, España é o sétimo produtor de leite de Europa, sendo Galicia a principal rexión produtora.

A pesar da importancia da tecnificación e a intensificación para garantir a produción de alimentos e satisfacer as demandas da sociedade, non debe ignorarse o feito de que os sistemas de produción de alimentos teñen un impacto significativo sobre o medio ambiente. Neste sentido, as emisións de gases de efecto invernadoiro procedentes da gandería e a sobre explotación dos caladoiros son dous das principais presións sobre os sectores lácteo e pesqueiro e marisqueiro, respectivamente. As accións para reducir o impacto ambiental dos alimentos non só afectan os produtores, senón tamén aos consumidores e a como as eleccións humanas nas súas dietas poden influír nos seus impactos de perfil sostible. Neste sentido, a Análise do Ciclo de Vida (ACV) resulta ser unha ferramenta útil para a avaliación dos produtos alimentarios, identificando os principais puntos conflitivos ao longo da cadea de subministración e permitindo propoñer estratexias de mellora. Do mesmo xeito, tamén pode influír no proceso de toma de decisións no desenvolvemento de iniciativas ou políticas.

Ademais de analizar o impacto da industria alimentaria, tamén é importante promover a comunicación dos resultados obtidos, para o que as etiquetas desempeñan un papel fundamental ao crear canles de comunicación directa entre produtores e consumidores que axudan a informar e sensibilizar. Entre elas atópanse as ecoetiquetas, que proporcionan símbolos recoñecibles e acreditados que garanten un nivel básico de respecto ao medio ambiente, e as etiquetas nutricionais, que achegan información desde o punto de vista nutricional. Con todo, é necesario mellorar algúns aspectos con respecto á metodoloxía da ECV e os criterios das etiquetas ecolóxicas á hora de analizar e comunicar os impactos dos sistemas de produción de alimentos.

Neste contexto, obxectivo principal desta tese é contribuír a un modelo máis sostible de produción e consumo de alimentos abordando unha serie de deficiencias identificadas na metodoloxía da ACV relacionadas coa etapa de análise dos impactos dos sistemas alimentarios e a súa posterior comunicación aos grupos de interese. Para iso, propuxéronse e aplicado tres acciones principais a unha serie de estudos de caso constituídos polos sectores de produtos do mar e lácteos no contexto da rexión española de Galicia: (i) crear novas perspectivas analíticas que amplíen o enfoque dos estudos ambientais da industria alimentaria realizados ata a data, (ii) desenvolver marcos metodolóxicos co fin de propoñer políticas baseadas en enfoques holísticos, e (iii)

propoñer indicadores compostos e ecoetiquetas para mellorar as canles de comunicación entre as partes interesadas da industria alimentaria. Estes aplicáronse a diferentes escalas nunha mostra de casos de estudo das industrias pesqueira e láctea principalmente no contexto de Galicia, como principal área produtiva de produtos asociados a estes sectores en España. Os resultados obtidos analizáronse para identificar as fortalezas e debilidades das novas metodoloxías propostas para analizar e comunicar o impacto dos produtos alimentarios, co obxectivo de pescudar se son extensibles a outros contextos rexionais ou sectores económicos.

As limitacións metodolóxicas específicas que se identificaron respecto a a aplicación do ACV na industria alimentaria han establecido a folla de ruta a seguir, xa que estas abordáronse ao longo dos capítulos da tese.

O **Capítulo 1** repasa os principais aspectos socioeconómicos vinculados á industria alimentaria, destacando o valor engadido en termos monetarios, así como os empregos vinculados a esta actividade económica na Unión Europea. Ademais, destaca as particularidades produtivas da produción alimentaria nas principais rexións españolas, con especial énfase no importante papel que desempeñan a nivel europeo os sectores pesqueiro e lácteo na rexión de Galicia. Doutra banda, identifícanse os principais impactos ambientais vinculados á produción de alimentos, destacando a importante fonte de emisións de gases de efecto invernadoiro (GEI) que supón a gandería, constituíndo un acelerador do cambio climático ou a influencia que ten a sobrepesca en aspectos clave como garantir a biodiversidade nos océanos. Con todo, o consumo de alimentos, e por tanto a demanda de alimentos, tamén desempeñan un papel fundamental nos impactos relacionados cos sistemas alimentarios, polo que cambiar os patróns alimentarios dos consumidores é crucial para aliñar a industria alimentaria co desenvolvemento sostible. Nesta situación, definir e promover novos patróns de produción e consumo de alimentos é fundamental para reverter a actual crise climática e iniciar unha era de desenvolvemento sostible. É entón cando entran en xogo as dietas ou hábitos alimentarios denominados "sostibles", que serían aqueles que garanten as necesidades nutricionais, o benestar e a saúde das persoas, a biodiversidade e a integridade dos sistemas naturais, ou que apostan pola patrimonio culinario dunha determinada rexión e alimentos de tempada, entre outros aspectos. Por iso, co fin de vincular os hábitos alimentarios coa sustentabilidade, desenvolvéronse diferentes guías alimentarias, algunhas delas enmarcadas polo país, rexión ou tipo de dieta na que se aplican. Tamén se destacou o papel das pirámides alimenticias e como evolucionaron nas últimas décadas integrando outros aspectos como a práctica habitual de deporte, converténdose así nunha guía práctica para un estilo de vida saudable e sostible.

Na actualidade disponse de diferentes ferramentas para analizar e cuantificar os impactos ambientais relacionados coa produción e o consumo de alimentos, entre as cales o ACV é uno dos máis importantes. O **Capítulo 2** revisa esta metodoloxía, que permite cuantificar os impactos potenciais asociados ao proceso de produción dun determinado sistema e destaca por considerar o concepto de ciclo de vida (Pensamento de Ciclo de

Vida, PCV). Isto significa que aborda unha perspectiva holística ao integrar todas as etapas que compoñen a cadea de produción, é dicir, desde a extracción das materias primas ata a xestión da etapa de fin de vida. O ACV tamén está normalizado a nivel internacional. No contexto da industria alimentaria, o ACV reviste un gran interese, xa que se utilizou amplamente a nivel práctico para analizar os impactos relacionados con diferentes sistemas de produción de alimentos e dietas e tamén se utilizou como ferramenta no proceso de toma de decisións, influíndo no desenvolvemento de iniciativas e políticas. Con todo, dada a complexidade e diversidade dos sistemas de produción de alimentos, a metodoloxía de ACV tamén presenta unha serie de deficiencias, como a falta de indicadores que aborden os impactos positivos en termos de provisión de nutrientes ou servizos ecosistémicos, a definición da función alimentaria en termos masivos ou económicos que ignoran os aspectos nutricionais, a súa falta de relación co concepto de economía circular (EC) ou a súa incapacidade para abordar unha perspectiva holística da sustentabilidade integrando as dimensións social e económica. Do mesmo xeito, destácanse as etiquetas alimentarias como medio de comunicación que inflúen nos hábitos alimentarios dos consumidores. Para iso, ofrécese unha visión xeral das principais etiquetas sanitarias e nutricionais, así como das ecoetiquetas baseadas no PCV, reiterando a importancia de crear medios sinxelos de comunicación entre produtores e consumidores que aborden unha perspectiva máis integrada, axuntando diferentes aspectos importantes dos sistemas alimentarios, como a sustentabilidade e a nutrición.

Partindo das carencias da metodoloxía de ACV á hora de analizar sistemas alimentarios previamente identificadas, no **Capítulo 3**. Para iso, propuxéronse ata tres liñas de actuación diferentes: (i) a creación de novas perspectivas analíticas que amplíen o enfoque dos estudos ambientais realizados ata o de agora na industria alimentaria, (ii) o desenvolvemento de marcos metodolóxicos para propoñer políticas baseadas en enfoques holísticos, e (iii) a proposta de indicadores compostos e ecoetiquetas para mellorar as canles de comunicación entre os actores da industria alimentaria. Todas estas accións pretenden contribuír a un modelo máis sostible de produción e consumo de alimentos. En consecuencia, estas accións leváronse a cabo ao longo dos seguintes capítulos da tese, utilizando diferentes estudos de caso da industria pesqueira e láctea no contexto da rexión española de Galicia.

No **Capítulo 4**, propuxéronse directrices metodolóxicas para chegar a un consenso sobre como avaliar os produtos pesqueiros utilizando un enfoque de ciclo de vida. Doutra banda, o concepto de nexo Auga-Enerxía-Alimentos (AEA) foi identificado como un bo candidato para abordar unha perspectiva máis ampla dos impactos ambientais da produción de produtos do mar, considerando ao mesmo tempo as súas contribucións positivas en termos de nutrición. Por iso, con base no anterior, propúxose un índice de nexo AEA (nAEA) co fin de avaliar de forma sinxela, mediante unha porcentaxe, unha serie de produtos pesqueiros da área atlántica europea. Ademais, o nAEA presentouse en forma dunha etiqueta ecolóxica fácil de ler, creando unha canle de comunicación útil entre as partes interesadas. Con todo, para superar algunhas das brechas identificadas na metodoloxía proposta, considerouse unha nova unidade funcional, que mostra o

desempeño ambiental e nutricional de cada produto do mar en termos do seu contido calórico e comestible. Este enfoque metodolóxico pode supoñer un paso adiante respecto a os estudos realizados ata agora, que só consideran o medio ambiente como un compartimento illado, grazas a que permite integrar determinados conceptos nutricionais, aínda que en futuras iteracións habería que ser máis ambicioso, integrando tamén outros aspectos sociais ou económicos para ter unha perspectiva holística da sustentabilidade.

Sobre a base do enfoque de nexo do AEA, isto aplicouse ao sector lácteo no **Capítulo 5**, tamén co obxectivo de obter un indicador único: o nAEA. Nesta ocasión estudáronse un centenar de explotacións leiteiras galegas, tendo en conta unha serie de modificacións. Un deles foi o descoñecemento do perfil nutricional de leite producido polas leiteiras, optando por avalialas segundo a súa capacidade para garantir a seguridade alimentaria a través da produción de leite, entendida como a capacidade produtiva media das vacas que compoñen a explotación. Ademais, aínda que non se deseñou ningún selo que representase isto, propuxéronse unha serie de estratexias de mellora para as granxas con notas máis baixas, como unha forma de realizar unha análise de sensibilidade e mellorar a súa desempeño ambiental e produtivo. Estes baseáronse na reformulación de forraxes, aditivos alimentarios para reducir as emisións de GEI e a implementación dun programa de benestar animal para reducir a perda de leite debido á mastitis. Unha vez máis, o nAEA demostrou ser un indicador útil e fácil de interpretar para identificar que granxas tiñan os peores resultados ambientais e produtivos, e para ver o alcance da mellora a través das estratexias propostas. Con todo, resultou importante alcanzar un consenso sobre este concepto á hora de definir que indicadores integrar, cal é o método máis adecuado para a súa normalización ou ponderación, así como como evitar enmascarar a influencia dos fluxos individuais.

Seguindo co obxectivo de propoñer marcos holísticos, no **Capítulo 6** ampliouse o enfoque da pegada de carbono mediante a análise dunha serie de fluxos de carbono asociados a unha determinada especie de peixe. Neste ciclo do carbono, considerouse un servizo ecosistémico en forma de carbono azul, entendido como o fluxo negativo de carbono que se acumula no fondo mariño cando os peixes morren de forma natural e prodúcese un proceso de remineralización. Para iso, realizouse un ACV xunto con información adicional como o cociente de mortalidade natural e por pesca ou o contido en carbono do exemplar de peixe. A partir dos resultados identificouse que as emisións derivadas da súa captura e posterior procesado non son compensadas polo servizo que presta como sumidoiro de carbono, polo que se propuxeron unha serie de medidas. Estas baseábanse na aplicación de melloras tecnolóxicas na frota pesqueira, a ampliación da tempada de veda e a modificación das fontes de proteínas na dieta. A través das súas hipotéticas aplicacións concluíuse que é necesaria unha combinación de medidas correctoras para configurar unha dieta neutra en carbono que inclúa o consumo de peixe fresco.

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Para ter en conta as diferentes actividades económicas que compoñen a industria dos produtos do mar, tamén se avaliou un produto da acuicultura: os mexillóns. Ademais,

avaliouse nun formato procesado, xa que o marisco en conserva desempeña un papel importante para garantir a seguridade alimentaria mundial, debido ao seu interesante perfil nutricional e ao feito de que se trata dun produto non perecedoiro. Por outra banda, este enfoque tamén permite cuantificar o impacto doutras actividades da industria alimentaria, como a transformación ou o envasado. Por tanto, seleccionouse un produto específico: mexillóns en escabeche en conserva ecolóxicos no **Capítulo 7** debido á posición de liderado de Galicia no sector da acuicultura do mexillón, para ser avaliado a través de diferentes metodoloxías que abordan os tres piares da sustentabilidade: (i) un estudo ambiental a través dun ACV seguindo o método da Pegada Ambiental de Produto, (ii) a estimación das cargas económicas derivadas dos impactos ambientais a través dunha serie de métodos de valoración monetaria, e (iii) un estudo social centrado na evolución do consumo e o gasto dos consumidores neste tipo de produtos no contexto español, así como a análise das diferentes certificacións coas que conta o produto para ser considerado como ecolóxico. Á súa vez, tamén se avaliou a súa versión estándar (é dicir, non ecolóxico) e algúns escenarios de mellora baseados na taxa de reciclabilidade dos seus envases e o uso dun mix enerxético máis renovable. Os resultados mostraron que a redución dos impactos ambientais e monetarios non era prometedora nin para os mexillóns ecolóxicos nin para os escenarios mellorados. Con todo, o perfil sostible do produto podería mellorarse ou promoverse con algunhas certificacións adicionais do piar social a través das prácticas implantadas na empresa produtora.

Por último, o concepto de sustentabilidade ampliouse mediante a consideración da circularidade. Ambos son complexos de abordar, polo que foi práctica habitual consideralos por separado, tanto nas políticas como na súa avaliación e seguimento. Con todo, a relación entre ambos para lograr un sistema de produción e consumo máis sostible é innegable. Por iso, no **Capítulo 8** abordouse un marco denominado CISU (indicadores de Circularidade e SUstentabilidade), que une ambas perspectivas para obter un único valor para a avaliación dos sistemas de produción. Ademais, seleccionáronse 50 granxas leiteiras galegas como casos de estudo para demostrar a aplicabilidade do marco proposto. Para iso, propuxéronse unha serie de indicadores de sustentabilidade e circularidade que se integraron para obter un indicador facilmente interpretable e que proporcionase unha vía de comunicación entre os actores que varían como un porcentaxe. Os resultados globais da mostra avaliada non lanzaron resultados prometedores, aínda que puxeron de manifesto o potencial da metodoloxía levada a cabo para implementar as prácticas das explotacións con maior puntuación co fin de mellorar o rendemento sostible e circular da cooperativa gandeira no seu conxunto. Con todo, para explotar o seu potencial a nivel multi-organizativo, a metodoloxía debería actualizarse para incluír outros aspectos interesantes como a simbiose industrial.

Para terminar cunha análise da tendencia nas últimas décadas, avanzouse de maneira significativa na cuantificación do impacto ambiental da produción e o consumo de alimentos a través de indicadores e metodoloxías estandarizadas, e a súa posterior comunicación a través de ecoetiquetas. Con todo, dado o nivel de contaminación dos sistemas alimentarios, a emerxencia climática actual e a complexidade de garantir a

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seguridade alimentaria a escala global, recoñécese a necesidade de reconsiderar e modificar as metodoloxías utilizadas ata a data. Por tanto, considerando a metodoloxía do ACV como punto de partida, propuxéronse unha serie de modificacións e ampliacións metodolóxicas, como a integración das perspectivas social e económica da sustentabilidade, o concepto de economía circular, xunto con algúns outros indicadores positivos en termos de servizos ecosistémicos ou provisión nutricional. Así, a partir dos achados da tese (**Capítulo 9**), púxose de manifesto que é imprescindible apostar por procedementos metodolóxicos máis ambiciosos, que vaian máis aló dos simples indicadores ambientais negativos, á hora de tentar resolver os actuais problemas de sustentabilidade relacionados cos sistemas de produción e consumo de alimentos. A pesar diso, co fin de implementar formas de analizar e comunicar patróns de consumo sostibles, resulta de especial importancia a estandarización dos procedementos metodolóxicos propostos, para que poidan ser tidos en conta no proceso de toma de decisións tras a súa integración nas políticas. Con todo, a identificación dos puntos fortes e débiles dos procedementos metodolóxicos novos, xunto coa súa aplicación en estudos de casos reais, deixa a porta aberta á súa reprodución noutros contextos e estudos de casos en forma de iteracións melloradas.

A modo de mensaxe para levar a casa, nesta tese desenvolvéronse unha serie de marcos metodolóxicos centrados na metodoloxía do ACV e aplicados ás industrias láctea e marisqueira nun contexto galego e español, partindo de varias carencias que se identificaron. Estas supuxeron un notable avance no ACV cando se integra con outros conceptos clave na industria alimentaria, como o nexo AEA ou a EC, pasando dunha visión puramente ambiental a outra máis ampla que inclúe múltiples aspectos como a sociedade, a economía, os servizos ecosistémicos ou a nutrición. Así mesmo, este cambio conceptual resulta ser unha importante contribución á literatura científica para os profesionais do ACV. Ademais, os indicadores compostos tamén se abordaron desde o punto de vista da certificación, propoñendo un deseño de etiqueta que integra os beneficios das etiquetas nutricionais coas ecoetiquetas, á vez que se opta por un deseño atractivo e fácil de entender. Desta forma, resólvese o problema de que aínda que o procedemento metodolóxico complícase na fase de análise debida á integración de varios conceptos, isto non supón unha desvantaxe á hora de ser aplicado polos produtores e entendido polos consumidores, mantendo un aura de compromiso coa sustentabilidade por parte de todos os actores da industria alimentaria. A partir dos resultados, pode dicirse que esta tese representa un paso adiante na aliñación da industria alimentaria co desenvolvemento sostible. Chegou o momento de achandar o camiño para a harmonización dos métodos de análises holístico de sistemas alimentarios sostibles baseados nun enfoque de ciclo de vida. Por tanto, a reproducibilidade dos procedementos metodolóxicos propostos a través de futuras iteracións e refinamentos é de suma importancia. A partir de aquí, o obxectivo para alcanzar será a materialización en accións promovidas por políticas máis holísticas que conduzan a estratexias cara a un sistema de produción e consumo de alimentos máis sostible.

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# Chapter 1

## *Food industry and sustainability in Spanish and Galician contexts*

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# Summary

Food production involves a diverse network of activities in the primary sector: agriculture, fishing or livestock farming, which constitute one of the main economic pillars of the EU. Spain stands out as the main producer of fruit, vegetables and olive oil, while Galicia, a coastal region in the Northwest (NW) of Spain, is one of the most important regions in the agri-food sector. In the marine sector, Galicia is a benchmark for quality and excellence, with the largest fishing fleet in Spain, as well as the aquaculture and canning industries, which are of particular importance. In the livestock sector, Spain is the seventh largest producer of milk in Europe, with Galicia being the main producing region.

Despite the importance of technification and intensification in ensuring food production and meeting society's demand, it should not be ignored the fact that food production systems have a significant impact on the environment. In this sense, GHG emissions from livestock farming and the overexploitation of fishing grounds are two of the main pressures on the dairy and fisheries and shellfish sectors, respectively. Actions to reduce the environmental impact of the food industry depend not only on producers, but also on consumers and how human choices in their diets may have an influence on its sustainable profile. To achieve healthy and sustainable diets, several guidelines and recommendations can be followed. In addition, these diets should be physically and economically accessible, as well as socio-culturally acceptable to all. The communication through food pyramids can provide useful information and in recent years they have been adapted to include important aspects (e.g., regular exercise) as well as other specificities such as highlighting culinary practices or gastronomic traditions of the region.

**Keywords**

Food production | Fisheries and shellfish sectors | Dairy sector | Climate change | Sustainable diets | Food pyramids

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## 1.1 Socioeconomic aspects of the food industry

The food industry is composed of a diverse network of agricultural, livestock or fishing activities involving the cultivation, production, processing, preservation, packaging, distribution, retailing and catering of foods that make up a diet, with a range of nutritional, health, economic, social and environmental impacts (Sadiku et al., 2019). Rice, cereals (mainly, corn and wheat), potatoes, sugar and chicken meat are among the main products produced in the world by countries such as China, India or Brazil (FAO, 2022a).

In the European Union (EU), food and drink productions provide around 5 million jobs, making it one of the most important industries in terms of added value, accounting for €73 billion in 2022 (FoodDrink Europe, 2022). In terms of consumption, household spending on food and non-alcoholic beverages varies between 9 % and 25 % in the different EU Member States. There are also large variations between European countries, with a difference of up to 50 g in the daily consumption of seafood products, or more than three times the difference in the consumption of milk and dairy products (EEA, 2022). Due to the orographic and climatological diversity of Europe, each country produces certain types of products with greater specialization or quality; to give some examples, Italy is the main producer of wine, France of sugar beet, Germany of rye or Poland of oats (Eurostat, 2022a).

Spain is the leading European producer of fruit, vegetables and olive oil (Eurostat, 2022a). In addition, the food and beverage sector is one of the most important in the country, representing almost 3 % of the workforce and 2.4 % of Gross Domestic Product (GDP) (MAPA, 2023). In terms of contribution, meats, beverages, bakery and pasta, fruits and vegetables and dairy were the sectors with the highest turnover (INE, 2022a). A more detailed analysis by autonomous communities shows that Andalusia, Catalonia, Castile and Leon, Valencia and Galicia are the top 5 according to the number of companies and jobs in the agri-food sector (INE, 2022b). However, there are major differences between them in the type of sector in which they are most specialized.

Galicia, a coastal region in NW Spain, is a benchmark in the agri-food sector, which accounts for up to a tenth of its GDP, with more than 2,500 companies, most of them with an international presence. Among the numerous agri-food activities carried out, fishing, shellfishing and aquaculture stand out, as well as dairy milk production (IGAPE, 2023). In addition, Galicia contributes around 10 % of the benefits of products such as milk or other dairy products (e.g., yogurt or cheese) at national level, while leading in certain shellfish species such as sardines, turbot, monkfish or octopus (MAPA, 2022a). A more detailed analysis of the fisheries and dairy sectors is presented below, focusing on the Spanish context and especially on the Galician region.

### 1.1.1. Fisheries and shellfish sectors

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Seafood products are a diverse group of more than 2,500 species of fish, invertebrates, algae and plants of aquatic ecosystems, which represent the largest wild food resource. Moreover, this type of food has interesting nutritional profiles, often rich

in essential micronutrients and healthy fatty acids (Tigchelaar et al., 2022). Global food production from fisheries and aquaculture reached 178 million tons in 2020, with equal contributions from both, although marine fisheries and inland aquaculture dominate. Of this amount, around 89 % is for human consumption and the remaining percentage is processed into fishmeal and fish oil. In addition, seafood consumption has grown at almost twice the rate of population growth over the period 1961-2019, reaching 20.5 kg net weight equivalent per capita, with the main drivers being increased supply and purchasing power, in addition to changes in consumption habits (FAO, 2022b).

The 27 EU Member States rank seventh in terms of fishery and aquaculture production, a sector dominated by the Asian continent with countries such as China, Indonesia, India or Vietnam. However, if the European continent is considered, it rises to third place with a production of about 17 million tons of seafood products in 2020, most of which are herring, blue whiting or mackerel. Moreover, despite the generalized rise in prices for this type of product, consumption has increased by up to 7 % in 2020 and is expected to continue to grow in the coming years. By countries, Portugal, Spain, Denmark and France stand out, with values ranging between 57 and 32 kg net weight per capita per year, with tuna, salmon and cod being the most consumed species (European Commission, 2022a).

As far as Spain is concerned, seafood products have an economic impact of more than 1 billion euros, representing 4 % for marine fisheries and 1.4 % for aquaculture of the total number of people employed in the primary sector in 2021 (MAPA, 2023, 2022b). From a regional point of view, Galicia plays a key role in fisheries, supported by the fact that, with a fleet of about 4,000 vessels, it represents more than half of the national fishing fleet. Among them, the artisanal fleet is the most numerous, fishing for octopus, cuttlefish or clams in the inland waters of the estuaries. It is followed by the purse seine fleet, which catches species such as blue whiting or sardines, on the west coast (for example, the ports of Cambados, Redondela or Portosín). Trawling, on the other hand, is conducted by a hundred vessels, mainly for species such as hake or monkfish along the Galician coast in the ports of Burela, A Coruña, Vigo or Ribeira. In addition, although to a lesser extent, part of the fleet is specialized in deep-sea fishing in EU and international waters of the Atlantic, Indian and Pacific Oceans, with more than 150 trawlers and longliners (Xunta de Galicia, 2023).

In addition to fishing, Galicia is also a major player in aquaculture and the canning industry. On the one hand, it is the first European region in seafood production, thanks to the high natural productivity of its estuaries, the main species being mussels, and in marine fish, representing 85 % of the total European production of flatfish such as turbot and sole (APROMAR, 2022). On the other hand, 80 % of canned seafood in Spain comes from Galicia, which is also the main producer in the EU and the second in the world after Thailand (Alimarket, 2022). Given the exceptional importance of this sector in Spain, a more detailed study of the consumption and total expenditure of the main seafood products between 2001 and 2021 per capita is depicted in **Figure 1.1**.

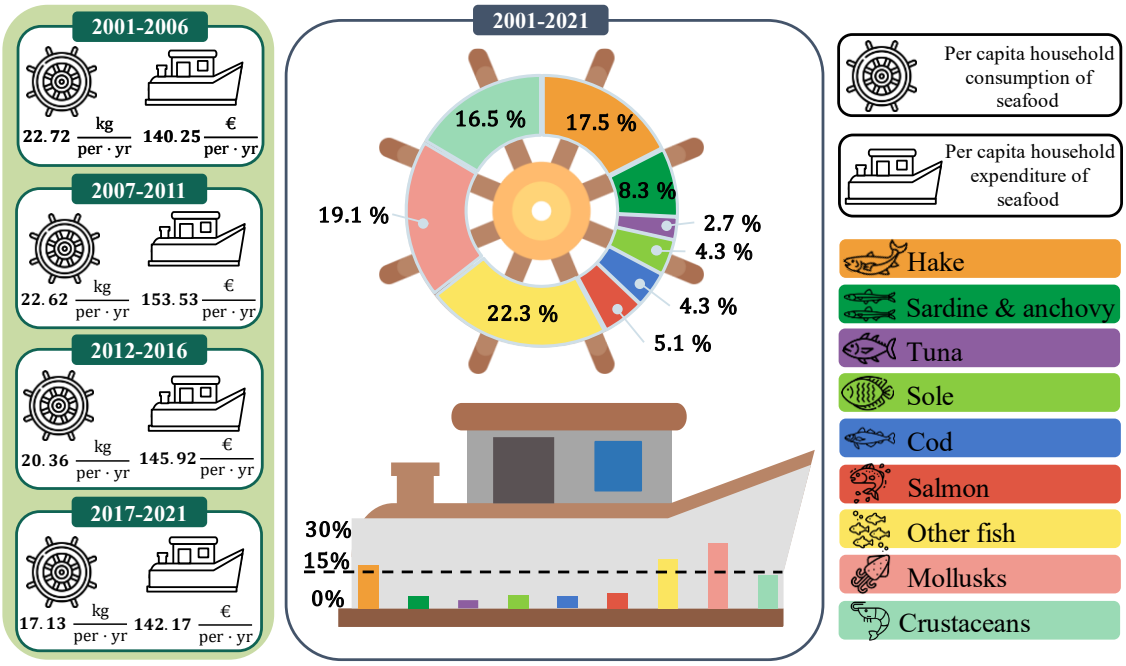



**Figure 1.1**. Per capita household consumption and household expenditure of seafood products in Spain. The total amount of both is shown in average values divided by different periods (2001-2006, 2007-2011, 2012-2016 and 2017-2021), and the relative weight by species appears for the period 2001-2021. Own elaboration using data collected from MAPA (2021a).

From these data, it can be seen that the annual consumption of seafood products per consumer has not stopped decreasing since the beginning of the 21st century, with the sharpest decline in the last 5 years (2017-2021), up to 3 kg per year. Moreover, expenditure has fluctuated over the years between €140 and €150 per capita per year, which makes it likely that a similar figure will be reached between the early 2000s and the 2020s. However, it is important to consider the exceptional situation on the demand and supply side caused by the COVID-19 pandemic, which led to a collapse in prices in the main seafood markets around the world, including Spain (Amos et al., 2022). In terms of per capita domestic consumption, other fish, such as mackerel or trout, mollusks (e.g., shrimp or prawns) and hake account for almost 60 % of the total. Crustaceans, which include clams, cockles, mussels, cuttlefish and octopus, represent more than 16 %, while sardines and anchovies account for less than half of this contribution. Finally, other fish species do not go beyond 5 % of the total, with the exception of salmon (5.1 %). In terms of expenditure by species, mollusks rank first with more than 25 %, which is not surprising since they are 7 to 8 times more expensive than other seafood products such as sardines and anchovies. They are followed by other fish, hake and crustaceans, with around 15 %, and the rest ranges from 6.2 % (salmon) to 3.3 % (tuna).

### 1.1.2. Dairy sector

Humans are the only animal that continues to drink milk after the lactation period (mainly provided by cows); however, it represents a fundamental pillar of a healthy diet for all age groups, with greater importance in pregnant women and children, due to its beneficial effect on bone and muscle growth (Marangoni et al., 2019). In terms of

production, the amount of milk produced worldwide is growing steadily, reaching around 930 million tons in 2022. This is largely due to demand from the Asian continent, which is expected to be the main producer with more than 400 million tons of milk. Moreover, this figure is expected to continue to rise, mainly due to countries such as India, Pakistan and China. In Europe, with more than 230 million tons, the continent has established itself as the second largest producer, although a decline is expected in the coming years (FAO, 2022c). By country, Germany and France are the main European producers, with averages of 22 % and 17 % respectively in 2021. They are followed by the Netherlands, Italy and Poland, which account for almost a third of European milk. With a smaller production volume, Spain ranks seventh with 5 % of the milk produced in Europe, between Denmark (4 %) and Ireland (6 %) (Eurostat, 2022b).

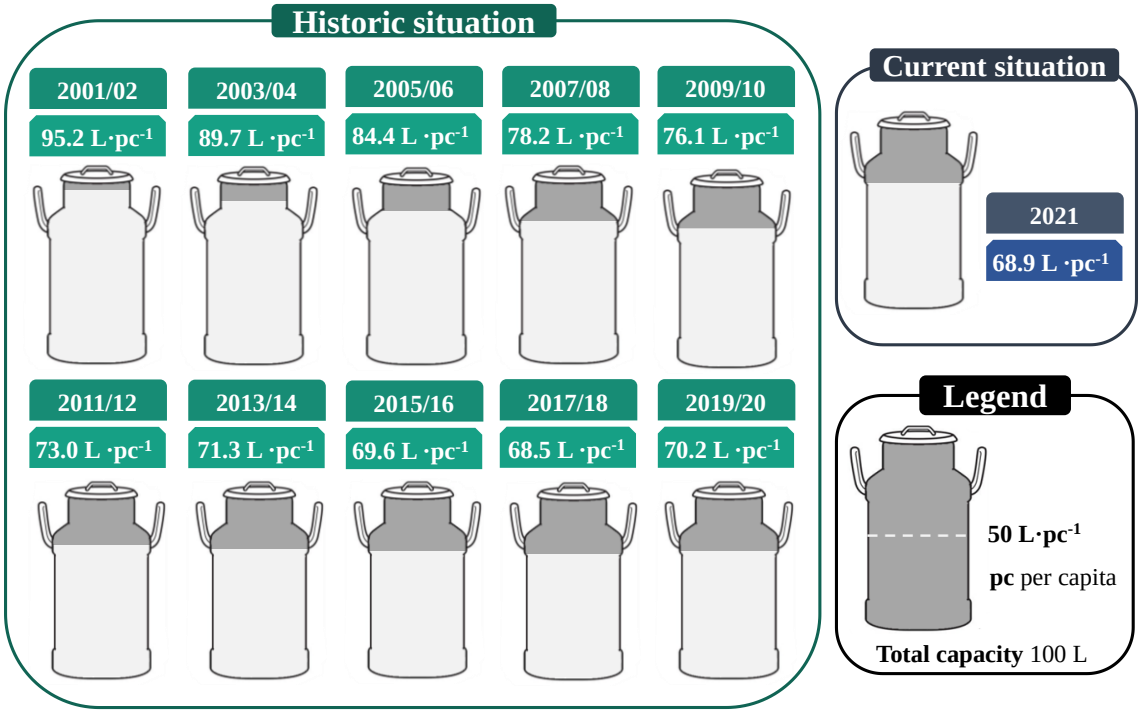



**Figure 1.2**. Comparison of the consumption of liters of milk per person in Spain in biannual periods (since 2001/02) versus the current situation (2021). Own elaboration using data collected from MAPA (2022d).

The origin of Spanish milk comes mainly from the northern regions, where Galicia stands out, accounting for around 40 % of total national production in 2021 (MAPA, 2022c). Regarding the consumption of cow milk in Spain, **Figure 1.2** shows the values of liters per capita for two-year periods in an overall interval of 20 years (from 2001 to 2021). Thus, it can be seen how milk intake levels have been decreasing steadily over the years, going from about 95 liters per person per year to less than 69 liters in 2021, this situation being more noticeable in the first decade. One of the main reasons for this decline is the increase in plant-based alternatives suitable for vegans and vegetarians (Park, 2021). On the other hand, during 2019/20 this trend shows a slight increase to over 70 liters per person. This change could be attributed to the effect caused by the exceptional situation of the state of alarm during the pandemic caused by COVID-19 on food

consumption in Spain, causing an increase in demand for certain types of food, including milk and dairy products (Cambeses-Franco et al., 2022b).

A closer look at the type of milk consumed in 2021 (**Figure 1.3**) shows that more than 60 % of milk was packaged, with the semi-skimmed variety being the most consumed. In addition, dairy derivatives accounted for about 30 %, with fermented varieties (e.g., yogurts) and cheeses standing out. On the other hand, fortified milks account for less than a tenth of consumption, with calcium-enriched milks being the most consumed, while for other product types (i.e., condensed, powdered and evaporated milks) constitute the minority group, with barely 0.5 % (MAPA, 2022c).

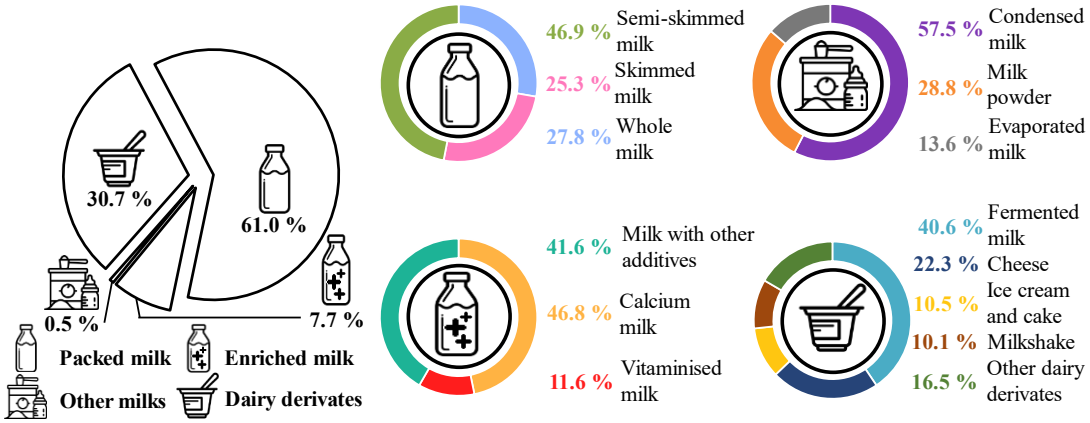



**Figure 1.3**. Average percentage of consumption of the different types of milks and dairy products in Spain in 2021. Own elaboration using data collected from MAPA (2022c).

From the social point of view, the family character of dairy farms in Galicia stands out, with an average of 48 cows, much lower than in other Spanish regions such as Aragon, Murcia or La Rioja, where each farm has about 300 cows (MAPA, 2022e). However, in recent years there has been a trend towards a reduction in the number of farms, but of larger size and with more intensive production, which has led to a reduction in the number of farms, with Galicia being the most affected in this regard, so that almost 30 % of farms have disappeared for the period 2015-2020 (López-Iglesias and Manuel-Lainez, 2022).

## 1.2. Environmental impacts of food production

The consequences of CC arise as one of the greatest threats to humanity in the coming years, posing a major problem for ecosystem preservation (Malhi et al., 2020). Likewise, CC is related to important monetary investments in terms of mitigation strategies or corrective actions (Frame et al., 2020). Thus, CC generates a range of environmental, economic and social impacts, and is an obstacle that needs to be addressed to achieve global sustainable development by 2030 (United Nations, 2015).

In this context, the food industry is seen as both a driver of CC and a major threat to its consequences. On the one hand, the food industry turns out to play a key role as a contributor to CC, as reflected in a study that predicted that this economic activity alone

would exceed the 2°C target of the Paris Climate Agreement for the next century under business as usual. It then hypothetically applied a range of mitigation strategies, concluding that changes in dietary patterns (based on a plant-based diet and limiting calories to recommended levels) and in the food supply chain (focused on higher yields, reduced food waste and improved efficiency) would result in reductions in GHG emissions ranging from 15 % to nearly 50 % (Clark et al., 2020). On the other hand, CC has negative impacts on food systems, both in terms of food quantity and quality (i.e., food security and safety), water and energy resources, as well as the presence of pests, diseases and difficulty in pollination. Moreover, all these environmental, social and economic impacts are occurring disproportionately across the world. As a result, they widen the inequality gap between regions and make it more difficult for humanity to feed itself sustainably (Fróna et al., 2021).

At the cost of producing food, the current food system is producing and at the same time suffering not only CC, which is related to about 25 % of GHG emissions, but also severe environmental degradation of various kinds, being a major water and land use demander and polluting soil and water through the use of fertilizers and pesticides, constituting a major cause of biodiversity loss. Moreover, this situation is expected to worsen further in the coming years due to population growth and trends in dietary patterns. Therefore, a change is needed to adapt it to the main international agreements on sustainability (FAO and WHO, 2019). In addition, depending on the food industry, certain impacts will have a more pronounced effect on the environment, so those most related to the dairy, fisheries and seafood sectors are briefly described below.

For the dairy sector, CC is undoubtedly the greatest environmental impact from the production of milk and dairy products, with the main GHG being methane ($CH_4$), nitrous oxide ($N_2O$) and carbon dioxide ($CO_2$) from ruminant digestion (i.e., livestock farming), the management of the manure produced, as well as activities related to cultivation, such as soil tillage. In addition, this activity also requires considerable amounts of basic resources such as fresh water, energy and arable land for livestock. Consequently, since dairy farming is linked to agricultural activities, the use of synthetic fertilizers and chemical pesticides also has several negative environmental impacts (e.g., heavy metal emissions and eutrophication) (Guzmán-Luna et al., 2022).

As for the fishing and seafood sector, the greatest threat to the oceans is overfishing, which occurs when food resources are extracted from the sea faster than the fishing grounds can replenish them. In this sense, changes in the food chain are due to the selective reduction of species of commercial interest (as well as related bycatch species). In addition, oil spills and waste from ships endanger marine fauna and flora, with special attention to plastic litter because of its potential contribution to humans, as it could be spread through the diet, especially in the case of microplastics. On the other hand, wastewater from the aquaculture industry is sometimes discharged directly into the marine ecosystem without adequate treatment, degrading water quality and impacting biota (Vázquez-Rowe, 2020).

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## 1.3. Towards more sustainable food habits

Given that food production is associated with significant environmental impacts, as well as various socioeconomic benefits, it is necessary to focus on promoting more sustainable eating habits. To this end, the transformation towards more sustainable food patterns, identifying all those key aspects that it should have and proposing a series of recommendations for its achievement, as well as the development of food guides adapted to the socio-cultural aspects of the region, are essential to achieve a sustainable food industry.

### 1.3.1. Recommendations for achieving sustainable food

A decade ago, the Food and Agriculture Organization of the United Nations (FAO) defined sustainable diets as those that have a low environmental impact and contribute to food and nutritional security and a healthy life for present and future generations. They are also protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically equitable and affordable, nutritionally adequate, safe and healthy, while optimizing natural and human resources. Consequently, up to six key components were identified when defining a sustainable diet: (i) food nutrient needs, food security and accessibility; (ii) well-being, health; (iii) biodiversity, environment, climate; (iv) cultural, heritage, skills; (v) organic, local, seasonal food; and (vi) equity, fair trade (FAO, 2010). Since then, various international bodies such as the FAO and the World Health Organization (WHO), have proposed a series of recommendations and guidelines to be followed to achieve a sustainable diet. Therefore, it was decided to summarize them all in the form of six key aspects, after a bibliographic review (FAO and WHO, 2019; WHO, 2020, 2019; FAO et al., 2022). On the other hand, given that a sustainable diet involves a wide range of concepts, an infographic is presented in **Figure 1.4** to facilitate its understanding.

- Food nutrient requirements, food security and accessibility. Reaching optimal levels according to the necessary nutritional requirements in a healthy way, facilitating physical and financial access to sufficient food. In addition to being healthy, the diet should be varied and balanced, including at least five servings of fruit and vegetables a day, legumes, nuts and whole grains. These should form the basis of an adequate diet, which can be supplemented in moderation with low-fat dairy products, eggs, poultry, seafood and lesser amounts of meat, preferably lean, while limiting consumption of fried or packaged foods and snacks.

  As for Caloric Intake (CI), it should not exceed 30 % in the form of total fat, with limits of 10 % for both saturated fats and free sugars, but a further reduction of 5 % is proposed for free sugars for the added health benefits, and less than 1 % for trans fats (to be replaced by unsaturated fats). On the other hand, salt intake should be limited to less than 5 g per day. It is also essential to maintain hydration levels by

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consuming water as the main drink, avoiding as far as possible any alcoholic or sugary beverages.

On the other hand, governments must improve food security by optimizing food production systems, ensuring adequate levels of production in the face of population growth and affordable prices for the most disadvantaged, while minimizing food waste along the production and supply chain through policy development. In addition, at the consumer level, simple actions such as planning food purchases can reduce both food demand and food waste.

- Wellness, health. This aspect is related to the promotion of human health in general. To this end, a healthy diet must help protect against malnutrition in all its forms: malnutrition, micronutrient deficiencies and obesity and other diet-related diseases (such as diabetes, heart disease, stroke and certain types of cancer). In addition, this should be accompanied by a healthy lifestyle based on regular physical exercise. Healthy feeding practices should be initiated at an early age, as breastfeeding promotes healthy growth and improves cognitive development, as well as having long-term health benefits later in life in terms of reduced risk of becoming overweight or developing diseases. In this regard, a framework consisting of six global nutrition targets has been proposed to improve maternal, infant and young child nutrition by 2025: (i) achieve a 40 % reduction in the number of stunted children under 5 years of age; (ii) achieve a 50 % reduction in anemia in women of reproductive age; (iii) achieve a 30 % reduction in low birth weight; (iv) ensure that child overweight does not increase; (v) increase the rate of exclusive breastfeeding in the first 6 months to at least 50 %; and (vi) reduce and maintain the rate of acute child malnutrition below 5 %.
  On the other hand, food safety must be promoted through a series of preventive practices to avoid the appearance of food-associated diseases due to the proliferation of microorganisms, insects or other animals. These are based on:
  - Keeping cooking areas, utensils and hands in good hygienic conditions in relation to the food to be managed.
  - Separating raw food from cooked food during storage and cooking.
  - Cook foods adequately, especially those of animal origin such as meats, as this will guarantee their optimal state of consumption.
  - Do not leave perishable foods at room temperature.
  - Always use potable water and prioritize the selection of fresh and healthy foods, as well as those processed for safety, trying to avoid consuming food beyond their expiration date.

- Biodiversity, environment, climate. To achieve and maintain a global food production system that respects the environment and enhances biodiversity in a CC context. To this end, a number of recommendations can be followed:
  - Decrease GHG emissions, water and land use, nitrogen and phosphorus application and chemical pollution to targets set by environmental agreements or climate policies.

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- Preserve and enhance animal and plant biodiversity within food systems, including that of crops, livestock, forest-derived foods and aquatic genetic resources, and avoid overfishing and overhunting.
- Minimize or avoid the use of antibiotics, hormones, chemical fertilizers and pesticides in food production.
- Another aspect to achieve a sustainable diet would be food packaging, as it is often made of plastic, a material that not only has a significant impact on the climate, but also affects multiple species due to the associated waste generated. Therefore, the first priority would be to avoid using it, then opt for reusable or biodegradable packaging and, finally, avoid or minimize those made of plastic materials.

- Culture, heritage, skills. Sustainable diets are based on respect for local culture, culinary practices, knowledge and consumption patterns, and values about how food is sourced, produced and consumed.
  All this means that, at the consumer level, food choices can be influenced by a range of socio-cultural aspects, beyond other environmental or health considerations. Nevertheless, they must be respected and protected, as they constitute an important part of the social pillar of sustainability in terms of culinary culture. In addition, ethnographic specificities must be identified to organize more effective campaigns to make healthy and sustainable food more desirable and enjoyable. To achieve these changes in eating habits, cross-sectoral cooperation between businesses, politicians, academics and consumers is essential.

- Organic, local and seasonal food. Priority should be given to foods that are more environmentally friendly in terms of production methods, locally sourced and seasonal. Whenever possible, choose foods that have a lower environmental impact, both in terms of production, due to more respectful practices (e.g., organic), and in terms of transportation, because they are locally sourced. Also, always prioritize seasonal foods, respecting their natural production cycles. This is because they are at their optimum point of consumption, are fresher and more nutritious, as well as indirectly contributing to the environment by reducing the impact of storage, refrigeration and associated food waste.

- Equity, fair trade. Avoid discriminatory practices along the food production, supply, preparation and consumption chain, such as those based on gender segregation, by ensuring fair trade that respects all actors in the food chain. In addition, there is considerable intracultural diversity in the prohibition of food according to age, gender or social status. Food also plays a key role in religious practice, defining practices through different norms, symbols and meanings. Therefore, possible policy options should take into account such restrictive or discriminatory measures based on religion or gender. On the other hand, it is necessary to ensure decent working conditions and prices that allow fair wages for both producers and consumers.

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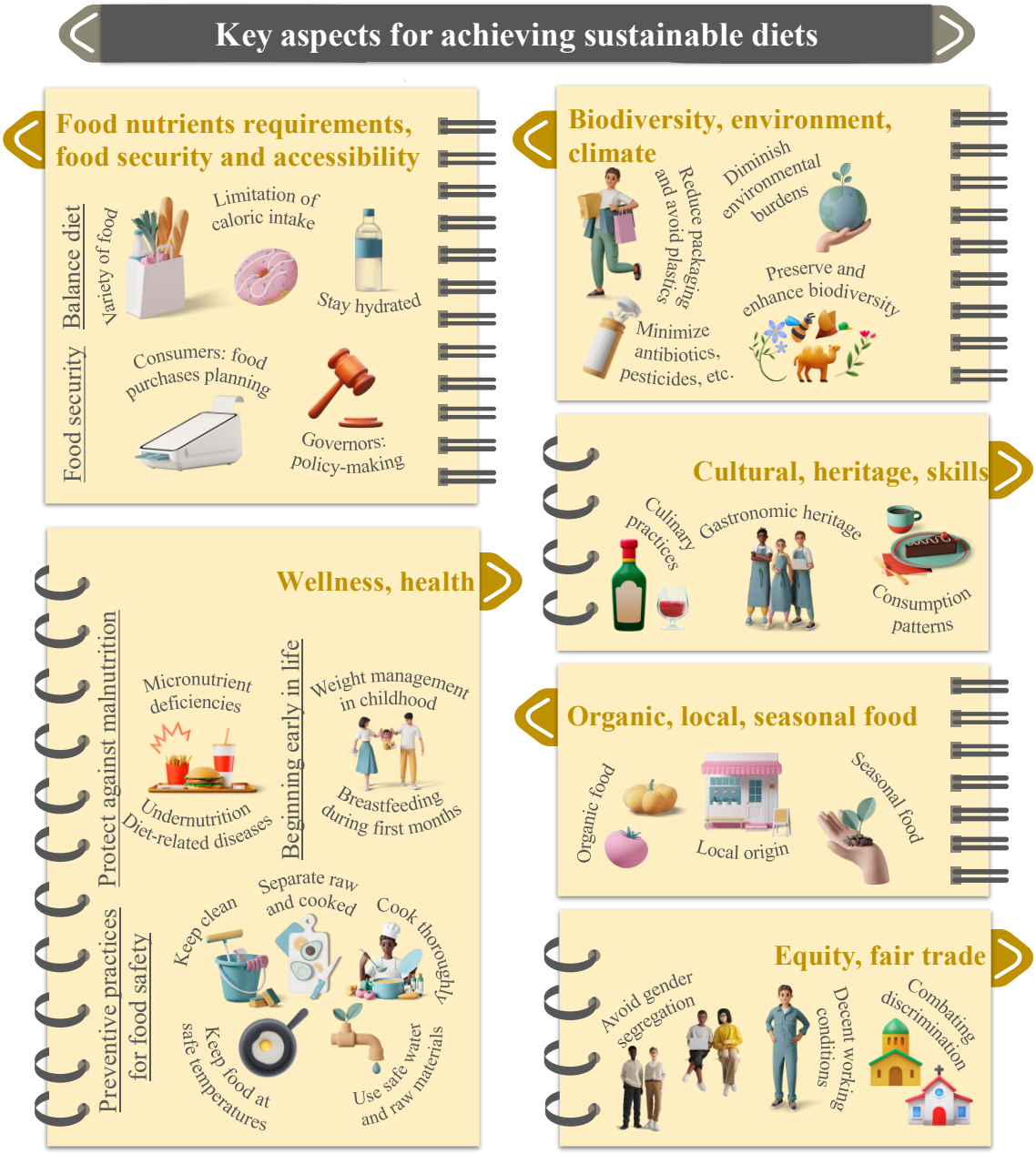



**Figure 1.4**. Key aspects and recommendations for achieving sustainable diets. Own elaboration using data collected from FAO and WHO (2019); WHO (2020, 2019); FAO et al. (2022).

### 1.3.2. Food-based dietary guidelines

Most food-based guidelines that have been published are used to educate consumers in response to public health and nutrition priorities, food production and consumption patterns, socio-cultural influences, accessibility of food products, etc.(FAO, 2016). In addition, one of its most common methods of representation is in the form of food pyramids or plates, as they allow creating a simple communication channel for all types of audiences, showing in a visual way the priority or proportions in which certain food groups should be included in a diet.

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The first food pyramid was created in the 1970s in Sweden, although its origin and function are not the same as they are today. This is because it was born as a consequence of rising food prices, so it was decided to establish a pyramid that prioritized accessible, nutritious, cheap and basic foods at the base (i.e. milk, butter, bread and cereals). After these, fruit and vegetables were placed in a middle position as aside dishes, while meat, fish and eggs were placed at the top. Two decades later, the United States Department of Agriculture published the first food pyramid focused on adapting a healthy diet, which placed the bread group at the base, cereals, rice and pasta (with a recommended intake of 6-11 servings), vegetables (3-5 servings) and fruit (2-5 servings), followed by animal products such as dairy products, legumes and nuts (2-3 servings) and finally fats, oils and sweets, which were recommended to be consumed sporadically. Later, at the turn of the 21st century, the same organization included external factors that should be complemented by a healthy diet in lifestyles, such as regular sporting activities (Marcus, 2013).

Subsequently, in the 2010s, an alternative to the pyramids was proposed, in which the food groups are now shown in a circular diagram in the shape of a plate to represent the recommended proportions of each food group. The Harvard School of Public Health proposed the "healthy eating plate". Half of the plate consists of vegetables and fruits, a quarter of whole grains, and a quarter of protein (i.e., fish, poultry, legumes or nuts, limiting those from red or processed meats). In addition, moderate use of fats from seeds such as olives and rapeseed, limiting butter. Finally, beverages were included, recommending water or herbal teas (Harvard University, 2011).

Recently, the Australian Nutrition Foundation proposed a variation of the traditional pyramid, updating it with current trends in dietetics and nutrition. Its main change is to focus on vegetables, moving them to the base of the pyramid, where five servings a day should be consumed, along with legumes, while two or three servings of fruit are recommended. Next are cereals, bread, pasta and other whole grains, which together with the above should make up 70 % of the diet. In the middle are dairy, fish, poultry, lean meat and nuts, and at the top are healthy fats such as olive oil, or other seeds oils, rich in unsaturated fats. Finally, it recommends using herbs and spices to season foods, limiting the use of salt and added sugars, and staying active with daily physical exercise (The Australian Nutrition Foundation, 2021).

However, a sustainable diet should not only be healthy, but also accessible, affordable and culturally acceptable depending on the ethnographic or religious aspects of a given region (Fanzo, 2019). In this regard, more than 100 countries around the world have developed national food-based dietary guidelines tailored to certain aspects (e.g., nutritional status, food availability, culinary cultures or eating habits). The main objective of these dietary guidelines is therefore to provide context-specific advice and principles on healthy diets and lifestyles that promote overall health and prevent all types of malnutrition (FAO, 2023). For this reason, there are now various adaptations depending on the region under consideration. To give just one example, a pyramid of the traditional

healthy Asian diet has been proposed, with white rice at the base and sake in the occasional alcohol category (Kanauchi and Kanauchi, 2019).

In the Spanish context, the Mediterranean diet is the most widespread and has been included in the list of Intangible Cultural Heritage of Humanity in 2013, because it is not only about eating habits in terms of quantity and frequency of consumption of certain types of food, but also about other cultural identities such as the hospitality of eating together through feasts or celebrations (UNESCO, 2023). Its main characteristics are the type of fat, mainly from olive oil, fish and nuts; cereals and vegetables, accompanied by meat or similar as a source of macronutrients and micronutrients from seasonal vegetables, as well as other herbs and spices (MDF, 2023).

In addition to the Mediterranean diet, there is also the European Atlantic diet, which includes the NW part of Spain (i.e., the region of Galicia) and the northern part of Portugal (Carballo-Casla et al., 2021). This is characterized by the consumption of fresh fruits and vegetables, bread, cereals, rice or pasta, together with a high consumption of seafood products, such as fish, shellfish or crustaceans, and a moderate consumption of meat and eggs (Vaz-Velho et al., 2016). Both the environmental impact, in terms of CF, and the nutritional quality of the recommended Atlantic diet have turned out to be similar to those of the Mediterranean diet (Esteve-Llorens et al., 2019a), although if we focus on current Galician dietary habits, the high consumption of beef and dairy products can translate into an additional 15 % of GHG emissions and a lower nutritional profile in terms of quality (Esteve-Llorens et al., 2019b).

Finally, in recent years, what used to be known as the healthy eating pyramid has evolved into an attempt to represent a lifestyle rather than just a diet. As a result, current healthy eating pyramids now include qualitative factors, such as frequency of physical activity, as well as cultural factors, such as the promotion in company. In this sense, the NAOS (Nutrition, Physical Activity and Obesity Prevention) strategy aims at social change in the promotion of healthy eating and the prevention of sedentary lifestyles (AESAN, 2011). To this end, a healthy life pyramid (known as the "NAOS pyramid") has been proposed, which is described as an adaptation and updating of the traditional food pyramid associated with the Mediterranean diet, based on four main points such as energy balance, the pursuit of nutritional balance, the practice of daily physical activity and healthier cooking techniques (AESAN, 2015).

## 1.4. Conclusions

The food industry is one of the main drivers of the economies of many European countries in terms of wealth and employment. Each of them specializes in a certain type of product, depending on a series of factors such as geographical characteristics or gastronomic traditions, with Spain standing out for its production of fresh products such as fruit and vegetables, as well as olive oil.

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Among the Spanish regions, Galicia is one in which the sectors related to food production have a greater presence, both nationally and internationally, especially highlighting seafood (fishing, aquaculture and processing sectors) and cow milk (dairy sector). However, the food industry itself is linked to a wide range of environmental constraints, for example because it is a heavy user of natural resources such as land and water, it triggers Global Warming (GW) or contributes to the loss of biodiversity and natural habitats. Thus, on the one hand, food production is associated with various socio-economic benefits, while on the other hand it has significant environmental impacts. There is therefore a close relationship between the three pillars of sustainability (i.e., environmental, social and economic) and the food industry.

Defining and promoting new models of food production and consumption is essential to reverse the current climate emergency and move towards sustainable development. To this end, an international consensus on what is meant by a sustainable diet, as well as basic recommendations at the consumer level to encourage its implementation, is of paramount importance.

Food pyramids are useful for establishing food-based dietary guidelines because they are generally easy to interpret and help to encourage the consumption of the staples of a healthy diet while at the same time limiting the less desirable foods. They have also been adapted over the years to include other aspects of sustainability, such as regular physical activity to maintain good health and the importance of creating community at mealtimes. However, it is essential that they are adapted to the specific characteristics of each region, to take into account its socio-cultural aspects, such as its culinary practices or gastronomic heritage.

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# Chapter 2

## *Limitations in assessing and communicating impacts in food production systems*

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# Summary

LCT is fundamental to promoting sustainable development of human activities. Various tools and methodologies have been developed for this purpose, of which LCA is the most widely used and internationally standardized. In relation to the food industry, LCA has been applied to several case studies of specific food systems to assess their potential impacts. It can also influence the decision-making process in the development of initiatives or policies. However, it has certain limitations, such as the lack of information on nutritional aspects of food within the FU and the limited impact categories addressed, lagging behind positive contributions such as socioeconomic outcomes or the focus on ecosystem services.

In addition to analyzing the impact of the food industry, it is also important to promote the communication of the results obtained, for which labels play a fundamental role by creating direct communication channels between producers and consumers that help to inform and raise awareness. These include ecolabels, which provide recognizable, reputable symbols that guarantee a basic level of environmental friendliness, and nutritional labels, which provide information from a nutritional point of view. However, food ecolabels should take a more holistic view, integrating accurate and validated information that the consumer can be aware of at the time of purchase. To this end, composite indicators are potential candidates for application in the food industry as a direct way to facilitate the understanding of both environmental and nutritional assessments.

**Keywords**

Life Cycle Assessment | Ecosystem services | Eco-labelling | Food products | Composite indicators | Holistic frameworks

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## 2.1. Defining the assessment framework: Life cycle thinking

LCT is a set of tools or actions that promote human activities through sustainable development, taking a holistic view of all the steps that make up the supply chain (i.e., from the extraction of raw materials to the management of the end-of-life process). Consequently, adopting a life cycle perspective means obtaining a comprehensive analysis of the environmental, economic and social aspects of products (or services) throughout their life cycle, which can lead to solutions for reducing their impacts (Mazzi, 2019).

To endorse the inclusion of the life cycle approach in business and government, the scientific community, together with other organizations, has promoted the development of several assessment tools. Among them, the LCA methodology is the most mature, as it includes international standards and guidelines to support its application, as well as being the most widely used worldwide (Hauschild et al., 2018).

LCA is a powerful and holistic methodology to assess the environmental aspects and its potential impacts during the life cycle of a certain product or system: from the provision of the raw materials needed, production, transport, use/consumption, up to the final treatment (e.g., recycling, reused or disposal in a landfill). Its principles and framework, as well as its requirements and guidelines are addressed through the International Organization for Standardization (ISO) through the standards ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), which present the development of an LCA study according to four interrelated stages: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment and (iv) interpretation (see **Figure 2.1**). A more detailed description of each step can be found in the following subsections (Hauschild et al., 2018; Shaked et al., 2015).

### 2.1.1. Stage 1: Goal and scope definition

To properly apply the LCA methodology, both the goal and scope of the study should be described at the initial stage to establish the context of the analysis. On the one hand, the objective should clarify some aspects, such as the motivation for conducting the study, the intended use or the audience to whom the results will be communicated. On the other hand, the scope definition should ensure that the breadth, depth and level of detail of the study are both suitable and sufficient to achieve the stated objective. To this end, the scope should include a description of the product system under assessment (together with its functions), as well as a definition about its FU and System Boundaries (SB). The FU is the quantification of the identified functions (or performance characteristics) of the product, intended to be used as the basis for reference calculations in relation to the inputs and outputs of the product system. In addition, during the definition of the SB, it should be indicated which life cycle stages, unit processes and flows have been considered within the product system. Lastly, other features should also be included, such as allocation procedures; impact categories selected together with data quality requirements, assumptions and limitations.

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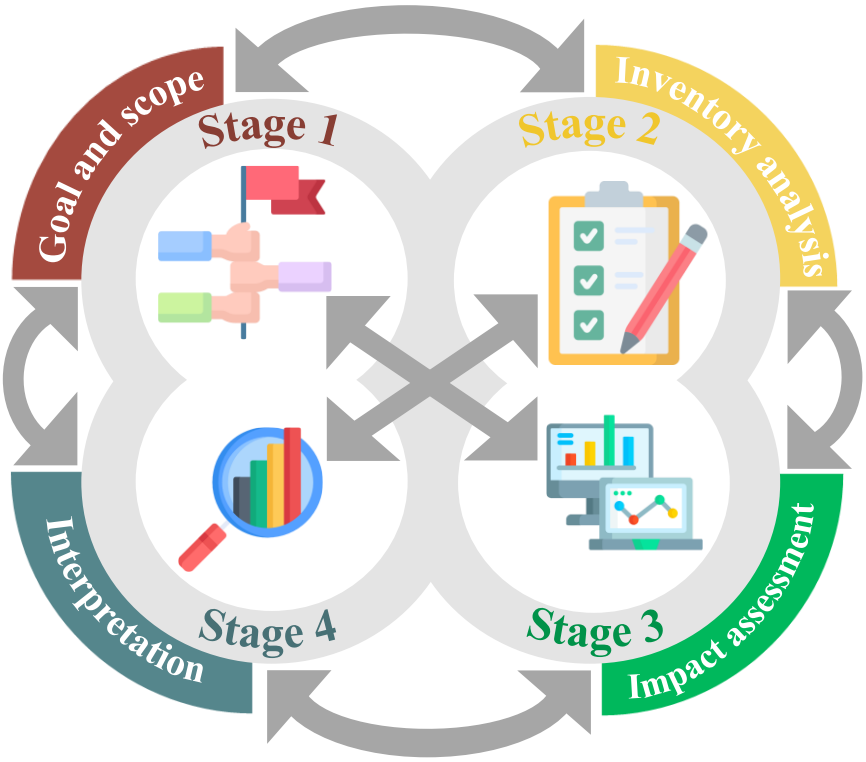



**Figure 2.1**. Stages of a Life Cycle Assessment study.

2.1.2. Stage 2: Inventory analysis

At this stage, data is collected in the form of an inventory, which is called the Life Cycle Inventory (LCI). This data includes the inputs of raw materials and energy; the outputs of products, by-products and waste; emissions to air, water and soil; and other environmental aspects. Then, with the data obtained, it will be necessary to conduct a series of calculations related to their validation and relationship with the unit processes and reference flows of the FU. Finally, in the case of a multi-functional system where two or more products are obtained, as well as systems for the recycling of intermediate products or waste, the need to carry out allocation procedures must be considered.

2.1.3. Stage 3: Impact assessment

The LCI obtained in the second stage of the LCA is used to assess the significance of potential environmental impacts. To understand these impacts, it is necessary to relate the LCI data to impact categories, category indicators and characterization models. This is followed by two steps, called classification and characterization, in which the LCI results are assigned to the impact categories selected, and the category indicator results are calculated. This will result in the LCI results, although there are some optional steps: normalization (calculation of the magnitude of the category indicator results in relation to the baseline information), grouping (organization and possible classification of impact categories), weighting (conversion and possible summation of indicator results across impact categories using numerical factors based on value judgements) or perform a data quality analysis to improve the reliability of the results.

2.1.4. Stage 4: Interpretation

Finally, when interpreting the results obtained during the LCA, the findings should explain limitations, reflect conclusions and provide recommendations for decision-makers, in line with the objective and scope of the study.

## 2.2. Limitations of Life Cycle Assessment in food production systems

LCT is particularly useful in ensuring the transition to more sustainable production models and consumption patterns. In this context, the LCA methodology has been widely applied over the years to food production systems and diets for different purposes. These include the identification of the main bottlenecks in the food production, distribution and consumption chain, the comparison of different diets or the evaluation of potential strategies to be applied in food waste management. Thus, LCA is not only used as an analytical tool, but can also play a fundamental role in the decision-making process, influencing production models, consumption patterns and the development of initiatives and policies (Notarnicola et al., 2017).

However, given the complexity and variability of food systems, there are still a number of issues that need to be addressed in the LCA studies conducted to date. Some of these relate to the difference in the number of LCA studies applied to certain food types in certain geographical regions compared to others, with an imbalance in favor of animal products and staple crops in developed countries. On the other hand, the impact categories addressed are limited, as they are mainly based on CC and do not address other positive impacts such as nutritional aspects, socio-economic performance or other ecosystem services (Cucurachi et al., 2019).

Regarding the CC impact category, normally, in LCA studies this is measured by means of the CF, which is the sum of all GHG emissions related to the GW, measured in terms of $CO_2$ equivalent through the use of a set of characterization factors, such as those proposed by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2019a) and standardized by ISO 14607 (ISO, 2018a). Notwithstanding, food production systems also contribute positively to the carbon cycle by creating carbon sinks through various agricultural practices (Bai et al., 2019). In addition, marine ecosystems are also important sinks for atmospheric $CO_2$. This is referred to as blue carbon, and its sequestration is not only carried out by the flora through coastal ecosystems such as mangroves (Macreadie et al., 2017), but also by its fauna. An example of this is fish of a certain size, whose carbon content in their bodies is sequestered after being remineralized when they reach the seabed (Mariani et al., 2020). In fact, this is one of the most underestimated carbon flows that must be taken into account when assessing the CF of fisheries (Feng et al., 2023).

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Therefore, it is recommended to use the LCA toolbox together with other methodologies to broaden the focus of the study. For example, to assess the nutritional performance of foods, there are several indicators available in the literature. One of the

most widely used indicators is the Nutrient Rich Food (NRF) index, which measures nutrient density results as the summatory of a set of nutrients to promote minus the detriment of a set of nutrients to limit (Drewnowski et al., 2009). Moreover, to ensure food security, which is the condition of having access to sufficient, affordable and nutritious food; aspects related to production yield should be integrated to address CC impacts on food production systems (Schneider and Asch, 2020). However, it is common for nutritional studies to be conducted separately from environmental studies, although foods with low environmental impact and those with a high nutritional value should be promoted in the same way to implement healthy and environmentally sustainable dietary patterns (Lacour et al., 2018). In line with these aspects, the WEF nexus concept addresses the linkages between food production and water and energy needs. This approach recognizes the synergies and trade-offs between food production and consumption and its contribution to water and energy management (Zhang et al., 2018). As a result, this concept opens the door to proposing holistic frameworks that allow for the integration of both positive (production yields or nutritional profiles) and negative (environmental burdens related to water consumption and energy requirement) impacts associated with food production and consumption.

Likewise, the most appropriate FU and allocation procedures to deal with multifunctionality, apart from data availability and process modelling, are additional aspects to be improved in the LCA studies of food products. Multifunctionality in food systems refers to the ability to produce more than one desired output (i.e., product), leading to the need to allocate total impacts to these outputs. In these situations, all inputs and emissions resulting from the process must be allocated to the product of interest. In this context, ISO 14044 (ISO, 2006b) proposes the following hierarchy of decisions: First, subdivision or expansion of the system should be used to avoid allocation. Second, allocation, which consists of distributing the inputs and outputs of the system among its various products or functions in a way that reflects the relevant and quantifiable relationships between them. When the second recommended option is followed, physical or economic allocations are the most common (Vidergar et al., 2021). However, neither the mass content nor the price adequately reflects the function of food, which is to feed and meet the demands of society (Weidema and Stylianou, 2020).

To implement a sustainable food system, the analysis of environmental indicators is not sufficient, as it must address the three pillars of sustainability: environmental, social and economic (Rosen, 2018). In the social field, UNEP (United Nations Environment Program) has developed methodological guidelines to include social aspects in studies based on LCA. This is founded on the estimation of a set of indicators that describe six stakeholder categories: i) workers, ii) local community, iii) value chain actors, iv) consumers, v) society and vi) children (Life Cycle Initiative, 2021). In monetary terms, Life Cycle Costing (LCC) analysis has been widely used for agri-food products, although there is no standardized procedure to reach consensus on some key issues, such as the type of data collected or the SB defined, making it difficult to obtain comparable studies (Degieter et al., 2022). Moreover, monetary results are more valuable when

complemented by LCA studies, the most common of which are those based on the concept of eco-efficiency, while others are based on the monetary valuation of environmental impacts thanks to specific characterization factors per impact category (Amadei et al., 2021).

Another concept related to sustainability is the CE. There are multiple interpretations of this concept in the literature, with around 100 definitions identified in 2017 by Kirchherr et al. (2017). Moreover, the diversity of interpretations of CE has increased in recent years, making it even more difficult to reach a consensus. However, the vast majority of definitions agree that its basic principles are based on the reduction, reuse, recycling or recovery of material supply, production and consumption to improve environmental quality, economic development and social equity (Kirchherr et al., 2023). Therefore, in addition to quantifying the environmental performance of a food production system using the LCA methodology, it is interesting to measure its circularity profile. In this context, the ISO has set up a technical committee to address the challenge of transitioning from the current linear economy to CE. The working group is developing a standard that provides a common understanding and principles of CE (ISO 59004). Two other standards are derived from it: ISO 59010, which captures CE strategies for transforming business models and value networks, and ISO 59020, which provides a framework for measuring and evaluating circularity outcomes. However, as ISO 59020 is still under development (ISO, 2022).

### 2.3. The importance of creating communicating channels

To create a future society that is fully aware of environmental issues, and to find a way to slow down CC, communication and education in this field are essential (Comfort and Park, 2018). Ways to tackle this goal include using social media, organizing events, producing and disseminating environmental education materials, and collaborating with stakeholders such as journalists or policy makers (Armstrong et al., 2018). However, it is not only necessary to share information, but to do so effectively so that the public begins to visualize the cause with a sense of engagement (Wamsler et al., 2020).

Two approaches can be distinguished when establishing communication channels for environmental protection, depending on the origin and direction of the message: (i) top-down, when the message is elaborated following a decision-making process by policy makers through guidelines that are communicated to the general public, and (ii) bottom-up, when the source of the message comes from the consumers who, through behavioral patterns, demand both new guidelines or policies and the modification of existing ones (Gallup, 2018).

In relation to the top-down approach, green policies should aim to promote the achievement of environmentally friendly behavior, which in turn consists of actions influenced by knowledge, motivation and constraints (Gkargkavouzi et al., 2019). Besides, environmental policies should be accompanied by media campaigns, where

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communicators must keep the message simple, balance emotions (e.g., fear and hope) and provide a pathway to promote climate action (de Vries, 2020).

Regarding the bottom-up approach, a survey conducted in the 2010s showed that almost 60 % of European Union (EU) citizens consider CC to be one of the most important challenges of the coming years (Baiardi and Morana, 2021). This is supported by the fact that consumers are willing to change their consumption habits to reduce their environmental impact (Li et al., 2020). As a consequence, manufacturers are prone to implement eco-innovation strategies in their products, as these are often linked to improved market performance by enhancing their social reputation, differentiating themselves from their competitors, and broadening their product range (Yang and Liu, 2021).

From the above, it can be concluded that both consumers and producers are undergoing a process of environmental awareness that has intensified in recent decades. However, this change is also being exploited by many companies to spread environmental misinformation, known as "greenwashing", with the objective of adapting to new consumption patterns and thus increasing their profit margins (Torelli et al., 2020). Greenwashing acts in the opposite direction of achieving sustainable development by creating a false sense of accomplishment, so it is up to governments to take action through regulatory policy to reverse its spread (Sun and Zhang, 2019).

Focusing on the case of food products, one of the most widely used communication channels between producers and consumers is labels, especially those that focus on health and nutrition aspects, as well as those that display environmental information (i.e., eco-labels). The following is a summary of the most relevant health and nutrition labels and LCA-based eco-labels. Likewise, an overview of all these front-of-pack (FoP) labels is shown in **Figure 2.2**.

### 2.3.1. Health and nutrition labels

Presenting nutritional information in a way that is understandable to any shopper is a key element in addressing the negative consequences of unhealthy diets (Al-Jawaldeh et al., 2020). There are three main types of FoP nutrition labels available on the market. On the one hand, reductive labels are those that provide objective information about food that is not open to interpretation, such as the Reference Intakes (RI) label, which shows the relative contribution of key nutrients in an adult's diet in terms of daily intake. On the other hand, interpretive labels include additional characteristics, such as words or symbols, which help the consumer understand the idea of some special feature of the food in terms of its health. In turn, there are two types of formats for interpretive labels: i) nutrient-specific, when they refer to a number of nutrients on an individual basis, such as the Multiple Traffic Lights (MTL) label or the Warning Signs (WS) of the nutritional profile of the food; and ii) summary indicator, which provides a general assessment of the nutritional profile of food. An example of the latter would be simple values in the form of colored letters, i.e., the Nutri-Score. There is also a hybrid version of the reductive and

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interpretive labels, such as the Health Star Rating (HSR), which provides a simple indicator in the form of a ranking of up to 5 stars along with nutrient-specific information (Kelly and Jewell, 2018).

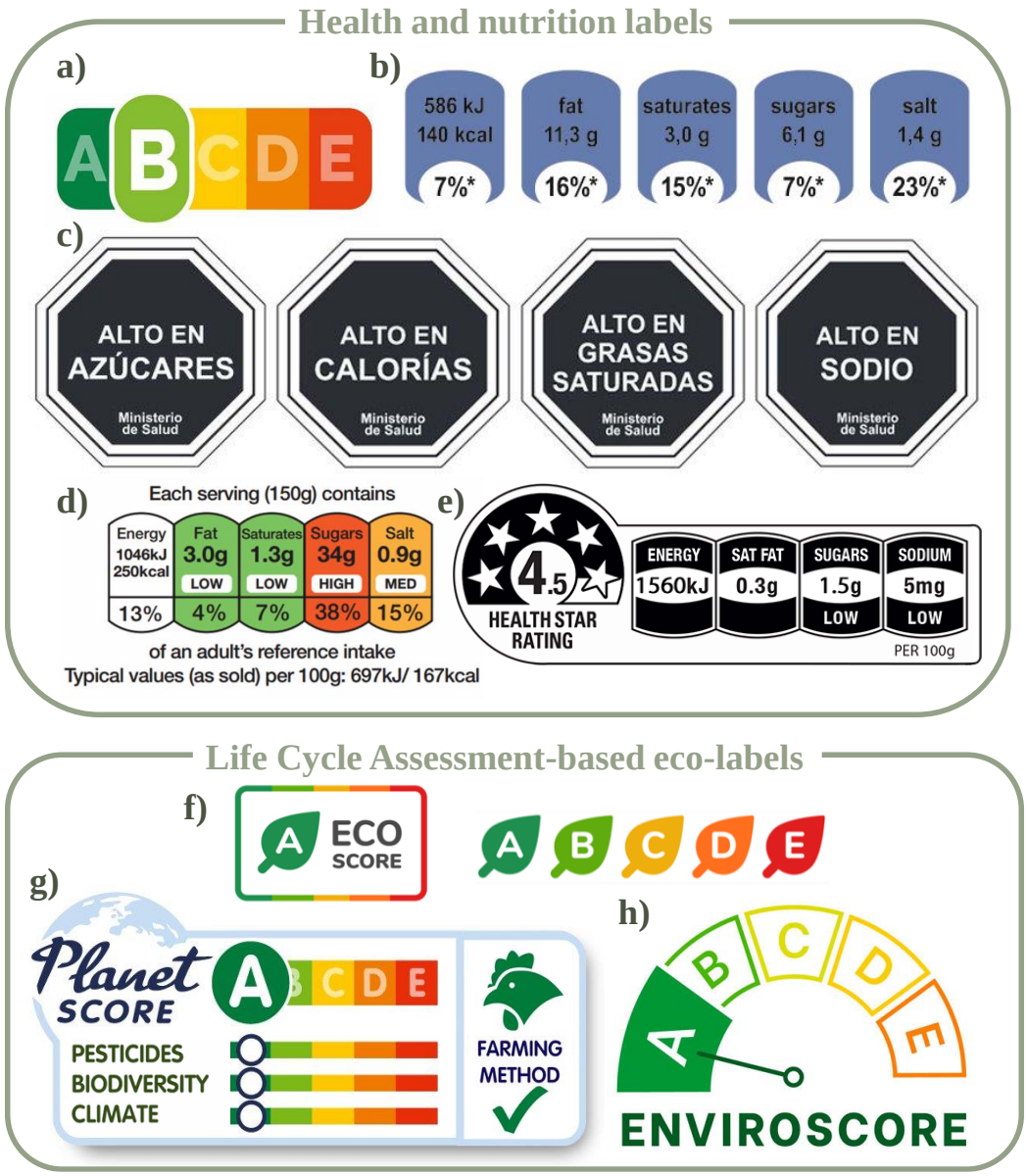



**Figure 2.2**. Overview of health and nutrition labels and life cycle assessment-based eco-labels covered: a) Nutri-Score, b) Reference Intakes, c) Warning Signs, d) Multiple Traffic Lights, e) Health Star Rating, f) Eco-Score, g) Planet-Score and h) Enviroscore.

The RI label started to be implemented in 2014 in Europe as an alternative for the Guideline Dietary Amount (GDA) originally designed in 1996 in the United Kingdom. Both are based on showing the consumer the relative daily contribution as a percentage of the main nutrients that make up the food. Originally, the GDA was based on values that varied for adults according to sex and for children, whereas the RI system is based on a single set of nutrients for an adult woman with no special dietary requirements with a CI of 2000 kcal, 70 g of total fat (20 g of them saturates), 260 g of carbohydrates (90 of them

sugars), 50 g of proteins and 6 g of sugars (FoodDrinkEurope, 2014). Thus, although it was intended to achieve harmonization across Europe in the way the nutritional information provided to consumers is represented, the change has rendered it unrepresentative for specific audiences. This is of concern in addressing some of the critical dietary problems relevant today, such as the increase in childhood obesity. Therefore, the information provided by this label should be understood as a general recommendation. However, the understanding and interpretation of the information can be complemented and enhanced by the MTL label (Talati et al., 2019). The abovementioned label consists of the fat, saturated fats, sugar and salt content being represented with traffic lights colors, i.e., green, amber and red, depending on their relative amounts: low, medium and high, respectively. The design of the MTL label is then easily understandable to consumers, making it more effective in discouraging the consumption of certain foods with a poorer nutritional profile by associating the color red with harmful to health, compared to other types of food labels (Acton et al., 2022).

The WS label consists of the display of short warning phrases contained in octagonal black and white signs, starting with "high in" followed by "calories", referring to products with high energy content, as well as specific nutrients of concern: sugars, saturated fats and sodium. This FoP label was first implemented in Chile in 2016 in connection to the Chilean Food Labeling and Marketing Law, with the aim of creating a regulatory framework that promotes healthy consumption patterns (Reyes et al., 2019). Subsequently, the recommended amounts of energy, sodium, sugars and saturated fats became increasingly restrictive, with limits being lowered after two gradual updates in 2018 and 2019 (MINSAL, 2022). Since then, many countries on other continents, such as Europe, Asia or Oceania, have decided to follow the example and apply it to their products. Part of the international influence comes from its ambition to be mandatory for all products containing soy, milk, peanuts, eggs, seafood, fish, gluten or tree nuts in their ingredients or used in their production. In fact, this has forced some food companies to reformulate their products so that the WS label does not appear (Quintiliano et al., 2020). On the negative side, relevant information is lost by not specifying the limits to which the warnings apply. In addition, although Chilean consumers consider the WS label useful and take it into consideration when configuring their shopping basket, it was also observed to have a greater impact on reducing purchase intentions for sugary beverages, flour-based foods and dairy products than for other types of labeled products (da Silva et al., 2022).

The Nutri-Score began to be displayed on food products on a voluntary basis following a decision by the French government in 2014, although it was first implemented in 2017. Since then, this labeling system has been recommended by several European countries, the European Commission and the WHO. It consists of simply assessing the overall nutritional composition of foods by means of a final value represented by a letter associated with a color. This value is placed in a range of five possibilities to rank products from best to worst: A (dark green), B (light green), C (yellow), D (orange) and E (red) (Hercberg et al., 2021). To determine the final score, certain nutritional components are

considered positive, such as fruits, vegetables, nuts, legumes, fiber, protein, rapeseed, walnut and olive oil. On the other hand, high energy density, sugar, saturated fat or salt are considered negative. Thus, a direct comparison between foods of the same category can be made at a glance on the front of the package, including the possibility to evaluate beverages (De Temmerman et al., 2021). However, there are other countries that oppose this label because of the algorithm it uses to rate foods. Some of these criticisms have been addressed following an update in 2022. This new version consisted of the modification of several aspects, such as the amount of content of some nutrients, the limits between categories, as well as a simplification to obtain the final calculation (Scientific Committee of the Nutri-Score, 2022). Nevertheless, a number of drawbacks of this labeling system remain. One of the most controversial would be not taking into account the degree of processing or the addition of additives. On the other hand, Nutri-Score does not take into account the contribution of other health-promoting components, such as vitamins or minerals. Likewise, it also does not consider additional sustainability aspects related to food, e.g., organic production or local origin (Włodarek and Dobrowolski, 2022).

The HSR system was introduced by the Australian and New Zealand governments in 2014. It is based on a scale that works in half-star increments, with 5 stars being the maximum and half-star being the minimum. In this way, a higher number of stars translates into a healthier product, as it increases with the amount of certain positive nutrients in a diet, such as fiber or protein, the amount of vegetable matter or legumes it contains, among other factors, while it decreases with the amount of certain risk nutrients (e.g., sugar and saturated fats). There is a basic version that shows only the number of stars obtained, and an advanced version that also shows the amounts of the main nutrients (Food Standards Australia New Zealand, 2023). The calculation of stars has been the subject of debate in the scientific community in relation to certain aspects. On the one hand, it takes into account the total amount of sugars, without distinguishing between natural sugars and added sugars, which is detrimental to certain products, such as dairy products. On the other hand, certification using the star rating system was criticized because it uses a certain amount of the product as a reference so that the final value obtained is as high as possible. In addition, the voluntary nature of the star rating system means that it is mostly shown on products with high scores, so it does not discourage the consumption of unhealthy products (Lawrence et al., 2019). Therefore, after 5 years of implementation, a revision of the algorithm has been conducted. Among the modifications implemented is the sugar and sodium content of the products to be certified (Food Standards Australia New Zealand, 2020).

These five health and nutrition labels have been compared in several papers in the literature. For example, one comparative analysis showed that the MTL label was the most positively perceived by consumers in terms of liking, trust, understandability, and desire for mandatory labeling (Talati et al., 2019). In contrast, a more recent study showed that the Nutri-Score was the label that generated the most attraction and aversion, followed by the MTL label. It was also concluded that these FoP labels are effective in

guiding consumers both towards healthier foods and away from those with poorer nutritional content (Pettigrew et al., 2023).

Nutrition labels should encourage healthier food choices, although this should be accompanied by educational campaigns from an early age (Ayaz et al., 2021). Furthermore, despite the increasing use of nutrition and other health-related labels on commercially available food products, the extent to which they improve health through reformulations is limited to small reductions in calories, salt, sugar, and saturated fat in certain food categories (Braesco and Drewnowski, 2023). On the other hand, one study concluded that consumers tend to prefer food labels related to environmental and social responsibility over other nutritional aspects (Tobi et al., 2019).

2.3.2. Eco-labels

Ecolabeling of products allows producers to highlight their specificities or advantages in terms of environmental impact throughout their life cycle, to inform and encourage consumers to make greener choices. Ecolabels are therefore communication tools that play a key role in making both production and consumption more sustainable (Wojnarowska et al., 2021).

On the producer side, social pressure to meet consumer demand for environmentally friendly products is a key driver. In addition, this can be associated with an increase in product value, which in turn is associated with a higher price. On the consumer side, ecolabels are often associated with higher-priced products and, although there is a willingness to pay for them, knowledge, awareness and trust are important factors in explaining the gap between intention and behavior (Meis-Harris et al., 2021).

Recently, LCA-based eco-labeling systems for food products have proliferated, especially in European countries, such as Enviroscore, Eco-Score or Planet-Score. Moreover, these three follow a visual representation very similar to that of Nutri-Score, with a score ranging from A (the preferred option) to E (the option to avoid) in a range of colors from green to red, although there are some differences.

Enviroscore is a recent eco-certification launched by academic and research institutions in the Basque Country (Spain) and the Netherlands, in collaboration with the European Institute of Innovation and Technology and the Basque Government. Enviroscore has been developed based on the PEF methodology, in which a set of normalization and weighting factors have been defined to aggregate 16 environmental impact categories into an Environmental Footprint Single Index (EFSI) for food and beverage products of the European food basket. The thresholds for each of the five categories (i.e., A, B, C, D and E) were defined according to the EFSI value thanks to the consultation with a panel of experts and other stakeholders using the Delphi method (Ramos et al., 2022). Eco-Score was launched in 2021, after being driven by a number of independent entities in France. In terms of its estimation, it is very similar to Enviroscore, considering the PEF method for the integration into a single value of 16 different impact categories. However, Eco-Score goes a step further by granting a bonus

or a reduction to the final score obtained through a series of criteria, such as the seasonality of ingredients, the percentage of recyclability of packaging or modes of production (e.g. holding the European Ecolabel) (Eco-Score, 2021). In addition, a social experiment was recently carried out in which 1 out of 4 shoppers was persuaded to make a more sustainable purchase thanks to the recommendations provided by this certification. Despite this, a more ambitious version, in which it was accompanied by other information such as the distance to the place of production or the absence of genetically modified ingredients, led to information overflow and a rebound effect (Weber, 2021).

In the case of Planet-Score, it was launched by the French Technical Institute for Organic Agriculture with the support of 16 non-governmental organizations in 2021. The final score is composed of 12 impact categories divided into 4 groups: (i) environmental health and toxicity, (ii) biodiversity and ecosystems, (iii) climate, carbon, and (iv) resources. In addition, three sub-indicators appear as comparability criteria between food products within a given category: pesticides, biodiversity and climate, which take into account aspects related to the use of pesticides and antibiotics, deforestation, local origin or agricultural practices, among others. Along with the above, an additional indication appears as to whether it complies with an animal welfare certification (Planet-Score, 2021).

However, there are several barriers to the application of these eco-labelling procedures, such as the need for qualified personnel, the workload involved in estimating the indicators and the difficulty in many cases of obtaining reliable data (Marrucci et al., 2021). Furthermore, eco-labels often focus on one or several specific environmental aspects of the product, so their combination with other regulatory instruments is necessary to extend this limited focus of action (Yokessa and Marette, 2019). In this context, the influence of choosing a shopping basket that is both healthy and environmentally sustainable was assessed using a combined Nutri-Score and Eco-Score approach. The study concluded that FoP labels, when accompanied by recommendations in the form of short messages, have the dual effect of encouraging consumers to consume foods that are more nutritious and less harmful to the environment (De Bauw et al., 2021). Based on the issue abovementioned, apart from the environmental assessment of products, eco-labels should take a holistic view of sustainability beyond the environmental assessment of products, which would broaden the pool of potential buyers to include those concerned with other aspects (Iraldo et al., 2020). To this end, composite indicators are potential candidates for implementation in the food industry, integrating, for example, environmental impacts along with nutritional performance in an easily understandable way to facilitate an effective communication channel between producers and consumers. However, composite indicators are not without their drawbacks, for while there is a gain in broadening the focus of the study and the interpretation of the results, there is also a loss in identifying the main hotspots (Barclay et al., 2019).

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# Chapter 3

## *Objectives of the thesis and roadmap*

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# Summary

Three lines of action have been proposed as strategies to overcome the shortcomings when assessing and communicating sustainability identified in **Chapter 2**. Consequently, a series of case studies of the seafood and dairy sectors in the context of the Galician region in Spain have been evaluated to address the following objectives: (i) the creation of new analytical perspectives that broaden the focus of environmental studies conducted so far in the food industry, (iii) the development of methodological frameworks to propose policies based on holistic approaches, and (iii) the proposal of composite indicators and eco-labels to improve communication channels between stakeholders in the food industry. All these actions are intended to contribute to a more sustainable model of food production and consumption.

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### 3.1. Objectives of the thesis

The food industry is of great economic and social importance. On the one hand, it is a sector that demands a very high number of jobs and therefore creates wealth. On the other hand, eating habits are a fundamental part of the lifestyle of any community. However, food production, transportation and cooking have several environmental impacts. In this regard, the LCA turns out to be a helpful tool for the assessment of food products, identifying the main hotspots throughout the supply chain and allowing proposed improvements strategies.

Notwithstanding, some aspects need to be improved with respect to the LCA methodology when analyzing food production systems, such as the need to include other aspects beyond environmental impact categories. In addition, the FU of LCAs of the food items need to show their true function in nutritional terms, leaving aside the one based on mass or monetary terms. Likewise, the above should be accompanied by ways of communication between stakeholders through composite indicators and eco-labels to promote a more sustainable food production and consumption system.

Hence, the main objective of this thesis is to promote a more sustainable model of food production and consumption through the improvement of the LCA methodology based on the main drawbacks identified, as well as the creation of effective communication channels between producers and consumers in the food industry. To this end, a series of actions have been proposed and applied to a series of case studies constituted by the seafood and dairy sectors in the context of the Spanish region of Galicia:

(i) To create new analytical perspectives that broaden the focus of the environmental studies in the food industry carried out so far. In this regard, it is of paramount importance to include additional aspects in the environmental impact profile of food products. Consequently, it is necessary to broaden the focus of the study from an analysis of individual environmental indicators to a multi-indicator perspective, with the purpose of including other aspects: nutritional features (**Chapter 4**), food security (**Chapters 5** and **7**), ecosystem services (**Chapter 6**), economic concerns (**Chapter 7**) and CE (**Chapter 8**).

(ii) To develop methodological frameworks with the aim of proposing policies based on holistic approaches. In relation to this issue, methodological guidelines were developed focusing on the interrelationships between food production, water consumption and energy requirements, i.e., WEF nexus (**Chapters 4** and **5**), the entire carbon cycle of fish, considering not only its CF related to fishing activities, but also the blue carbon avoided to be sequestered in the form of an ecosystem service (**Chapter 6**), as well as on the relationships between the concept of sustainability and CE (**Chapter 8**).

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(iii) To propose composite indicators and eco-labels for improving the communication channels between stakeholders in the food industry. Concerning this aspect, simple communication channels on food sustainability between academics, producers and consumers should be established to create effective links to build more awarded communities. For this purpose, both easily understandable composite indicators (**Chapters 4**, **5**, **7** and **8**) and an eco-label design (**Chapter 4**) have been proposed.

## 3.2. Roadmap

The specific methodological limitations which have been identified regarding the application of the LCA into the food industry have established the roadmap to be followed, since these have been addressed throughout the chapters of the thesis. A more detailed description by each chapter is shown, while a summary appears collected in **Figure 3.1**.

- Chapter 1 describes the relationship between the food industry and the three pillars of sustainability: society, economy and environment. To this end, it highlights the fundamental role of this economic activity, focusing on the Spanish region of Galicia, in terms of income and employment generation. It also describes a series of environmental impacts associated with the food production and supply chain, emphasizing its role as a driver of CC. In this context, it is essential to focus on feeding the population through sustainable consumption patterns. To this end, the main actions recommended by international organizations to achieve sustainable diets are summarized. On the other hand, food guides that try to inform consumers about healthy eating habits are analyzed, describing the role of food pyramids and how they have evolved over the years to include lifestyle habits. Finally, the two main diets established in Spain are described, according to their socio-cultural characteristics: the Mediterranean diet and the European Atlantic diet.

- Chapter 2 begins with existing ways of assessing and communicating sustainability of food products. In this regard, it first highlights the fundamental role of the LCA methodology in assessing negative environmental impacts. Next, a description of the main barriers of the LCA are identified when assessing food production systems, such as the no consideration of positive aspects, the overlooking of socio-economic aspects or not addressing their nutritional function. In addition, in terms of communication, food labels tend to present information in isolation, making a strong distinction between environment and health and ignoring their interrelationship in achieving a sustainable diet.

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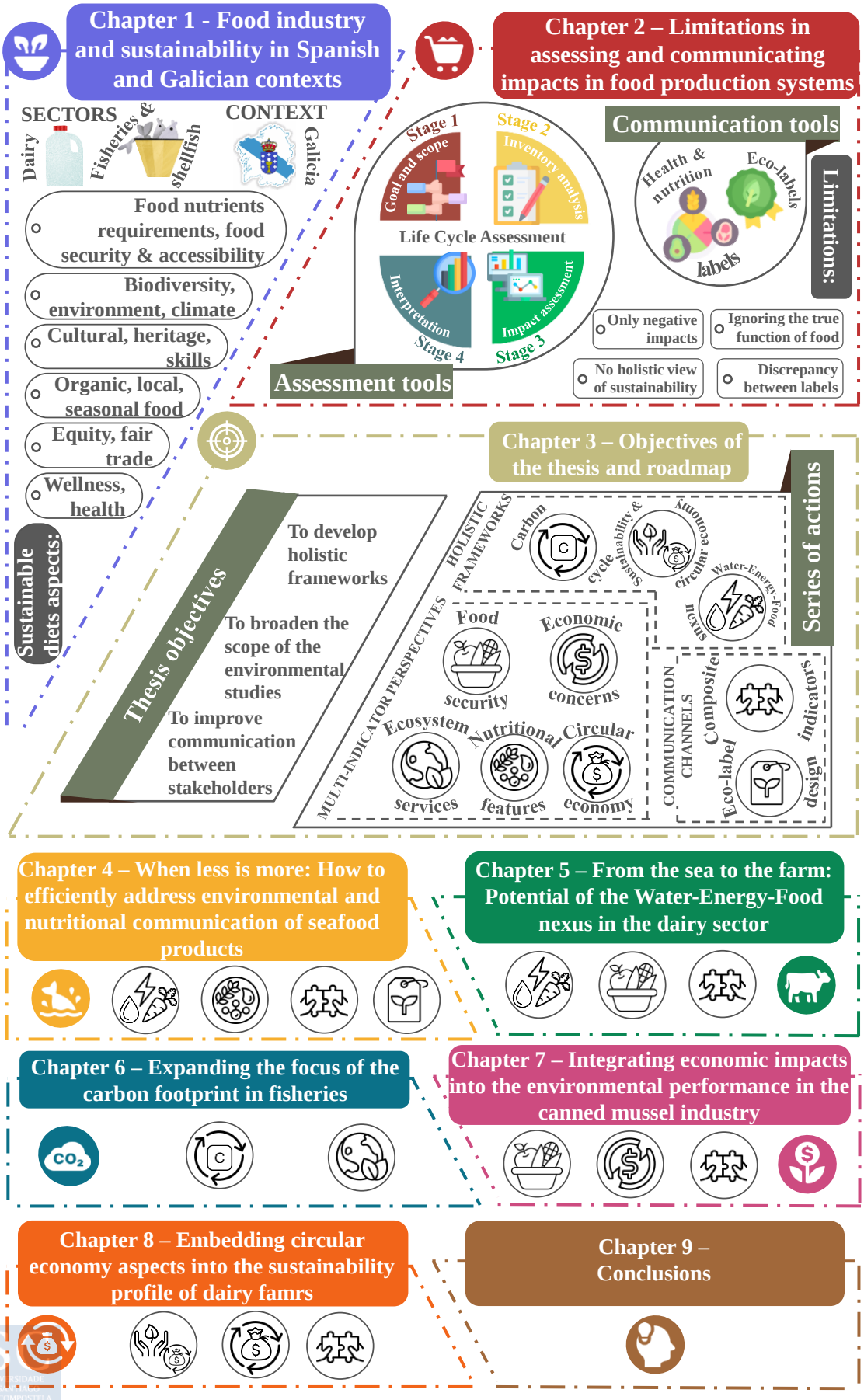



**Figure 1.1**. Roadmap of the thesis chapters.

- Chapter 4 recommends a series of methodological guidelines to be followed to establish a common LCA procedure applied to products from the fishing, aquaculture and processing industries. It then proposes that seafood products should be assessed by means of a single indicator, expressed as a percentage, which is easily understandable to the general public and presented in the form of an eco-label. To this end, an approach based on the WEF nexus is used, taking into account both the main environmental impacts associated with this type of product and their nutritional benefits. Finally, the results of a series of case studies located in the European Atlantic area are presented through a sensitivity analysis.

- Chapter 5 adapts the methodology described in Chapter 4 to estimate an index of the WEF nexus for the dairy sector. In this way, environmental sustainability and productivity level are jointly evaluated to make a comparative assessment of 100 farms in Galicia. In addition, different improvement strategies are proposed to improve the composite indicator: modification of fodder formulation, addition of feed additives that lead to a reduction of GHG emissions during the digestion process and implementation of an animal welfare program that contributes to the reduction of food waste caused by mastitis.

- Chapter 6 aims to estimate the carbon cycle associated with mackerel fishing, which is subsequently processed for sale. To this end, the impact of this economic activity in terms of GHG emissions is quantified by conducting an LCA to estimate its CF. In addition, the approach is extended to include the blue carbon that is prevented from being sequestered due to fishing activities. This blue carbon is understood as the ecosystem service of sequestering the carbon contained in the body of the fish, which is remineralized as a result of its natural death (without predation) when it reaches the seabed. Based on the results of total carbon sequestered, a series of improvement strategies are proposed, based on reducing the CF of the fishing fleet, as well as extending the closed period, making a change in dietary patterns to replace the protein deficiency of fish with other foods.

- Chapter 7 focuses on the aquaculture production of mussels in rafts in Galicia. In this context, an environmental assessment is conducted using a series of indicators for a specific product: OCPM. Likewise, the monetary impacts are evaluated according to the mitigation measures related to the reduction of their environmental impacts. Then, a comparative evaluation of, on the one hand, the margin of improvement (from an environmental and economic point of view) compared to a non-organic production system is carried out. On the other hand, hypothetical cases of application of a series of improvement actions promoted by the EU have also been considered, based on the improvement of the recycling rates of the materials that make up the product packaging and the reconfiguration of the energy mix in Spain through the promotion of renewable sources. Finally, the features of the canning sector in Galicia are described, highlighting the trends in the production and consumption of this kind of

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product and the economic potential of the sector. All this with the aim of guaranteeing food security (physical and monetary) through canned seafood products.

- Chapter 8 proposes a methodological framework for integrating circularity and sustainability indicators into a single composite index. To do so, it is necessary to assess sustainability from an environmental, social and economic perspective. On the other hand, a circular system is understood as one that minimizes the use of external resources, maximizes waste prevention and optimizes both production and consumption. Furthermore, given the importance of the dairy sector in terms of biodiversity loss, land use change and GHG emissions, it was decided to select 50 Galician dairy farms as a case study. The sample is divided into 5 groups of equal size to establish a ranking to identify trends and hotspots from the point of view of sustainability and circularity.

- Chapter 9 provides a synthesis of all the results of the thesis as a whole based on the main findings and draws general conclusions in an integrated manner based on the results of each chapter.

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# Chapter 4

## *When less is more: How to efficiently address environmental and nutritional communication of seafood products**

* This chapter is based on the following publication: **Entrena-Barbero, E.**, Ceballos, S., Cortés, A., Esteve-Llorens, X., Moreira, M.T., Villanueva-Rey, P., Quiñoy, D., Almeida, C., Marques, A., Quinteiro, P., Dias, A.C., Laso, J., Margallo, M., Aldaco, R., Feijoo, G. (2023). Methodological guidelines for the calculation of a Water-Energy-Food nexus index for seafood products. Science of the Total Environment, 877, 162845. https://doi.org/10.1016/j.scitotenv.2023.162845

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# Summary

Life cycle indicators have emerged as useful tools for identifying and communicating the environmental impacts of a system because they are accessible and intuitively understandable by consumers. However, their focus on a single environmental problem is one of their main drawbacks. In addition, LCA studies have demonstrated a lack of homogeneity in addressing impacts associated with seafood production systems, which are often assessed individually. To address these issues, the concept of the WEF nexus has raised awareness of the links between universal rights to clean water, energy security, and food.

Therefore, the objective of this chapter is, on the one hand, to provide technical guidance to shed light on the harmonization of LCA studies applied to the seafood sector and, on the other hand, to propose a methodology to estimate a WEF nexus index (WEFni). To this end, an integrative perspective was adopted, selecting four indicators to be integrated into a single score varying in percentage: carbon, water, energy and nutritional footprints. Likewise, the WEFni was presented in the form of an easy-to-read eco-label for the comparative evaluation of seafood products, thus creating a useful communication channel between stakeholders: producers and consumers. In addition, the methodology was applied to different case studies of fishery, aquaculture and processing production systems in the European Atlantic area in the framework of the NEPTUNUS project.

Finally, a sensitivity analysis was conducted according to a caloric and edible FU, as well as the modification of the weighting factors assigned to each footprint, in which significant variations in the WEFni of most of the case studies were reported. Therefore, although the methodological guidelines supporting the WEFni have great potential to serve as an eco-labelling tool for other food products, certain aspects should be re-evaluated, such as additional socio-economic indicators, to establish a solid benchmark for conducting comparable analyses.

**Keywords**

Environmental footprints | Nutritional index | Composite index | Eco-label | Seafood sector

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### 4.1. Methodological guidelines for the proposal of a Water-Energy-Food nexus index for seafood products

The "ecological footprint" aims to quantify the environmental impacts associated with human activities (Moffatt, 2000). Since the development of this concept, several footprints have emerged, most of them based on the LCA methodology (Hauschild et al., 2018). Moreover, footprints can be applied in a wide variety of contexts: from agri-food systems (Notarnicola et al., 2017) to cities (Rama et al., 2021). According to Hauschild et al. (2018), their main strengths lie in the fact that they are (i) suitable for communicating information to non-environmental experts, (ii) accessible and intuitive, and (iii) provides a rough estimation when little data is available. Footprints can also raise environmental awareness and provide a link between LCT and policy makers (Ghita et al., 2018), but focusing on a single environmental problem is one of their main weaknesses.

In terms of LCA literature focused on the seafood sector (i.e., fisheries, aquaculture, and processing), these have proliferated over the past two decades. Despite this, there are currently certain discrepancies in the way they are addressed, such as the definition of the system considered, its boundaries or function. In addition, the impact categories considered are often evaluated individually, without a global analysis highlighting their interrelationships to obtain more solid and representative results (Ruiz-Salmón et al., 2021b). However, the first steps towards a common LCI have been taken to provide a standardized framework (Avadí et al., 2020).

Consequently, on the one hand, the assessment of environmental impacts of seafood production as independent indicators may lead to limited interpretations, although a combination of them, taking into account their synergies, is of interest to broaden the scope of the study. On the other hand, the consideration of taking a holistic view to integrate the positive nutritional contributions of these foods with their environmental impacts remains largely unexplored. For example, in the case of fisheries, decarbonization policies focus on quantifying GHG emissions. However, other positive contributions associated with fish consumption, such as the low proportion of GHG emitted per kg of protein provided, are often overlooked (Entrena-Barbero et al., 2022a).

Based on these premises, the concept of "WEF nexus" arises with the aim of promoting the inseparable links between resource use to provide the basic and universal rights of food provision, water supply and energy security (Biggs et al., 2015). Associated with the nexus approach underlies the idea of recognizing synergies and trade-offs in resource management rather than prioritizing specific resources (Proctor et al., 2021). Moreover, in recent years, the food industry has become an object of study to improve the current situation due to the multiple obstacles it has to address, such as food waste (Kibler et al., 2018), high levels of pollution (Parker et al., 2018) or food shortages in the supply chain (Singh et al., 2021). In relation to the latter, seafood can be crucial to tackle malnutrition due to its high nutritional value (Golden et al., 2021). However, fisheries also face a number of sustainability challenges related to the recovery of fish stocks

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(Worm et al., 2009), the financial stability of fishermen (Holland et al., 2020), as well as the consequences of CC (Plagányi, 2019).

**Table 4.1**. Main features of the Water-Energy-Food nexus index methodology applied to seafood products. Own elaboration using data collected from Ceballos-Santos et al. (2024).

| **Features** / **Indicators** | **Environmental assessment** | | | **Nutritional assessment** |
|---|---|---|---|---|
| | Carbon footprint | Water footprint | Energy footprint | Nutritional footprint |
| Goal and scope | Both environmental and nutritional assessments of any activity related to seafood products for human consumption from fisheries, aquaculture or processing sectors | | | |
| Functional unit | 1 kg of seafood, either landed at port or produced at the aquaculture or factory gates, including the associated packaging material for processed seafood products | | | Percentage basis (i.e., 100 g of final product) |
| System boundaries | Cradle-to- (port/farm/factory) gate | | | Not applicable |
| Allocation rules | Mass allocation | | | Not applicable |
| Life cycle inventory analysis | To obtain good quality primary data, surveys are recommended to be completed by the responsible agents for further analysis | | | Nutritional databases |
| Impact categories | Global Warming | Water use (freshwater consumption) and freshwater eutrophication and marine eutrophication (water degradation) | Sum of non-renewable energy (fossil, nuclear and biomass) and renewable energy (biomass, wind, solar, geothermal and water) | Nutrient Rich Food (NRF) index (Drewnowski, 2009) |
| Characterization | Global Warming Potential in a 100-year time horizon (IPCC, 2021) | AWARE (Boulay et al., 2018) for water use and ReCiPe (Struijs et al., 2009) for freshwater eutrophication and marine eutrophication | Cumulative Energy Demand (Frischknecht et al., 2007) | NRF12.2, balance between 12 nutrients to be promoted (protein, omega-3, K, Ca, Fe, Mg, I, Se and Vitamins A, C, D and E) and 2 nutrients to be limited (saturated fat and Na) |
| Units | kg $CO_2$ eq. | µPt (after normalization and weighting of the three impact categories) | MJ | Dimensionless |
| Normalization | Reverse linear normalization of a sample from 0 (highest value of the footprint) to 1 (lowest value of the footprint) (see **Equation 5**) | | | Linear normalization of a sample from 0 (lowest value of the footprint) to 1 (highest value of the footprint) (see **Equation 6**) |
| Weighting factors | 25 % | 25 % | 25 % | 25 % |
| Integration | Sum of the four weighted values: Water-Energy-Food nexus index (0 – 100) | | | |

In this context, the European Union has opted for the promotion of sustainable production as a strategy for the development of the fisheries sector, improving the use of marine resources while enhancing economic and environmental aspects for regions with productive sectors linked to the sea of notable importance, the so-called “blue growth” (European Commission, 2017). Moreover, this strategy has already been applied to

control fisheries management plans, although there are still many problems in biological (depletion of fishing grounds) and economic (low profitability margins) terms (Costello et al., 2016). This has led the fishing industry to incorporate some measures, such as improving resource efficiency through technological advances or environmental certifications (Boonstra et al., 2018). As a result, there is a growing interest in conducting LCA studies of seafood products (Ziegler et al., 2016), despite the fact that there is still no standardized methodology.

The aim of this chapter is therefore to provide technical guidance with the dual objective of, on the one hand, shedding light on the harmonization of LCA studies applied to the fisheries sector and, on the other hand, estimating a WEFni, thus following an integrative perspective for seafood eco-labeling. This composite indicator takes into account both the negative contribution of seafood products according to their environmental impacts (following a multi-footprint perspective): CF, Water Footprint (WF) and Energy Footprint (EF), as well as its positive contribution in terms of nutrient intake thanks to the assessment of a Nutritional Footprint (NF). To this end, the following issues were addressed: (i) selection of the most appropriate functional unit (FU) to make comparisons between seafood products; (ii) definition of the SB, identifying mandatory and optional elements; (iii) consideration of the minimum LCI data required for each stage, as well as the most appropriate allocation factors; (iv) identification of the Life Cycle Impact Assessment (LCIA) methodologies to calculate the selected environmental footprints: CF, WF and EF; (v) nutritional characterization of seafood products to estimate the associated NF and (vi) integration of the four indicators into a single value (i.e., the WEFni) to be presented in the form of an eco-label, which will allow the creation of a communication channel between producers and customers. An overview of the methodology is shown in **Table 4.1** (Ceballos-Santos et al., 2024).

For the proper development of this methodological guide, the following documents were revised: (i) ISO 14040 and ISO 1044 standards on LCA (ISO, 2006a, 2006b); (ii) suggestions for updating the PEF method (Zampori and Pant, 2019); (iii) PEFCR guidance (European Commission, 2018a); (iv) PAS 2050-2:2012 Assessment of Life Cycle greenhouse gas emissions - Supplementary requirements for the application of PAS 2050:2011 to seafood and other aquatic food products (BSI, 2012) and (v) ISO 22948:2020 carbon footprint for seafood - Product category rules (CFP-PCR) for finfish (ISO, 2020).

Finally, these methodological guidelines have been applied to a sample of more than 50 case studies based on the production of seafood through fishing, aquaculture and processing for several countries in the European Atlantic region: Spain, Portugal, France and Ireland (Laso et al., 2022). Furthermore, the results obtained have been presented and evaluated in a sensitivity analysis, thus making available to other LCA practitioners a useful database based on seafood production from a WEF nexus perspective, to promote its reproducibility and the improvement of the methodology proposed in future estimates.

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## 4.2. Assessing the environmental impacts of seafood products

The two international standards related to LCA (i.e., ISO 14040 and ISO 14044) were taken as reference to perform the assessment of the environmental impacts of seafood products. Thus, the procedure was divided into 4 interrelated steps.

### 4.2.1. Goal and scope definition

On the one hand, the aim was to propose common guidelines for the development of LCA studies for seafood products in relation to the calculation of three environmental footprints: CF, WF and EF. On the other hand, the scope covered all activities related to seafood products for human consumption from fisheries, aquaculture or processing sectors, including fresh and preserved products through techniques such as freezing, salting or canning. Therefore, the production of fish oil, fish meal or any other product used for animal feed was excluded.

#### 4.2.1.1. *Functional unit*

As the calculation of the environmental footprint is based on a comparative assessment of seafood products from an environmental sustainability point of view, the following FU was chosen: 1 kg of seafood, either landed at the port or produced at the aquaculture or factory gate, including the associated packaging material for processed seafood products.

#### 4.2.1.2. *System boundaries*

The different approaches that can be considered in an LCA study according to the stages covered in the seafood supply chain are shown in **Figure 4.1**. This guide provides flexibility for LCA practitioners to define the SB, but some rules should be applied: (i) the minimum scope will be cradle-to-(port/farm/factory) gate, including surveys to collect information from fisheries, farming activities or processing facilities, respectively; (ii) life cycle stages included and excluded will be indicated; (iii) a system diagram or flow chart will be provided; (iv) the FU and reference flow will be consistent with the chosen SB (Helmes et al., 2020).

Therefore, to define the different SB in a seafood LCA study, up to three different types of systems were considered possible: fishing, aquaculture and processing. When defining the SB for a fishing system, the vessel operations related to the production, transport and consumption of the required inputs (e.g., coolants, nets, baits, etc.) should be included. Vessel maintenance should also be considered, with vessel construction as an optional element. With this in mind, and based on previous scientific articles, the SB for assessing the environmental impacts associated with fishing activities should include the elements listed in **Figure 4.2** (Avadí and Fréon, 2013; Villanueva-Rey et al., 2018).

For aquaculture production systems, the recommended elements are those shown in **Figure 4.3**, including aquafeed production, where appropriate, and aquaculture operations. For facility construction, this is an optional element due to the difficulty of

obtaining good quality data on capital equipment. In addition, unwanted process outputs, such as wastewater, should be included in the SB, as well as direct emissions from the use of fossil fuels (if these are burned directly in boilers or similar).

As shown in **Figure 4.4**, the SB of the processing systems can be divided into the processing stage (e.g., washing, cooking, freezing, etc.) and packaging operations. The most common elements considered within the SB of the seafood processing systems are electricity, fuel (e.g., diesel or natural gas), water, plastics, chemicals and additives (any element included in the packaging together with the seafood products, such as sauces). For packaging operations, all elements that make up the packaging are relevant (whether the seafood is canned or simply filleted). Items used to transport the seafood through the facility, such as polystyrene trays or wooden pallets, should be considered, taking into account the reuse rate and shelf life. Finally, the treatment of waste generated should be included in the SB. The most common are organic residues that can be converted into products or by-products (e.g., fish guts and bones), and waste from packaging operations (e.g., plastics or aluminum).

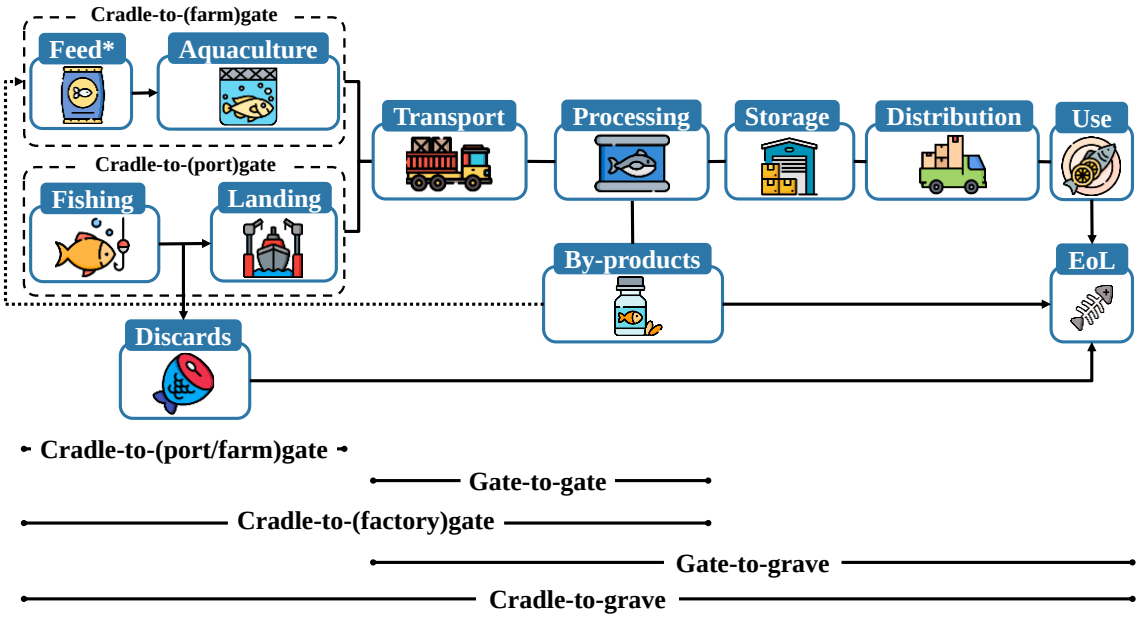



**Figure 4.1**. System boundaries of an LCA study and the stages of the seafood supply chain covered. *External feeding is an optional element in aquaculture, as it is not necessary for some products (e.g. mussels or seaweed). The dotted arrow indicates feeding from by-products.

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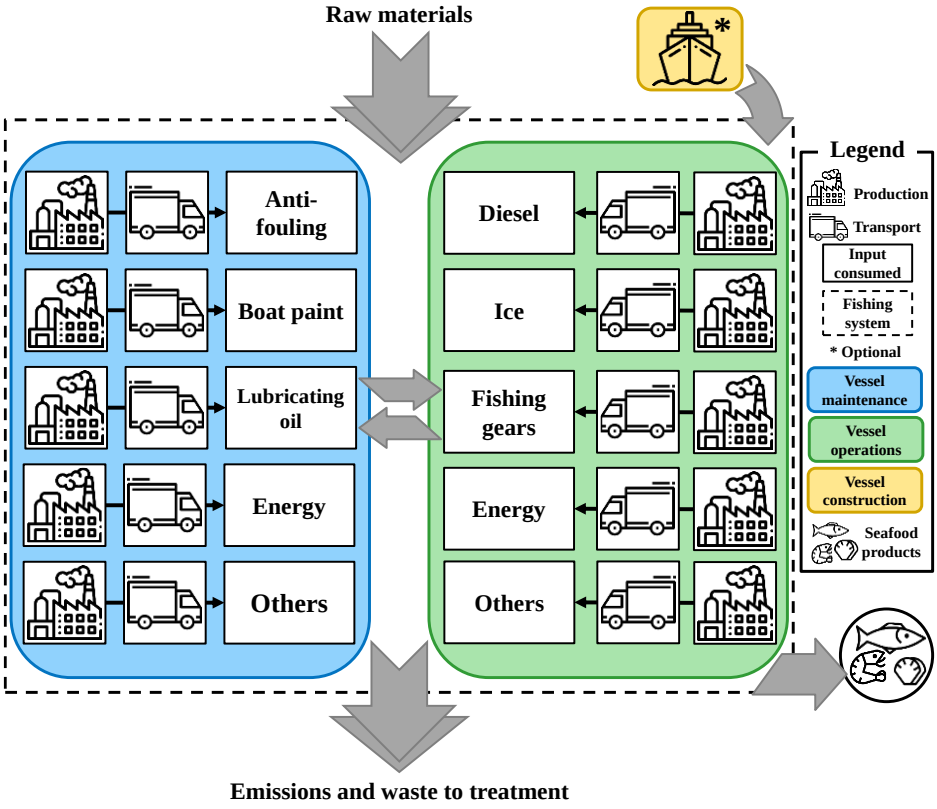
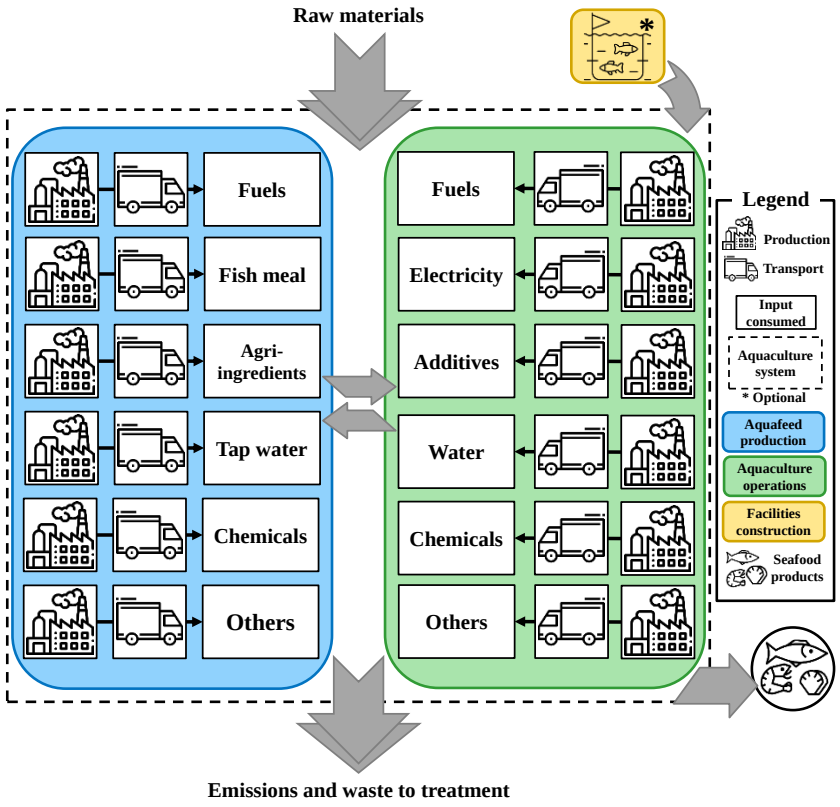



**Figure 4.2**. System boundaries for fishing systems in an LCA study.




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**Figure 4.3**. System boundaries for aquaculture systems in an LCA study.

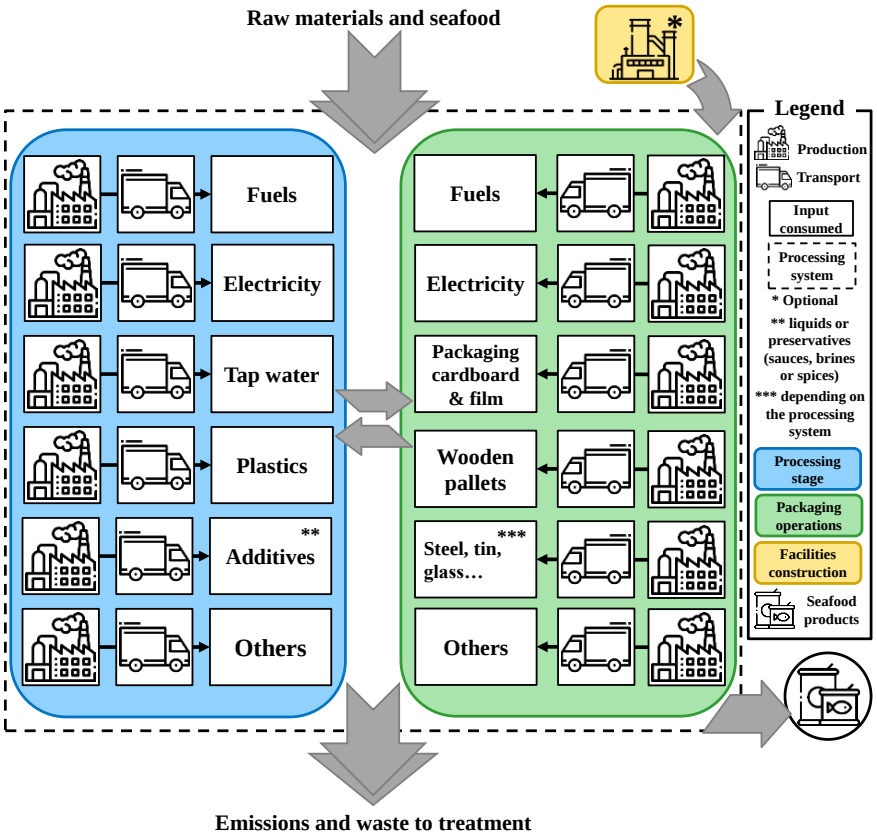



**Figure 4.4**. System boundaries for processing systems in an LCA study.

4.2.1.3. *System boundaries exclusions*

For seafood LCA studies, data on elementary flows to and from systems that contribute to at least 99 % of the reported environmental impacts should be included. A satisfactory test of the exclusion rules is then carried out using a combination of expert judgment, based on experience with similar systems and sensitivity analysis, where it is possible to understand how the ignored input or output could affect the results. An example of this is the construction phase of fishing vessels and aquaculture facilities and processing factories, which are optional items to be included in the SB in this guide. This is due to their long lifetime, which means that their relative contributions are negligible when comparing environmental impacts to annual production levels. However, if good quality data is available, this guide encourages the inclusion of the construction phase. For water consumption, some exclusions can be considered to simplify data collection, such as the amount of water incorporated in seafood meat, as its contribution is unlikely to affect the total WF. In addition, in the case of aquaculture, other aspects, such as the volume of brackish water abstracted and discharged into the same receiving water body, should be excluded as they are not included in the water use impact assessment.

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### 4.2.2. Inventory analysis

#### 4.2.2.1. *Data collection*

Data collection is the most important step in an LCA study, as the LCI directly influences the quality and representativeness of the results (Ciroth et al., 2020). Obtaining primary data should be a priority, although secondary information from scientific studies and databases can be used to fill some gaps and for background processes (e.g., chemical production or electricity generation). To obtain good quality primary data, it is recommended to conduct surveys for further analysis (i.e., skippers for studies and fisheries managers in the case of aquaculture and shellfish processing facilities).

#### 4.2.2.2. *Emissions modelling*

With regard to emissions to air from fuel combustion (usually diesel or natural gas), it is strongly recommended that actual measurement data be collected. This is because fuel emissions are determined, among other uncontrollable factors, by the variability of sea storms and crew expertise (Vázquez-Rowe and Tyedmers, 2013). However, due to the difficulty of monitoring these emissions, they can be estimated using different approaches available in the literature. **Table 4.2** shows an example of the modelling of 1 ton of diesel burned in a ship, using the emission factors for $CO_2$, $CH_4$ and $N_2O$ from the IPCC guidelines (IPCC, 2019a), while sulfur and nitrogen oxides ($SO_X$ and $NO_X$, respectively), particulate matter (PM), heavy metals, among others, were collected by the Air Pollution Emission Inventory Guidebook (EMEP/EEA, 2019a). The latter reference can also be considered to estimate $CO_2$ emissions in relation to the consumption of lubricating oil, resulting in about 613.07 kg of $CO_2$ emitted per ton of lubricating oil consumed, after considering a calorific value of 0.0418 TJ per kg (EMEP/EEA, 2019a).

As for direct emissions to water derived from the use of antifouling paint, these should be quantified according to the recommendations in the fisheries LCA literature: two thirds of the original antifouling paint applied to the vessel (Hospido and Tyedmers, 2005). In addition, its production should be modelled taking into account its average chemical composition. **Table 4.3** shows an example of modelling the production and emissions in relation to the consumption of 1 kg of antifouling paint through the Ecoinvent database v3.8 (Moreno Ruiz et al., 2021).

When collecting specific data for the estimation of the WF indicator, the following parameters should be considered (ISO, 2014): (i) quantities (mass or volume) of water as input (water withdrawal) and output (released in the same watershed in the same period, the same watershed but in a different period, a different watershed or ocean); (ii) types of water resources used (i.e., surface water, seawater, rainwater, groundwater); (iii) data describing water quality parameters (e.g., chemical characteristics); (iv) geographical location of water used or affected (including water withdrawal or release); (v) emissions to air, water, and soil that affect water quality. In addition to the above, the following recommendations should be considered depending on the system being evaluated:

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**Table 4.2**. Emissions related to the combustion of 1 ton of marine diesel oil. Own elaboration using data collected from EMEP/EEA (2019a); IPCC (2019a). Calorific value for marine diesel oil: 42,700 $kJ \cdot kg^{-1}$.

| Pollutant | Unit | Value | Pollutant | Unit | Value |
|---|---|---|---|---|---|
| $CO_2$** | $kg \cdot TJ^{-1}$ | 74,100 | Pb* | g | 0.13 |
| $CH_4$** | $kg \cdot TJ^{-1}$ | 7 | Cd* | g | 0.01 |
| $N_2O$** | $kg \cdot TJ^{-1}$ | 2 | Hg* | g | 0.03 |
| $NO_X$* | kg | 78.5 | As* | g | 0.04 |
| $SO_X$* | kg | 20 | Cr* | g | 0.05 |
| CO* | kg | 7.4 | Cu* | g | 0.2 |
| NMVOC* | kg | 2.8 | Ni* | g | 1 |
| TSP* | kg | 1.5 | Se* | g | 0.01 |
| Benzo(b)fluoranthene* | g | 0.01 | Zn* | g | 1.2 |
| Benzo(k)fluoranthene* | g | 0.01 | PCB* | mg | 0.038 |
| Benzo(a)pyrene* | g | 0.002 | HCB* | mg | 0.08 |
| Indeno(1,2,3-cd)pyrene* | g | 0.001 | PM10* | kg | 1.5 |
| | | | PM2.5* | kg | 1.4 |

**Table 4.3**. Inputs needed and emissions related to the production and consumption of 1 kg of antifouling. Own elaboration using data collected from Hospido and Tyedmers (2005).

| Flow | Unit | Value | **Process** (Moreno Ruiz et al., 2021) |
|---|---|---|---|
| **Inputs From Technosphere** | | | |
| **Materials/fuels** | | | |
| Copper oxide | kg | 0.32 | Copper oxide {RER}\| production |
| Paraffin | kg | 0.30 | Paraffin {RER}\| production |
| Rosin size | kg | 0.34 | Rosin size, for paper production {RER}\| production |
| Sodium silicate | kg | 0.040 | Sodium silicate, without water, in 37% solution state {RER}\| sodium silicate production, furnace liquor, product in 37% solution state |
| **Outputs To Technosphere** | | | |
| **Emissions to water** | | | |
| Copper oxide | kg | 0.21 | - |
| Paraffins | kg | 0.43 | - |
| Silicate particles | kg | 0.030 | - |
| **Waste to treatment** | | | |
| Waste paint | kg | 0.33 | Waste paint {Europe without Switzerland}\| market for waste paint |

- For fisheries systems, direct freshwater consumption during fishing vessel operations required for conservation (e.g., ice consumption) and during fishing vessel maintenance (e.g., vessel cleaning) need to be considered.

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- For aquaculture systems, direct water consumption and water quality degradation are key factors to consider. In the specific case of closed aquaculture systems, water consumption occurs during egg, larval or fry production and during the grow-out phase, and includes water evaporated from the system, incorporated into shellfish and used to wash ponds and equipment. Water quality degradation can occur on-site at aquaculture facilities (Gephart et al., 2017), as well as through the release of eutrophying emissions from fuel combustion

- In the case of processing systems, it is important to consider the direct consumption of freshwater for seafood processing activities (e.g. washing, freezing, etc.), evaporation of water during processing (e.g. cooking, boiling, etc.) and intentional addition of freshwater to the product (e.g. use of water as a preservative liquid for canned products). The direct degradation of water quality is mainly related to the discharge of wastewater from processing activities and the release of eutrophying emissions from fuel combustion.

**Table 4.4**. Consumption demand (in %) by energy source in Spain during the period 2017-19. Own elaboration using data collected from AIB (2020).

| **Energy source** | **Process** (Moreno Ruiz et al., 2021) | **Consumption demand in 2017-19 (%)** |
|---|---|---|
| Renewables (unspecified) | Electricity, high voltage {ES}\| heat and power co-generation, biogas, gas engine | 0.32 |
| Solar | Electricity, high voltage {ES}\| electricity production, solar tower power plant, 20 MW | 1.7 |
| Wind | Electricity, high voltage {ES}\| electricity production, wind, >3MW turbine, onshore \| Cut-off, U | 2.2 |
| Hydro | Electricity, high voltage {ES}\| electricity production, hydro, pumped storage | 1.1 |
| Biomass | Electricity, for reuse in municipal waste incineration only {ES}\| treatment of municipal solid waste, incineration \| Cut-off, U | 0.48 |
| Nuclear | Electricity, high voltage {ES}\| electricity production, nuclear, pressure water reactor | 33.3 |
| Fossil (unspecified) | Electricity, high voltage {ES}\| electricity production, natural gas, conventional power plant | 1.5 |
| Lignite | Electricity, high voltage {ES}\| electricity production, lignite | 7.3 |
| Hard coal | Electricity, high voltage {ES}\| electricity production, hard coal | 13.4 |
| Gas | Electricity, high voltage {ES}\| electricity production, natural gas, combined cycle power plant | 32.8 |
| Oil | Electricity, high voltage {ES}\| electricity production, oil | 5.9 |

Data for electricity mix can be obtained from several sources. First, the supplier-specific electricity product/mix is obtained directly from the utility. In addition, it should be certified in the case of the energy origin assurance statement (e.g., instruments proving the origin of the electricity from renewable sources). Secondly, the country-specific residual electricity mix is modelled on the basis of reliable data. Third, other relevant data can be found in the publications of the International Energy Agency and other relevant national authorities. For example, in the Spanish context within the Atlantic area, the

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database of the Association of Issuing Bodies could be used, considering a sufficiently long period to avoid annual energy fluctuations (e.g., three-year period: 2017 to 2019). In addition, the different energy sources used to generate electricity in Spain should be modelled (see **Table 4.4**).

4.2.2.3. *Allocation strategies*

If a system performs more than one function (i.e., provides more than one good or service), it is considered multifunctional. In the literature on LCA applied to seafood, most studies are multiproduct systems, because several fishing gears catch bycatch species and aquaculture facilities use by-products as feed ingredients or are oriented towards a multi-species farming system. Similarly, it is common for processing plants.

Regarding the different allocation methods, some authors point out that mass content is a straightforward and simple way to allocate environmental loads in a food LCA study, while economic allocation is a good alternative when the fleet is responsible for catching species with large differences in monetary value. In contrast, other authors argue that mass accounting is scientifically implausible and that economic accounting is a rough approximation of the amount of material and energy flows associated with the system under study (Ayer et al., 2007; Winther et al., 2009). Consequently, after reviewing the advantages and disadvantages of the different types of allocation available, the allocation rules recommended in this guide are summarized in **Table 4.5**, giving priority to mass allocation over the economic alternative, since it is the simplest and most repeated method for seafood products, avoiding the natural fluctuation of their market price (Vázquez-Rowe et al., 2011). Thus, as a second option, and if reliable economic data are available, economic allocation can be applied with a minimum average period of three years.

**Table 4.5**. Allocation rules according to the seafood production system.

| Process | Allocation | Modelling instructions |
|---|---|---|
| Fishing co-product allocation | Mass | Despite the selectivity of the fishing gear, several species are caught in addition to the target species. In this sense, the allocation will be made according to the total amount of species caught (including by-catch species). |
| Aquaculture co-product allocation | Mass | Aquaculture operations normally focus on the production of a single species, although in some cases it is possible that several species may be produced together. In such cases, the same procedure as for fisheries allocation will apply. |
| Processing co-product allocation | Mass | Different products can be made from the same species of seafood. For example, hake can be used to produce fillets, tails, fish sticks and croquettes. In this case, the total annual production of each production line is used to determine the allocation factors. In addition, it is important to note that the edible weight should be used to determine the annual production. |

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4.2.2.4. *End-of-life modelling*

The PEF methodology recommends modelling the EoL stage using the Circular Footprint Formula (CFF). This CFF is promoted with the objective of including the entire

life cycle of the material used: the virgin and recycled fractions used in the manufacturing stage, the percentage of the material to be recycled after use, as well as the waste management of the non-recyclable fraction: incineration or landfill disposal (European Commission, 2018a). The formula, the description of the parameters considered, as well as their respective values are available in Annex C of "Suggestions for updating the PEF method" (Zampori and Pant, 2019) for several material flows.

4.2.3. Impact assessment

This section describes the different considerations and calculation methodologies selected for each of the environmental footprints that make up the WEFni: CF, WF and EF. The principles, requirements and guidelines for quantifying and reporting of the CF of a product can be found in ISO 14067 (ISO, 2018b), in line with international standards on LCA (i.e.,, ISO 14040, 14044). In this regard, this guide encourages the use of the last version available of the following characterization method: the 100-year time horizon GW Potentials proposed by the IPCC (IPCC, 2021).

The procedure to calculate the WF of a seafood product should follow the PEF guidance (European Commission, 2018a; Zampori and Pant, 2019). Moreover, according to ISO 14046 (ISO, 2014), the WF profile of a product may include impact categories related to both freshwater consumption and water pollution. Therefore, the WF of a seafood production system should integrate one category for freshwater consumption (referred to as water use in the PEF method) and two categories for water pollution (freshwater eutrophication and marine eutrophication). The PEF method recommends the following characterization methods: AWARE (Boulay et al., 2018) for the water use impact category, and ReCiPe (Struijs et al., 2009) for the freshwater eutrophication and marine eutrophication impact categories. Normalization and weighting should also be performed using the appropriate factors from the PEF guidelines to aggregate the WF impacts into a single indicator resulting from the sum of the weighted results of the three impact categories.

In terms of energy consumption, this can be modelled following different approaches based on the goal and scope of the LCA conducted. Notwithstanding, the assessment method should consider the energy consumed throughout the entire life cycle of a given process, product, or service, both directly and indirectly (e.g., electricity consumption and energy embodied in the production of raw materials, respectively). In this sense, the Cumulative Energy Demand (based on Lower Heating Values) will be the LCIA method implemented to calculate the EF (Frischknecht et al., 2007), as it is consistent with the PEF method.

4.2.4. Interpretation of results

The results of the three environmental footprints obtained can be interpreted individually to identify the main hotspots of the seafood products assessed from an environmental point of view. Subsequently, the CF, WF and EF together with the NF will

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form the basis of a normalization, weighting and integration to obtain a single indicator, the WEFni.

### 4.3. Estimating the nutritional profile of seafood products

To estimate a NF for seafood products, the aim was to characterize them from a nutrient concentration point of view. For this purpose, the Nutrient Rich Food (NRF) index, version NRF9.3, was used as a reference, as it is the indicator that best correlates with the reported benefits of food in terms of nutrient intake (Fulgoni et al., 2009). This index takes into account a balance between the positive contribution of 9 nutrients to be promoted (NP) and the negative contribution of 3 nutrients to be limited (NL) (Drewnowski et al., 2009). Therefore, to calculate the nutritional profiles of seafood products, a modified version of the NRF9.3 index was proposed: the NRF12.2 index, based on 12 NP and 2 NL. Compared to the NRF9.3 index, the NRF12.2 index excluded one NP (dietary fiber) and one NL (added sugars) because they are not present in seafood. Similarly, four NP were included: one fatty acid (omega-3), two minerals (iodine and selenium) and one vitamin (vitamin D), as seafood is an important source of these nutrients in the diet (Burk, 2007; Kris-Etherton et al., 2002; Lock et al., 2010; Nerhus et al., 2018).

For the estimation of the NRF12.2 index, the NP and NL values were relativized according to a set of recommended values (RVs) and maximum recommended values (MRVs), respectively. For this purpose, information was collected by various databases, assuming average values between men and women for an adult person (over 18 years of age), as summarized in **Table 4.6**. Similarly, the NPs were limited to the maximum RV to avoid any benefit from over-consumption. In this way, those seafood products that contain a very high amount of a specific nutrient (e.g., omega-3 in blue fish) do not receive a disproportionately high NF compared to other fish species (e.g., white fish). Finally, the NF of a seafood product "i" was estimated in relation to **Equations 4.1-4.3**, where nutrients are expressed as percentages (i.e., per 100 g of final product).

For processed seafood, liquids or preservatives considered edible (e.g., sunflower oil or tomato sauce) should be included. Otherwise, in the case of non-edible preservative liquids, only the drained weight of the seafood product should be taken into account (e.g., sardines in brine). Thus, the final NRF12.2 index for processed seafood is equal to the weighted sum of each of its ingredients, i.e., the main food (seafood) together with the other additional ingredients (see **Equation 4.4**).

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**Table 4.6**. Recommended values (RV) and maximum recommended values (MRV) per capita. Own elaboration using data collected from *EFSA (2017); **FDA (2020).

| Nutrients to be Promoted (NP) | | Nutrients to be Limited (NL) | |
|---|---|---|---|
| **Nutrient** | **RV (g)** | **Nutrient** | **MRV (g)** |
| Protein* | 57 | Saturated fat** | 20 |
| Omega-3* | 0.25 | Na* | 2 |
| K* | 3.5 | | |
| Ca* | 0.95 | | |
| Fe* | 0.0135 | | |
| Mg* | 0.325 | | |
| I* | 0.000175 | | |
| Se* | 0.00007 | | |
| Vitamin A* | 0.0007 | | |
| Vitamin C* | 0.1025 | | |
| Vitamin D* | 0.000015 | | |
| Vitamin E* | 0.012 | | |

$$NRF12.2_i = NP12_{i,j} - NL2_{i,k} \quad \textbf{Eq 4.1}$$

$$NP12_{i,j} = \sum_{j=1}^{12} \frac{(nutrient_{i,j})_{capped}}{RV_j} \cdot 100 \quad \textbf{Eq 4.2}$$

$$NL2_{i,k} = \sum_{k=1}^{2} \frac{nutrient_{i,k}}{MRV_k} \cdot 100 \quad \textbf{Eq 4.3}$$

Where:

| | |
|---|---|
| i | seafood product assessed. |
| $NRF12.2_i$ | nutrient rich food index (NRF12.2) of the seafood product "i". |
| j | nutrients to be promoted (protein, omega-3, K, Ca, Fe, Mg, I, Se and vitamins A, C, D and E). |
| k | nutrients to be limited (saturated fat and Na). |
| $NP12_{i,j}$ | contribution of "j" according to the seafood product "i". |
| $RV_j$ | recommended value for "j". |
| $(nutrient_{i,j})_{capped}$ | "j" of the seafood product "i" (each "j" is capped at its corresponding RV). |
| $NL2_{i,k}$ | contribution of "k" according to the seafood product "i". |
| $MRV_k$ | maximum recommended value for "k". |
| $nutrient_{i,k}$ | "k" of the seafood product "i". |

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$$NRF12.2_i = \sum_{j=1}^{n} NRF12.2_j \cdot X_j \quad \textbf{Eq 4.4}$$

Where:

| | |
|---|---|
| i | seafood product assessed. |
| $NRF12.2_i$ | nutrient rich food index (NRF12.2) of the seafood product "i". |
| j | ingredient included in the content of the processed seafood product. |
| $NRF12.2_j$ | nutrient rich food index (NRF12.2) of the ingredient "j". |
| $X_j$ | percentage of the ingredient "j". |
| n | number of ingredients that constitute the seafood product "i". |

### 4.4. Eco-labelling seafood products through a Water-Energy-Food nexus index

Once the different indicators had been selected and assessed, a process of normalization, weighting and integration was carried out to obtain a composite index integrating them: the WEFni. On the one hand, normalization was used to express the values of the indicators in such a way that they could be compared among the case studies evaluated. In this sense, a linear percentage normalization (from 0 to 1) can be made by differentiating between the three seafood production systems (i.e., fishing, aquaculture and processing). However, it is possible to analyze other subdivisions within the same system (e.g., fishing gear in fishing systems). For this purpose, the maximum and minimum values of each footprint were taken as a reference. Thus, while the fishery product with the lowest environmental footprint in terms of CF, WF or EF received a score of 1, the rest of the seafood products were proportionally reduced in their scores, taking into account the cases with the maximum environmental footprints with a normalized value of 0. On the contrary, since the NF should be as high as possible, the seafood products with the highest and lowest values become scores of 1 and 0 respectively (see **Equations 4.5** and **4.6**).

On the other hand, with regard to the weighting process, the four indicators in question were considered to be equally representative of the WEF nexus concept, and therefore, with a total of four indicators, each received a relative weighting factor of 25. Their integration was summed, resulting in the WEFni, which scores seafood products with a single value ranging from 0 to 100. The weighting and integration procedures, once the normalized values of the footprints have been obtained, appear in **Equation 4.7**.

$$EnF_{n_i} = \frac{EnF_{max} - EnF_i}{EnF_{max} - EnF_{min}} \qquad \textbf{Eq 4.5}$$

$$NF_{n_i} = \frac{NF_i - NF_{min}}{NF_{max} - NF_{min}} \qquad \textbf{Eq 4.6}$$

Where:

i seafood product assessed.

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$EnF_{n_i}$ normalized value of the environmental footprints (i.e., CF, WF and EF) for the seafood product "i".

$EnF_{max}$ maximum value of the environmental footprints (i.e., CF, WF and EF) within the sample assessed.

$EnF_{min}$ minimum value of the environmental footprints (i.e., CF, WF and EF) within the sample assessed.

$EnF_i$ value of the environmental footprints (i.e., CF, WF and EF) for the seafood product "i".

$NF_{n_i}$ normalized value of the nutritional footprint for the seafood product "i".

$NF_{max}$ maximum value of the nutritional footprint within the sample assessed.

$NF_{min}$ minimum value of the nutritional footprint within the sample assessed.

$NF_i$ value of the nutritional footprint for the seafood product "i".

$$WEFni_i = \sum_{j=1}^{4} Y_{i,j} \cdot W_j \qquad \textbf{Eq 4.7}$$

Where:

i seafood product assessed.

$WEFni_i$ Water-Energy-Food nexus index of the seafood product "i" (0-100).

j footprint (carbon, water, energy or nutritional footprints).

$Y_{i,j}$ normalized value of the seafood product "i" for the footprint "j" (0-1).

$W_j$ weighting factor of the footprint "j" (25 for each footprint).

Finally, the WEFni is expressed in a front-end ecolabelling format applied to seafood products, with the objective of serving as a communication channel for consumers, allowing a narrative of the indicators considered through a single value, as well as direct comparison with other seafood products. Regarding the success and acceptance of the WEF nexus eco-label in the market, two key factors need to be considered: consumer understanding and acceptance, and the interest of retailers in marketing their seafood products (Weitzman and Bailey, 2018). With this in mind, the design was chosen to represent the WEFni in a percentage range (from 0 to 100 %), integrated in a range of 4 colors: red (0-24 %), yellow (25-50 %), blue (51-75 %) and green (76-100 %), see **Figure 4.5**.

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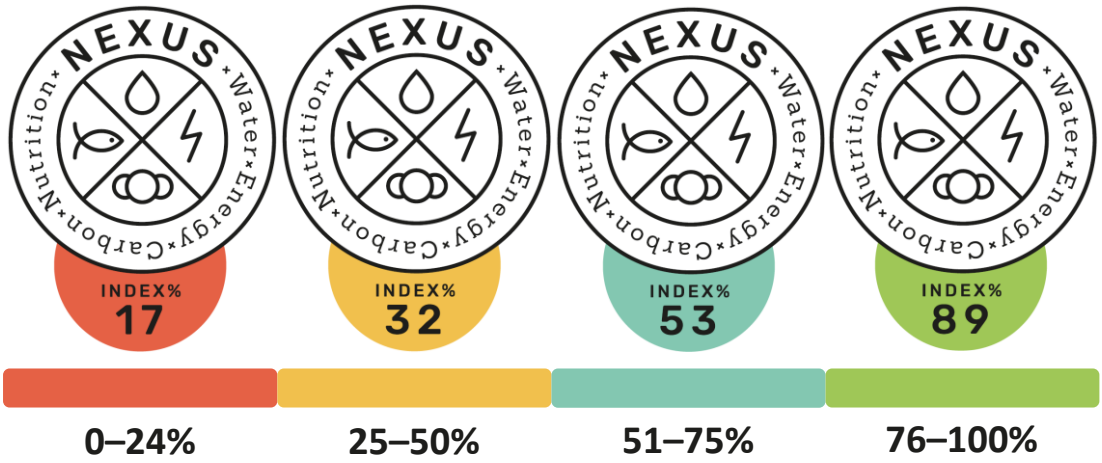



**Figure 4.5**. Design of the Water-Energy-Food nexus eco-label for seafood products applied to four hypothetical case studies.

## 4.5. Application of the methodological guidelines in the European Atlantic region by carrying out a sensitivity analysis

The methodology was applied by the NEPTUNUS project partners to a series of case studies that can be divided into three different systems: fisheries, aquaculture and processing. More than 50 case studies were carried out for fisheries, covering different fishing gears (e.g., trawl, purse seine, pole and line), fish and shellfish aquaculture and freezing, salting, canning or smoking related to processed seafood products. All the case studies were from the European Atlantic area, more precisely from the following countries: France, Ireland, Portugal and Spain. The study period was between 2011 and 2019. Given the exceptional circumstances that occurred in the fisheries sector during the COVID-19 pandemic, in terms of changes in both consumption habits and seafood supply chains, this period was excluded from the sample to avoid misrepresentations of the results (Ruiz-Salmón et al., 2021a). Following the guidelines, the FU was set at 1 kg of seafood either landed at the port, produced at the farm or delivered at the factory gate, including the associated packaging of processed seafood products. The results in terms of both individual footprints (i.e., CF, WF, EF and NF) and the compositive index (WEFni) of each case study can be consulted in Ceballos-Santos et al. (2024).

Later, with the purpose of conducting a sensitivity analysis of the results obtained, two key factors in LCA studies were modified: on the one hand, the FU and, on the other hand, the weighting process. These modifications were applied both individually and jointly, thus obtaining three different scenarios, consisting in the modification of: (i) FU, (ii) weighting process and (iii) both FU and weighting process.

### 4.5.1. Functional unit

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According to the WEFni guide, a mass-based FU was chosen for the seafood assessment for three main reasons: (i) to avoid the common regional price differences over time (Costello et al., 2020); (ii) it has been the most widely used FU in the seafood

LCA literature in the last decade (Ruiz-Salmón et al., 2021c), which facilitates comparisons with other studies; and (iii) it allows for simple and accessible calculations, which promotes reproducibility.

Nevertheless, a part of the mass, in this case 1 kg, does not fully represent the nutritional properties of the food (Weidema and Stylianou, 2020). Therefore, to improve the results, it is essential to include nutritional aspects in the FU of the food production system under evaluation (Heller et al., 2013). Based on this premise, most LCA studies follow three approaches based on (i) single nutrients, such as digestible Protein Content (PC) (Sonesson et al., 2017), (ii) multiple nutrients in the form of composite indicators (e.g., NRF), or (iii) dietary contexts (McAuliffe et al., 2020). Notwithstanding this, when calculating the WEFni, the nutritional profile was covered by integrating a seafood-specific NF (i.e., NRF12.2). Therefore, in this case, it was decided to opt for the estimation of the satiating capacity of seafood products through a caloric- and edible-based FU, called FUce. For this purpose, **Equation 4.8** was applied, taking into account the values of the CI of each sample. In addition, as it is not plausible to make comparisons between species with very different edible portions (EPs), e.g., hake and mussels, this factor was also considered.

Likewise, the $FU_{ce}$ was relativized to the amount of seafood in the form of the calories needed to meet the daily per capita demand according to the reference seafood intake (RSI) suggested in the planetary health diet proposed by the EAT-Lancet commission: 40 kcal (Willett et al., 2019). The values taken into consideration for each case study can be consulted in Ceballos-Santos et al. (2024).

Lastly, two assumptions were taken into account to address the sensitivity analysis. On the one hand, case studies having more than one species as target were disregarded, since averaging both CI and EP would lead to obtaining a $FU_{ce}$ not representative of the case study. In addition, for processed seafood products containing additives or sauces (e.g., olive oil), as these were already assessed through the NF, only the CIs and EPs of seafood species were considered.

$$FU_{ce} = \frac{RSI}{CI \cdot EP} \qquad \textbf{Eq 4.8}$$

Where:

| | |
|---|---|
| $FU_{ce}$ | caloric- and edible-based functional unit (g seafood·(person·day)$^{-1}$). |
| RSI | reference seafood intake per day: 40 kcal·(person·day)$^{-1}$ (Willett et al., 2019). |
| CI | caloric intake of the specimen (kcal·g edible$^{-1}$). |
| EP | edible portion of the specimen (g edible·g seafood$^{-1}$). |

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4.5.2. Weighting process

Considering the different weighting methods commonly used in LCA studies (Andreas et al., 2020), a combination of two techniques was used. On the one hand, panel weighting, which is based on the opinion of a group of people, in this case the NEPTUNUS project consortium. The partners in this project consisted of about 25 men and women LCA practitioners from academia and the private sector with different professional ranks, such as PhD students, professors, junior and senior sustainability consultants, etc. On the other hand, binary weighting, which takes into account zero or equal weights. Consequently, the sensitivity analysis was carried out by giving equal importance to environmental protection and food promotion: a weighting factor of 50 for environmental footprints (with an equal weight of 16.67 for CF, WF and EF) and a weighting factor of 50 for NF.

4.5.3. Sensitivity analysis

The results obtained for the different case studies after performing the sensitivity analysis applied to the FU, the weighting process and the consideration of both approaches, were divided by fisheries (**Figure 4.6**), aquaculture (**Figure 4.7**), and processing (**Figure 4.8**) systems. Moreover, given the large number of case studies to which sensitivity analysis was applied (58), it was decided to group the fisheries and processing case studies by fishing gear and type of processing, respectively. Notwithstanding, the individual results for each case study are compiled in Ceballos-Santos et al. (2024).

Regarding the fishing systems (**Figure 4.6**), when the sensitivity analysis was conducted in relation to the FU, it was observed that all fishing gears, except trawls and purse seines, have decreased their WEFni. This was triggered by the $FU_{ce}$ assigned to each target species. A lower $FU_{ce}$ translates into a lower amount of seafood (in mass) to satisfy the RSI per person per day: 40 kcal (Willett et al., 2019), resulting in a lower environmental impact (i.e., lower CF, WF, and EF) and a higher WEFni. Moreover, the $FU_{ce}$ assigned to each species depends in turn on both its CI and its EP. Thus, it was identified that for several species captured by trawls or purse seines (e.g., saithe, European pilchard or Atlantic mackerel), the lowest $FU_{ce}$ were recorded, varying approximately between 35 and 45 g of catches per person per day. Conversely, more than 90 g of catches per person per day of octopus or common sole are needed to satisfy the RSI, thus leading to the largest reduction for pots and traps, as well trammel net in terms of WEFni.

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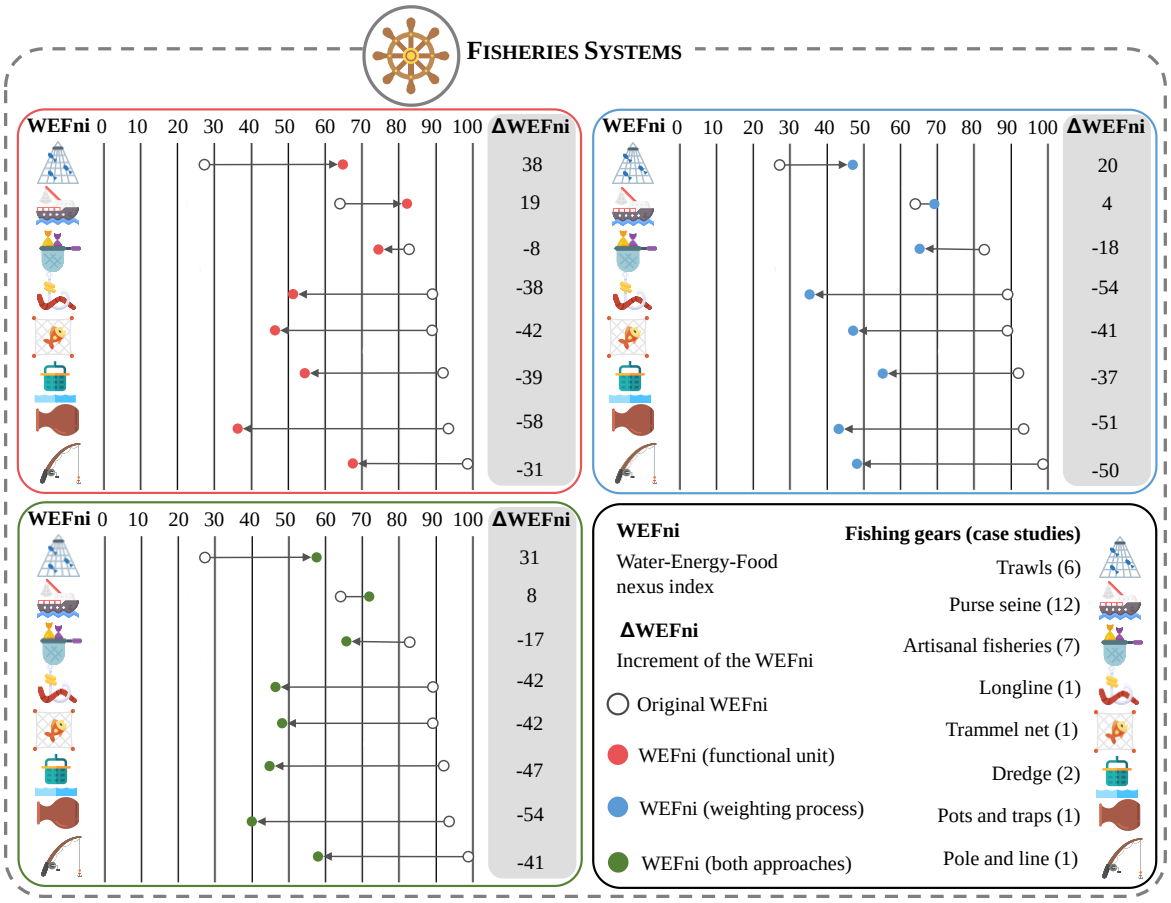



**Figure 4.6**. Water-Energy-Food nexus index results of the sensitivity analysis for fisheries systems. Own elaboration using data collected from Ceballos-Santos et al. (2024).

Similar results were reported when the weighting process was modified. In this case, the NF associated with each species now turns out to be the key factor in increasing or decreasing WEFni. This was because, by giving equal importance to the environment and food pillars, the weighting factors assigned to each environmental footprint (i.e., CF, WF, and EF) has decreased with respect to the baseline scenario (from 25 % to 16.67 %), while the nutritional aspects have seen their contribution double: from 25 % to 50 %. Therefore, the increase in the WEFni for trawls and purse seines can be justified from the point of view that the target species of these fishing gears were those with the highest NFs, showing values usually higher than 270 for the NRF12.2 (e.g., Atlantic cod, chub mackerel and horse mackerel). Consequently, this positioned them above the average for the entire sample of fishing systems: around 230. On the opposite side were the low NFs for European hake (213.61) and skipjack tuna (210.32), implying that longline (minus 54 points) and pole and line (minus 50 points) revealed the largest reductions.

Likewise, when both approaches (FU and weighting process) are considered within the sensitivity analysis of fisheries systems, a similar trend was observed once again, being trawling and purse seine the only groups which increased its WEFni by 31 and 8 points, respectively. Conversely, pots and traps, dredge, longline and trammel net were the groups with the highest reductions (from 54 to 42 points). Finally, when all fishing gears are compared with each other, artisanal fisheries and purse seine benefit the

most from the sensitivity analysis, moving from sixth and seventh place, respectively, to at least the top two according to the WEFni. In the opposite situation was pots and traps, which dropped from second place to the bottom of the ranking.

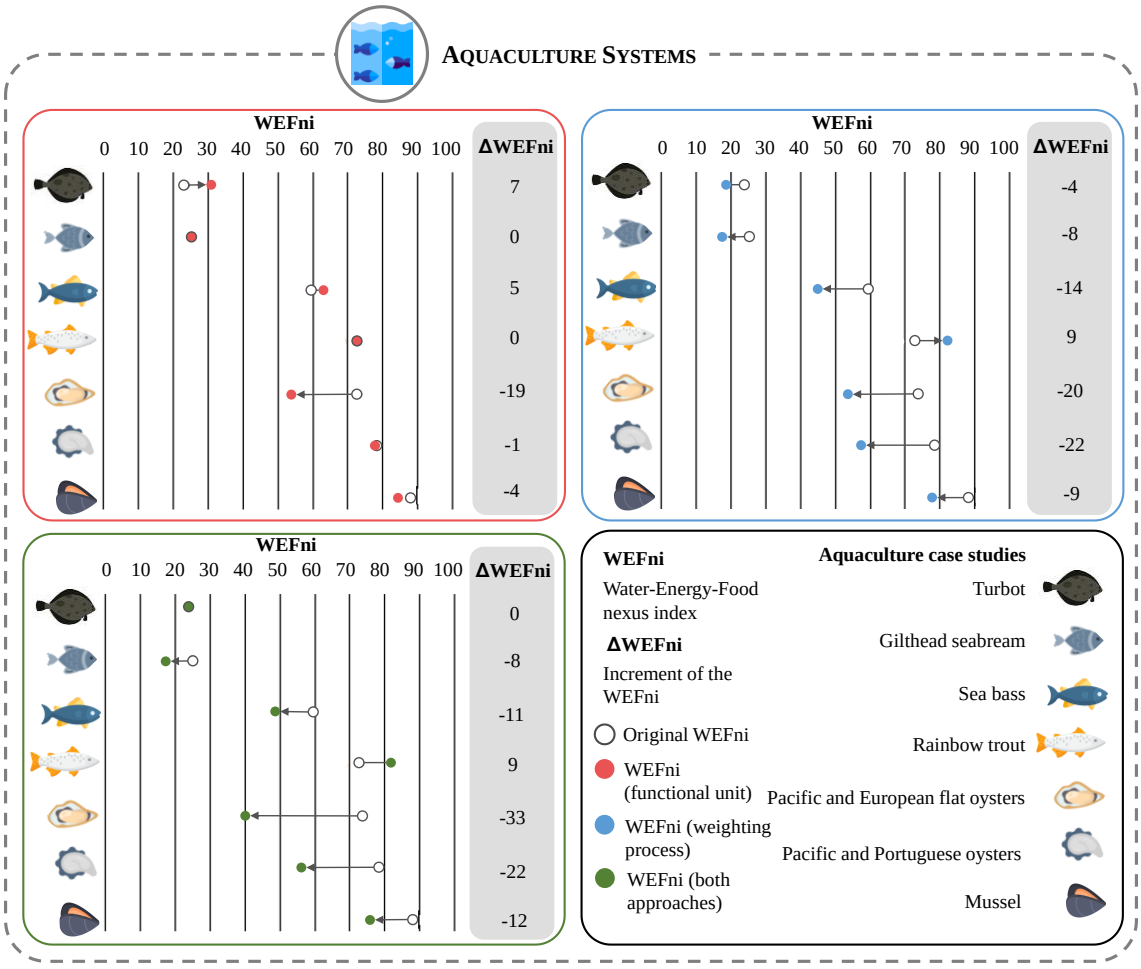



**Figure 4.7**. Water-Energy-Food nexus index results of the sensitivity analysis for aquaculture systems. Own elaboration using data collected from Ceballos-Santos et al. (2024).

Concerning aquaculture systems (**Figure 4.7**), from the seven case studies, two groups can be differentiated: fish (turbot, gilthead seabream, sea bass, rainbow trout) and shellfish (Pacific and European flat oysters, Pacific and Portuguese oysters, and mussels) aquaculture. The $FU_{ce}$ of the fish aquaculture group has on average 81.49 g of catch per person per day to meet the RSI, a much lower value compared to shellfish aquaculture (266.67 g and 416.67 g for mussels and oysters, respectively). This translates into fish aquaculture case studies slightly improve their WEFni (up to 7 points), while there is a decrease for all shellfish aquaculture case studies. Moreover, the sensitivity analysis compromising the weighting process implies reductions in almost all case studies, with a higher decrease in shellfish than in fish. This was because fish have a worse environmental performance in terms of CF, WF, and EF; thus, in principle, this should have increased their WEFni by decreasing the total weighting of these three footprints (from 75 % to 50 %). However, by increasing the weighting factor of the NF the WEFni was decreased, as certain fish register worse values, such as gilthead seabream (194.06)

or turbot (207.02) compared to the shellfish species analyzed, i.e., oyster and mussel, with NF equal to 210.00 and 267.12, respectively. When the two approaches were addressed together, a homogenization is beginning to emerge for almost all case studies between WEFni values ranging from 50-80 points. Lastly, according to the ranking, although both groups tend to reduce their differences no change in positions occurred, with fish aquaculture case studies remaining in first place.

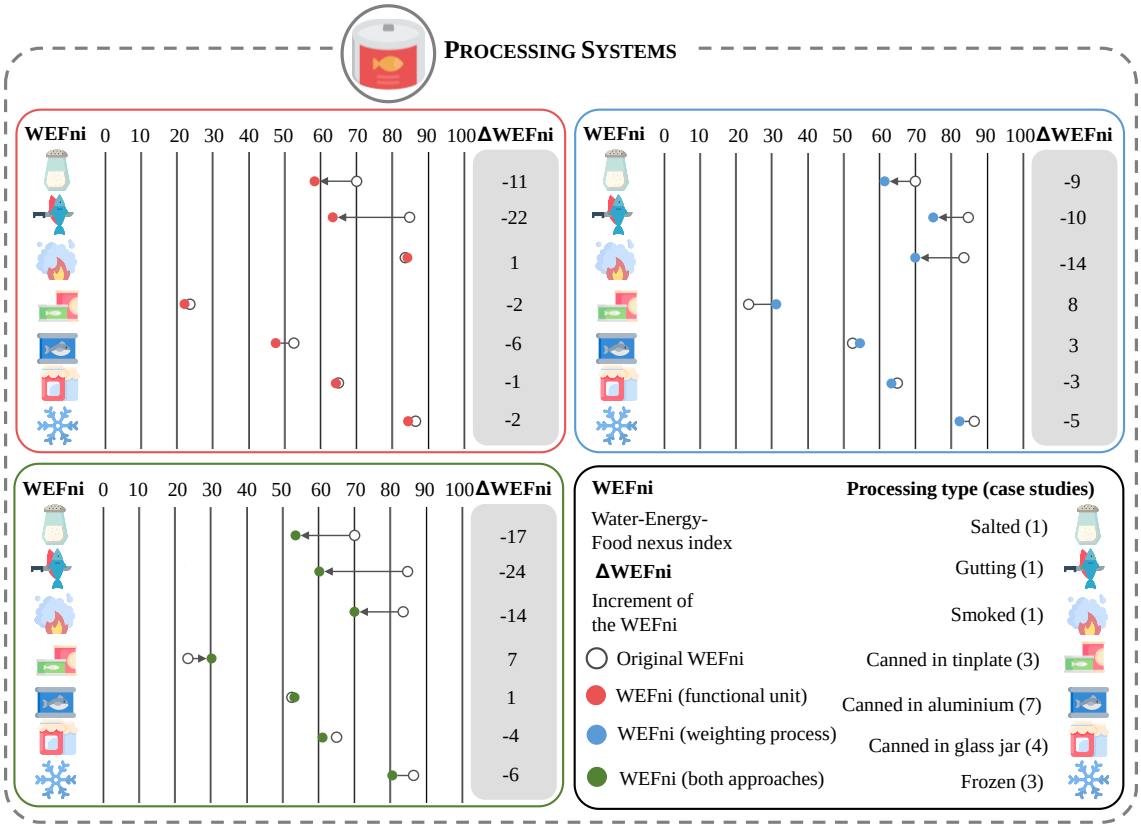



**Figure 4.8**. Water-Energy-Food nexus index results of the sensitivity analysis for aquaculture systems. Own elaboration using data collected from Ceballos-Santos et al. (2024).

In relation to processing systems (**Figure 4.8**), the sensitivity analysis of the FU affected mostly salted and gutted products, decreasing their WEFni by 11 and 22 points, respectively, while for the remaining processed systems, i.e., smoked, canned (in tinplate, aluminum or glass jar) and frozen, the results remained almost unchanged. This can be explained by the $FU_{ce}$ reported by each case study for the salted and gutted processes: 72.07 and 190.48 g of catches per person per day for Atlantic cod and Atlantic scallop, respectively. These values are affected by the low EP of the great Atlantic scallop (25 %) and by the low CC of cod (74 kcal per 100 g edible). Consequently, both case studies were in disadvantage compared to the others, being mainly composed by species such as albacore tuna, European anchovy or Atlantic chub mackerel, which contain high values for both CC and EP, thus having a much lower FUce (46.71 g of catches per person per day). The modification of the weighting process led to small reductions in the WEFni for canned in glass jar (3 point) and frozen (5 points) process systems. Conversely, for salting, gutted and smoking processes, this variation implied a reduction of at least 9 points,

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caused by the low NFs of cod, great Atlantic scallop and salmon, respectively. These trends were exacerbated when the combined effects of FU and weighting process were analyzed, with further reductions in the WEFni for salted (17 points) and gutted (24 points) processing systems. There were little variations in the ranking of the different types of processing, with frozen products still occupying the first place, while canned (in any format) and salted products were the worst WEFni performers.

### 4.6. Advantages and disadvantages of the methodological guidelines

Approaching LCA studies applied to seafood products that focus on a single indicator can provide useful information about the system being evaluated. However, when trying to broaden the scope according to a WEF nexus perspective, it becomes crucial to consider the interdependencies between water demand (WF), energy requirements (EF) and nutritional score of the seafood (NF) in the context of CC (CF). In view of the above, the integration of several indicators through a single value (i.e., the WEFni) that varies by a percentage could be a potential win-win option in terms of visualization of the results, especially for the average consumer, who often has no prior knowledge of environmental or nutritional issues. On the negative side, it would be more difficult to identify important critical points, such as a non-optimized energy production process or an excess of fuel burned in relation to the catches obtained. This in turn would lead to a lack of precision in masking the individual contributions of some of the indicators (e.g., the individual influences of each nutrient within the NF). In terms of SB, although the case studies in this guide have been defined for fisheries, aquaculture, and processing, a fourth case would need to be included, as there are currently many hybrid seafood production systems that combine aspects of fisheries and aquaculture (Klinger et al., 2013).

The FU selected was based on the mass content of the seafood products assessed. However, this does not reflect the true basic function of food, which is to feed the population (Weidema and Stylianou, 2020). Therefore, there is a changing trend where the nutritional perspective is beginning to be considered when conducting environmental impact studies of food (McAuliffe et al., 2020).

Nevertheless, this shortcoming was partially addressed by taking into account a specific nutritional index (NRF12.2). In addition, the results of the sensitivity analysis carried out showed that the WEFni was significantly modified, implying a reclassification of the fishing gear groups as well as for the processing types, while for the aquaculture systems a certain improvement was observed for fish farming compared to shellfish farming. Therefore, this suggests that, on the one hand, a re-evaluation of the chosen mass FU may be necessary, as the FUce has led to a better definition of the actual function of seafood production systems: to meet the recommended daily intake (i.e., the RSI), thus ensuring food security within the WEF nexus. On the other hand, to better represent the perspective of the WEF nexus in the context of the study, the process of equal weighting of individual indicators when deriving a WEFni could also be reconsidered.

In the context of the procedures used to obtain the WEFni values, the methods for normalizing and weighting the footprints are not yet standardized, and ISO does not support their use for LCA comparisons (Andreas et al., 2020). On the one hand, to propose an external normalization procedure, it would be necessary to consider relevant, official or known parameters to establish general criteria during the decision-making process. In this line, Pizzol et al. (2017) proposed some approaches, such as aggregate, production-based or consumption-based normalization. However, the one proposed by WEFni is based on an internal normalization with the aim of making a comparison between seafood products. On the other hand, weighting is even more controversial than normalization, as the decision-making process in this respect is often based on subjective opinions rather than scientific grounds. In this context, several weighting techniques can be applied: panel weighting (based on the opinion of a group of people), binary weighting (for zero or equal weights) or monetary weighting (according to monetary valuation), among others (Andreas et al., 2020). Furthermore, although several mathematical methods are available to determine the weights of a set of indicators in an objective manner, known as multi-criteria decision analysis (Odu, 2019), it was decided to prioritize simplicity by choosing to consider the same weight for all indicators, thus opening the door to easy replication of the methodology in other case studies.

After analyzing the advantages and disadvantages of the proposed methodological framework, the main challenge is to lay the foundations for a harmonized procedure to assess both environmental impacts and nutritional values of seafood products through a novel single index, expressed in an eco-label, allowing comparisons between them. Similarly, this guide is only a starting point for the NEPTUNUS project consortium to create a database of LCIs assessed by the WEFni. However, it is essential to encourage LCA practitioners to adapt the seafood production studies available in the literature to the specificities of the WEF nexus approach.

### 4.7. Challenges and priorities of the eco-label implementation

For producers interested in implementing the voluntary WEF nexus eco-label, it is necessary to implement a certification scheme. Given that the methodological guidelines have been implemented for the first time in a European context, it would be crucial for a European eco-labelling institution to delegate competences to other national institutions. In this way, companies could implement the WEF nexus eco-label through national institutions as a sign of transparency for their consumers and as a leadership in environmental policy. Therefore, the WEF nexus eco-label was designed primarily for public understanding and to encourage producers to conduct the implementation process. To this end, it was decided to cover only the WEFni, although it might be interesting to put some additional information online (e.g., through a code that can be scanned with a smartphone), such as the values of the four footprints together with a brief description of the calculation procedure. Similarly, the eco-label should be renewed each fishing season (i.e., annually), with the aim of encouraging the company to be certified to draw up a strategic plan to remain at the forefront of environmentally friendly measures, while at

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the same time creating a distinctive mark for the WEFni obtained compared to other seafood products.

With regard to eco-labels for seafood products, these are increasing as awareness of more sustainable production and consumption grows (Hilger et al., 2019). As a result, 'greener' markets are expected to be the way forward in the coming years (Prieto-Sandoval et al., 2020). Nevertheless, as economic value is often the most influential factor in consumer choice (Barclay and Miller, 2018), eco-labelling will only gain market share if it allows consumers to positively differentiate the most sustainable products and best practices to prioritize them over price. For example, Neumayr and Moosauer (2021) concluded from a survey that consumers prefer intuitive eco-labels with traffic light colors. In this context, previous studies have reported that consumers are willing to pay 15-30 % more if the eco-label guarantees that the seafood is healthy and sustainably produced (Cantillo et al., 2021). From the producers' point of view, they are sometimes concerned about adding new labels because it may mean higher costs for packaging materials or less visibility of their own brand, as well as label overload and gaps in understanding that could lead to confusion (van Asselt et al., 2021).

## 4.8. Conclusions

The methodological guidelines described in this work lay the foundations for the estimation of a new WEFni that attempts to provide a holistic approach to the comparative assessment of seafood products, penalizing their environmental impact while positively considering their nutritional value. In addition, this composite indicator has been translated into an easy-to-understand eco-label that seeks to pave the way for producers and consumers to produce and purchase, respectively, seafood products by communicating their compliance with sustainability criteria.

Likewise, with the aim of applying the proposed eco-label to the main products of the seafood market supply chains in the near future, it may be necessary to carry out several iterations of the proposed methodology, to check its robustness and flexibility. The modification of certain aspects such as the footprints, FU or allocation methods selected, as well as the normalization and weighting procedures considered, may be addressed to better approach the true state of the seafood sector under the umbrella of the WEF nexus thinking.

Finally, to extend this certification to other food sectors, it would be necessary to reconsider which are the best indicators to follow a WEF nexus perspective. For example, an NF proposal should be made that is adapted to the type of food or sector. In addition, the NF should be tailored to meals or diets (e.g., serving size or caloric content) to make comparisons between different food types.

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# Chapter 5

## *From the sea to the farm: Potential of the Water-Energy-Food nexus index in the dairy sector**

* This chapter is based on the following publication: **Entrena-Barbero, E.**, Rebolledo-Leiva, R., Vásquez-Ibarra, L., Fernández, M., Feijoo, G., González-García, S., Moreira, M.T. (2023). Water-Energy-Food nexus index proposal as a sustainability criterion on dairy farms. Science of the Total Environment, 874, 162507. https://doi.org/10.1016/j.scitotenv.2023.162507

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# Summary

Cow milk is an essential source of nutrients in the human diet at all stages of life. However, the decline in cow milk consumption over the years has been due to increased consumer awareness of animal welfare and the environmental impacts associated with its production and supply. This has led to a number of initiatives to mitigate the impact of livestock production, many of which do not take into account the multi-perspective view of environmental sustainability. Thus, the WEF nexus emerges as a framework to consider the complex synergies between carbon emissions, water demand, energy demand and nutritional value. In this study, an adaptation of a harmonized WEF nexus approach has been proposed and applied to evaluate a sample of 100 dairy farms located in Galicia (NW Spain).

To this end, a methodological procedure based on the selection, evaluation, normalization, weighting and integration of three life cycle indicators: CF, WF and EF, as well as milk yield, was carried out to obtain an easy-to-understand single value, the WEF nexus index (WEFni), which varies in percentage (from 0 to 100). The results show that the WEFni values obtained range from 31 to 90, highlighting significant differences between the farms evaluated. A classification by groups was then carried out to identify trends. In addition, in the group with the worst WEFni, consisting of 8 farms with an average WEFni of 39, three improvement actions focused on fodder substitution, inclusion of feed additives in the diet and implementation of a cow welfare program were applied to determine the potential reduction in the two main hotspots identified: purchased fodder and milk production level. Given the proposed methodology, this could provide a roadmap for promoting a more environmentally sustainable food industry, although further studies are needed to move towards a standardized WEFni.

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**Keywords**

Milk production | Environmental indicators | Feeding additives | Animal wellbeing | Composite index

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## 5.1. Addressing sustainability in the dairy sector through a single value

Milk is considered a mainstay of a healthy diet, not only during growth but at all stages of life, due to its composition based on proteins, fats, minerals and vitamins, among other micronutrients (Marangoni et al., 2019). Moreover, its content of calcium and vitamin D is linked to the development and maintenance of several physiological processes, such as bone protection or blood coagulation (Pereira, 2014).

In terms of production, Europe has consolidated its position as the second largest producing continent in the world, only behind Asia (FAO, 2021a). Among the main producing countries in Europe, Spain ranks seventh with a share of more than 5 % (European Commission, 2020a). The origin of Spanish milk comes mainly from the northern regions, where Galicia stands out, accounting for 39 % of total national production between 2017 and 2021. During this period, Castile and Leon, as well as Catalonia are the next producing regions, but with a much smaller volume of production, accounting for 13 % and 10 % respectively, while Asturias and Andalusia each account for 9 % (MAPA, 2022e). The relative production rate per Autonomous Community is shown in **Figure 5.1**.

Nevertheless, despite the recognized importance of dairy milk as a staple food, its consumption by Spaniards has been steadily decreasing over the years (MAPA, 2022b). The reason behind this trend could be explained by the increased purchase of plant-based alternatives (e.g., oat, rice or soy drinks), mainly due to vegan dietary patterns or food intolerances (Munekata et al., 2020). In addition, other social aspects such as animal welfare, ethical principles or environmental concerns could act as drivers for the transition towards a diet based on animal-free food (Kolbe, 2018).

Regarding the environmental impacts associated with dietary patterns, dairy products have been among the main contributors to GHG emissions and water demand in certain European and American diets (Cambeses-Franco et al., 2022). In the current CC crisis, about 15 % of global GHG emissions are linked to agricultural activities, constituting sources of $CO_2$, $CH_4$ and $N_2O$ from enteric fermentation in ruminants and from crop-related activities (tillage and use of synthetic fertilizers) (Jantke et al., 2020). Likewise, the impact of dairy farms in terms of water demand is also significant, as they represent the third largest contributor in the agricultural sector with a share of 7 %, only behind other products such as meat (22 %) and cereals (27 %) (Mekonnen and Hoekstra, 2012). In terms of the energy requirements of the on-farm facilities, animal housing and automatic milking stand out as the main electricity consumers (Todde et al., 2018). However, the introduction of this technology has been a major breakthrough in the dairy sector, allowing production to be increased by up to 12 % (Jacobs and Siegford, 2012). Furthermore, no differences in animal stress have been found compared to hand milked cows (Jerram et al., 2020).

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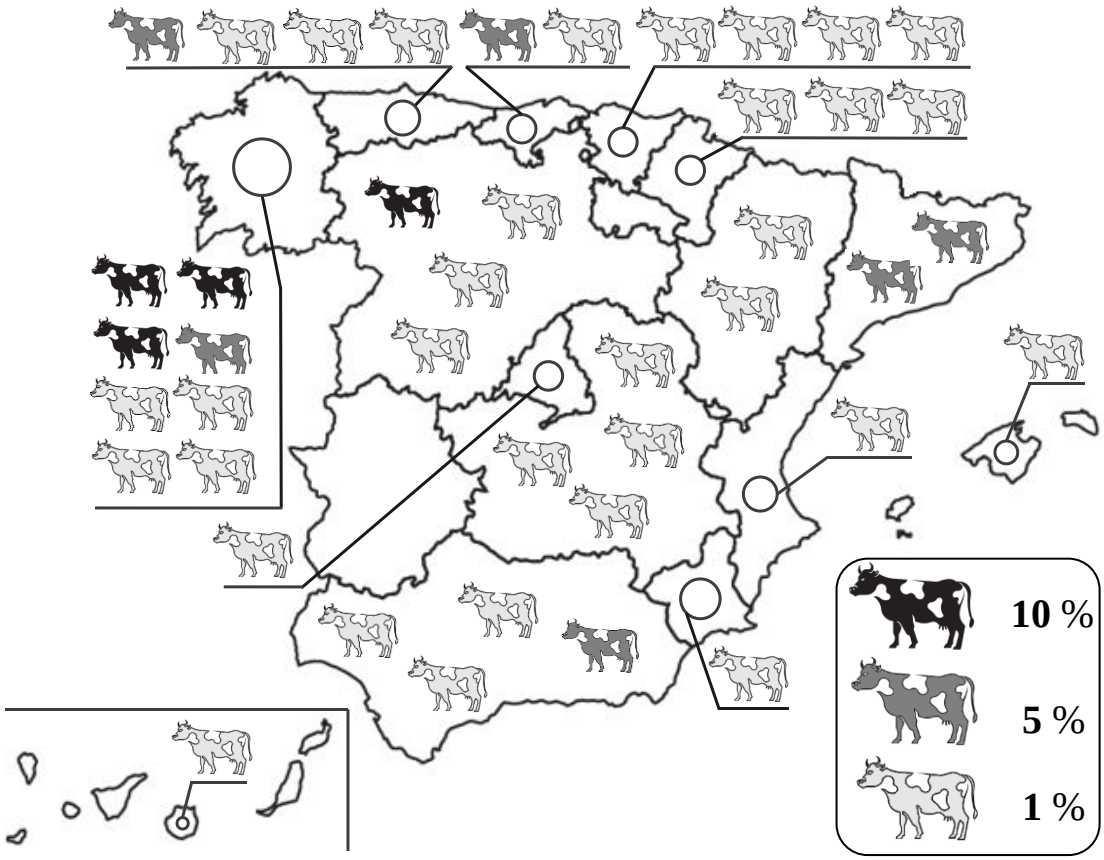



**Figure 5.1**. Average percentage of milk production in the Autonomous Communities of Spain during 2017-2021. Own elaboration using data collected from MAPA (2022e).

In the same way, under the premise of the narrow range of profits often associated with milk sales, productivity turns out to be a key factor (Hanrahan et al., 2018). Consequently, it is also essential to minimize food losses to maintain the economic stability of dairy farms (Redlingshöfer et al., 2017). A clear example of this is mastitis, an infectious disease that causes inflammation of the mammary glands, resulting in alterations in milk production (Bhakat et al., 2020).

Hence, with the purpose of tackling both the environmental and economic concerns related to milk production in the context of new consumption patterns and the animal welfare awareness of the current society, several strategies motivated by regulatory frameworks have emerged (Hennessy et al., 2020). Some of them focus on reducing $CH_4$ emissions derived from ruminant digestion through the use of feed additives (Kholif et al., 2021). Of these, the addition of algae is proving to be the most convincing measure to reduce the GW impact of livestock activities (Honan et al., 2021). Although some studies have shown that this modification of animal feed does not affect the quality of the final product, a longer-term analysis of the effects of dietary changes with different species of algae, in addition to the ideal dosage, is essential to obtain reliable and safe results (McCauley et al., 2020). Similarly, it has been noted in the literature that mastitis is one of the main diseases of mammalian animals (Gupta et al., 2020), which significant negative currency implications for the dairy sector (Puerto et al., 2021). Notwithstanding, this could be partially eradicated by training and educating

farmers through routine tasks based on barn cleaning, animal health and general herd welfare (Petersson-Wolfe et al., 2018). In addition, many other management strategies have been applied to address specific issues such as water scarcity (Payen et al., 2018), energy requirements (Pagani et al., 2016), food waste (March et al., 2019) or climate contribution (Martinsson and Hansson, 2021).

Thus, although there is a trend towards integrating analytical methodologies such as eco-efficiency and circularity (Rebolledo-Leiva et al., 2022), most studies focus on specific challenges and fail to consider a holistic approach that integrates several of the issues related to dairy production systems. It is then that the concept of the WEF nexus emerges as a framework for considering the complex relationships between water demand, energy requirements and food supply (Zhang et al., 2018). This approach has been applied to assess different systems such as wastewater treatment (Panagopoulos, 2022; Panagopoulos and Giannika, 2022a, 2022b), urban and smallholder agriculture (Haitsma Mulier et al., 2022; Oviroh et al., 2023), irrigation systems (Cui et al., 2022), local and urban communities (Ding et al., 2023; Huang et al., 2023), among others.

In agri-food systems, the WEF nexus approach has been used to evaluate different fertilization practices (Fabiani et al., 2020), the combination of dairy farms with short rotation coppice willow systems (Livingstone et al., 2021), and integrative strategies of water saving, renewable energy production and animal welfare improvement (Sobrosa Neto et al., 2018). Similarly, Entrena-Barbero et al. (2023) proposed a methodology for estimating a WEFni applied to seafood products. Despite this, no analogous proposal and application has yet been considered in livestock systems, with the aim of studying, from a holistic approach, the synergies of environmental pressures related to climate, water and energy perspectives together with milk production. Therefore, the objective of this chapter was to propose a methodological adaptation of the framework proposed by Entrena-Barbero et al. (2023) to be applied to the dairy sector. In addition, a set of 100 dairy farms located in Spain was benchmarked, being grouped by the WEFni obtained. Finally, a series of improvement actions were hypothetically applied with the aim of using the WEFni as an indicator for the pursuit of environmental sustainability and food security.

### 5.2. Introducing the case study

The proposed WEF nexus methodology was applied to a set of 100 farms during an annual milk production campaign. These dairy farms were located in the Autonomous Community of Galicia (NW Spain), in the provinces of Lugo (79 farms), La Coruña (18 farms) and Pontevedra (1 farm), while two farms (farms 61 and 68) bordered the Principality of Asturias. They are all members of the same livestock cooperative, which promotes competitiveness by developing actions aimed at economic and social cooperation through technical and material support. The farms are equipped with automatic milking systems, with annual production ranging from 269 $m^3$ to 5,289 $m^3$ of raw milk. Similarly, although most of the farms' income comes from the sale of milk, they also sell the cows that have passed the lactation stage to slaughterhouses, with an annual

production of 600-37,400 kg of meat. The difference in these figures is due to the size of the herd, which varies from 31 to 717 cows, consisting of lactating cows, dry cows and heifers. In addition, most of these farms are family-owned, with some 30 years of experience, and also raise smaller animals, such as chickens or pig to diversify their income.

As far as the feed system is concerned, it consists mainly of maize and grass silage from the farm fields, which are located close to the farms (from 10 to 880 hectares). On the other hand, some farms have meadows from which the cows receive an additional nutritional supplement by grazing, depending on the availability of grass. However, this is not enough to meet the feed requirements. Consequently, it is necessary to buy feed with different formulas from four factories that work for the cooperative, as well as additional cereals (alfalfa, straw, oats, etc.) from external supply centers. Fertilization comes from two different sources: one is the direct application of commercial synthetic fertilizers, and the other is organic cow manure. The latter is managed by storing it in covered concrete pits with sufficient capacity to be emptied every three to four months. It is therefore compatible with the rotation of fields according to the sowing and harvesting periods of grass and maize.

## 5.3. Adaptation of the Water-Energy-Food nexus methodology to the dairy sector

To achieve the objective of this chapter, the methodology has been divided into six steps (see **Figure 5.2**): (1) selection of indicators that best represent the environmental and food dimensions of the system under assessment, (2) calculation of the selected indicators, (3) normalization, (4) weighting and integration into a single score, (5) group classification, and (6) evaluation of improvement actions applied to the group of dairy farms with the worst performance in the WEFni.

### 5.3.1. Step 1: Selection of indicators

Three life cycle indicators were selected to estimate the environmental impacts associated with milk production: CF, WF and EF. These footprints are traditionally considered when assessing a food system following a WEF nexus philosophy (Laso et al., 2022). On the other hand, the food pillar has typically been estimated using several nutritional indicators, such as nutrient density (Drewnowski, 2009). Nevertheless, in this methodology, the milk yield (MY) per cow was considered. The reason for this is that this indicator allows the comparison of a sample of dairy systems producing the same product (i.e., raw milk). Furthermore, this indicator addresses the concept of food security, one of the core elements of the WEF nexus concept (Fernández-Ríos et al., 2021).

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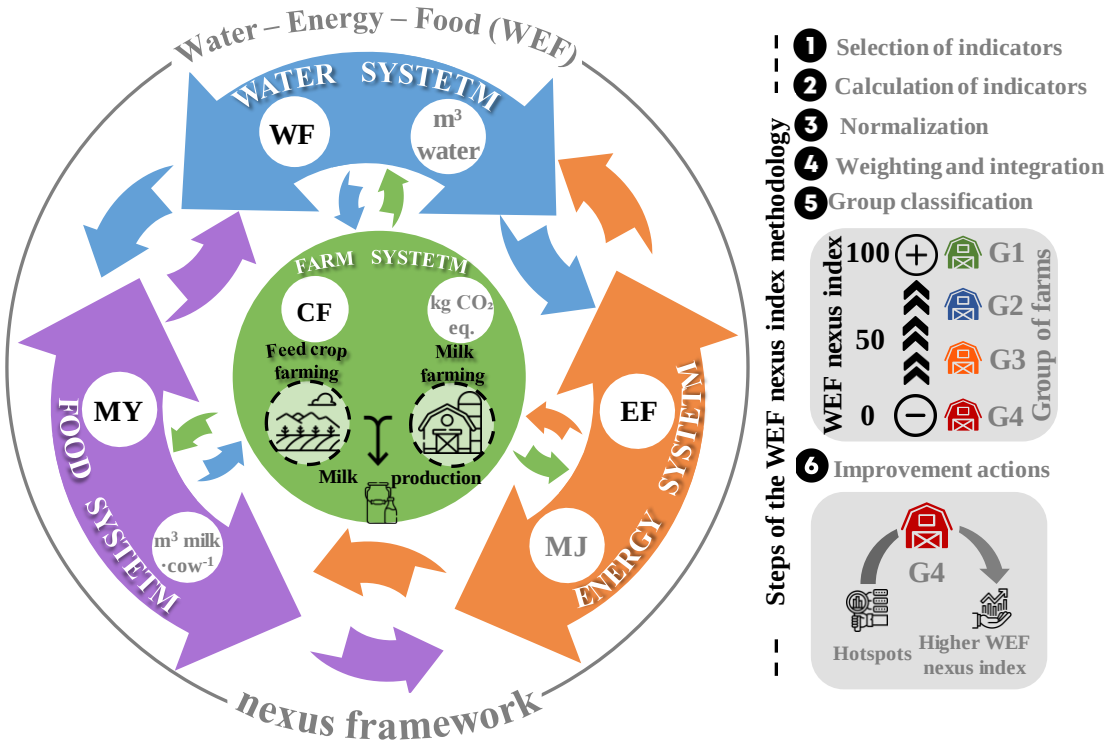



**Figure 5.2**. Water-Energy-Food (WEF) nexus framework (left side) and steps of the methodology followed (right side) for the implementation of a WEF nexus index (varying from 0 to 100) on dairy farms, calculating a series of indicators: carbon footprint (CF, kg $CO_2$ eq.), water footprint (WF, $m^3$ of water), energy footprint (EF, MJ), and milk yield (MY, $m^3$ of milk per cow), as well as the improvement actions for the group with the worst scores (fourth group: G4).

5.3.2. Step 2: Calculation of indicators

5.3.2.1. *Goal definition and functional unit*

The CF, WF and EF indicators were calculated using the LCA methodology with an attributional approach according to ISO 14040 and 14044 guidelines (ISO, 2006a, 2006b). To do this, it was necessary to define the objective of the study, which was to quantify the impacts associated with the production of one liter of raw milk (FU). This FU was chosen because milk production is the main function of a dairy farm (Baldini et al., 2017).

5.3.2.2. *Data collection and system boundaries*

Primary data were collected by the 100 farms through face-to-face interviews, corresponding to a production period of one year (2020) and identifying all relevant processes related to the farm activities. For this, the recommendations of the European Dairy Association (EDA, 2018) were followed, considering the productive system consisting of two stages: the cultivation of feed for the cows (feed crop cultivation) and the herd handling and milking (milk farming). For the first stage, the agrochemicals (i.e., pesticides and synthetic fertilizers) used on the crops were considered, as well as the supplies needed to carry out the machinery activities (lubricating oil and diesel). On the

other hand, the milk farming stage included fodder, water, as well as other flows for sanitation (cleaning products), nutrition (supplementary feeding), rest (cow bedding) and energy (for the milking parlor). In addition, the main waste streams generated by farms (e.g., plastics, cardboard, wastewater) were also recorded. Concerning background processes, the Ecoinvent database v3.8 (Moreno Ruiz et al., 2021) was used. With all this information, the system boundary was defined following a cradle-to-farm gate approach. Thus, all processes from raw materials extraction until raw milk production were considered (see **Figure 5.3**).

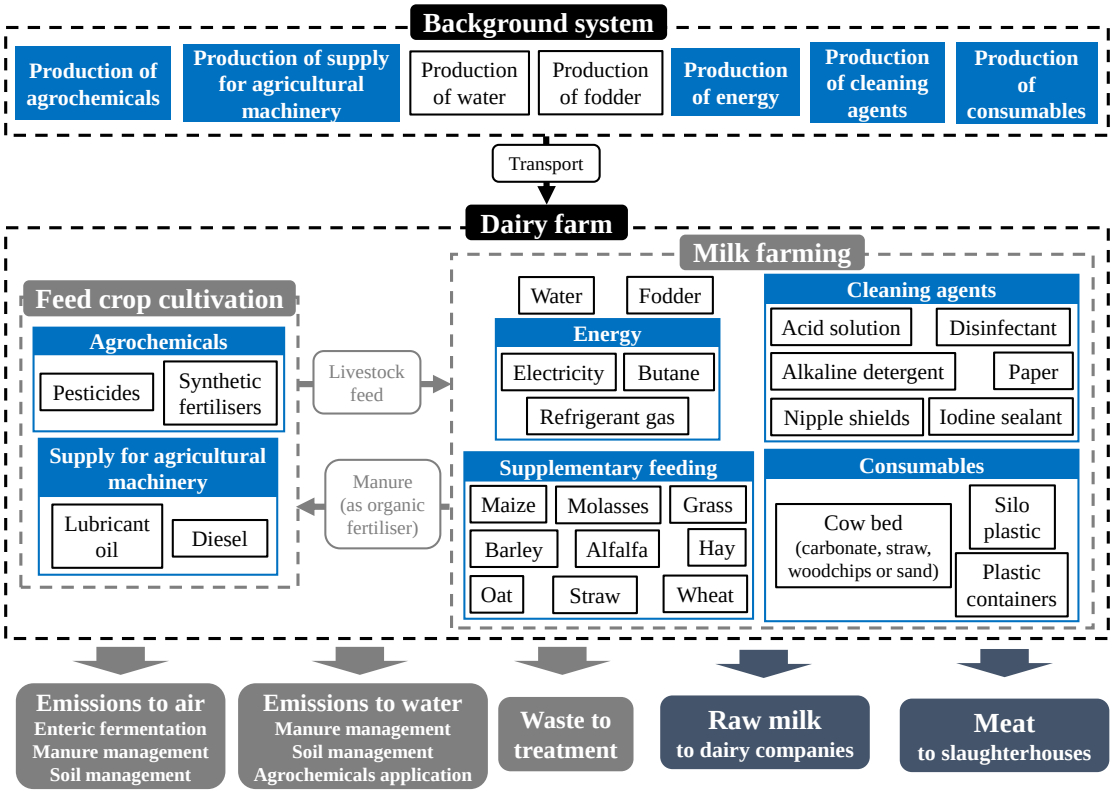



**Figure 5.3**. Boundaries, inputs, products (milk and meat) and undesired flows (emissions to air and water and waste to treatment) of the systems considered (background system and dairy farm) during the milk production.

5.3.2.3. *Burden allocation methods*

Given that dairy farms under study are multi-functional systems, an allocation method was employed to distribute the environmental burdens between meat and milk products. Mass, economic, and energy allocations are the most used methods for beef and dairy farming systems (Kyttä et al., 2022). However, taking into account that the revenue values used for the economic allocation may be affected by price fluctuations in the Spanish market during 2020 (MAPA, 2020a), and the energy content is similar for all dairy farms, the mass allocation method was selected as the reference approach to carry out the WEFni methodology.

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5.3.2.4. *Modelling and assumptions*

Regarding fodder production, up to 52 different fodders were used in the sample evaluated, being modelled according to the Ecoinvent database v3.8 (Moreno Ruiz et al., 2021), characterized based on the relative proportions of the 17 ingredients by which they were constituted.

**Table 5.1**. Average life cycle inventory for the 100 dairy farms.

| **Inputs from technosphere** | | | |
|---|---|---|---|
| **Supplementary feeding** | **kg** | **Supply for agricultural machinery** | **kg** |
| Maize | 123,441 | Diesel | 10,624 |
| Grass | 94,293 | Lubricant oil | 105 |
| Straw | 11,702 | **Agrochemicals** | **kg** |
| Alfalfa | 3,199 | Pesticides | 77 |
| Others | 29,462 | Synthetic fertilizers | 27,332 |
| **Cleaning agents** | **kg** | **Consumables** | **kg** |
| Alkaline detergent | 551 | Silo plastic | 418 |
| Acid solution | 185 | Plastic containers | 110 |
| Disinfectant | 287 | | **t** |
| Paper | 110 | Cow bed (carbonate, straw woodchips or sand) | 209 |
| Nipple shields | 6.9 | | |
| | **L** | **Energy** | |
| Iodine sealant | 306 | | **kWh** |
| **Water** | **L** | Electricity | 38,737 |
| | 3,655,752 | | **kg** |
| **Fodder** | **kg** | Butane | 300 |
| | 332,010 | Refrigerant gas | 0.30 |
| **Outputs to nature (field emissions)** | | | |
| **Emissions to air** | **kg** | **Emissions to water** | **kg** |
| $CH_4$ (enteric fermentation) | 13,410 | $NO_3^-$ (manure management) | 475 |
| $CH_4$ (manure management) | 4,067 | $NO_3^-$ (soil management) | 583 |
| $N_2O$ (manure management) | 37 | P | 20 |
| $NH_3$ (manure management) | 4,278 | Heavy metals | 3 |
| $N_2O$ (soil management) | 672 | **Emissions to soil** | **g** |
| $NH_3$ (soil management) | 1,439 | Heavy metals | 836 |
| **Outputs to technosphere** | | | |
| **Products** | **kg** | **Waste to treatment** | **kg** |
| Raw milk | 1,103,740 | Plastic to recycling | 529 |
| Meat | 13,203 | Paper to recycling | 340 |
| | | Urban solid waste | 192 |
| | | Tins to recycling | 6 |
| | | | **$m^3$** |
| | | Wastewater | 798 |

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Field emissions play a key role in the environmental performance of agri-food systems. Therefore, emissions from agrochemicals application, manure and soil

management, and enteric fermentation were estimated following the Tier 1 of the IPCC guidelines (IPCC, 2019a). These emissions were: i) $CH_4$ from enteric fermentation and manure management, ii) $N_2O$, iii) ammonia ($NH_3$) and iv) nitrate ($NO_3^-$) from manure and soil management (i.e., fertilizers application). In the case of $NH_3$ and $NO_3^-$ emissions calculation, the distribution factors reported by Denier Van Der Gon & Bleeker (2005) were used. This is, the N emitted in the gas phase as $NH_3$ and $NO_3^-$ in proportions of 90 % and 10 %, respectively. Regarding the emissions from mineral fertilizers such as: $PO_4^{3-}$ (leaching to ground water and run-off to surface water), P (erosion to surface water), and heavy metals (Cd, Cu, Zn, Pb, Ni, Cr) to ground and surface water (leaching), and to the soil (through erosion) were estimated following the guidelines of Nemecek et al. (2019). Pesticide emissions were calculated using the PestLCI Consensus model (Fantke et al., 2017). This model allows for estimating the fraction of the applied quantity of pesticides emitted to soil, water and air.

Regarding the electricity production mix, data from the Association of Issuing Bodies (AIB, 2019) was taken into account. For the electricity modelling, it was considered the average values of the different generation sources in the electricity grid profile of Spain during a five-years period (2015-2019), avoiding annual energy fluctuations. Furthermore, the construction of the infrastructures as well as their maintenance phase are outside the SB. This is often a recurring decision in LCA studies for dairy products, as the contribution of capital goods are not relevant for the environmental footprints (EDA, 2018). In addition, manure from livestock has not been considered as a system product, as it is reused as organic fertilizer in the feed crops cultivation stage. Finally, the LCI associated to each farm was built and compiled, appearing an average for the 100 dairy farms compiled in **Table 5.1**.

5.3.2.5. *Estimation of the environmental footprints*

To transform the inventory data into environmental impacts, the LCIA method must be chosen. For the CF indicator, the characterization factors relative to the GW potentials (over a time horizon of 100 years) collected in the sixth assessment report of the IPCC (IPCC, 2021) were considered, following the recommendation suggested by the International Dairy Federation (IDF, 2015). Regarding the WF indicator, the AWARE method (Boulay et al., 2018) was used in line with the Product Environmental Footprint Category Rules (PEFCR) developed by the EU Joint Research Centre (EDA, 2018). In terms of EF, the cumulative energy demand (Low Heating Values) (Frischknecht et al., 2007) was applied, as this is one of the most appropriate LCIA methodologies for environmental evaluations relative to energy requirements, apart from being aligned with the PEFCR. The SimaPro software v9.4 was used to conduct the calculation procedures for the CF, WF and EF indicators.

5.3.2.6. *Estimation of the milk yield*

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The productivity of the dairy cows can be measured through the product yield per animal (Gill et al., 2021). Thus, information about the annual milk production, as well as

the composition of the herds for identifying the number of cows in lactation stage in each farm were utilized. Lastly, the MY indicator was estimated thanks to **Equation 5.1**.

$$\text{MY } (\text{m}^3 \text{ milk} \cdot \text{cow}^{-1}) = \frac{\text{Annual milk production } (\text{m}^3 \text{ milk})}{\text{Number of lactating cows}} \quad \textbf{Eq 5.1}$$

5.3.3. Step 3: Normalization

In this step, all indicators were normalized into a range from 0 to 1 to aggregate the four indicators, as they have different units. This normalization was carried out using the **Equation 5.2** depending on whether the indicator contributes negatively (CF, WF and EF) or positively (MY: **Equation 5.3**) to the WEFni.

$$X_{ij} = \frac{Y_i^{max} - Y_{ij}}{Y_i^{max} - Y_i^{min}}, \forall \text{ j} \quad \textbf{Eq 5.2}$$

$$X_{ij} = \frac{Y_{ij} - Y_i^{min}}{Y_i^{max} - Y_i^{min}}, \forall \text{ j} \quad \textbf{Eq 5.3}$$

Where:

| | |
|---|---|
| i | indicator, i = {CF, WF, EF, MY}. |
| J | dairy farm evaluated, j = {1, …, 100}. |
| $X_{ij}$ | normalized value of each indicator i of farm j. |
| $Y_{ij}$ | value of the indicator i of farm j. |
| $Y_i^{max}$ | maximum value of the indicator i of the sample assessed (100 farms). |
| $Y_i^{min}$ | minimum value of the indicator *i* of the sample assessed (100 farms). |

5.3.4. Step 4: Weighting and integration

For each analyzed farm, the results obtained from the previous step were aggregated into a single score (i.e., the WEFni), through a weighting sum procedure. Thus, a range value of 0-100 was obtained following **Equation 5.4**. The computation of each weight (namely $W_{CF}$, $W_{WF}$, $W_{EF}$ and $W_{MY}$ for each indicator) was conducted using a Multiple Criteria Decision Making (MCDM) method to determine objectively the weights used in the aggregation procedure (Alemi-Ardakani et al., 2016). One of the most commonly used MCDM approaches is the criteria importance through intercriteria correlation (CRITIC) method (Lin et al., 2020) proposed by Diakoulaki et al. (1995). Briefly, this method uses the results obtained from the normalized indicators (i.e., $X_{ij}$ from **Equation 5.2** and **Equation 5.3**) to determine the conflict among them through their correlation. In this sense, if there is a strong positive correlation among indicators, the conflict among the normalized indicators will be lower, as well as the assigned weight (Wen et al., 2022). The standard deviation of the sample for each indicator is then used to

show the degree of information contained in each one. The higher the standard deviation, the greater the amount of information and, in turn, the higher the weight (Wen et al., 2022). For a more detailed information about the mathematical procedure conducted, see Entrena-Barbero et al. (2023b).

$$\mathrm{WEFni}_{j} = (X_{CFj} \times W_{CF}) + (X_{WFj} \times W_{WF}) + (X_{EFj} \times W_{EF}) + (X_{MYj} \times W_{MY}) \quad \textbf{Eq 5.4}$$

Where:

| | |
|---|---|
| $\mathrm{WEFni}_j$ | WEF nexus index of farm j. |
| $X_{CFj}$, $X_{WFj}$, $X_{EFj}$, $X_{MYj}$ | normalized value of farm j for the CF, WF, EF and MY, respectively. |
| $W_{CF}$, $W_{WF}$, $W_{EF}$, $W_{MY}$ | weight for the CF, WF, EF and MY, respectively. |

5.3.5. Step 5: Group classification

Once the WEFni had been obtained for each dairy farm, a group classification was carried out based on the performance of this score. In this sense, all farms were divided into four groups (G1, G2, G3 and G4) based on quartiles (i.e., each group represents one quartile, G1 = Q1, ..., G4 = Q4). The first (Q1) and fourth (Q4) quartiles represent the highest and lowest WEFni values of the sample, respectively.

5.3.6. Step 6: Improvement actions

After the group classification, three actions were considered, based on feeding and animal wellbeing, to estimate the potential improvement of both environmental and productivity performance, and consequently, the WEFni. For feeding, actions to reformulate the current fodder composition and improve cow feeding were evaluated, while for animal wellbeing, a welfare program was considered. In addition, these measures were studied both individually and together (as there is no incompatibility between them) in hypothetical scenarios. These measures were applied to the group with the worst WEFni (i.e., G4). In addition, it is important to note that the reformulation of the fodder composition was calculated using data from the analyzed farms, whereas the improvement of cow feeding, and the establishment of an animal welfare program were estimated using data from the literature. As a result, the reformulation of the diet was focused on the reduction of CF, WF and EF, the improvement of cow feeding was only related to CF and the establishment of an animal welfare program modified the 4 indicators that integrate the WEFni.

5.3.6.1. *Reformulate fodder composition*

Across the sample of dairy farms evaluated, 52 fodders were used with different ingredients formulations. These forages were then subjected to environmental analysis. They were also evaluated nutritionally by identifying their PC on a percentage scale of the main ingredients (barley, maize, wheat, soy, rapeseed and oat), which represent nearly 90 % of the total composition. In this way, the one with the lowest environmental impacts

will replace the fodders currently used in G4 farms, since the aim was to improve the WEFni as much as possible.

**Table 5.2**. Carbon, water and energy footprints (CF, WF and EF) per kg, as well as PC of the 52 fodders used in the 100 farms. Protein content (PC): Rapeseed (32 %) (Lamminen et al., 2017), barley (10.6 %), maize (8.4 %), wheat (11.7 %), soy (35.9 %) and oat (16.9 %). Own elaboration using data collected from BEDCA (2006).

| Fodder | Farm | CF (kg $CO_2$ eq.) | WF ($m^3$) | EF (MJ) | PC (%) | Fodder | Farm | CF (kg $CO_2$ eq.) | WF ($m^3$) | EF (MJ) | PC (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| F1 | 1, 2, 4, 6 y 12 | 1.0 | 1.5 | 20.2 | 20.2 | F27 | 37 | 1.2 | 2.0 | 23.1 | 19.1 |
| F2 | 3 | 1.3 | 2.6 | 23.9 | 21.3 | F28 | 38 | 1.9 | 1.5 | 26.7 | 23.5 |
| F3 | 5, 26, 33, 34, 39, 43, 47 & 48 | 0.9 | 2.3 | 21.6 | 17.2 | F29 | 39 | 0.93 | 2.3 | 21.7 | 19.3 |
| F4 | 7 | 1.1 | 2.5 | 22.5 | 19.3 | F30 | 41 | 1.7 | 1.8 | 26.2 | 21.3 |
| F5 | 8 | 1.1 | 3.0 | 22.6 | 18.7 | F31 | 42 | 1.7 | 1.5 | 25.0 | 23.9 |
| F6 | 9 | 1.2 | 2.2 | 23.0 | 17.3 | F32 | 44 | 1.2 | 2.1 | 21.8 | 20.8 |
| F7 | 10 & 45 | 1.4 | 0.94 | 20.3 | 17.4 | F33 | 46 | 1.2 | 2.2 | 23.5 | 18.7 |
| F8 | 11, 15 & 40 | 0.89 | 2.8 | 21.4 | 28.8 | F34 | 50 | 1.2 | 1.9 | 23.1 | 17.1 |
| F9 | 13 | 1.2 | 2.4 | 22.6 | 16.1 | F35 | 51 | 1.8 | 1.7 | 26.8 | 23.2 |
| F10 | 14 | 1.1 | 2.5 | 23.2 | 20.4 | F36 | 52 | 1.4 | 1.7 | 23.8 | 21.4 |
| F11 | 16 | 1.2 | 3.1 | 23.3 | 15.5 | F37 | 53 | 1.9 | 1.3 | 26.0 | 27.1 |
| F12 | 17 & 49 | 0.99 | 2.1 | 21.3 | 17.1 | F38 | 54, 56, 66, 68, 71, 74, 76 & 82 | 1.5 | 3.0 | 23.4 | 23.2 |
| F13 | 18, 24, 31 & 33 | 0.84 | 2.4 | 20.9 | 20.4 | F39 | 55 | 1.7 | 1.3 | 25.7 | 24.2 |
| F14 | 19 | 1.2 | 2.3 | 22.9 | 16.8 | F40 | 57 | 1.4 | 1.9 | 23.6 | 21.3 |
| F15 | 20 | 1.2 | 1.7 | 17.9 | 22.8 | F41 | 58 | 1.7 | 1.5 | 23.4 | 24.6 |
| F16 | 21 | 1.0 | 2.3 | 21.46 | 20.63 | F42 | 59, 61, 62, 64, 67, 69, 77-79, 81, 84-94 & 96-99 | 1.5 | 1.74 | 24.4 | 22.18 |
| F17 | 22 | 1.1 | 2.4 | 22.5 | 18.9 | F43 | 60 | 1.7 | 1.6 | 24.8 | 24.6 |
| F18 | 23 | 0.79 | 3.9 | 20.8 | 16.2 | F44 | 63 | 1.6 | 2.7 | 22.8 | 20.9 |
| F19 | 25 | 1.9 | 1.8 | 26.9 | 12.3 | F45 | 65 | 1.8 | 1.7 | 25.6 | 25.5 |
| F20 | 27 | 1.1 | 2.7 | 22.5 | 27.1 | F46 | 70 | 1.6 | 1.7 | 24.5 | 23.7 |
| F21 | 28 | 2.2 | 1.3 | 28.2 | 15.7 | F47 | 72 | 1.3 | 2.4 | 23.2 | 20.7 |
| F22 | 29 | 1.2 | 2.2 | 22.9 | 25.9 | F48 | 73 | 1.3 | 3.3 | 21.8 | 16.2 |
| F23 | 30 | 1.3 | 2.1 | 23.3 | 17.2 | F49 | 75 | 1.5 | 3.3 | 23.7 | 23.5 |
| F24 | 32 & 34 | 0.92 | 2.3 | 21.6 | 20.9 | F50 | 80 & 100 | 1.6 | 1.8 | 24.4 | 23.7 |
| F25 | 35 | 1.3 | 2.3 | 23.5 | 19.3 | F51 | 83 | 1.3 | 2.2 | 22.9 | 19.7 |
| F26 | 36 | 2.1 | 0.68 | 27.9 | 19.8 | F52 | 95 | 0.67 | 2.1 | 18.2 | 20.7 |

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According to the CF, WF, and EF values obtained (see **Table 5.2**), the fodder 52 (F52) from the farm 95 has been selected. This decision is based on the fact that dairy farms belong to the same cooperative and region, which could guarantee the availability of the fodder selected. Therefore, it could be a feasible practice for farms of group G4 to improve their environmental performance. Later, it will be discussed whether the best environmental choice is also a good alternative from a protein-content point of view.

5.3.6.2. *Upgrading cow feeding*

Two types of feeding additives can be distinguished: inhibitors and modifiers rumen preventing $CH_4$ emissions (Ungerfeld, 2018). Among the ruminal modifiers, lipids, tannins and essential oils stand out, whereas ruminal inhibitors are made of 3-nitroxypropanol (3NOP), halogens (algae) and nitrates (Haque, 2018). Of these, the addition of algae to ruminant feed is proving to be the most convincing action to reduce GW impacts associated with livestock activities (Honan et al., 2021). Among them, the seaweed *Asparagopsis armata* is the most promising (Félix et al., 2021). Its addition in a proportion of 0.5 % on the diet could result in a $CH_4$ reduction equal to 26.4 % without compromising MY or digestive issues (Roque et al., 2019). In this way, this additive has been hypothetically applied to the fodders of group G4. However, the environmental implications arising from its manufacturing stage have not been considered, since although this is a source of uncertainty, 3NOP has demonstrated to have net GHG emissions reductions in dairy cattle (Feng and Kebreab, 2020).

5.3.6.3. *Animal wellbeing program*

The FRISKKO health care system (Hogeveen, 2005) for dairy herds was assumed to be implemented on the Galician farms studied. This corresponds to a mastitis prevention program that indirectly increases the MY indicator. The program is a decalogue of actions based on the optimization and exhaustive control of the cleanliness, rest and general well-being of the cows, through practices such as the continuous maintenance of the barn, dry bedding and a good, clean and friendly milking technique. To achieve this, farmers are supported by regular visits from veterinarians to improve animal management, avoiding the use of external chemical agents (antibiotics or hormones) (Ekman and Østerås, 2003). It is also necessary to monitor animals that have previously had mastitis, as they are more likely to be re-infected. It may therefore be beneficial to milk them last to prevent the spread of infection (Mbindyo et al., 2020).

Accordingly, it is assumed that the aforementioned protocol for the care of healthy cows is applied on farms from group G4. To do this, the results of a real case study previously implemented in a Galician dairy farm were taken into account. In this case, a net improvement in milk production of 8 % per lactating cow was achieved (Hospido and Sonesson, 2005). In this context, the higher the amount of milk produced per cow, the higher the MY indicator. In addition, an increase in the total amount of milk produced by

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the farm means that each environmental footprint will decrease if it is related to each liter of milk produced (i.e., its FU).

### 5.4. Evaluation of 100 dairy farms through a Water-Energy-Food nexus index

Firstly, after carrying out steps 1 and 2 of the proposed methodology, it is recorded average values per FU (1 L of raw milk) of 1.15 kg $CO_2$ eq., 1.04 $m^3$ and 10.31 MJ were obtained for the CF, WF and EF footprints, respectively. On the other hand, in relation to the MY indicator, a range value of 5.45-15.45 $m^3$ of milk per cow was observed. This shows a large variation between farms, as some of them achieve up to three times higher production with the same number of cows. Secondly, after the normalization (step 3) and the weighting and integration procedures (step 4), the WEFni of the farms was obtained (see **Figure 5.4**). The average value of the WEFni was 70, ranging from 31 (farm 52) to 90 (farm 38). The mean values obtained for each indicator, after normalization, were 17, 15, 17 and 21 for CF, WF, EF and MY respectively. Subsequently, the group classification (step 5) divided the sample of farms into four equally distributed quartiles, taking as reference the minimum (31) and maximum (90) values of the WEFni. For each group, **Table 5.3** shows the WEFni range, the number of farms that make up the group and the values obtained for the four individual indicators (with the corresponding standard deviations). As can be seen from the above table, the size of the groups varied considerably. On the one hand, most of the farms were classified in the G1 and G2 groups (i.e., those with the best scores). About 25 % of the sample were classified in the G1 group, while more than half (i.e., 56 farms) were in the G2 group with WEFni values between 61 and 75. The situation is different for the other two groups. G3 is composed of eleven farms, while G4 is represented by six farms, representing only about 10 % and 5 % of the sample respectively. This means that up to 83 % of the sample have relatively similar results (G1 and G2), with average WEFni of 83 and 70 respectively. The remaining 17 farms are characterized by an average WEFni below 55 (G3 and G4).

**Table 5.3**. Main characteristics of each group: Water-Energy-Food nexus index (WEFni) range, number of farms, average values (in bold) and standard deviation of the four indicators: Carbon footprint (CF), water footprint (WF), energy footprint (EF) and milk yield (MY), and the average WEFni.

| Group | WEFni range | Nº farms | CF (kg $CO_2$ eq.) | WF ($m^3$ water) | EF (MJ) | MY ($m^3$ milk·$cow^{-1}$) | WEFni |
|---|---|---|---|---|---|---|---|
| **G1** | 75-90 | 27 | **1.00** ± 0.29 | **0.79** ± 0.24 | **8.72** ± 5.2 | **13.69** ± 1.9 | **83** ± 6.7 |
| **G2** | 61-75 | 56 | **1.13** ± 0.20 | **0.99** ± 0.60 | **9.83** ± 3.2 | **11.55** ± 1.4 | **70** ± 4.4 |
| **G3** | 46-61 | 11 | **1.35** ± 0.13 | **1.56** ± 0.22 | **13.68** ± 2.7 | **10.85** ± 1.1 | **55** ± 4.3 |
| **G4** | 31-46 | 6 | **1.65** ± 0.10 | **1.60** ± 0.24 | **15.69** ± 2.2 | **8.56** ± 1.1 | **39** ± 3.8 |

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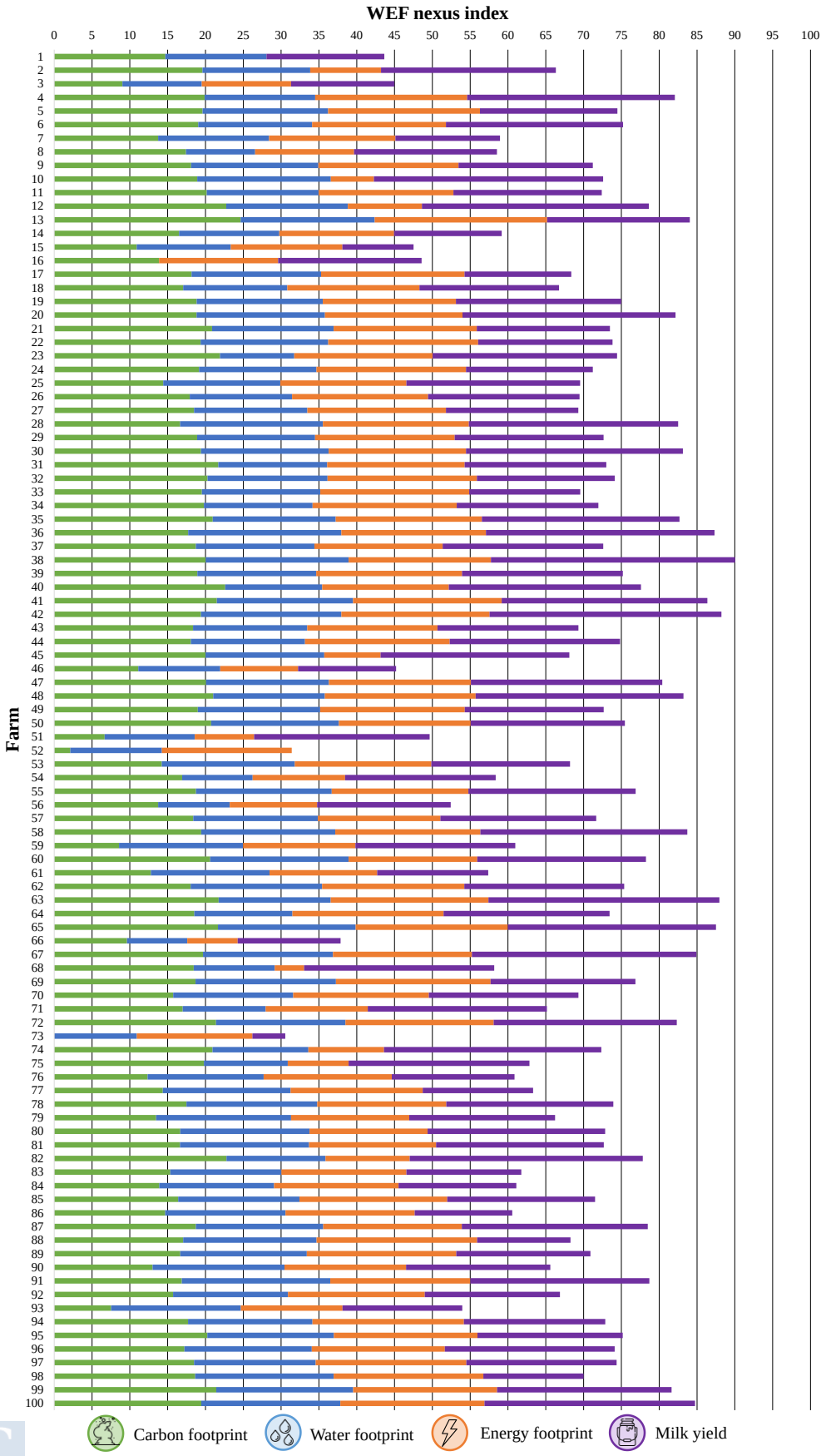



**Figure 5.4**. Water-Energy-Food nexus index divided per indicator for the set of 100 dairy farms.

According to the values obtained for each indicator, a more detailed analysis of the main differences between the groups was carried out. It was found that there were fewer differences between the best performing groups, especially for the CF and EF footprints, with an increase of only 0.13 kg $CO_2$ eq. and 1.11 MJ, respectively, when comparing G2 with G1. Conversely, the transition from G2 to G3 shows the largest differences of all the indicators, mainly for WF, with an increase of 0.57 $m^3$ and 3.85 MJ for the EF indicator. Furthermore, the largest change between G3 and G4 occurs in the CF and MY indicators, with an increase of 0.30 kg $CO_2$ eq. and a decrease of 2.29 $m^3$ milk per cow, respectively. Of all the groups, the EF and MY indicators showed the greatest variation in mean and standard deviation between groups. On the contrary, CF and WF showed small differences between groups. Finally, based on the average values of the WEFni, the differences between one group and the next were similar and with an increasing trend: 13 (G1 and G2), 15 (G2 and G3) and 16 (G3 and G4), while their standard deviations were decreasing. This could be related to the smaller differences between the groups with the lowest scores (G3 and G4), because they contain a smaller number of farms compared to the group with the highest scores (G1 and G2).

After analyzing the main characteristics of the groups, a contribution analysis was carried out to identify the main hotspots associated with the three environmental footprints considered (see **Figure 5.5**). For CF, the main hotspot is field emissions and enteric fermentation, accounting for between 50 % and 55 % of the total. A more detailed analysis of this main contributor shows that $CH_4$ emissions from enteric fermentation during the digestion process of ruminants account for up to 55 % of total emissions. In terms of field emissions, cow manure management is a source of $CH_4$ and $N_2O$ with a relative contribution of 17 % and 1 % respectively. Soil management is another source of $N_2O$, accounting for about a third of total emissions (27 %). On the other hand, the fodders are the second most important source of $N_2O$ with a contribution of between 32 % and 39 %. The differences between the groups could be explained, apart from the size of the rations given to the cows, by the proportion of ingredients that make up the fodder. On average, the main components are maize (35.5 %), soy (25.7 %), rapeseed (16 %), barley (10.2 %), wheat (2 %) and molasses (1.9 %). Nevertheless, some farms in G4 use fodders with a relatively higher proportion of maize (farms 3 and 46), soy (farm 66) or both (farm 52), which could be related to their lower WEFni values. In relation to the other categories, these are of minor importance, as the global contribution of all of them barely exceeds 10 % of the total GHG emissions related to milk production.

Concerning WF, fodders represent the biggest water demander, with an average contribution of 60 %, although this figure rises to 65 % for G3 and G4 farms. The second largest contributor is the direct water consumed for various purposes: animal hydration, farmer cleaning or facilities disinfection. These results are in line with the study conducted by Krauß et al. (2016), which reported that the water used in the barn for drinking or cleaning purposes was significantly lower compared to the water used for feed production. On the other hand, two different trends can be observed in the groups with the highest WEFni (G1 and G2). Here, the supplementary feeding has a much lower

contribution to the WF in comparison with the production of agrochemicals (around 5 % and 12 % respectively); while the opposite situation occurs in groups G3 and G4 with contributions of 14 % and 6 % for the supplementary feeding and the agrochemicals production, respectively. The above may be because farms from G1 and G2 require a smaller amount of supplementary feeding to meet the nutritional requirements of the animals, although the water demand goes to the agrochemicals used in the crop fields owned by farmers. With respect to the rest of the categories, the one that stands out the most are consumables, which account for about 4 % of the WF.

According to the energy demand, the contribution of fodder once again stands out with values from 65 % to 75 %. Furthermore, the impact of the supplementary feeding is gradually increasing as the WEFni decreases (from values around 9 % to 20 % for groups G1 and G4, respectively), which is analogous to what was observed for the case of the WF. With respect to the remaining contributors, the consumption of consumables (around 6 %) such as cow bedding materials or plastics to carry out forage harvesting work, as well as the consumption of lubricating oil and the use (and combustion) of fuel in agricultural machinery (about 5 %), turn out to be greater contributors in comparison with the direct electricity consumption in the facilities, which only accounts for around 4 %.

Lastly, the improvement actions (step 6) proposed in this work: reformulating fodder composition, upgrading cow feeding, and an animal wellbeing program were evaluated, considering both their individual and joint implications, in the six dairy farms of G4 (1, 3, 46, 52, 66, and 73). The potential improvements in terms of WEFni are summarized in **Figure 5.6**.

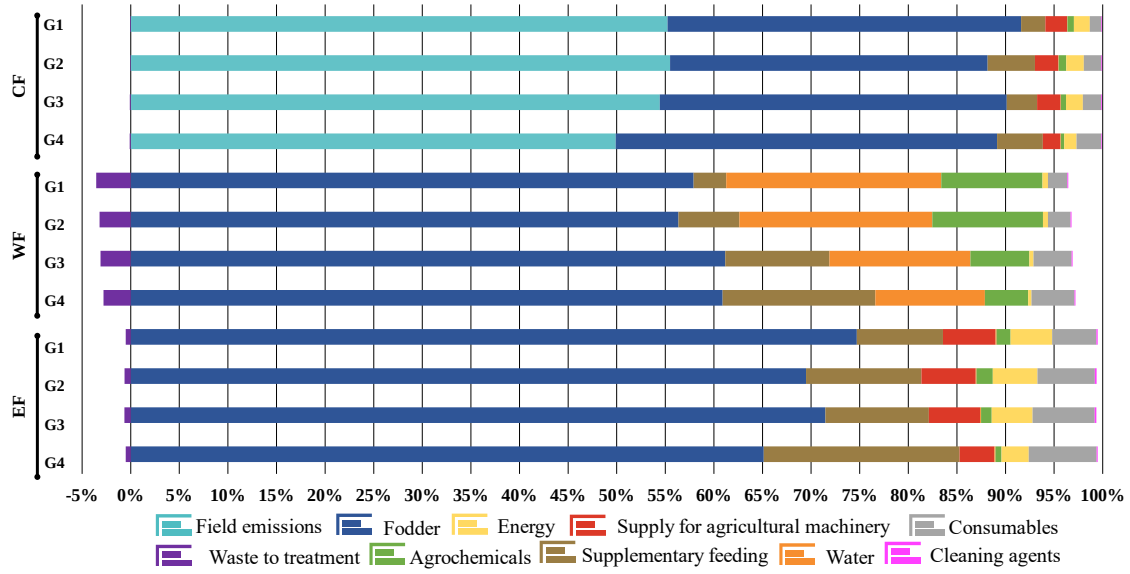



**Figure 5.5**. Contribution of each category in the four identified groups (G1, G2, G3 and G4) per environmental footprint: Carbon footprint (CF), water footprint (WF), energy footprint (EF).

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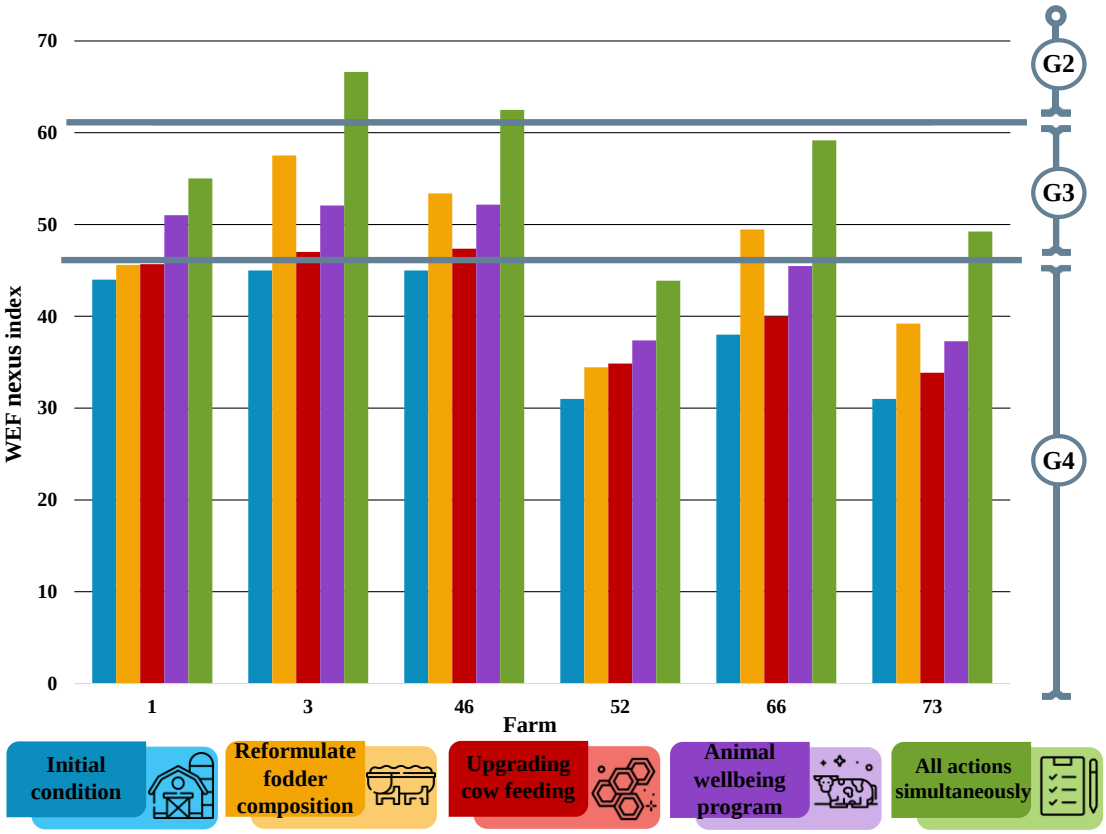



**Figure 5.6**. Water-Energy-Food nexus index of each improvement action, as well as its jointly contribution, in comparison with the initial condition.

The reformulation of the fodder composition is the most promising alternative among the three strategies proposed in four out of six farms of G4. The improvement of the WEFni could be more than 10 points in farms 3 and 66, due to the high environmental impact of the purchased cow fodder (F2 and F38 respectively). As has been showed previously, fodder constitutes one of the main contributors in the three environmental footprints (see **Figure 5.5**). Consequently, their substitution by one with a lower environmental impact is crucial to obtain a higher WEFni. It is also important to note that these actions are aimed exclusively at improving the environmental performance of G4 dairy farms.

Therefore, further analysis is required to consider, for instance, the economic aspects of this substitution, as cow feeding has demonstrated to be a key aspect for maximizing the profitability level of dairy farms (Ruviaro et al., 2020). From a nutritional point of view, the action promoted by the substitution of F52 focuses on the proportion of the main components already used by farmers. In this sense, rapeseed (39.8 %), maize (32.5 %) and barley (15.7 %) are the largest components of F52. Therefore, G4 farms should increase or reduce the proportion of these components, where appropriate. For instance, farm 1 should reduce soy and maize proportions, while farms 46 and 52 should reduce the content of maize and soy to increase the amount of barley and rapeseed. On the other hand, comparing the fodder F52 with F38 and F47 used on farms 66 and 73, respectively; the latter have similar maize proportions, while F2 (farm 3) has similar

proportions in terms of barley content. In the same way, they all have to reduce the percentage of soy (up to 23 % on farm 66) and increase the rapeseed content (around 40 % for farm 73). This means that, in general terms, feed changes are based on the substitution of protein-rich ingredients.

Likewise, the assessment of the PC of fodders showed that the proposed substitution is suitable for some farms of G4. The fodder F52 (PC: 20.68 %) presents values close to the average of the rest of the fodders (PC: 20.64 %), constituting a better alternative in comparison with F1 (PC: 20.15 %), F33 (PC: 18.69 %) and F48 (PC: 16.18 %), employed in farms 1, 46 and 73, respectively. Despite the above, F52 is not always the most suitable alternative in terms of PC, since it involves a lower protein intake compared to F26 (PC: 34.09 %). Based on this, although the PC was measured to evaluate whether the substitution could be optimal in nutritional terms, it has been remarked that the changes proposed in cow feeding have only been justified with the aim of achieving an environmental reduction. Thus, further analysis by animal welfare specialists would be required to avoid any negative consequences for animal nutrition.

In the opposite way, the improvements in the WEFni regarding the upgrading of the cow feeding are not so much effective, since it increases the values about 2-4 points. One of the reasons behind this could be related with the fact that this action only involves the improvement of one of the four indicators which encompass the WEFni. However, in farm 52 this action turns out to be better than reformulating fodder composition. This farm used a fodder (F36) which has a better environmental performance compared to the remaining farms. Furthermore, farm 52 uses a low amount of commercial fodder, as most of the cow feed comes from their own fields. Despite of this, the development of new feed additives to mitigate the CF associated with ruminant digestion is currently being studied (Feng and Kebreab, 2020). Therefore, they can lead to improvements in the fodder formulation to identify the one that best meets the nutritional requirements of cows with a lower environmental burden. To this aim, these new feeding additives must overcome first certain regulatory processes until they become available in the market (Escribano, 2018).

An animal wellbeing program obtains remarkable and almost identical results for the farms of G4 (varying between 6 and 7 additional points). The good values obtained by this action are justified by the fact that it represents an improvement in all the indicators that make up the WEFni. This demonstrates the importance of focusing on increasing the performance of the production process, as it will also result in a reduction of environmental impacts when these are relativized by a FU related to the milk production yield.

In the light of the results obtained when the three actions are undertaken simultaneously, half of the farms of G4 achieve to be within G3, while two of them (farms 3 and 46) could be classified in G2. Therefore, for the implementation of a continuous improvement strategy, it is recommendable to start with the action that has registered the

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best improvement results (i.e., reformulate fodder composition), and then gradually implement the rest of the measures.

Finally, the improvement actions presented in this work were consistent with the hotspots identified, since the type and amount of feed provided to the animals have proven to be a critical factor in the environmental performance of dairy farms. Consequently, the modification (reformulate fodder composition) or enhancement (upgrading cow feeding) of the fodder used turns out to be a potential candidate to be studied to decrease the environmental impacts involved in milk production. Besides, this could be related not only to a greater or lesser number of resources to meet the nutritional demand, but also to the quantity of milk obtained during the production process (animal wellbeing program). The adoption of these changes should always be accompanied by technical support to farmers, since the refusal of them to implement any measure can be a major obstacle during the process (Fleming and Vanclay, 2009). Furthermore, a long evaluation period (at least two years of the milk production campaign) should be considered to assess the performance of the proposed improvement actions.

### 5.5. Water-Energy-Food nexus index in the decision-making process

On the one hand, the indicators used in this study to encompass a WEF nexus approach were selected aiming to represent the main climate and social drivers that are causing increased pressure on water, energy and food resources, as originally defined by Hoff (2011). Regarding climate drivers, three footprints focusing on CC, water demand and energy requirements (CF, WF and EF, respectively) were chosen to provide a comprehensive perspective of the environmental issues related to the dairy industry. CF is a key indicator to accomplish the environmental targets in the mitigation of the climate crisis. Moreover, it also responds to the demand of society for a more transparency process in the environmental declarations of dairy products, apart from promotes the development of green policies (Gollnow et al., 2014). As for water use (WF), this is mainly related to the use of green water (i.e., rainwater), although large amounts of blue water from rivers, lakes or aquifers is also needed, which often leads to local water shortages during periods of drought (Shine et al., 2020). Additionally, achieving optimal levels of energy efficiency is also a vital environmental issue, since a significant share of GHG emissions come from the energy consumption (EF) through two sources: direct consumption in the farm (lighting, cooling, automatic milking systems, among others), and indirect demand from the production of consumables such as cleaning agents or animal feed (Todde et al., 2017). In terms of social drivers, the MY indicator was considered as an alternative for addressing the food security purpose. Thus, its rationale is based on the need to increase the production efficiency to accomplish the food demand of an exponentially growing population (Fukase and Martin, 2020). However, it should also be noted that employing an output-oriented FU (i.e., 1 L of raw milk at the dairy gate) leads to the three environmental indicators are directly related to the amount of raw milk produced (i.e., the MY). Hence the use of another indicator that also reflects aspects of food security assurance (e.g., the level of food wastage) may be an issue to explore in future iterations of the WEFni methodology.

On the other hand, the individual analysis of the indicators allows the identification of specific hotspots (e.g., GHG emissions from enteric fermentation or water demand for feed production), while their aggregations into composite indicators leads to an easy interpretation that facilitate understand the complexities of agri-food production systems, reducing trade-offs and increasing synergies among stakeholders (Endo et al., 2017). Furthermore, this is fundamental for benchmarking environmental performances of products or entities, enabling policy makers to propose continuous improvement strategies focused on those aspects that most affect the WEFni. Notwithstanding, the integration of perspectives may entail the loss of information, although the CRITIC method may provide adequate solutions, as it allows determining the weight of each indicator through a mathematical approach (Jahan et al., 2016). In this sense, it could be relevant to assess to what extent the selection of the aggregation method would affect the final overall score.

## 5.6. Water-Energy-Food nexus approaches in the literature

This section has reviewed the literature on WEF nexus approaches in terms of two main issues: (i) the number and type of dimensions it consists of and (ii) the case studies applied to the dairy sector.

As its name already indicates, the WEF nexus is composed of three dimensions (i.e., water, energy and food). Nevertheless, this approach has also been addressed in pairs or by including additional dimensions to the nexus. With respect to studies that have analyzed the interrelationships of the nexus in pairs, the most common have focused on the water pillar with respect to the other two pillars, i.e., the Water-Food (WF) nexus and the Water-Energy (WE) nexus. The former (WF) is focused on the agri-food sector to understand the relationship between food production yield and water consumption (Corona-López et al., 2021), while the latter (WE) focuses on the water sector, specifically on the energy requirements for the water extraction and distribution, as well as for wastewater treatment, purification or desalination tasks (Hamiche et al., 2016). On the other hand, those papers that have wanted to broaden the scope of the WEF nexus have included other aspects, mainly based on their environmental impact. In this regard, there is a lack of consensus on how to specifically name this external factor, leading to the nexus being referred as WEFE (environment or ecosystem) and WEFC (climate or carbon) (Sambo et al., 2023). This, in turn, is reflected in the several ways they are approached, as according to the WEFE nexus even environmental factors have been included such as socio-economic outcomes or CE indicators (Correa-Cano et al., 2022; Nika et al., 2022). In addition, an approach consisting of up to five dimensions has been coined for the purpose of assessing country-level policy implications in Latvia (Sušnik et al., 2022), or anthropogenic impacts on ecosystem services in Sweden (van den Heuvel et al., 2020), called the WEFLC nexus after including the land and climate dimensions.

With the purpose of carrying out a methodological comparison to other studies available in the literature, only one paper was identified (Livingstone et al., 2021) related to the application of a WEF nexus perspective to a dairy farming system. They evaluated

a dairy farm combined with a short willow rotation system. In addition, a WEF nexus approach was followed, considering a number of indicators such as GW potential, profit, milk production, gross energy production and eutrophication potential. Thus, to identify methodological aspects of the WEF nexus framework, additional studies related to agri-food systems were revised. In this regard, Fabiani et al. (2020) selected a series of indicators for measuring the performance of fertilization techniques through five key aspects: water, energy, food, cost, and gross margin. The authors assigned an equal weight to each indicator, according to a normalization process ranging from 1 to 5, corresponding to a deterioration or improvement, respectively, with respect to a given baseline scenario, and evaluated this with a normalized value of 3. In addition, El-Gafy (2017) integrated some indicators into a single score having considered water and energy consumptions, as well as mass and economic productivities. However, the author does not follow a life cycle perspective. Furthermore, the indicators were normalized by applying the same technique proposed in this paper, while no clear information was provided on the weights assumed in the aggregation step. Finally, Sobrosa Neto et al. (2018) proposed a model to address the WEF nexus concept within beef cattle production, integrating water savings through the rainwater harvesting, generating renewable energy, while improving animal welfare thanks to thermal comfort. However, this study was focused on these practical strategies rather than proposing a methodological approach. The papers abovementioned reflected that the WEF nexus approach has been differently addressed, mainly motivated by the objective of the study. Thus, some issues require clarification and standardization for proper development of the WEFni methodology: the use of a life cycle perspective (i.e., environmental footprints), the sustainability dimension to be assessed, how to obtain unbiased weights for the proposed indicators, as well as the aggregation procedure to obtain a single score.

## 5.7. Conclusions

This chapter introduced an adaptation of a methodology for calculating a WEFni using a holistic approach that combines GHG emissions, water demand, energy requirements and productivity performance for the dairy sector. Likewise, this methodology was applied to benchmark 100 dairy farms and identify the main associated hotspots. On the other hand, farms were grouped according to their WEFni to identify similarities in their animal husbandry practices. Finally, three improvement actions were hypothetically applied to estimate the potential improvement in the WEFni performance.

The WEFni ranged from 31 to 90, showing large differences in the sample of farms assessed, since more than three quarters of the farms were grouped in the two groups with the highest WEFni. This could be mainly due to the MY indicator, which showed differences of up to three times between farms, in addition to being the indicator with the highest weighting factor (32 %). In terms of the individual performance of the footprints, the main hotspot was field emissions and enteric fermentation in the CF (54 %), followed by fodder production (36 %). Conversely, fodder was the critical factor for the WF and EF indicators, with contributions of 63 % and 71 % respectively. In this respect, the reformulation of the fodder proved to be the most promising improvement

measure. On the opposite side would be the improvement of cow feed by means of algae-based additives. However, since feed additives are still in the development phase, they could become a potential alternative in the coming years.

The proposed adaptation of the WEFni methodology could become a useful decision-making tool for all stakeholders which constitute the dairy sector, thanks to its ease of interpretation. In addition, this approach makes it possible to address the perspectives of environmental sustainability and productivity to identify best practices and potential trade-offs between them. As a result, it is expected to provide a roadmap for promoting a more sustainable food industry and to open the door for academics and practitioners to replicate it in other food sectors. In this regard, further studies are essential to standardize the WEFni concept in the literature, as well as the need to consider the integration of a socio-economic perspective. Finally, as the WEFni is influenced by the type and number of indicators that make it up, in addition to the weighting procedure used, these are some of the issues that could be of interest in the future development and improvement of the WEF nexus approach.

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# Chapter 6

## *Expanding the focus of the carbon footprint in fisheries**

* This chapter is based on the following publication: **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. Science of the Total Environment, 847, 157558. https://doi.org/10.1016/j.scitotenv.2022.157558

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# Summary

The adoption of the 2030 Agenda for Sustainable Development must address the balance between sustainable growth and tackling CC. In this context, forests can help reduce GHG emissions, but unfortunately equivalent solutions in the ocean are often disregarded. Moreover, the complexity of determining the real environmental impact of fishing is not a trivial issue. The aim of this study is therefore to broaden the scope and analysis, for the first time, the entire carbon cycle associated with the life cycle of a fish: the Atlantic mackerel (*Scomber scombrus*) from a fishery in the Cantabrian Sea (Spain). From this carbon cycle assessment, it is estimated that fishing activity has prevented 871.7 tons of carbon (in the form of blue carbon) from being sequestered each year. This figure is based on the proportion of fish that would have died naturally if they had not been caught, reaching the seabed where the carbon in their bodies would have been re-mineralized.

In addition to these results, it is essential to implement a series of measures aimed at counteracting the amount of carbon that could have been sequestered on the seabed as a result of the natural death of fish if they had not been caught. To this end, it is shown that the implementation of technical improvements to vessels, the replacement of the fuel currently used and the rearrangement of fishing routes, combined with an extension of the closed fishing season and a commitment to an omnivorous diet, can reduce the carbon flow by almost 90 % of the blue carbon that has been prevented from being sequestered by fishing. A consequential approach can then be used to determine the contribution of the proposed changes on the corresponding carbon flows, to be uses as decision criteria in fisheries regulation and environmental management policies.

**Keywords**

Carbon sequestration | Carbon cycle | Carbon footprint | Dietary patterns | Fishery policies

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### 6.1. Blue carbon sequestration as a potential marine ecosystem service

Recently, the situation created by COVID-19 has indirectly led to remarkable changes in the fisheries sector (Campbell et al., 2021). The various activities necessary to supply fish products from production to the final consumer have been affected not only by new sanitary measures, but also by a change in consumption habits. On the positive side, the reduction in extractive fishing activity has led to improvements in marine ecosystems. However, this situation cannot be maintained in the long term as dietary patterns are affected by the lack of one of the main sources of protein and micronutrients (FAO, 2021b). Therefore, environmental protection of marine ecosystems must be balanced with their sustainable use.

On a broader horizon, extractive fishing activities have continued to increase over the last half century, which could be related to the current depletion of marine stocks, although gaps in data availability prevent drawing firm conclusions (Lam et al., 2020). On the other hand, environmental impacts associated with human activities are negatively affecting the viability of stocks (Cinner et al., 2022).

To reverse this trend, it is necessary to examine the current challenges in quantifying the environmental profile of fishing activities and to propose measures to protect fish production and maintain the supply chain. In this line, the estimation of the GW potential is essential to quantify the total amount of GHG emissions, commonly known as CF. For its proper estimation, it is common to follow an LCA methodology, which is increasingly used to carry out an environmental sustainability analysis of seafood products (Ruiz-Salmón et al., 2021c).

Likewise, different $CO_2$ sequestration techniques are currently being investigated as a CC mitigation strategy. In the case of terrestrial ecosystems, $CO_2$ is removed from the air and stored as organic matter through photosynthesis of the plant mass (Falkowski et al., 2000), this is the case for forests (Jandl et al., 2007), although there are others such as mangrove forests, tidal marshes or seagrass meadows (Alongi, 2012), which imply almost two orders of magnitude greater in terms of carbon sequestration (Wedding et al., 2021). Despite their importance, coastal ecosystems suffer from a high rate of human disturbance (around 40 % in the 20th century), which may be a source of their long-term carbon capture and storage (Irving et al., 2011). All of this is associated with ecological damage that, in monetary terms, can amount to billions of dollars per year (Pendleton et al., 2012).

This type of organic carbon, sequestered and stored in both plant mass and sediments beneath coastal and marine ecosystems, is commonly referred to as "blue carbon" (Macreadie et al., 2019). Within this conceptual framework, a number of projects have emerged. One of them is the International Blue Carbon Initiative, which consists of governments, research institutions and other organizations working together to both protect and restore these types of ecosystems, with the aim of reducing the impacts of global CC (The Blue Carbon Initiative, 2018).

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In terms of the ocean's carbon sequestration potential, more than 80 % of global carbon circulates in its waters, and half of this is sequestered in marine sediments (IUCN, 2017). In recent years, the significant contribution of inland waters has become increasingly apparent, making them suitable for inclusion in CC strategies (Battin et al., 2009). Indeed, this gas exchange could be considered as the most important ecosystem service provided by marine ecosystems (Hori et al., 2019). Moreover, beyond the role of water in the carbon cycle, its biota also plays a role in controlling the exchange of carbon between ecosystems through various chemical processes (Schmitz et al., 2018). For example, in terms of flora, the combination of seagrasses and low herbivore predation leads to the accumulation of high amounts of carbonaceous organic matter, which is stored in marine sediments through detritus (Howard et al., 2018).

Regarding fauna, fish produce carbon during their lifetime in the form of carbonates, which are then excreted through osmoregulatory reactions (Wilson et al., 1996). This flow has a remarkable impact on the inorganic carbon cycle, accounting for up to 15 % of all carbonates produced in the ocean.

However, fish contribute to the carbon cycle not only when they are alive, but also when they are dead. In fact, this is one of the most underestimated carbon flows in the sea, resulting from the natural decomposition of fish carcasses once they reach the seabed. Its importance lies in the fact that it is moderately easy to control, as it is directly linked to fishing through two different pathways: changing fishing seasons with a view to reducing fishing effort would reduce the CF, and at the same time increasing fish stocks would improve the marine biomass and thus the blue carbon sequestered on the seabed (Mariani et al., 2020).

Consequently, given the current situation of depleting fish stocks and increasing pollution, it is important to change the management of the fisheries sector to increase its sustainability in line with restrictive environmental legislation. To this end, this study presents a novel methodology based on the identification of the full carbon cycle of a specific species (*Scomber scombrus*), integrating blue carbon and LCA approaches. This could prove to be a useful tool for identifying the GHG hotspots of fishing activities, in addition to being used to propose mitigation measures for environmental policies.

## 6.2. Approaching the full carbon cycle of a fish species

### 6.2.1. Purpose of the study

The main objective of this study is to characterize the carbon cycle associated with the life cycle of a specific fish species: *Scomber scombrus*, as a representative example of a Spanish fishery species abundant in the Atlantic Ocean and the Mediterranean Sea.

Therefore, this study proposes a methodological framework that aims to establish a tool to estimate, in a relatively simple way, the impact of the fishing sector on the environment beyond its direct consequences (its CF). This has been made possible by quantifying the blue carbon contained in the body of the fish, which is prevented from

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being sequestered on the seabed by natural death after being caught during the development of fishing activity (death by fishing). To do this, it is necessary to identify the different subsystems involved in the global carbon cycle, and to identify and assess the different flows of carbon involved, to estimate a final value according to the main inputs and outputs.

Once the whole carbon cycle has been characterized, the next objective was to modify the carbon flows by assuming different scenarios for improved fisheries management to try to mitigate the amount of carbon avoided to be sequestered by fisheries in terms of blue carbon. Consequently, the ultimate goal of this chapter was to enable a working tool that broadens the approach to carbon flows considered so far in the LCA literature.

### 6.2.2. Scope definition

The species chosen for the carbon cycle approach was Atlantic mackerel (*Scomber scombrus*), due to its considerable importance in the overall fish stocks of Iberian waters, as well as the availability of year-round consumption in a relatively cost-effective manner, providing a healthy and protein-rich source at an affordable cost in the markets (Mercasa, 2020).

To define the total life cycle of this species, data on natural and fishery mortality were compiled from previous studies carried out in the Bay of Biscay (NE Spain) (Sánchez & Olaso, 2004). On the other hand, the catch data correspond to mainly primary data collected through face-to-face surveys for a fleet operating in the NW Cantabrian Sea during the 2018-2019 season. Once the fish was landed in the ports, processing (freezing), management of discards from the processing plant (including anaerobic co-digestion of waste and energy recovery in a cogeneration plant) and final human consumption were considered to identify the different carbon streams of the carbon cycle. All other carbon streams associated with the logistics of transporting fish from the port to the processing plant and from there to the various points of sale, as well as other contributions associated with the preparation of fish for human consumption, are outside the scope of this study.

### 6.2.3. Methodological framework

Different subsystems have been proposed as the most influential in the whole fish carbon cycle, as shown in **Figure 6.1**: fish fate, fishing activity, food processing, waste management and food intake. In this sense, the carbon flows of each subsystem, as well as their interactions, have been considered.

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| Carbon stream | Acronym |
|---|---|
| Blue carbon flow | $C_{BC}$ |
| Fish catching carbon flow | $C_{FC}$ |
| Fishing footprint carbon flow | $C_{FF}$ |
| Process emissions carbon flow | $C_{PE}$ |
| Food waste carbon flow | $C_{FW}$ |
| Waste treatment carbon flow | $C_{WT}$ |
| Avoided emissions carbon flow | $C_{AE}$ |
| Food processed carbon flow | $C_{FP}$ |
| Human metabolism carbon flow | $C_{HM}$ |

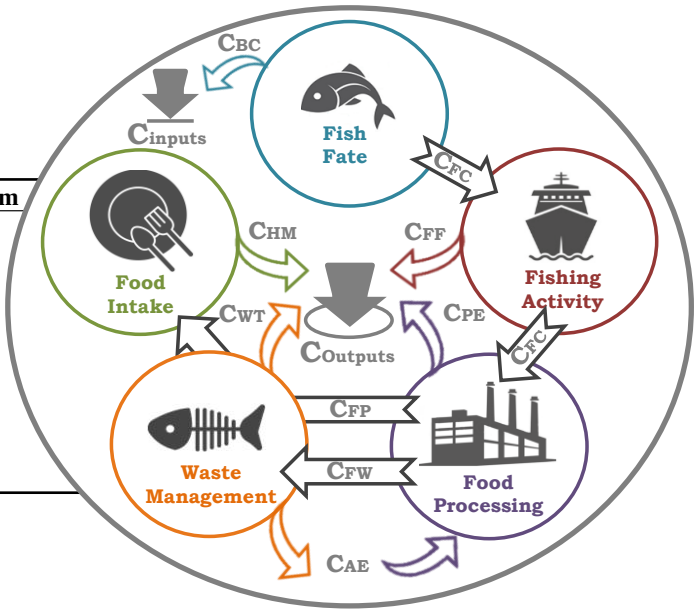



**Figure 6.1**. Carbon cycle of a fish. Each circle illustrates a subsystem: fish fate, fishing activity, food processing, waste management and food intake. The grey circle represents the full carbon cycle, with its inputs ($C_{BC}$, $C_{AE}$), and its outputs ($C_{FF}$, $C_{PE}$, $C_{WT}$, $C_{HM}$).

The methodology followed for estimating the carbon flows associated with each of the subsystems is described below.

6.2.3.1. *Fish fate subsystem*

This subsystem considers two carbon flows: one input, blue carbon flow, and the other, the carbon flow from fish catching, which is transferred to the second subsystem (fishing activity). On the one hand, the fish catching carbon flow was calculated by taking into account the whole-body carbon content of Atlantic mackerel removed from the ocean by fishing. Czamanski et al. (2011) estimated a carbon content of around 46.8 % for this specimen in a study that conducted the elemental characterization of several species from the Bay of Biscay in terms of C, N and P. Although this is a value from a different region than the current case study, very small elemental differences have been found in fish species regardless of their location, time of capture or nutritional value (Tanner et al., 2000). Therefore, using data collected by a fishing fleet located in the Cantabrian Sea in relation to the annual catch of *Scomber scombrus* (2019 season), the amount of carbon extracted from fishing activity was calculated (**Equation 6.1**) in units of tons of carbon per year ($tC \cdot year^{-1}$).

$$C_{FC}\ (tC \cdot year^{-1}) = \text{Carbon fish content (\%)} \cdot \text{Annual fish catch } (t \cdot year^{-1}) \qquad \textbf{Eq 6.1}$$

Where:

| | |
|---|---|
| $C_{FC}$ ($tC \cdot year^{-1}$). | Fish catching carbon flow, in tons of C per year |
| Carbon fish content (*Scomber scombrus*) | 46.8 % (Czamanski et al., 2011). |
| Annual fish catch (*Scomber scombrus*) | 930 t (primary data). |

On the other hand, the blue carbon flow is based on natural and fishery mortality rates. Hence, when fish die of natural causes (no predation), if the carcasses are of a certain size (greater than 30 cm in length), they are more likely to sink quickly and reach the seabed, leaving insufficient time for them to decompose in the water column. They represent an input to the carbon cycle, which is then given a negative sign (-tC·year$^{-1}$), as their biological carbon content is sequestered on the seafloor for long periods of time, up to millions of years, through a remineralization process known as "blue carbon sequestration" (Macreadie et al., 2019). Its calculation (**Equation 6.2**) is derived from the procedure of Mariani et al., (2020), which assumes that the stock is in equilibrium and that it is fished at a maximum sustainable yield level, which is the maximum catch that can be removed from a population by fishing over an indefinite period of time under average environmental conditions (Froese et al., 2019). For this study, fisheries data and mortality rates were collected by Ecopath with Ecosim trophic modelling in the Cantabrian Sea. This tool uses a trophic mass balance approach and reports values of 0.14 and 0.29, for the fishery and natural mortality rates of Atlantic mackerel, respectively (Sánchez & Olaso, 2004).

$$C_{BC}\ (-tC \cdot year^{-1}) = C_{FC}\ (tC \cdot year^{-1}) \cdot SF \qquad \textbf{Eq 6.2}$$

Where:

$C_{BC}$ Blue carbon flow (-tC·year$^{-1}$). The negative symbol is only to signal that it is an input of the fish carbon cycle.

$C_{FC}$ Fish catching carbon flow (tC·year$^{-1}$).

$SF\ (\text{sequestration factor}) = \text{Natural mortality rate} \cdot \text{Fishery mortlity rate}^{-1}$

Natural mortality rate (*Scomber scombrus*) 0.29 (Sánchez and Olaso, 2004).

Fishery mortality rate (*Scomber scombrus*) 0.29 (Sánchez and Olaso, 2004)

6.2.3.2. *Fishing activity subsystem*

The fishing footprint carbon flow was calculated thanks to the employment of an attributional LCA methodology (ISO, 2006a, 2006b). The goal was the estimation of the CF associated with the Atlantic mackerel captured by a fleet of trawlers in the Cantabrian Sea relative to one year of fishing campaign (2019). For that, the SB of the fishing activities (**Figure 6.2**) were defined following a cradle-to-boat gate approach, considering all the inputs and outputs from the production of the raw materials, transport and consumption phases until the fish caught are returned to port. The FU selected was 1 ton of Atlantic mackerel in perfect conditions to be processed.

All the necessary data for the LCI were collected directly through interviews with fishermen who were provided with a set of questionnaires, which were filled in with relevant information corresponding to the annual consumption of marine diesel oil, marine lubricating oil, refrigerant gas (R507), ice, paint, antifouling, trawl nets and water intake, as well as the infrastructure materials required for the construction of the vessel. Additionally, for certain flows consumed during the fishing vessel operations (e.g.,

emissions from the burning of the marine diesel), it was necessary to consider certain assumptions and conduct the modelling of their impacts. For that, the guidelines for achieving a common approach in LCA studies for seafood products proposed by Entrena-Barbero et al. (2023) were followed. On the other hand, the amount of the main material used in the vessel construction (steel), which was estimated based on the average tonnage of the fishing fleet composed of 24 vessels (40 tons) and operating time (40 years).

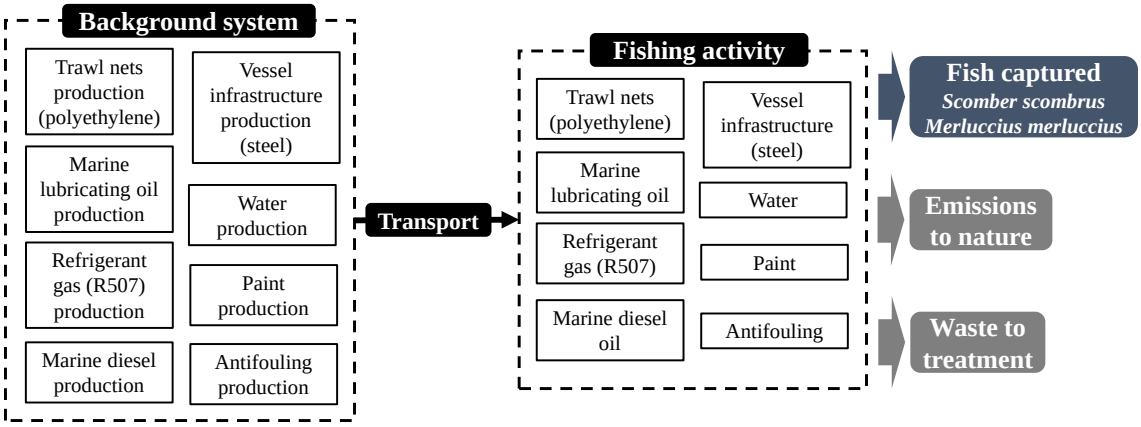



**Figure 6.2**. System boundaries of the fishing activity.

**Table 6.1**. Life cycle inventory per 1 ton of Atlantic mackerel (*Scomber scombrus*).

| **Inputs** | | | **Outputs** | | |
|---|---|---|---|---|---|
| **Material** | | | **Product** | | |
| Trawl nets (polyethylene) | 0.97 | kg | *Scomber scombrus* fished | 1 | ton |
| Vessel infrastructure (steel) | 1.0 | kg | | | |
| Marine lubricant oil | 2.0 | kg | | | |
| Ice | 203.3 | kg | | | |
| Refrigerant gas (R507) | 20.33 | g | | | |
| Water | 325.2 | mL | | | |
| Paint | 0.21 | kg | | | |
| Antifouling | 0.12 | kg | | | |
| **Energy** | | | | | |
| Marine diesel | 396.9 | L | | | |

For sharing the environmental burdens between the target specimen and other secondary species, a mass allocation was performed: *Scomber scombrus* with 930 tons of captures (94.51 %) and *Merluccius merluccius* with 54 tons (5.49 %). Inventory data (see **Table 6.1**) was implemented in the SimaPro software v9.4 and the characterization factors from the ReCiPe v1.1 2016 Midpoint method (Huijbregts et al., 2017) were used to estimate the GW impact category (i.e., the CF). In addition, the Ecoinvent database v3.8 (Moreno Ruiz et al., 2021) was used for the modelling of the background processes involved in the production of the required inputs.

Once the CF related to fishing was obtained having selected the GW impact category per FU (t $CO_2$ eq.·t $fish^{-1}$), the carbon flow associated to the fishing footprint was calculated using the **Equation 6.3** having considered the annual catch of the 2019 season (930 tons) from primary data.

$$C_{FF}\ (tC \cdot year^{-1}) = CF_{fishing}\ (t\ CO_2\ eq. \cdot t^{-1} fish) \cdot \text{Annual fish catch}\ (t \cdot year^{-1}) \qquad \textbf{Eq 6.3}$$

Where:

| | |
|---|---|
| $C_{FF}$ | Fishing footprint carbon flow ($tC \cdot year^{-1}$). |
| $CF_{fishing}$ | Carbon footprint of fishing (t of $CO_2$ eq.·t $fish^{-1}$). |
| Annual fish catch (*Scomber scombrus*) | 930 tons (primary data). |

6.2.3.3. *Food processing subsystem*

Primarily, this subsystem has a carbon flow output (process emissions carbon flow) that derives from the processing of the Atlantic mackerel fished. This basically consists of freezing (individual quick-freezing method) and packaging (plastic wrapping and cardboard box) of the fish for subsequent marketing.

For its estimation, an analogous calculation methodology of the fishing activity subsystem was followed. Then, after the SB definition (**Figure 6.3**), primary data at factory scale was compiled to elaborate an LCI of all material and energy inputs required for the processing of frozen fish (**Table 6.2**), as well as to calculate the CF associated with the industrial process (**Equation 6.4**). Likewise, electricity consumption has been modelled taking into account the consumption of the different energy sources in a three-year average for the Spanish electricity context, as proposed Entrena-Barbero et al. (2023).

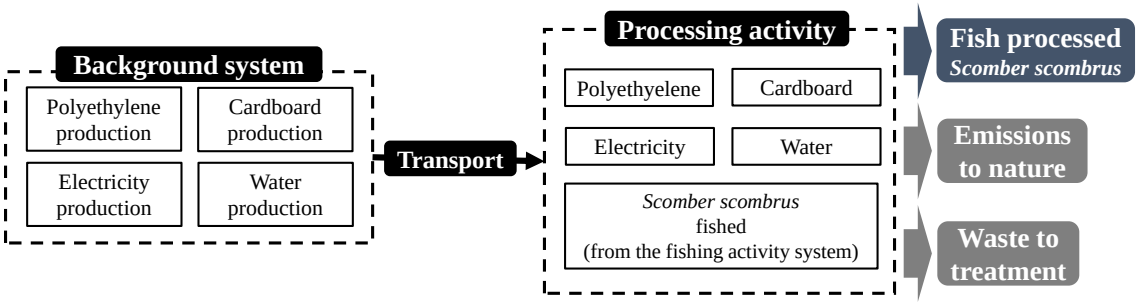



**Figure 6.3**. System boundaries of the processing activity.

**Table 6.2**. Life cycle inventory per 1 ton of freezing Atlantic mackerel (*Scomber scombrus*).

| **Inputs** | | | **Outputs** | | |
|---|---|---|---|---|---|
| **Materials** | | | **Products** | | |
| *Scomber Scombrus* fished | 1,003.9 | kg | *Scomber scombrus* processed | 1 | ton |
| Polyethylene | 0.40 | kg | | | |
| Cardboard | 25.0 | kg | **Waste to treatment** | | |
| Water | 78.7 | L | Wastewater | 78.6 | L |
| **Energy** | | | Polyethylene | 1.2 | kg |
| Electricity | 59.0 | kWh | Cardboard | 1.2 | kg |

$$C_{PE}\ (tC \cdot year^{-1}) = CF_{processing}\ (t\ CO_2\ eq. \cdot t^{-1} fish) \cdot \text{Annual fish catch}\ (t \cdot year^{-1}) \quad \textbf{Eq 6.4}$$

Where:

| | |
|---|---|
| $C_{PE}$ | Process emissions carbon flow ($tC \cdot year^{-1}$). |
| $CF_{processing}$ | Carbon footprint of processing (t of $CO_2$ eq.·t $fish^{-1}$). |

Annual fish catch (*Scomber scombrus*) 930 tons (primary data).

Secondly, from the factory two different carbon flows emerge depending on the comestible content of the Atlantic mackerel: the edible portion will be the input (food processed carbon flow) for the food intake subsystem (**Equation 6.5**), while the uneatable part will be the input (food waste carbon flow) of the waste management system (**Equation 6.6**).

$$C_{FP}\ (tC \cdot year^{-1}) = \text{Edible content}\ (\%) \cdot \text{Carbon fish content}\ (\%) \cdot \text{Annual fish catch}\ (t \cdot year^{-1}) \quad \textbf{Eq 6.5}$$

Where:

| | |
|---|---|
| $C_{FP}$ | Food processed carbon flow (tC·year$^{-1}$). |
| Edible content (*Scomber scombrus*) | 71 % (FAO, 1989). |
| Carbon fish content *(Scomber scombrus*) | 46.8 % (Czamanski et al., 2011). |
| Annual fish catch (*Scomber scombrus*) | 930 tons (primary data). |

$$C_{FW}\ (tC \cdot year^{-1}) = \text{Inedible content}\ (\%) \cdot \text{Carbon fish content}\ (\%) \cdot \text{Annual fish catch}\ (t \cdot year^{-1}) \quad \textbf{Eq 6.6}$$

Where:

| | |
|---|---|
| $C_{FW}$ | Food waste carbon flow (tC·year$^{-1}$). |
| Inedible content (*Scomber scombrus*) | 29 % (FAO, 1989). |
| Carbon fish content *(Scomber scombrus*) | 46.8 % (Czamanski et al., 2011). |
| Annual fish catch (*Scomber scombrus*) | 930 tons (primary data). |

6.2.3.4. *Waste management subsystem*

The discard fraction has been processed in an anaerobic digester to valorize biogas production (Ivanovs et al., 2018). In addition, this waste management process will be coupled to a combined heat and power (CHP) plant, while at the same time reducing GHG emissions by supplying electricity to the processing plant, making it an ideal candidate as an input (-tC·year$^{-1}$) to the fish carbon cycle (avoided emissions carbon flow).

First, the digester input mass flow (**Equation 6.7**) was characterized in terms of volatile solids content to estimate the theoretical biogas production yield (**Equation 6.8**).

For this purpose, standard temperature and pressure conditions were assumed, as well as the use of sewage sludge as inoculum (Eiroa et al., 2012). On the other hand, 60 % of $CH_4$ in the biogas was considered for the calculations (Anukam et al., 2019).

$$\text{Digester input}\ (t\ \text{waste}) = \text{Inedible content}\ (\%) \cdot \text{Annual fish catch}\ (t \cdot year^{-1}) \quad \textbf{Eq 6.7}$$

Where:

| | |
|---|---|
| Inedible content (*Scomber scombrus*) | 29 % (FAO, 1989). |
| Annual fish catch (*Scomber scombrus*) | 930 tons (primary data). |

$$Biogas_{CH_4}(m^3) = DP\ (t\ VS) \cdot MY\ (m^3 \cdot t\ waste^{-1}) \cdot MC\ (\%) \quad \textbf{Eq 6.8}$$

Where:

$Biogas_{CH4}$ Amount of the theoretical $CH_4$ content ($m^3$) of the biogas.

DP Degradable portion (t volatile solids).

$$\text{DP (t VS)} = \text{Digester input (t waste)} \cdot \text{DM (\%)} \cdot \text{VP (t VS} \cdot \text{t waste}^{-1})$$

DM Dry matter content (32 %) (Eiroa et al., 2012).

VP Volatile portion (0.851 t VS·t $waste^{-1}$) (Eiroa et al., 2012).

MY Methane yield (0.35 $m^3$·t $waste^{-1}$) (Eiroa et al., 2012).

MC Methane content (60 %) (Anukam et al., 2019).

Once the output composition was defined, the amount of potential electricity from the biogas was calculated using **Equation 6.9** (Arias et al., 2020; McAllister et al., 2011).

$$\text{Electricity generated (kWh)} = Biogas_{CH_4} \cdot \rho_{CH_4} \cdot LHV_{CH_4} \cdot TC \cdot E \qquad \textbf{Eq 6.9}$$

Where:

$Biogas_{CH4}$ Amount of the theoretical $CH_4$ content ($m^3$) of the biogas.

$\rho_{CH4}$ Methane density (0.656 kg·$(m^3)^{-1}$) (McAllister et al., 2011).

$LHV_{CH4}$ Methane lower heating calorific value (50,000 kJ·$kg^{-1}$) (McAllister et al., 2011).

TC Transformation coefficient (0.000278 kWh·$kJ^{-1}$) (McAllister et al., 2011).

E Efficiency of cogeneration plant (32 %) (Arias et al., 2020).

After this, two carbon flows associated with this subsystem were estimated. On the one side, there is an input: the carbon flow related to the electricity produced in the CHP plant (**Equation 6.10**), as well as an output of the carbon flow related to the waste treatment emissions derived from the activities carried out in the industrial facility (**Equation 6.11**). The CHP plant was implemented in the food processing factory, so the electricity production derived from anaerobic digestion is used to supply the energy demand of the processing industry. Thus, the negative value of the avoided emissions carbon flow was used to offset the process emissions carbon flow from the food processing subsystem.

$$C_{AE}\ (\text{tC} \cdot \text{year}^{-1}) = \text{Electricity generated (kWh)} \cdot \text{EF (t } CO_2\text{eq} \cdot \text{kWh}^{-1}) \qquad \textbf{Eq 6.10}$$

Where:

$C_{AE}$ Avoided emissions carbon flow (tC·$year^{-1}$).

EF Emission factor (0.000707 t $CO_2$ eq·$kWh^{-1}$) (EPA, 2020a).

$$C_{WT}\ (\text{tC} \cdot \text{year}^{-1}) = \text{Biogas production } (m^3) \cdot \text{EF (kg C} \cdot (m^3)^{-1}) \cdot \left(MW_{CO_2eq} \cdot MW_C^{-1}\right) \qquad \textbf{Eq 6.11}$$

Where:

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$C_{WT}$ Waste treatment carbon flow (tC·$year^{-1}$).

EF Emission factor (0.1474 kg C·$(m^3)^{-1}$) (EPA, 2008).

$MW_{CO2eq}$ Molecular weight ($CO_2$ eq) (44.01 g·mol$^{-1}$).

$MW_C$ Molecular weight (C) (12.01 g·mol$^{-1}$).

6.2.3.5. *Food intake subsystem*

The carbon content of the edible portion will be emitted as $CO_2$ after its consumption in the diet (human metabolism carbon flow). For its calculation (**Equation 6.12**), a specific catabolic reaction was taken into account together with a human emission factor: 818.8 kg of $CO_2$ per ton of fish. The latter was estimated considering an average nutritional content of the degradable constituents per 100 g of Atlantic mackerel: proteins (16.70 g) and fats (20.33 g) (BEDCA, 2006), as well as its relative emissions in units of g of $CO_2$ emissions per 100 g of fish: 27.45 and 54.43 for proteins and fats, respectively (Muñoz et al., 2008).

$$C_{HM}\ (tC \cdot year^{-1}) = \text{Total edible content (t fish)} \cdot HEF\ (t\ CO_2 \cdot t\ fish^{-1}) \quad \textbf{Eq 6.12}$$

Where:

$C_{HM}$ Human metabolism carbon flow (tC·year$^{-1}$).

$\text{Total edible content (t fish)} = \text{Edible content (\%)} \cdot \text{Annual fish catch } (t \cdot year^{-1})$

Edible content (*Scomber scombrus*) 71 % (FAO, 1989).

Annual fish catch (*Scomber scombrus*) 930 tons (primary data).

HEF Human emission factor (0.8188 t $CO_2$·t fish$^{-1}$) (BEDCA, 2006; Muñoz et al., 2008).

6.2.4. Scenarios for improving fisheries management

Once the carbon cycle had been characterized, the aim was to modify the values considered in the pursuit to determine the robustness of the proposed method, as well as to find the best options to achieve full compensation of the avoided blue carbon sequestration. Therefore, three different scenarios were proposed to address the current imbalance of the full cycle of the Atlantic mackerel fishery: A (reducing the fishing footprint), B (extending the closed season) and C (a combination of the two).

6.2.4.1. *Scenario A: Reducing the fishing footprint*

With regard to scenario A, the principles of the measures to reduce the fish footprint are related to minimizing the impact caused by fuel, as it has been shown to be the main environmental impact of fishing activities (Avadí & Fréon, 2013). Consequently, the implementation of three different mitigation measures was proposed: technological improvements in the vessel infrastructure (scenario A1), the use of an alternative fuel (scenario A2) and the optimization of the navigation route (scenario A3), as well as all possible combinations between them (scenarios A1-2, A1-3, A2-3 and A1-2-3).

For the first option (A1), there are procedures to minimize fuel consumption related to hull shape and propulsion systems. However, those based on optimizing propeller design and speed stand out, as they have been shown to be the most promising

improvement options, with energy efficiency gains in the range of 10-20 % (Schau et al., 2009). In this case, assuming that the various design improvements described above are implemented in the fleet under study, it was assumed that it would be possible to achieve a 15 % reduction in fuel consumption.

In scenario A2, liquefied natural gas (LNG) was selected as a potential short-term alternative to traditional fuel (diesel) due to the long-standing interest in its use in shipping for both economic and environmental reasons, as well as its suitable implementation in some currently operating fleets (Burel et al., 2013). This alternative can reduce the $CO_2$ emission factor by 20 % (Herdzik, 2011).

Scenario A3 implies the implementation of a new sea route planning that reduces fuel consumption by moderating vessel speed, even if this means longer fishing days. As a result, more efficient voyages result in both lower energy demand and lower GHG emissions (Mesquita et al., 2017). Indeed, a modelling study of a voyage from Portugal to Norway following these assumptions reported up to 15 % less fuel consumption and a 16 % lower $CO_2$ emission factor (Vettor et al., 2016). In this case study, a 10 % reduction was assumed for both fuel consumption and $CO_2$ emissions.

6.2.4.2. *Scenario B: Extending the closed season*

The total catches used in this study were estimated on the basis of 141 working days per year, with the reduction in catches made possible by extending the closed season. This option is increasingly used due to social awareness of the overexploitation of many fishing grounds, despite its undoubted negative economic impacts (Cohen et al., 2013).

The closed fishing season was extended by three different periods of one (scenario B1), three (scenario B2) and five (scenario B3) weeks respectively, taking into account that one week consists of six working days. It is therefore necessary to re-estimate all the carbon flows in the carbon cycle, which will result in a lower avoided blue carbon flow and a lower carbon flow outflow. The estimation of the fishing avoided to be captured was conducted by **Equation 6.13**. However, it will also lead to a shortfall in protein intake (see **Equation 6.14**) due to a reduced supply of fish. To this end, according to the main diets recommended in Spain: Mediterranean diet, South European Atlantic diet, and Spanish dietary guidelines (González-García et al., 2020), several diets (vegetarian, carnivorous and omnivorous) have been proposed as being able to compensate for this protein shortage through other potential sources: legumes and meat (Semba et al., 2021).

Therefore, the modus operandi followed was to estimate the amount of protein lost from fish that will not be caught due to the extension of the closed fishing season and to replace it in an equitable manner with three other sources of protein based on different dietary patterns: vegetarian diet (chickpeas, beans and lentils), carnivorous diet (beef, chicken and pork) and omnivorous diet (chicken and chickpeas, pork and beans and lentils). For example, in the case of the carnivorous diet, if a protein shortage of 75 kg is assumed due to the extension of the closed fishing season, this amount of protein is

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replaced equally by beef, chicken and pork, which means 25 kg of protein from each of them.

The environmental impact of all the feeds was then calculated in terms of kg of $CO_2$ eq. per kg protein supplied (González-García et al., 2020) (see **Table 6.3**), and a final value was obtained for each of the diets considered by summing them by means of **Equation 6.15**. These results will be taken into account to obtain the carbon balance of the different B-scenarios, with the possibility of obtaining better or worse results depending on the environmental profile of the proposed diet compared to that previously established (carbon flow of the fishing footprint).

**Table 6.3**. Protein content (PC) and carbon footprint (CF), as well as its ratio for each food proposed to replace the protein deficiency to have a lower fishing of Atlantic mackerel. [1](BEDCA, 2006), [2](González-García et al., 2020), *This study.

| Food | PC[1] (kg protein·kg$^{-1}$) | CF[2] (kg $CO_2$ eq·kg$^{-1}$) | CF per PC (kg $CO_2$ eq·kg protein$^{-1}$) |
|---|---|---|---|
| Atlantic mackerel | 0.19 | 1.3* | 6.9 |
| Beans | 0.22 | 0.51 | 2.3 |
| Chickpeas | 0.20 | 0.67 | 3.3 |
| Lentils | 0.25 | 1.0 | 4.2 |
| Beef | 0.21 | 24.7 | 119.9 |
| Chicken | 0.23 | 2.5 | 10.8 |
| Pork | 0.21 | 4.9 | 23.9 |

$$\mathrm{FA_n}\ (\mathrm{t \cdot year^{-1}}) = \text{Annual fish catch}\ (\mathrm{t \cdot year^{-1}}) - \text{Fishing factor}_\mathrm{n}\ (\mathrm{t \cdot year^{-1}}) \quad \textbf{Eq 6.13}$$

Where:

FA Fishing avoided, amount of fish avoided to be captured (t·year$^{-1}$).

n Number of weeks of the extension of the closed fishing season (1, 3 or 5 weeks).

Annual fish catch (*Scomber scombrus*) 930 t (primary data).

$$\text{Fishing factor}_\mathrm{n}(\mathrm{t \cdot year^{-1}}) = \text{Annual fish catch}\ (\mathrm{t \cdot year^{-1}}) \cdot (\text{Fishing days}_0 \cdot \text{Fishing days}_\mathrm{n}{}^{-1})$$

Fishing $days_0$ Number of working days without an extension of the closed fishing season (141 days).

Fishing $days_n$ number of working days with an extension of the closed fishing season (135, 123 or 111 working days for the three proposals: 1, 3 or 5 weeks of extension of the closed fishing season, respectively, considering that 1 week has 6 working days).

$$\mathrm{PA_n}\ (\mathrm{t \cdot year^{-1}}) = \mathrm{FA_n}\ (\mathrm{t \cdot year^{-1}}) \cdot \mathrm{PC}\ (\mathrm{t\ protein \cdot t^{-1}}) \quad \textbf{Eq 6.14}$$

Where:

PA Protein avoided, amount of protein from the Atlantic mackerel avoided to be consumed (t protein·year$^{-1}$).

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n Number of weeks of the extension of the closed fishing season (1, 3 or 5 weeks).

FA Fishing avoided, amount of fish avoided to be captured (t·year$^{-1}$).

PC Protein content, amount of protein from the Atlantic mackerel (0.19 t protein·year$^{-1}$) (BEDCA, 2006).

$$\text{Diet footprint}_{xn}\ (\text{tC} \cdot \text{year}^{-1}) = \sum_{y=1}^{3} \frac{\text{PA}_n\ (\text{t protein} \cdot \text{year}^{-1})}{3} \cdot \text{Meal}_y\ (\text{t CO}_2\ \text{eq} \cdot \text{t protein}^{-1}) \qquad \textbf{Eq 6.15}$$

Where:

Diet footprint impact of the consumption of foods that make up each diet (tC·year$^{-1}$).

x Type of diet, vegetarian, carnivorous or omnivorous.

n number of weeks of the extension of the closed fishing season (1, 3 or 5 weeks).

PA Protein avoided, amount of protein from the Atlantic mackerel avoided to be consumed (t protein·year$^{-1}$).

Meal Impact from every food according to its protein content (t $CO_2$ eq·t protein$^{-1}$).

y Each of the three meal groups proposed per type of diet: beans, chickpeas and lentils (vegetarian), beef, chicken and pork (carnivorous) and chicken and chickpeas, pork and beans, and lentils (omnivorous).

6.2.4.3. *Scenario C: Combination of scenarios A and B*

Finally, the combination of scenarios A and B was considered feasible to reduce as much as possible the outputs of the carbon flows of the whole carbon cycle, to compensate for the blue carbon that has been prevented from being sequestered on the seabed. To this end, the results of the reductions achieved (in percentage terms) in each scenario (A+B) are aggregated to try to cover the target set even better. For this purpose, two main criteria: the amount of carbon that can be reduced, as well as the viability of its development, will be the determining factors applied to each scenario (A and B) to choose which will appear in the final scenario (C).

## 6.3. Estimation of avoided blue carbon to be sequestered

The results obtained for each carbon flow using the methodology described above are summarized in **Table 6.4**. However, to facilitate their analysis, the main carbon flows representing each subsystem have been presented in **Figure 6.4** in units of tons of carbon (tC) per year.

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**Table 6.4**. Carbon flows values for each subsystem included in the Atlantic mackerel life cycle.

| Subsystem | Carbon flow | Carbon (t/year) | Direction |
|---|---|---|---|
| **Fish fate** | Blue carbon ($C_{BC}$) | -901.6 | Input avoided |
| | Fish catching ($C_{FC}$) | 435.2 | Transition |
| **Fishing activity** | Fishing footprint ($C_{FF}$) | 1227.0 | Output |
| | Fish catching ($C_{FC}$) | 435.2 | Transition |
| **Food processing** | Process emissions ($C_{PE}$) | 166.5 | Output |
| | Food processed ($C_{FP}$) | 309.0 | Transition |
| | Food waste ($C_{FW}$) | 126.2 | Transition |
| **Waste management** | Food waste ($C_{FW}$) | 126.2 | Transition |
| | Waste treatment ($C_{WT}$) | 23.1 | Output |
| | Avoided emissions ($C_{AE}$) | -53.0 | Input |
| **Food intake** | Food processed ($C_{FP}$) | 309.0 | Transition |
| | Human metabolism ($C_{HM}$) | 253.0 | Output |
| **System – Carbon cycle** | Inputs ($C_{Inputs}$) | -931.5 | Total Inputs |
| | Input from waste management | -29.9 | Input |
| | Outputs ($C_{Outputs}$) | 1646.5 | Total Outputs |
| | **Reduction target** | **-871.7** | **Input avoided** |

The first subsystem, fish fate, is composed of two streams: fish catch and blue carbon, which imply carbon flows of 435.2 and -901.6 t·year$^{-1}$, respectively. These values derive from the carbon content of the species (46.8 %) (Czamanski et al., 2011) according to the catches corresponding to the 2019 fishing year which was 930 tons of Atlantic mackerel, as well as the individual contribution of fishery (0.14) and natural (0.29) mortality rates with respect to the total mortality rate (0.43). These scores lead to a carbon sink subsystem, as the carbon flow from sunk biomass is higher (as a cause of the natural mortality rate) than the carbon flow from fish catch due to the lower fishery mortality rate. However, this is a common finding in other species, such as horse mackerel, blue whiting, anchovy, sardine or squid where the natural rate is higher (Sánchez & Olaso, 2004).

The second subsystem, fishing activity, involves a transition carbon flow related to the carbon content of the fish caught (fish catch) to the food processing subsystem. On the other hand, during the fishing activity, there is another carbon flow from the emissions of the fishing activity, whose value (1227 tC) comes from an emission of approximately 1.32 t of $CO_2$ eq·t fish$^{-1}$, similar in comparison to that reported by Iribarren et al. (2011) for a Galician fleet with the same target species and fishing gear (0.88 t $CO_2$ eq. per ton of fish).

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Considering the third subsystem (food processing), the carbon flow related to the catch of fish of the previous subsystem is split into two flows, one related to the food part of the catch (carbon flow food processing: 309 tC) and the other related to the part

considered as waste (carbon flow food waste: 126.2 tC). In addition, this subsystem has an impact through process emissions of 166.5 tC per year. However, this is related to the waste management subsystem, which contributes to the overall carbon cycle with a carbon flow of -29.9 tC, thanks to the value of avoided emissions (53 tC) compared to the on-site emissions of the waste treatment plant (23.1 tC). These values can be better understood by focusing on the $CH_4$ production rate (0.35 L·g $SV^{-1}$) compared to other fish species, such as tuna, sardine or marlin, with $CH_4$ production yields of 0.28, 0.25 and 0.26 L·g $SV^{-1}$, respectively (Eiroa et al., 2012). Unlike other food waste, it is at an intermediate point between the values obtained with cauliflower stems (0.33 L) and mango (0.37 L), although there are other wastes with considerably higher methanogenic potentials such as onion peel (0.40 L) or lemon peel waste (0.47 L) (Ji et al., 2017).

The last subsystem (food intake) is associated with $CO_2$ released by human metabolism through digestion of processed food, this constitutes an immutable carbon flow of the cycle reporting 253 tC per year (approximately 15 % of the total outputs).

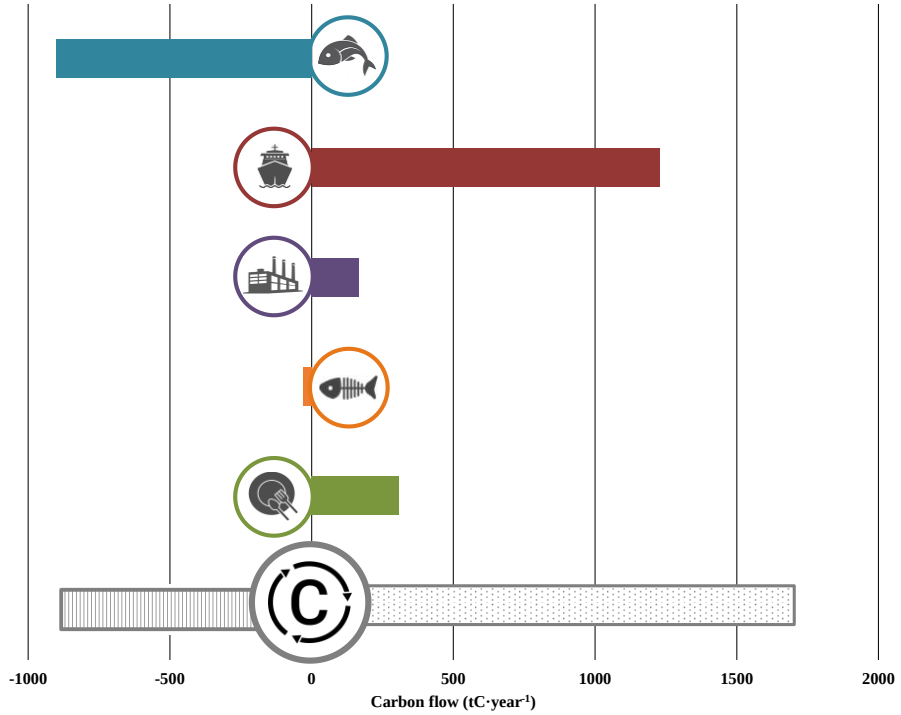



**Figure 6.4**. Carbon flows for each subsystem: fish fate (blue), fishing activity (red), food processing (purple), waste management (orange) and food intake (green), included the total inputs (vertical stripes) and outputs (dotted) of the whole carbon cycle (grey) of the Atlantic mackerel life cycle fishing and processing per year.

Finally, the total carbon system includes all five subsystems, distinguishing between inputs and outputs. In terms of inputs, the reduction target in relation to avoided input is -871.7 tC, as thanks to the contribution of the waste management subsystem it can be achieved an additional carbon flow contribution of -29.9 tC. Nevertheless, this is only a small amount and to reverse the dominance of outputs over inputs, the most viable solution is to reduce the identified outputs. Given that the fisheries footprint is the

dominant quantified output (more than 73 % of the total output contribution), it makes sense to combine efforts to reduce this carbon flow.

## 6.4. Towards the carbon neutrality of the fishing industry

### 6.4.1. Scenario A: Reducing the fishing footprint

The reported results of the reduction achieved (in %) for the different proposed A-scenarios in relation to the carbon target set (-871.7 tC) are shown in **Figure 6.5**. Scenario A-1 reports an imperceptible result, with only a 2.5 % reduction above the previously set target. The reason behind this result may be due to the fact that although fuel consumption has been reduced by 15 %, trawling, the fishing gear used to catch Atlantic mackerel, has proven to be one of the most energy efficient, reporting values of 0.354 kg of fuel per kg of fish captured (Jafarzadeh et al., 2016). The same is true for this case study, where the energy efficiency was calculated: 0.337 kg fuel·kg fish$^{-1}$, obtaining similar values in relation to the previous study.

Fuel substitution by LNG (scenario A2) is the proposal with the best result achieved among the three alternatives with a 22.8 % reduction, however, this has various drawbacks. Among them, it involves an investment for configuration costs, prior training courses for fishermen are required, as well as having to maintain stricter safety conditions (Jafarzadeh et al., 2017). Despite this, in a comparative study against other suitable alternatives, LNG has reported the most promising results in terms of particulate matter production, photochemical ozone, acidification, eutrophication and total energy extracted (Brynolf et al., 2014).

Regarding the scenario A3 (route planning), this is where the worst results are obtained, with only a 2.4 % reduction. The implementation of this scenario, which reports a 10 % reduction in both fuel consumption and $CO_2$ emissions, is based on the modification of the navigation route through the weather forecast at sea, as storms with high wind and waves will result in higher fuel consumption for the ship. Despite that, fish prices is still the main reason to go fishing (Bastardie et al., 2013).

Having studied the different A-scenarios individually, it is now time to explore all possible combinations between them. As expected, the common action of all of them is the one that achieves a significant percentage of reduction (38.5 %), but it is also the one that implies the highest number of obstacles for its implementation. To this end, it might be more interesting from a feasibility point of view to compare the different scenarios that combine only two alternatives. Among them, scenario A2-3 stands out above the rest with a reduction of 36 %, while scenario A1-3 only achieves a 15 % reduction, achieving worse results than other scenarios that implement individual actions (scenario A2). On the other hand, scenario A1-2 exceeds the results reported for scenario A2, but only by a little (25.4 %).

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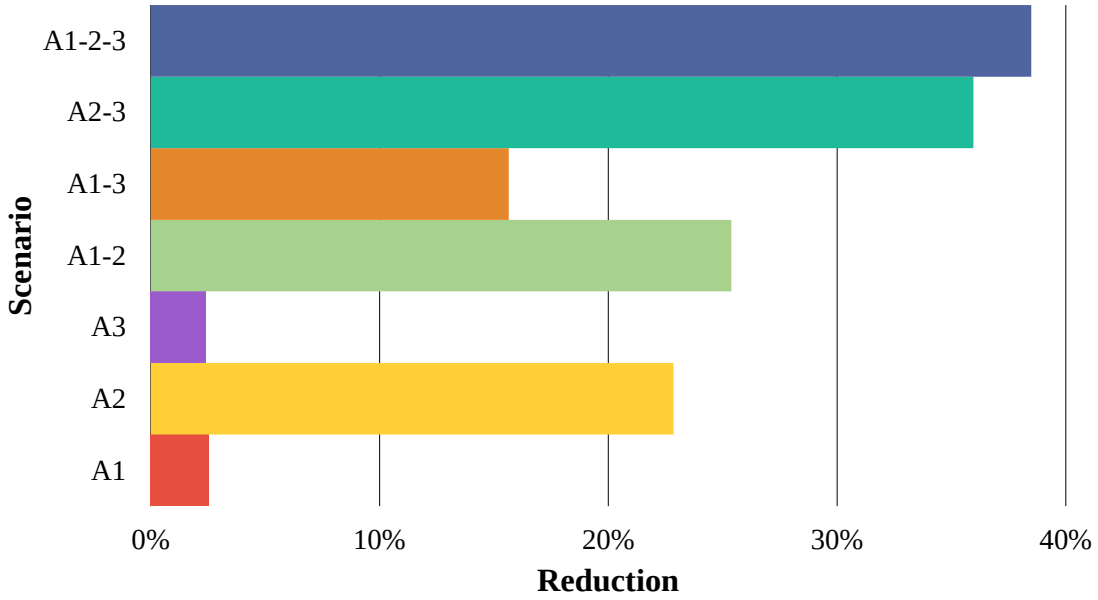



**Figure 6.5**. Contribution of A-scenarios in the reduction of the target set (- 871 tC).

6.4.2. Scenario B: Extending the closed season

Scenario B involves different implications due to the prolongation of the closed fishing period. Among them, on the one hand, there is the immediate consequence of fishing a smaller number of fish per year, consequently, there will be less amount of protein in human diets. Therefore, three diets of a vegetarian, carnivorous and omnivorous nature (including other protein sources), have been proposed for counteracting the shortage of fish protein. Each of them is composed of three main meals that would be consumed equally so that their nutritional values satisfy the protein gap produced. This is why the CF of each meal has been calculated in terms of tC. After that, the sum of the three meals integrates the environmental loads of the diets (diet footprint). Finally, this final value will be balanced with the fishing footprint, allowing to know whether the transition in dietary patterns can be more (reduction) or less (increase) environmentally sustainable (**Figure 6.6**).

According to scenario B1, it can be seen little differences between the vegetarian and omnivorous diets, as both achieve similar reduction results (15.2 % and 11 %, respectively). In contrast, in the case of the carnivorous diet, an increase of more than 25 % is shown, demonstrating that a meat-based diet leads to a more significant environmental impact rather than a fish-based one. The above has been the subject of discussion in other scientific publications available in the literature, where meat consumption has been shown to have a greater impact on the environment in terms of GHG emissions (up to 53 % higher) compared to fish eaters (Scarborough et al., 2014).

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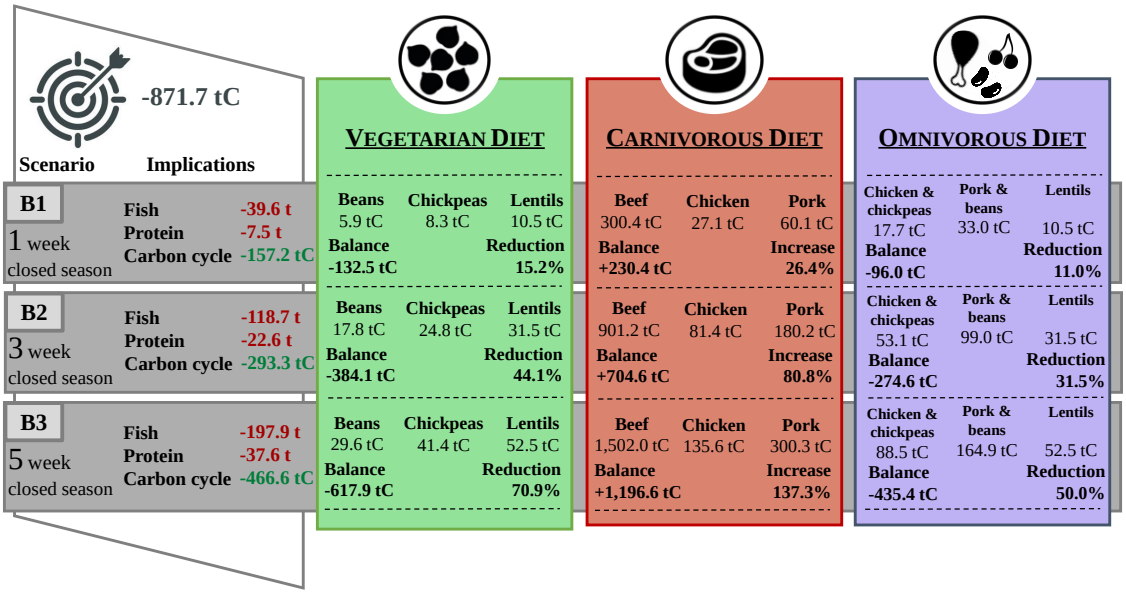



**Figure 6.6**. Implications of the B-scenarios to the fish shortage, protein scarcity and the reduction in the fishing footprint, as well as the balance of each one of the diets proposed: fishing footprints reduction plus the contributions of the diets (summatory of the CFs of the three meals) and their percentage of reduction (or increase) according to the target of reduction set (−871.7 tC).

On the other hand, the scenario B2 shows greater differences in the results obtained for the two potential alternatives that remain: the vegetarian and omnivorous diets, with reduction percentages of 44.1 % and 31.5 %, respectively. This remarkable value of the vegetarian diet can be explained by the low environmental impacts reported for beans, chickpeas and lentils. This is in line with the study by Reijnders & Soret (2003), in which they calculate that for each gram of fish protein about 14 times more fossil fuel consumption is required compared to vegetable protein.

As expected, a five-week longer closed fishing season (scenario B3) achieves the best results. However, this would mean reducing the current fishing season in place (141 days) by almost 18 %, unleashing significant economic and social barriers, although it is a difficult task to estimate, in monetary terms, all the costs (loss of employment, instability of the fishing sector) and revenues (ecological conservation, improvement of ecosystem services provided) involved (Failler & Pan, 2007).

### 6.4.3. Scenario C: Combination of scenarios A and B

Finally, in scenario C (**Figure 6.7**) the main contributors of A-scenarios (A1-2, A2-3 and A1-2-3) have been aligned to the positive implications achieved for the omnivorous diet (scenarios B1, B2 and B3), as it has reported good results in terms of reducing the fish footprint, as well as being more appropriate if people might be willing to make a transition to more environmentally friendly eating habits.

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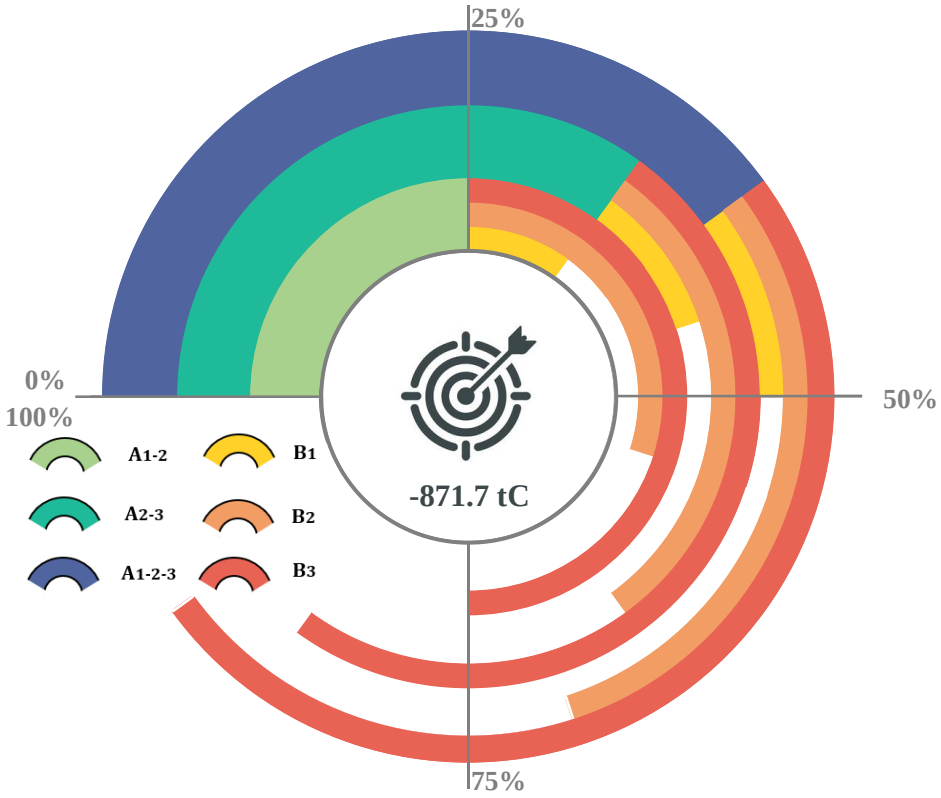



**Figure 6.7**. Results of the combined actions of the main contributions of A-scenarios (A1–2, A2–3 and A1–2–3) and the omnivorous diet of scenario B (B1, B2 and B3) in the reduction of the target set (−871.7 tC).

From the aggregation of the first alternative considered in the omnivorous diet of the scenario B (B1) with A-scenarios, it is shown that all three scenarios achieve percentages between 25-50 %. Therefore, extending the closed fishing season by only one week per year seems insufficient, as it can only reach half of the target set. When it moves to the combination of A-scenarios with B2, the results are placed in the second quadrant of the circumference, obtaining more relevant results up to 67 % and 70 %, for scenarios A2-3+B2 and A1-2-3+B2, respectively. Finally, establishing a five-week extension of the closed fishing season (scenario B3) reports the most promising values, with reductions from 75 % to 88 %. Thus, in view of the results obtained, although the main objective was not achieved with the current proposed measures, it can be avoided to be emitted up to 770 tC into the atmosphere from the Atlantic mackerel fishery.

## 6.5. Conclusions

The methodology developed in this study can be used as an indicator for estimating the main carbon flows associated with the capture, processing, consumption and waste management of the target fishery. Furthermore, although it has been applied to a specific species (*Scomber scombrus*) where catches are consumed after processing, there is the possibility of modifying the carbon cycle through the different subsystems considered to cover other species, fishing gear and farming practices (aquaculture).

In the carbon cycle balance, it has been shown that reducing fishing effort reduces the impact of fishing activity (in terms of CF) and has a double benefit in terms of carbon sequestration: on the one hand, some of the fish not caught will die naturally (more carbon sequestered) and, on the other hand, it will contribute to increasing the population of the target species, which in turn will result in a greater amount of biomass whose carbon will be sequestered in the future.

If the current fishing fleets were to implement various environmental measures, such as technological improvements to vessels, the use of alternative fuels or the restructuring of shipping routes, their impact (i.e., their CF) could be reduced. The same is true if the annual fishing ban is extended by a few weeks, and if the shortage of fish on the market is compensated for by changes in dietary habits towards other less polluting sources of protein. However, both approaches are needed to achieve more promising results.

Ultimately, the approach taken here could point the way to further studies on zero carbon policymaking, with a focus on fisheries. However, it is essential to promote a better understanding of the natural dynamics of marine community structure, together with assessments of natural and fishing mortality rates and the true potential of blue carbon sequestration processes.

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# Chapter 7

## *Integrating economic impacts into the environmental performance in the canned mussel industry**

* This chapter is based on the following publication: **Entrena-Barbero, E.**, Feijoo, G., González-García, S., Moreira, M.T. (2023). Addressing environmental and economic impacts in the sustainable production profile of organic canned pickled mussels. Cleaner Environmental Systems, 11, 100152. https://doi.org/10.1016/j.cesys.2023.100152

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# Summary

One type of food that can help ensure food security is canned seafood, since its consumption stands out as a long-lasting option with all the nutritional benefits of fresh products. At the same time, several policies have been developed to provide a roadmap for global food security. At the European Union level, the PEF can be highlighted as a common approach to estimate and communicate the environmental impacts associated with (food) products, based on the LCA methodology.

Based on the promotion of products that are sustainable while guaranteeing food security, it was decided to select a product for evaluation: OCPM. These are harvested in the Galician Firths, having the particularity of avoiding resources of fossil origin, thus promoting recycled materials, as well as using a traditional pickled sauce made from several organic certified ingredients, among others. The selected product was evaluated in terms of the three dimensions of sustainability: (i) environmental, using the PEF method, in which it was also proposed a non-organic alternative, apart from two improved scenarios (in terms of improved recycling rates of aluminum and cardboard and an upgraded renewable electricity grid mix); (ii) economic, through the monetary implications of the environmental impacts and (iii) social, through a dual perspective, i.e. from a consumer point of view in relation to the Spanish market and from a producer point of view in relation to different types of certifications.

Regarding the environmental dimension, the transition to organic mussel aquaculture has not brought major environmental benefits, the most promising alternative being the improvement of the electricity grid mix. Similarly, the results obtained in terms of economic impacts were not very promising, since only 9 % of them could be avoided when comparing the standard scenario for mussel aquaculture with a scenario that considers all the improvement strategies. From a social point of view, the per capita consumption of canned seafood in Spain has continued to grow over the last decades. In terms of the OCPM, this product has the organic certification for the ingredients that make up the pickle, as well as the Protected Designation of Origin of Galicia. However, there are some key aspects that are not certified, such as the commitment to using vessels belonging to local coastal communities.

In conclusion, the procedure followed in this chapter proves to be a direct and relatively simple way to evaluate a food product from a sustainable point of view, although a more appropriate assessment of the social and economic dimensions is needed, through a social LCA (S-LCA) and LCC, to follow a full life cycle approach.

**Keywords**

Food security | Seafood products | Organic production | Product Environmental Footprint | Monetary Valuation

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### 7.1. Considering the economic impacts into environmental performance

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 et al., 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 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 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 PEF. This aims to create a common framework for estimating and communicating the potential environmental impacts associated with products (goods or services) based on 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 industry, 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 GDP in 2050 (Fujimori 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 et al., 2022).

## 7.2. The role of canned seafood in ensuring food security

One type of food that meets the achievement to pave a way towards environmentally friendly, healthy and affordable diets 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-CF dietary patterns (Entrena-Barbero et al., 2022b). 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, 2022d). 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 (NW 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).

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On the basis of ensuring products that are sustainable while guaranteeing food safety, it was decided to select one product for evaluation: OCPM. These organic mussels are harvested in the deep, clear waters of the Galician Firths on Spain's NW 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, 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 to identify factors that would affect its ability to be incorporated into a sustainable production process.

### 7.3. Literature review of the application of Life Cycle Assessment in mussels

Several studies related to LCA methodology applied to mussel production systems are available in the literature. 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 CC and eutrophication through carbon sequestration by

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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 (DEA) to set efficiency targets for mussel rafts based on their environmental impacts associated (Lozano et al., 2009).

Consequently, two main conclusions can be drawn. 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 chapter 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.

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## 7.4. Sustainability assessment of canned pickled mussels

### 7.4.1. Environmental analysis

For the analysis of the product under study, an environmental LCA was performed. For this purpose, the two international standards were followed (i.e., ISO 14040 and ISO 14044) (ISO, 2006a, 2006b) which divide the methodology into 4 steps: (I) goal and scope definition, (II) inventory analysis, (III) impact assessment and (IV) interpretation of results.

#### 7.4.1.1. *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 FU. This product has a net weight of 115 g and is made up 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, 2022b; 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 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 **Figure 7.1**).

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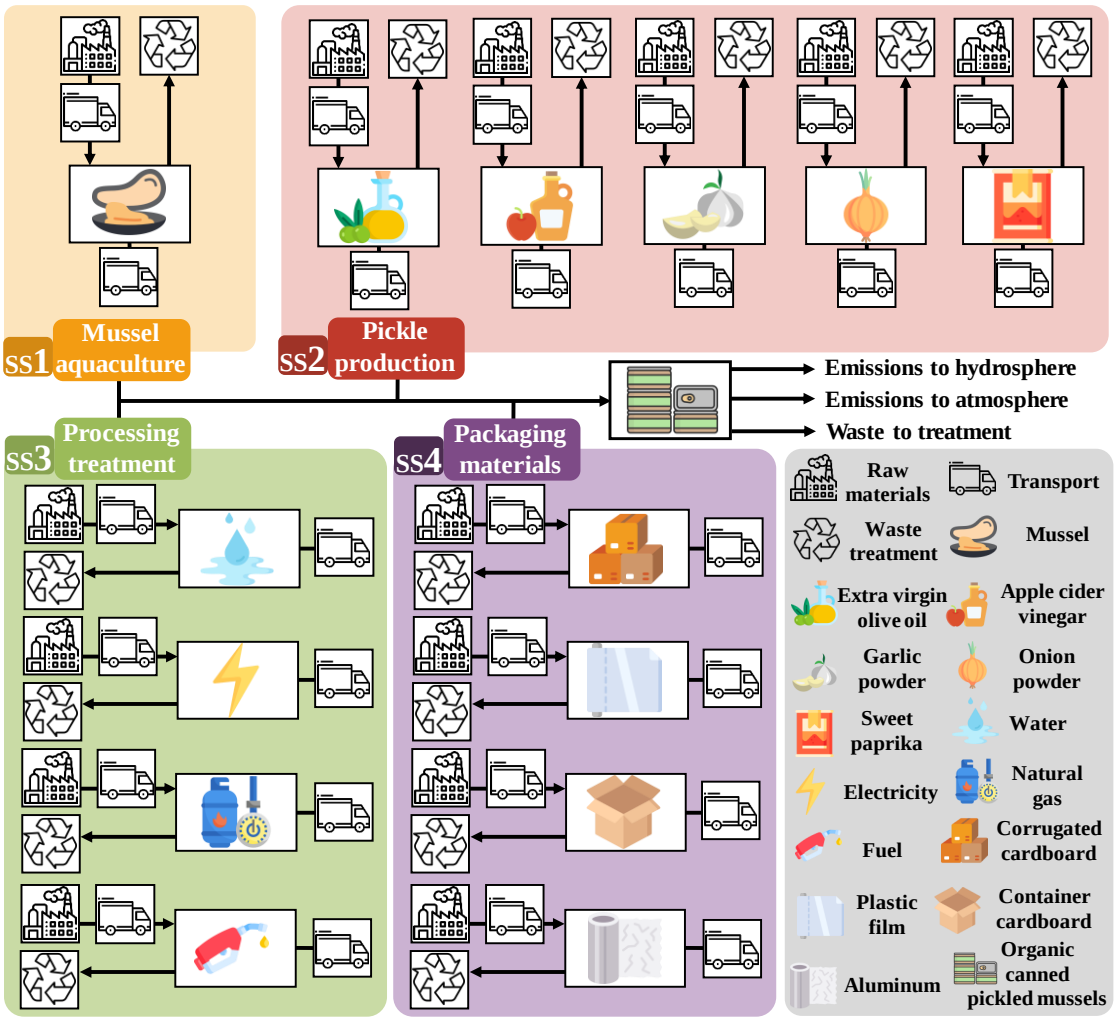



**Figure 7.1**. System boundaries of the organic canned pickled mussels, detailed according to 4 subsystems.

Thus, according to **Figure 7.1**, the system under study can be further divided into four subsystems (SSs): SS1 – mussel aquaculture, SS2 – pickle production, SS3 – processing treatment and SS4 – packaging materials. Each of these is described in more detail below.

SS1. Mussel 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 to 6 months), it is necessary to relocate them at the rate of 2 to 4 final ropes per pre-fattening rope. Finally, once the

mussels reach the desired commercial size, which is around 8 to 10 cm, they are extracted from the ropes, which reach an average weight of 40 kg of mussels after approximately 6 to 8 months of fattening stage. Likewise, several 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, 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 mussel aquaculture are used other non-environmentally friendly alternatives derived from fossil resources such as tar oil.

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.

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.

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 7.2**.

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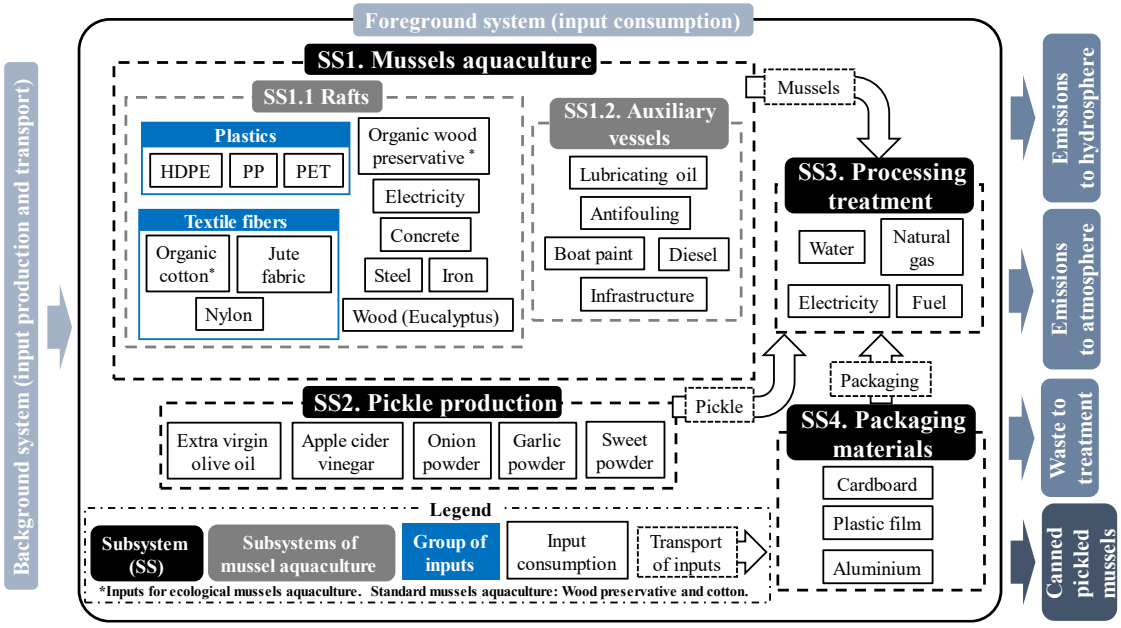



**Figure 7.2**. Flow diagram of the system boundaries of canned pickled mussels.

7.4.1.2. *Step II: Inventory analysis*

*A. 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 by 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).

**Table 7.1**. Life cycle inventory of the four subsystems per functional unit (1 can of pickled mussels). *Values for standard aquaculture. **Inputs for organic aquaculture. Standard aquaculture: Wood preservative and cotton (non-organic).

**INPUTS FROM TECHNOSPHERE**

| **SS1 – Mussel aquaculture** | | |
|---|---|---|
| **Raft** | **Unit** | **Value** |
| Concrete | g | 1.6 |
| Iron | g | 1.9 |
| Wood (Eucalyptus) | $cm^3$ | 6.5 |
| Organic cotton** | mg | 74.4 |
| Nylon | g | 0.5 |
| Jute fabric | mg | 2.5 |
| Steel | mg | 38.9 |
| HDPE | mg | 46.5 |
| PP | µg | 49.2 |
| PET | mg | 2.6 |
| Organic wood preservative** | µL | 409.6 |
| Electricity | Wh | 0.30 |
| **Auxiliary vessel** | **Unit** | **Value** |
| Vessel infrastructure | g | 1.8 / 3.4* |
| Diesel | mL | 4.3 / 8.0* |
| Lubricating oil | mg | 71.5 / 133.9* |
| Boat paint | mg | 40.9 / 76.7* |
| Antifouling | mg | 20.5 / 38.3* |
| **Transport** | **Unit** | **Value** |
| Captured mussels | kg·km | 1.7 |
| **SS2 – Pickle production** | | |
| **Ingredient** | **Unit** | **Value** |
| Extra virgin olive oil | g | 18.2 |
| Apple cider vinegar | g | 11.7 |
| Onion powder | mg | 30.0 |
| Garlic powder | mg | 30.0 |
| Sweet paprika | mg | 30.0 |
| **Transport** | **Unit** | **Value** |
| Extra virgin olive oil | kg·km | 15.9 |
| Apple vinegar | kg·km | 1.6 |
| Onion powder | kg·km | 301.2 |
| Garlic powder | kg·km | 301.2 |
| Sweet paprika | kg·km | 18.0 |

| **SS3 – Processing treatment** | | |
|---|---|---|
| **Material** | **Unit** | **Value** |
| Water | L | 2.5 |
| Natural gas | g | 40.1 |
| Electricity | Wh | 0.3 |
| Fuel oil | mL | 59.3 |
| **Transport** | **Unit** | **Value** |
| Cooked mussels | kg·km | 0.3 |
| **SS4 – Packaging materials** | | |
| **Material** | **Unit** | **Value** |
| Aluminum | g | 18.0 |
| Cardboard | g | 12.2 |
| Plastic film (LDPE) | g | 0.10 |
| **Transport** | **Unit** | **Value** |
| Aluminum | kg·km | 0.3 |
| Cardboard | kg·km | 6.7 |
| Plastic film (LDPE) | kg·km | 0.01 |

**OUTPUTS TO TECHNOSPHERE**

| **SS1 – Mussel culture** | | |
|---|---|---|
| **Waste** | **Unit** | **Value** |
| PP waste | g | 3.8 |
| PET waste | mg | 10.7 |
| Textile waste | mg | 174.5 |
| **SS3 – Processing treatment** | | |
| **Waste** | **Unit** | **Value** |
| Biowaste | g | 3.9 |
| Wastewater | L | 2.5 |
| **SS4 – Packaging materials** | | |
| **Waste** | **Unit** | **Value** |
| Plastic to recycling | g | 0.6 |
| Cardboard to recycling | g | 4.9 |
| **Transport** | **Unit** | **Value** |
| Plastic to recycling | kg·km | 0.08 |
| Cardboard to recycling | kg·km | 0.61 |

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*B. 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 LCI by FU is shown in **Table 7.1**, appearing collected the main differences between the organic and standard procedures for the mussel aquaculture (i.e., OCPM and nOCPM, respectively).

*C. Modelling processes and assumptions*

To establish the LCI processes, the Ecoinvent database v3.8 (Moreno Ruiz et al., 2021) was used. 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 Entrena-Barbero et al. (2023) was followed, which considered the environmental implications related to diesel burning, the air emissions related to the consumption of lubricating oil, as well as the environmental implications of the antifouling production.

Processing treatment: For emissions related to natural gas and fuel oil consumed during processing treatment, the emission factors for $CO_2$, $CH_4$ and $N_2O$ from the IPCC (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 considered 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 v3.8 (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

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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 7.2**).

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.

**Table 7.2**. Inputs and outputs for the production of organic extra virgin olive oil related to the amount in a can of pickled mussels (18.18 g). Own elaboration using data collected from Laso et al., 2017); Maffia et al., (2020).

| Flow | Unit | Value | Flow | Unit | Value |
|---|---|---|---|---|---|
| **Inputs From Technosphere** | | | | | |
| **Materials/fuels** | | | | | |
| Lubricating oil | mg | 6.3 | Fertilizer (other) | µg | 0.1 |
| Ammonium sulfate | mg | 185.4 | Pesticide (Dimethoate) | µg | 3.4 |
| Fertilizer (N) | mg | 0.2 | Pesticide (Glyphosate) | µg | 94.1 |
| Fertilizer (P) | mg | 0.2 | Pesticide (other) | µg | 31.2 |
| Fertilizer (K) | mg | 0.9 | Copper (oxide) | µg | 40.7 |
| Organic matter (compost) | mg | 0.3 | Water | mL | 12.9 |
| **Electricity/heat** | | | | | |
| Electricity | Wh | 14.8 | Gasoline | mg | 21.0 |
| Diesel | g | 2.0 | | | |
| **Outputs To Technosphere** | | | | | |
| **Waste to treatment** | | | | | |
| Pomace | g | 54.2 | Oil waste | g | 13.7 |

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 7.3**, while for the rest of the flows it was the one included by default in the waste treatment of the Ecoinvent database v3.8 (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 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).

**Table 7.3**. Parameters considered in the Circular Footprint Formula per material. Own elaboration using data collected from Zampori and Pant (2019).

| | **Parameters** | | | | | |
|---|---|---|---|---|---|---|
| | A | R1 | R2 | R3 | Qsin/Qp | Qsout/Qp |
| **Definition** / **Material** | Allocation factor of burdens and credits between supplier and user of recycled materials | Proportion of material in the input that has been recycled from a previous system | Proportion of the product that will be recycled in a subsequent system | Proportion of the material in the product that is used for energy recovery | Quality of the ingoing secondary material (recycled material) | Quality of the outgoing secondary material (recyclable material) |
| Steel | 0.20 | 0.18 | 0.95 | 0.009 | 1 | 1 |
| Aluminum | 0.20 | 0 | 0.50 | 0.089 | 1 | 1 |
| Cardboard | 0.20 | 0.47 | 0.75 | 0.045 | 0.85 | 0.85 |
| PET | 0.50 | 0 | 0.44 | 0.100 | 0.90 | 0.90 |
| HDPE | 0.50 | 0 | 0.23 | 0.138 | 0.90 | 0.90 |
| PP | 0.50 | 0 | 0 | 0.178 | 0.90 | 0.90 |
| Plastic film (LDPE) | 0.50 | 0 | 0.28 | 0.129 | 0.75 | 0.75 |

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 CE targets for the percentage of these materials to be recycled by 2030: 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, 2022b). 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 7.4**). Lastly, the main features of all scenarios appear collected in **Table 7.5**.

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**Table 7.4**. Consumption demand (in %) by energy source in Spain during the period 2018-19 (AIB, 2020) and expected distribution in 2030. Own elaboration using data collected from European Commission (2022b).

| **Energy source** | **Process** (Moreno Ruiz et al., 2021) | **Consumption demand (%)** | |
|---|---|---|---|
| | | **2018-19** | **2030** |
| Renewables (unspecified) | Electricity, high voltage {ES}\| heat and power co-generation, biogas, gas engine \| Cut-off, U | 0.25 | 1.9 |
| Solar | Electricity, high voltage {ES}\| electricity production, solar tower power plant, 20 MW \| Cut-off, U | 1.8 | 13.7 |
| Wind | Electricity, high voltage {ES}\| electricity production, wind, >3MW turbine, onshore \| Cut-off, U | 2.3 | 17.7 |
| Hydro | Electricity, high voltage {ES}\| electricity production, hydro, pumped storage \| Cut-off, U | 1.1 | 8.4 |
| Biomass | Electricity, for reuse in municipal waste incineration only {ES}\| treatment of municipal solid waste, incineration \| Cut-off, U | 0.45 | 3.4 |
| Nuclear | Electricity, high voltage {ES}\| electricity production, nuclear, pressure water reactor \| Cut-off, U | 34.8 | 20.3 |
| Fossil (unspecified) | Electricity, high voltage {ES}\| electricity production, natural gas, conventional power plant \| Cut-off, U | 1.4 | 0.90 |
| Lignite | Electricity, high voltage {ES}\| electricity production, lignite \| Cut-off, U | 8.5 | 4.9 |
| Hard coal | Electricity, high voltage {ES}\| electricity production, hard coal \| Cut-off, U | 9.6 | 5.6 |
| Gas | Electricity, high voltage {ES}\| electricity production, natural gas, combined cycle power plant \| Cut-off, U | 33.4 | 19.5 |
| Oil | Electricity, high voltage {ES}\| electricity production, oil \| Cut-off, U | 6.4 | 3.7 |

#### 7.4.1.3. *Step III: Impact assessment*

The 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 v9.4 was used and the Environmental Footprint (EF) method (European Commission, 2021a) was selected.

#### 7.4.1.4. *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.

**Table 7.5**. Main features of the scenarios considered in the life cycle assessment of canned pickled mussels. Own elaboration using data collected from European Commission (2022b); European Parliament (2017).

| Scenario | Main features | Sources |
|---|---|---|
| Standard aquaculture | Standard mussel aquaculture:<br>• On average, 1 auxiliary vessel serves 2.7 rafts.<br>• Non-organic cotton for the nets.<br>• Use of tar oil as wood preservative for the rafts.<br>• Standard agricultural production for the pickling ingredients. | Mainly primary data |
| Organic aquaculture | Organic mussel aquaculture:<br>• Reduced resource consumption: lower ratio of auxiliary vessels used per raft (1 auxiliary vessel serves 5 ecological rafts).<br>• Organic cotton for the nets.<br>• Organic wood preservative for the rafts in the substation of fossil-based alternatives.<br>• Organic pickling ingredients. | |
| Improved recycling rates | Updated recycling rates for key packaging materials in line with European CE targets for 2030:<br>• Aluminum: 60 %.<br>• Cardboard: 85 %. | (European Parliament, 2017) |
| Improved electricity mix | Updated Spanish electricity mix in line with the European Commission REPowerEU plan for 2030:<br>• 45 % from renewable sources. | (European Commission, 2022b) |
| All improvement actions | Measure applied during the production of canned pickled mussels:<br>• Organic aquaculture.<br>• Improved recycling rates.<br>• Improved electricity mix. | Mainly primary data (European Parliament, 2017) (European Commission, 2022b) |

### 7.4.2. Combining environmental and economic indicators

For the monetarization of the environmental impacts, Amadei et al. (2021) was taken as reference, who conducted a literature review 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 7.6**), 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, 2021a). 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. An overview of the procedure followed was depicted in **Figure 7.3**. 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.

**Table 7.6**. Average values of the monetary valuation method (MVM) relative to 2019 considered in each impact category (IC): 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). Own elaboration using data collected from Amadei et al. (2021).

| IC | MVM | Average value | Unit |
|---|---|---|---|
| CC | Damage cost | 0.27 ± 0.27 | €·(kg $CO_2$ eq.)$^{-1}$ |
| | Abatement cost | 0.064 ± 0.033 | |
| | Budget constraint | 0.11 ± 0 | |
| | Averting behavior | 0.13 ± 0.040 | |
| | Market price | 0.13 ± 0 | |
| | Mixed approach | 0.10 ± 0.041 | |
| ODP | Damage cost | 55.4 ± 30.9 | €·(kg CFC11 eq.)$^{-1}$ |
| | Budget constraint | 134.0 ± 0 | |
| | Averting behavior | 96.8 ± 65.2 | |
| | Abatement cost | 35.4 ± 3.1 | |
| | Mixed approach | 756.0 ± 0 | |
| IR | Damage cost | 0.21 ± 0.39 | €·(kBq U-235 eq.)$^{-1}$ |
| POF | Damage cost | 3.5 ± 5.2 | €·(kg NMVOC eq.)$^{-1}$ |
| | Mixed approach | 18.4 ± 0 | |
| | Abatement cost | 5.9 ± 0 | |
| PM | Damage cost | 798,000.0 ± 0 | €·(disease inc.)$^{-1}$ |
| HTN | Damage cost | 153,000.0 ± 0 | €·(CTUh)$^{-1}$ |
| | Other approaches | 166,000.0 ± 0 | |
| HTC | Damage cost | 704,000.0 ± 0 | €·(CTUh)$^{-1}$ |
| | Other approaches | 919,000.0 ± 0 | |
| AC | Damage cost | 0.35 ± 0 | €·(mol H+ eq.)$^{-1}$ |

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**Table 7.6 (cont.)**. Average values of the monetary valuation method (MVM) relative to 2019 considered in each impact category (IC): 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). Own elaboration using data collected from Amadei et al. (2021).

| | | | |
|---|---|---|---|
| FEU | Damage cost | 1.4 ± 0.82 | €·(kg P eq.)$^{-1}$ |
| | Contingent valuation | 76.600.0 ± 0 | |
| MEU | Damage cost | 6.0 ± 4.8 | €·(kg N eq.)$^{-1}$ |
| | Abatement cost | 5.8 ± 2.5 | |
| | Contingent valuation | 10.3 ± 0 | |
| EC | Contingent valuation | 0.00004 ± 0 | €·(CTUe)$^{-1}$ |
| | Damage cost | 1.4 ± 0.82 | |
| LU | Other approaches | 0.0002 ± 0 | €·Pt$^{-1}$ |
| WU | Other approaches | 0.01 | €·(m$^3$ depriv.)$^{-1}$ |
| RUF | Budget constraint | 0.01 | €·(MJ)$^{-1}$ |
| | Averting behavior | 0.01 | |
| | Market price | 0.010 ± 0.006 | |
| RUM | Market price | 7.5 ± 8.2 | €·(kg Sb eq.)$^{-1}$ |
| | Mixed approach | 19,200.0 | |

### 7.4.3. Social evaluation

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.

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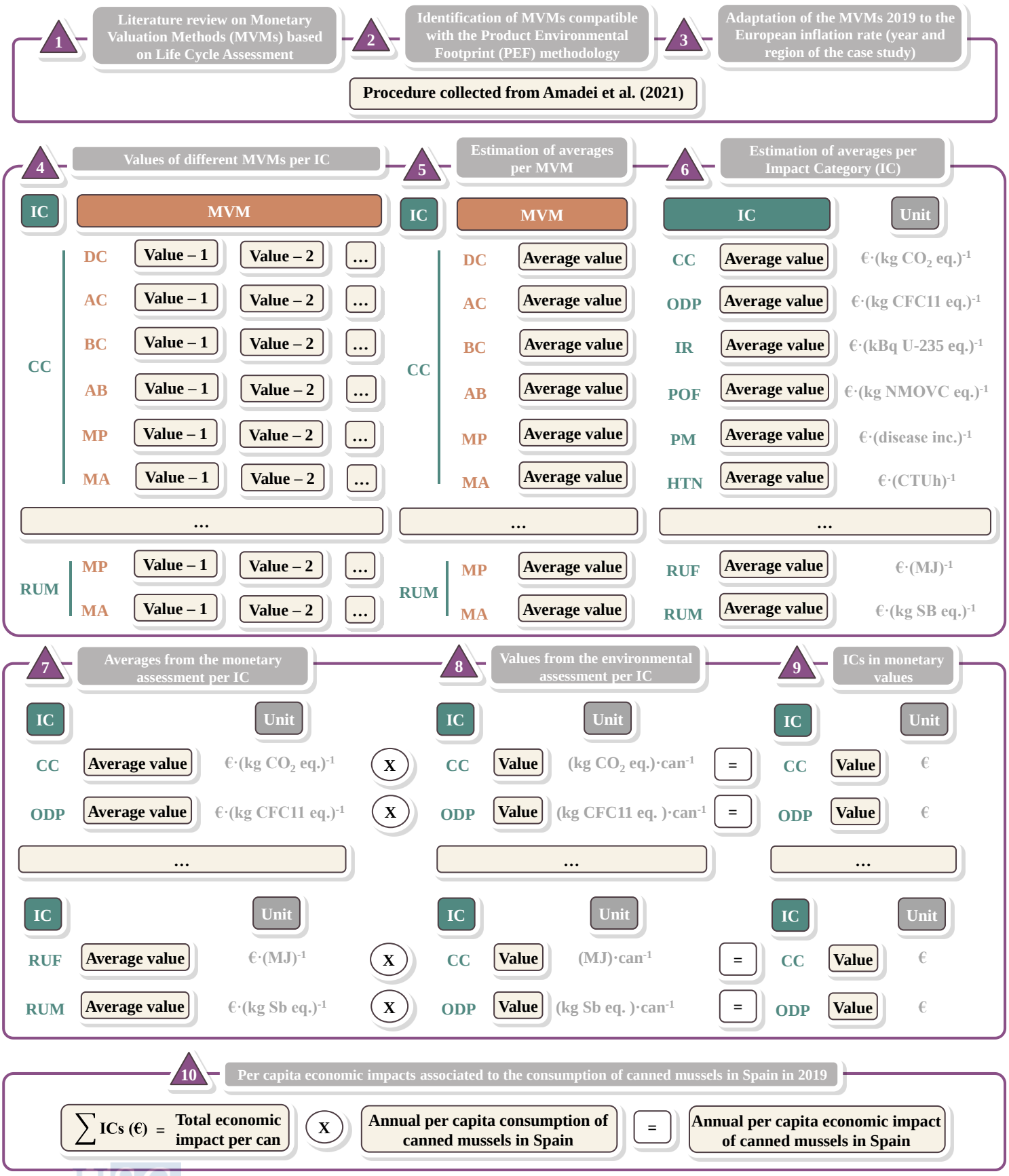



**Figure 7.3**. Methodology followed consisted of 10 steps by estimating the annual per capita economic impacts associated to the consumption of canned mussels in Spain. MVMs: DC (damage cost), AC (abatement cost), BC (budget constraint), AB (averting behavior), MP (market price), MA (mixed approaches).

## 7.5. Sustainability performance of canned pickled mussels

### 7.5.1. Environmental impacts

Considering the values for the organic aquaculture scenario and with the purpose of identifying the main hotspots, the relative contribution of each SS was analyzed per IC (see **Figure 7.4**). 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 because 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. 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. 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 WF 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 **Figure 7.5**.

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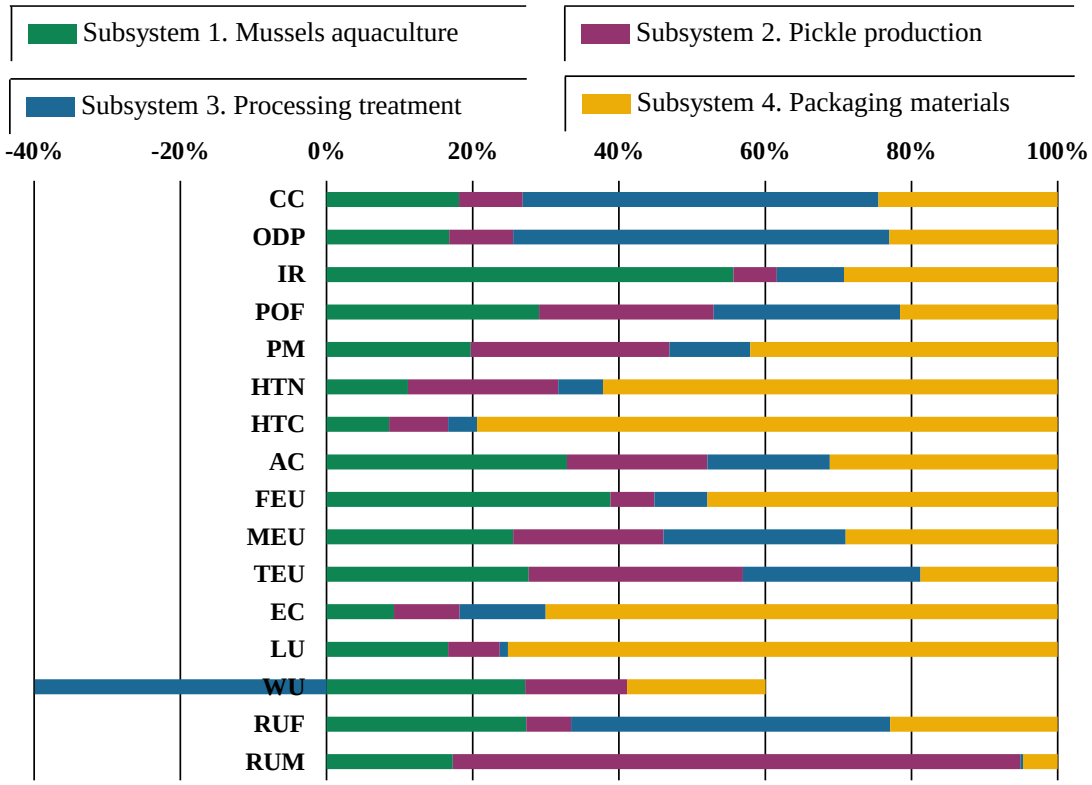



**Figure 7.4**. Relative contributions of each subsystem for the organic mussel aquaculture per impact category: Climate change (CC), ozone depletion (ODP), ionizing radiation (IR), photochemical ozone formation (POF), particulate matter (PM), human toxicity, non-cancer and cancer (HTN and HTC, respectively), 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).

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 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 to produce pickle, 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.

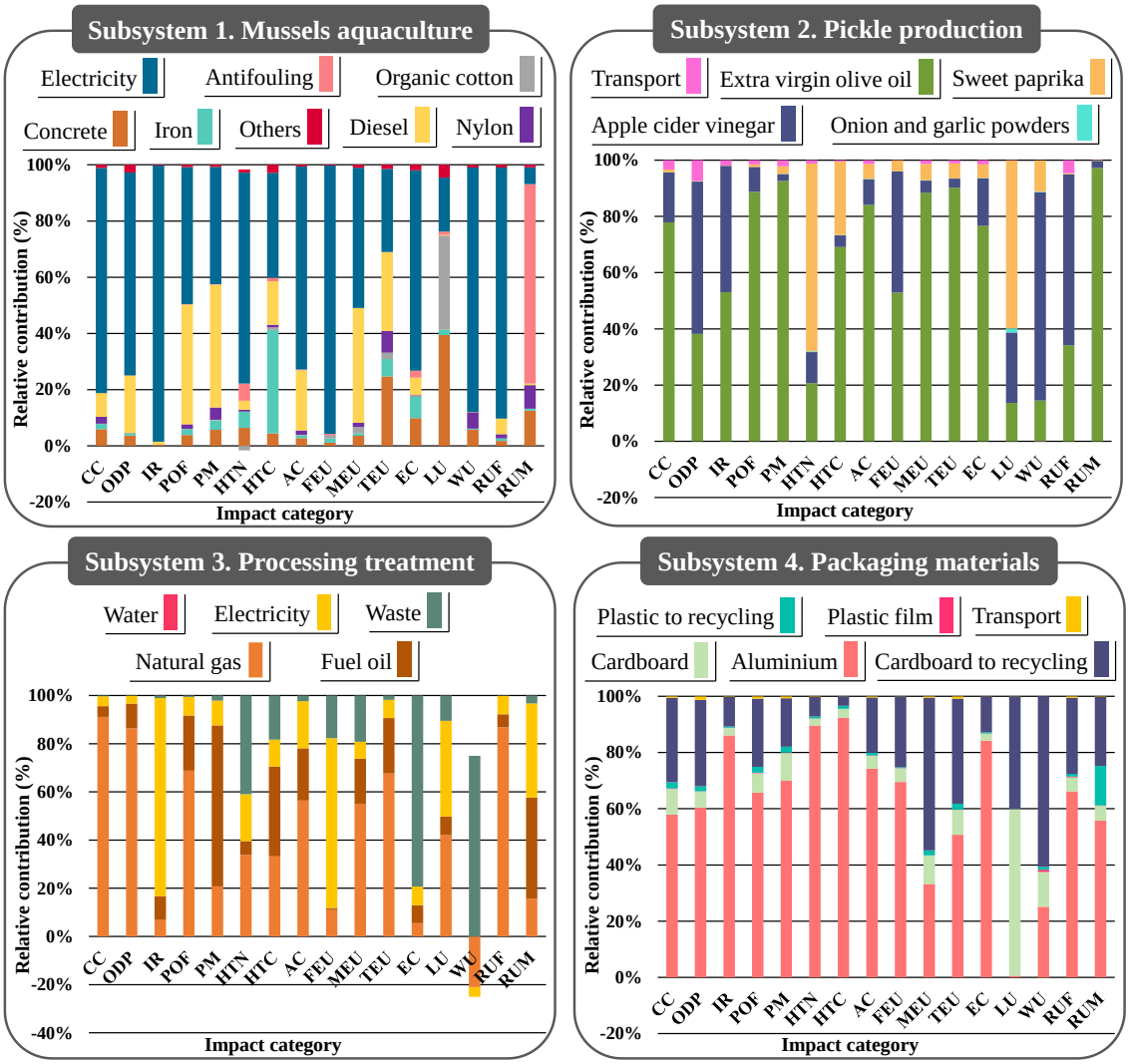



**Figure 7.5**. Relative contributions of flows in each subsystem for the organic aquaculture scenario per impact category: Climate change (CC), ozone depletion (ODP), ionizing radiation (IR), photochemical ozone formation (POF), particulate matter (PM), human toxicity, non-cancer and cancer (HTN and 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).

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.

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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 **Figure 7.6**.

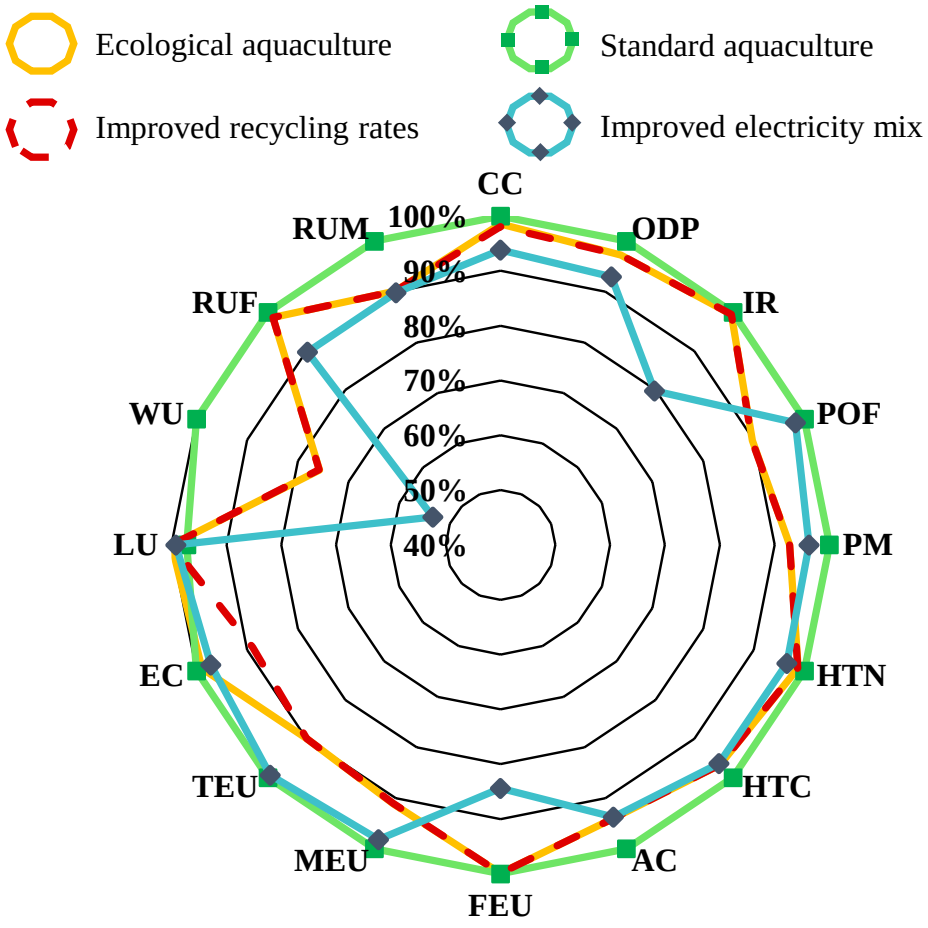



**Figure 7.6**. Percentage comparison among the scenarios of the canned pickled mussels per impact category: Climate change (CC), ozone depletion (ODP), ionizing radiation (IR), photochemical ozone formation (POF), particulate matter (PM), human toxicity, non-cancer and cancer (HTN and HTC, respectively), 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).

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 7.4**). 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 **Figure 7.4**). 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 7.4**).

Finally, the results in **Figure 7.6** are influenced by the modelling of the main characteristics considered for each scenario in **Table 7.5**. 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 considered 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 modeled 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 **Figure 7.4** and **Figure 7.5**). 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 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.

### 7.5.2. Monetary implications of the environmental impacts

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 with meeting such an annual demand for every scenario are shown in **Figure 7.7**, having also compared them on a percentage basis.

As can be observed in **Figure 7.7** 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

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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 µPt and 0.1 euros their annual environmental and economic contributions, respectively, related to the consumption of canned mussels.

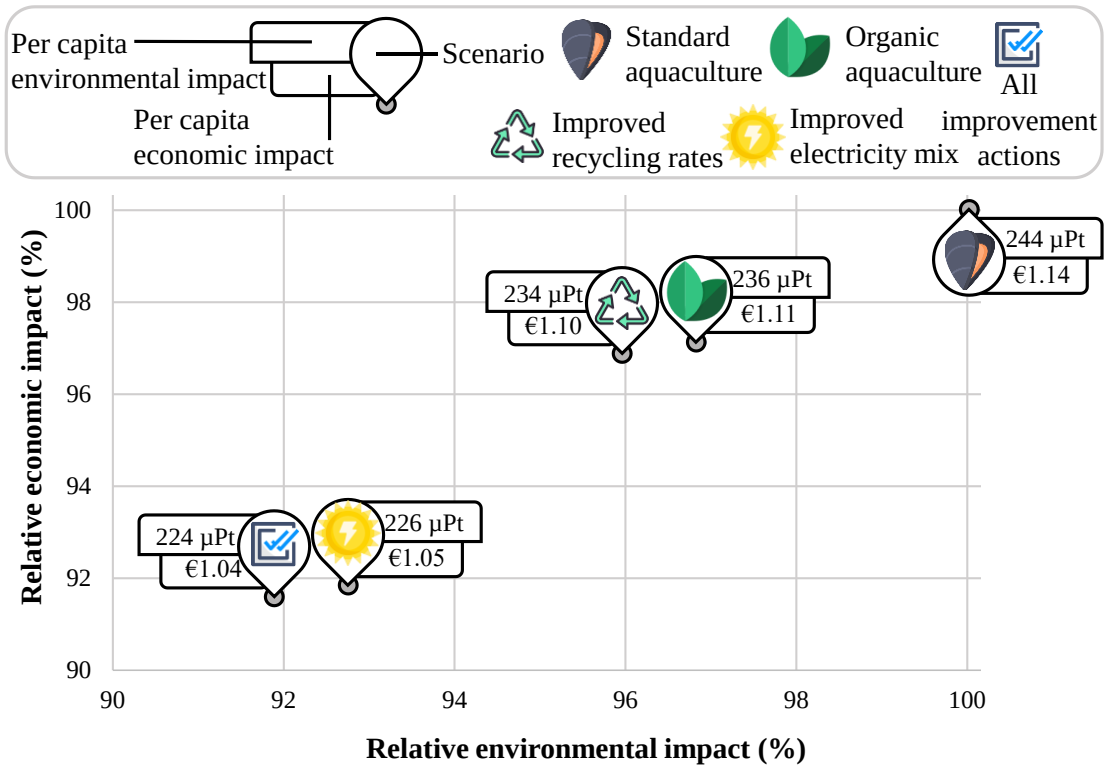



**Figure 7.7**. Comparison among scenarios of the canned pickled mussels through their relative environmental and economic impacts.

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 CE concept could have achieved more favorable values. For instance, commissioning a biorefinery 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 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 perform 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 7.6**): 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 economic availability (Cai and Leung, 2022).

### 7.5.3. Consumers and producers' aspects

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 **Figure 7.8** shows per capita consumption and total expenditure for the main canned seafood products since 2001. From this figure consumption per consumer has not stopped growing since the 21st century. This means that total annual expenditure per household has almost doubled (from

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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, 2021b, 2020b). 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 % the of 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 and 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 chapter, 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 analyzing consumer behavior concluded that social responsibility is a more important factor than environmental responsibility (Plank and Teichmann, 2018).

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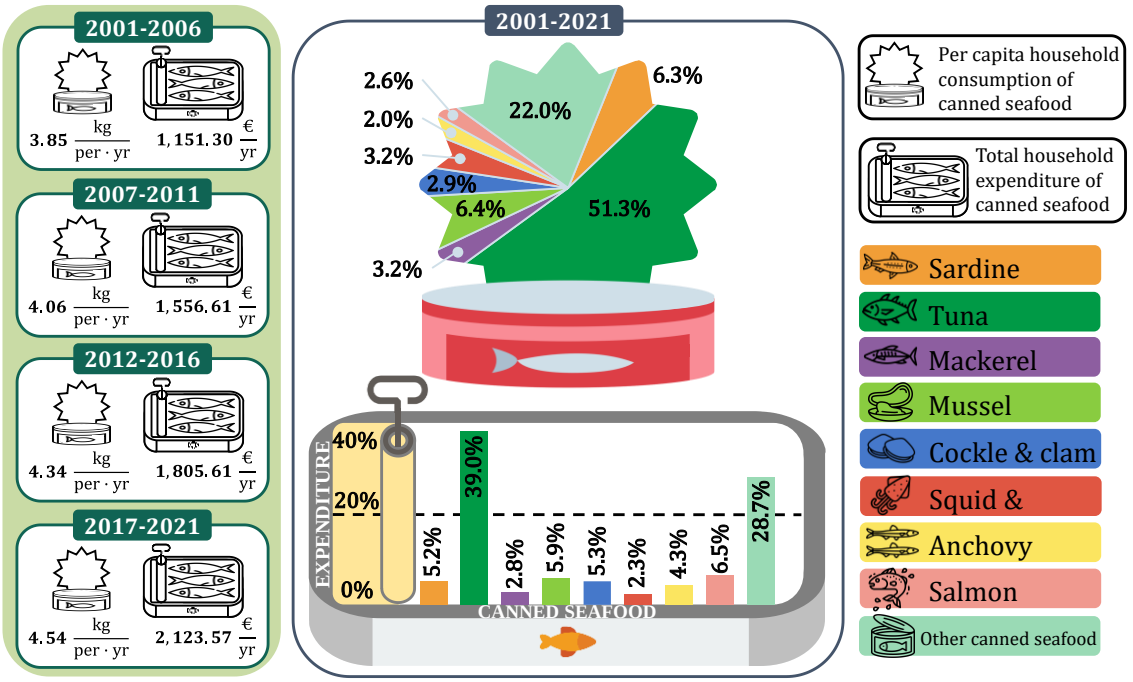



**Figure 7.8**. Per capita household consumption and total household expenditure of canned seafood products in Spain. The total amount of both is shown on average values divided by different periods (2001-2006, 2007-2011, 2012-2016 and 2017-2021), and the relative weight by species appears for the period 2001-2021. c MAPA (2021a).

To reverse this issue, the international organization 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 program 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 environmentally responsible manner, (5) use resource efficiently, (6) be a good neighbor 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).

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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 (LCSA) (Valdivia et al., 2021). Consequently, their applications are highly encouraged to evaluate the social dimension of sustainability in a more appropriate way.

Finally, despite the environmental LCA carried out goes a step further by broadening the focus to take monetary impacts into consideration, this chapter does not consider the impact on the three pillars of the sustainability in a positive way. 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, 2021b). 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).

## 7.6. 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, virgin olive oil, natural gas, as well as aluminum for mussel aquaculture, pickle production, processing treatment and packaging materials, respectively. Furthermore, the transformation of standard mussel aquaculture into an environmentally friendly alternative has not brought major environmental benefits. Similarly, improving the recycling rates of the main packaging materials for this seafood product (i.e. aluminum and cardboard) has not significantly reduced the environmental impact either. On the contrary, the improvement of the Spanish electricity mix has emerged as the most promising alternative. However, the greater difficulty of increasing energy production from renewable sources compared to the recycling rates of aluminum and cardboard must be taken into account. 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

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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.

Therefore, switching from organic to standard consumption of the product analyzed in this chapter does not have a major impact at the personal level, but when considering the nutritional needs of a country, major differences begin to emerge. However, the economic impacts are not as pronounced as might be expected because they were estimated by directly applying the characterization factors from the environmental impacts, so other methodologies should be applied to make more robust comparisons. On the other hand, it is crucial to keep in mind the many advantages of organic aquaculture over standard aquaculture in the social dimension of sustainability, which was not quantified. This shows that it is not advisable to draw premature conclusions about a product when assessing its sustainability from an environmental perspective alone. It also highlights the need for future methodologies to quantitatively analyze them from a social and economic perspective to make comparisons from a holistic point of view.

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.

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# Chapter 8

## *Embedding circular economy aspects into the sustainability profile of dairy farms**

* This chapter is based on the following work to be published: **Entrena-Barbero, E.**, Zepon Tarpani, R. R., Fernández M., Moreira, M.T., Gallego-Schmid, A. Integrating circularity as an essential pillar of dairy farms sustainability. Submitted to Journal of Cleaner Production.

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# Summary

The concepts of circularity (C) and sustainability (S) have emerged to monitor or promote sustainable production and consumption, being included in many initiatives and policies in different contexts. However, the definition and assessment of both is still under debate in the scientific community. In addition, the interrelationship between the two concepts makes it difficult to propose standards that can reach international consensus. For this reason, they have commonly been analyzed individually through a series of indicators that present different units, which hinder their comparison with each other and with other case studies. As a result, the identification of synergies between what can be considered sustainable or circular has been neglected, and the proposal of more holistic and more effective improvement strategies has been overlooked. In this context, this chapter aims to propose a novel framework as a first step towards rectifying this problem, referred to as the CIrcularity and SUstainable (CISU) framework. Furthermore, the focus has been placed on the food industry, and more specifically on the dairy industry, as it currently suffers from multiple dilemmas related to the three pillars of sustainability (i.e., environment, society and economy), in addition to the need for strategies focused on the CE, such as CC, generational replacement, price volatility and resource scarcity.

To this end, 50 Spanish dairy farms located in the region of Galicia were selected to estimate a simple but robust indicator to facilitate communication between stakeholders varying in percentage: the Composite Dairy Farm Index (CDFi). This was the result of integrating a set of 9 C indicators and 21 S indicators. The results obtained showed a relative homogeneity among dairy farms, as well as some room for improvement, with the CDFi (scores from 0 to 100) varying from 36 to 64 points. The results indicate that minimizing reliance on external cow feed, the use of home-grown feed and proper field management are essential to achieve a circular and sustainable milk production system. In addition, the ranking of the set of farms can lead to a way of proposing correct actions, so that the practices carried out in the farms with better scores can be implemented in those with worse scores, being a direct way of improvement at the cooperative level. This chapter helps to propose a novel and useful framework, relatively easy to use for LCA practitioners, which can be adapted to different companies and products to assess the implementation of CE principles. However, the proposed methodology can only be applied at the company or product level, so future iterations should focus on its scalability up to the meso level to evaluate an entire supply chain, including other additional aspects beyond C and S indicators, such as industrial symbiosis.

**Keywords**

Milk production | Life Cycle Sustainability Assessment | Circular Economy | Multi-criteria Decision Analysis | Composite index

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### 8.1. Bringing together circularity and sustainability assessments

Currently, the definition of CE adopts numerous options which implies that uncertainty and subjectivity can be reflected in each circularity (C) assessment study (Niero and Kalbar, 2019). Moreover, it is common to find studies with different units of measurement (e.g. mass, energy or monetary) for quantification, which can pose difficulties when making direct comparisons between products or processes with similar characteristics (Linder et al., 2017). Under the premise of commitment to CE, different policies and regulations are being developed around the world. At the international level, the ISO 59004 standard covers all its aspects related to CE, including public procurement, production or distribution, as well as broader areas such as changing consumer behavior (Gosh, 2020). At the European level, the Circular Economy Action Plan identifies some key products in the value chain for which, given the existing climate crisis, it is urgent to propose a series of actions to form an integrated policy framework (European Commission, 2020b).

Regarding sustainability (S), there are up to seven different approaches to address it: ecological, political, ethical, socioeconomic, democratic, lifestyle and theological (Vogt and Weber, 2019), in addition to the three dimensions on which it is usually articulated: environment, society and economy (Rosen, 2018). All these discrepancies reach consumers who, despite their willingness to opt for sustainable products, find it difficult to make the right choices (Naspetti et al., 2021). One of the new techniques implemented to achieve sustainable practices is the creation of "communities of practice". In them, co-creation is encouraged through the transfer of knowledge among the actors involved to promote more sustainable practices, where the experience of researchers is communicated to advisors willing to translate and transfer skills to professionals in the sector (Triste et al., 2018).

Given the different initiatives to implement both C and S, there is a growing interest in creating frameworks to evaluate these two concepts concomitantly, such as the Sustainable Circular System Design (Abokersh et al., 2021) or the Sustainability and Circularity Evaluation of the Business Model (Antikainen and Valkokari, 2016). Even when the analyses are combined, gaps remain, such as considering only the environmental aspect in the case of S or not providing specific guidance for selecting and assessing C and S indicators.

The agricultural and dairy sectors are major sources of GHG emissions (EPA, 2020b), as well as being a major driver of biodiversity loss and natural habitat transformation (Chaudhary et al., 2016). The main reason these two sectors contribute to the same impacts is that they both share a mixed focus on agricultural crops for livestock and farming. Both systems are threatened by the same S-related problems: CC (Zandalinas et al., 2021), resource scarcity (Tian et al., 2018), price volatility (Schulte et al., 2018) and generational replacement (Góngora et al., 2019). Given the above, numerous projects, policies and research are proliferating to reverse the current negative trend of agricultural and livestock activities based on the concepts of CE and S (Basso et

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al., 2021; Velasco-Muñoz et al., 2021). As examples in that sense, European agricultural production and rural livestock systems have committed to implement small-scale anaerobic digesters for biogas production from animal manure and other wastes (O'Connor et al., 2021). For irrigation of crop fields, reclaimed water (i.e. treated wastewater) has potential to be used as a substitute for freshwater from natural sources (López-Serrano et al., 2022). Likewise, waste milk is often used for feeding dairy calves (Firth et al., 2021).

In relation to the pursuit for a possible solution to the problem of waste or by-product management, industrial symbiosis emerges as an associative approach between waste-generating and waste-using companies, which generates environmental, economic and social benefits through the creation of collaborative business networks based on CE practices at the meso-level (Neves et al., 2020). Additionally, there are currently several methodologies to assess the S of dairy products indirectly through Material Flow Analysis (Rebolledo-Leiva et al., 2022), DEA (Cortés et al., 2021), as well as LCSA (Chen and Holden, 2018). However, it is still debated whether it is necessary to include additional product specifications (e.g., CF) when performing C analysis, as some authors argue that C should be considered a means to sustainable development and not a goal in itself (Corona et al., 2019). However, no study has so far addressed the challenge of measuring C and S from an integrative perspective in the dairy sector, which makes it the ideal sector to evaluate a framework combining CE and S indicators due to its relevance as staple food.

Therefore, despite the growing concern to improve the S of products by decreasing their impacts through C strategies, the main objective of this chapter is to fill this gap in the literature by proposing a novel framework for the holistic integration of CIrcularity and SUstainability indicators (CISU). In addition, CISU has been adapted for application in the DAiry SEctor (CISUDASE) on 50 farms in the region of Galicia (NW Spain).

## 8.2. CIrcularity and SUstainability (CISU) framework

The CISU framework is structured in four steps: (I) selection of indicators, (II) calculation of indicators, (III) integration of indicators through three consecutive sub-steps: normalization, weighting and aggregation, and (IV) interpretation of results (see **Figure 8.1**).

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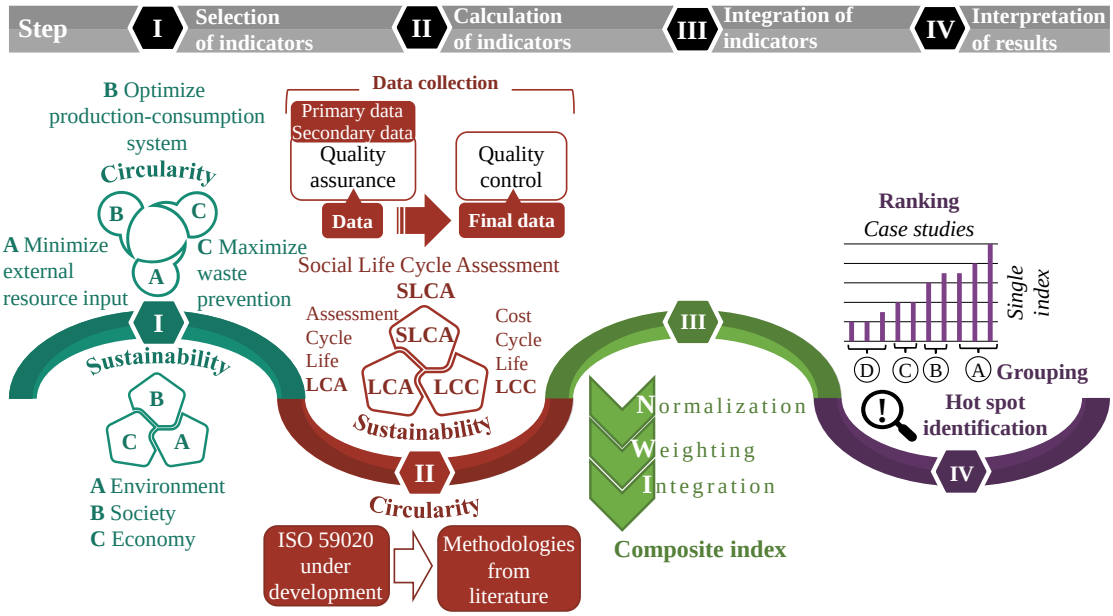



**Figure 8.1**. Framework for the integration of CIrcularity and SUstainability indicators (CISU).

8.2.1. Step I: Selection of indicators

Regarding the selection of C indicators, three types of indicators related to the fundamental principles of CE are proposed: (A) minimize external resource input, (B) optimize production-consumption system and (C) maximize waste prevention (Velenturf & Purnell, 2021), while according to sustainability indicators, its three domains: (A) environment, (B) society and (C) economy, should be considered, as this is the most widespread practice worldwide among practitioners (James and Magee, 2016).

8.2.2. Step II: Calculation of indicators

Firstly, the collection of information should consist of primary data to meet the needs of the study as accurately as possible through the application of a system that ensures confidence requirements. However, this is not an easy task, as it requires a quality assurance team to conduct and interpret all types of actions (e.g. surveys, interviews and/or direct observation). If this information is not available, it will be supplemented with secondary data from other sources, such as books, research papers or relevant statistics.

Two other standards are derived from it: ISO 59010, which captures CE strategies for transforming business models and value networks, and ISO 59020, which provides a framework for measuring and evaluating circularity outcomes. However, since ISO 59020 is still under development, the proposal for C indicators can be approached and justified on the basis of bibliographic references that consider the principles of the CE and the particularities of each production sector evaluated.

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For the calculation of the C indicators, the ISO has set up a Technical Committee (ISO/TC 323). This working group is in charge of developing a standard that provides a common understanding and principles of CE (ISO 59004). Two additional standards are related: ISO 59010, which captures CE strategies for transforming business models and value networks and ISO 59020, which provides a framework for measuring and evaluating circularity performance. However, since ISO 59020 is still under development, the proposal of C indicators can be approached and justified based on bibliographic references that consider the principles of CE and the particularities of each productive sector being evaluated.

Concerning the estimation of S indicators, LCA, S-LCA and LCC methodologies can be considered for the purpose of assessing the S of products (Kloepffer, 2008). LCA environmental indicators can be calculated according to ISO 14040 and 14044 (ISO, 2006a, 2006b). The selection of indicators for the social aspects can be based on the S-LCA methodological approach proposed by the UNEP (Life Cycle Initiative, 2021) and LCC can be used to assess the economic aspect of a product system. This life cycle procedure aims to compile all costs related to a product over its lifetime and can be translated as the difference between cost (i.e. initial and subsequent investments, as well as recurring cost streams, such as material capital) and revenue (Sesana and Salvalai, 2013). Although there is currently no consensus on how to apply it, great efforts are being made to build a standard at the international level as for LCA (Swarr et al., 2011). However, finding monetary valuation factors to compare production cost and environmental impacts to be used during the decision-making process represents a considerable challenge (Amadei et al., 2021).

### 8.2.3. Step III: Integration of indicators

Multicriteria decision analysis (MCDA) is a mathematical procedure that allows a decision to be made between different scenarios through the evaluation of multiple conflicting criteria (Ceballos et al., 2016). Different approaches can be taken into consideration, being one to consider equal importance to all the S aspects (environment, society and economy). Similarly, MCDA can be used to standardize a number of indicators so that they can be integrated and compared through a common unit (Ahi and Searcy, 2015). Moreover, C indicators have demonstrated to be a strong relation with the S ones (Terra et al., 2022) and, therefore, the same methodology could be considered to define the indicators used for the framework. Thus, considering the aspects just mentioned and the perspective that the framework should be simple enough to promote its implementation by policymakers and to foster knowledge transfer among stakeholders, the integration of the S and C indicators can be carried out applying a three consecutive phases: normalization of values, weighting of the indicators and aggregation into a single final score.

#### 8.2.3.1. *Normalization of the values*

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Normalization involves the first procedure for integrating the C and S indicators. This is necessary since these have different units. In this framework, **Equations 8.1** and

**8.2** are applied according to the particularities of the sub-indicator to be normalized: (i) directly proportional to the single index (i.e., the minimum and maximum values of these sub-indicators should be assigned with 0 and 1, respectively); and (ii) inversely proportional to the single index (i.e., the maximum and minimum values of these sub-indicators should be assigned with 0 and 1, respectively).

$$N_{n,k} = \frac{K_n - Kmin_k}{Kmax_k - Kmin_k} \quad \textbf{Eq 8.1}$$

$$N_{n,k} = \frac{Kmax_k - K_n}{Kmax_k - Kmin_k} \quad \textbf{Eq 8.2}$$

Where:

| | |
|---|---|
| n | option “n” being evaluated. |
| k | circularity or sustainability sub-indicator. |
| $N_{n,k}$ | normalized value (0 – 1) for sub-indicator k and option n. |
| $K_n$ | value of sub-indicator k for option n. |
| $Kmin_k$ | minimum value for sub-indicator k. |
| $Kmax_k$ | maximum value for sub-indicator k. |

8.2.3.2. *Weighting of the indicators*

In this second sub-step, an egalitarian perspective regarding the number of sub-indicators is conducted to choose the values of the weighting factors. Thus, considering a total score of 100 (desirable for a single index that varies in percentage as it allows easy interpretation), an equal weighting was considered for each aspect (50 for circularity and 50 for sustainability). Subsequently, the same procedure was applied for the indicators (i.e., weights of 16.67 for environmental, social and economic indicators; as well as for minimizing the input of external resources, optimizing the production-consumption system and maximizing waste prevention) and subsequent subcategories (i.e., sub-indicators composing the indicators). However, different weights could be attributed to give distinct importance to C versus S or vice versa, depending on the particularities of the case study or the approach followed to perform a sensitivity analysis (Mantalovas and Di Mino, 2020). The same procedure was applied to the corresponding indicators and sub-indicators of the C and S indicators.

8.2.3.3. *Aggregation into a single index*

Finally, aggregation into a single index is performed according to **Equations 8.3-8.5**.

$$C_n = \sum_{c=1}^{C} W_c \cdot N_{n,c} \quad \textbf{Eq 8.3}$$

$$S_n = \sum_{s=1}^{S} W_s \cdot N_{n.s} \quad \textbf{Eq 8.4}$$

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$$CI_n = C_n + S_n \quad \textbf{Eq 8.5}$$

Where:

| | |
|---|---|
| n | option "n" being evaluated. |
| $C_n$ | circularity aspect (0 – 50) score for option n. |
| $S_n$ | sustainability aspect (0 – 50) score for option n. |
| c | circularity sub-indicator. |
| s | sustainability sub-indicator. |
| C | total number of circularity sub-indicators. |
| S | total number of sustainability sub-indicators. |
| $W_c$ | weight of circularity sub-indicator. |
| $W_s$ | weight of sustainability sub-indicator. |
| $N_{n,c}$ | normalized value (0 – 1) for circularity sub-indicator and option n. |
| $N_{n,s}$ | normalized value (0 – 1) for sustainability sub-indicator and option n. |
| $CI_n$ | composite index (0 – 100) being evaluated for option n. |

#### 8.2.4. Step IV: Interpretation of results

After the calculation of the single index for the system or product in question, the last step is the interpretation of the results. For this purpose, it is recommended to group the results to carry out a comparative analysis and distinguish particularities or trends. The identification of critical points that contribute most to the single score should be carried out to implement improvement strategies aimed at minimizing environmental, economic and social impacts, while representing an improvement in the C profile of the system or product under study.

### 8.3. CIrcularity and SUstainability in the DAiry SEctor (CISUDASE) framework

The four steps of the CISU framework previously described were herein adapted to evaluate the dairy sector in the form of a framework extension called CISUDASE. In addition, it was applied to a specific case study: raw milk produced on 50 dairy farms in the Spanish region of Galicia (NW Spain). The CISUDASE framework is summarized in **Figure 8.2**.

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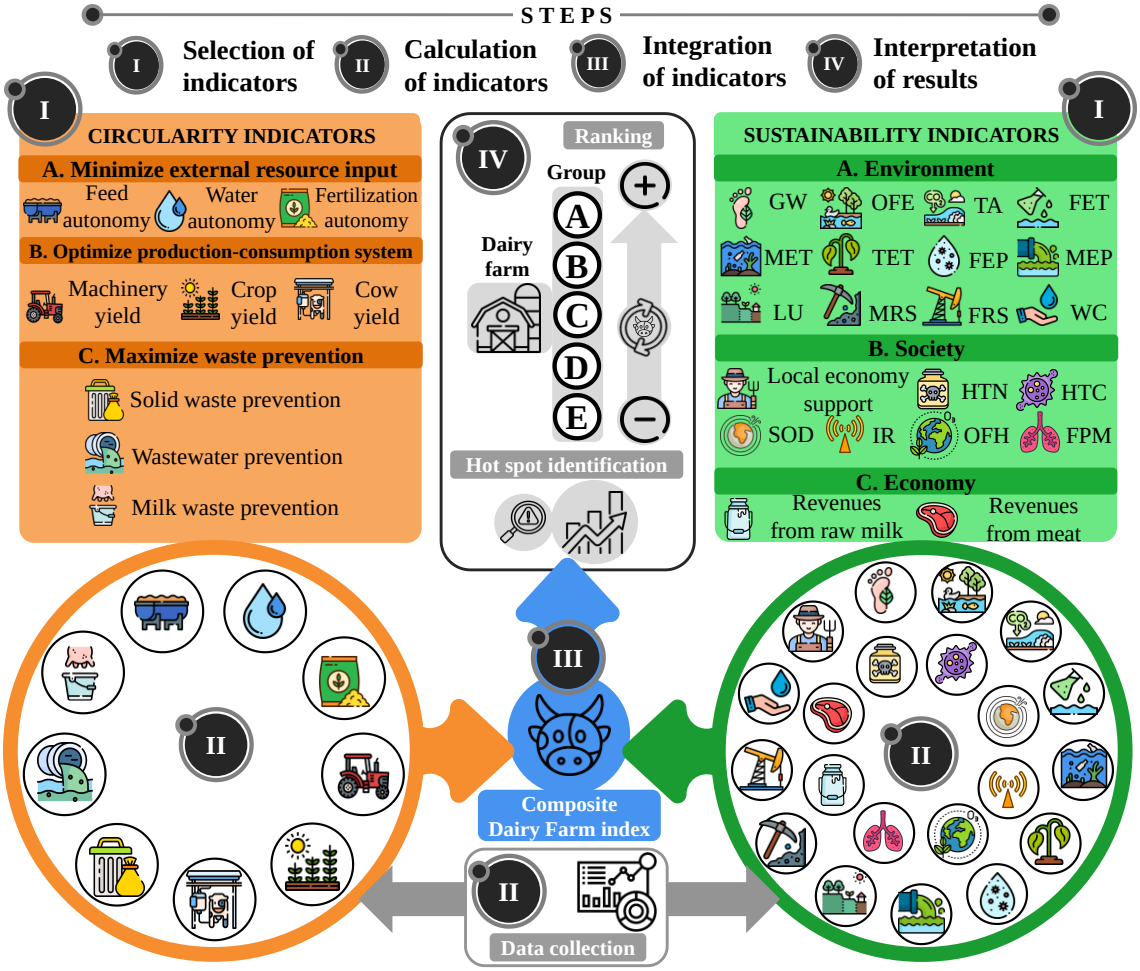



**Figure 8.2**. Framework extension for the integration of CIrcularity and SUstainability indicators in the DAiry SEctor (CISUDASE). GW: global warming; OFE: ozone formation, terrestrial ecosystems; TA: terrestrial acidification; FET: freshwater ecotoxicity; MET: marine ecotoxicity; TET: terrestrial ecotoxicity; FEP: freshwater eutrophication; MEP: marine eutrophication; LU: land use; MRS: mineral resource scarcity; FRS: fossil resource scarcity; WC: water consumption; HTN: human non-carcinogenic toxicity; HTC: human carcinogenic toxicity; SOD: stratospheric ozone depletion; IR: ionizing radiation; OFH: ozone formation, human health; FPM: fine particulate matter formation.

### 8.3.1. Step I: Selection of indicators

#### 8.3.1.1. *Circularity indicators*

Three indicators emerge to estimate the C of dairy farms: (A) minimize external resource input, (B) optimize production-consumption system and (C) maximize waste prevention.

*(A) Minimize external resource input*

This indicator is used for estimating the level of minimization of external resource input, applied to dairy farms is their self-sufficiency in milk production. Such autonomy can be considered as the ability to produce nearby or on attached crop fields the total

amount of feed required by the cattle (Fernandez-Mena et al., 2020) or the availability of their own means to fertilize crop fields (e.g. cow manure) and consequently, avoid dependence on external suppliers (Grillot et al., 2018). Hence, three sub-indicators have been proposed to estimate resource input:

- Feed autonomy: This indicator measures the extent to which the farms' own crop fields provide feed to livestock mainly in the form of grass, maize and silage. If these feeds are not sufficient to meet the feed requirements, the farms must purchase them from other suppliers outside the assessed region. Therefore, the higher proportion of feed produced by the farms compared to what they have had to buy elsewhere translates into greater autonomy for the farmers. Therefore, this indicator gives an estimate of the level of independence of the dairy farm in terms of meeting the feed needs of the cows.

- Water autonomy: Water used on farms for drinking, cleaning and hygiene can come from own or external sources, i.e., from wells or from the mains supply, respectively. Water can be used for drinking (cows only), cleaning (milking parlor) and hygiene (cows and farmers). Then, the availability of well water compatible with a greater number of different uses can translate into greater autonomy to cope with water shortages or possible leaks that may occur in the general water supply network.

- Fertilization autonomy: The use of organic fertilizer (e.g., cow manure produced in the dairy farms) is related to the minimization of commercial synthetic fertilizers.

*(B) Optimize production-consumption system*

Another aspect to consider when measuring the C of farms is the efficiency of their milk production system. More efficient production systems translate into lower resource demand per liter of raw milk produced (Vasa et al., 2017). Thus, three sub-indicators within the productive chain have been chosen to describe this indicator:

- Machinery yield: The amount of feed provided by the crop fields in relation to the fuel needed to run the fleet of agricultural machinery.

- Crop yield: It is estimated as the area of crop fields in relation to the amount of feed produced.

- Cow yield: The raw milk production of dairy cows relative to the total feed intake (from crops and elsewhere) provided by farmers.

*(C) Maximize waste prevention*

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The waste management system for dairy farms is usually very similar, with waste streams being transported to specialized managers (i.e., recycling or energy recovery

plants and wastewater treatment plants, for solid and liquid waste, respectively). However, according to the waste hierarchy established by the European Union in the Waste Framework Directive 2018/851 (European Parliament, 2018), the option of preventing waste generation should be the preferred option. Therefore, it has been decided to differentiate farms on the premise of proportion between the amount of milk produced and the generation of waste streams, either in the form of solid waste (e.g., plastics from silos), liquid waste (e.g., wastewater from cleaning water) or milk waste. Three sub-indicators can be derived from the above:

- Solid waste prevention: The proportion of solid waste in relation to raw milk produced by dairy cows.
- Wastewater prevention: The proportion of wastewater in relation to the raw milk produced by dairy cows.
- Milk waste prevention: The ratio of milk loss due to mastitis in relation to the raw milk produced by dairy cows.

8.3.1.2. *Sustainability indicators*

Following the CISU framework, the S of the milk production process was evaluated considering the three pillars for which it is composed as indicators: (A) environment, (B) society and (C) economy, this practice being also common in previous studies on dairy production (Segerkvist et al., 2020).

*(A) Environment*

For the assessment of the environmental performance of the dairy farms, 12 life cycle impact categories from the ReCiPe Midpoint 2016 method (Huijbregts et al., 2017) were considered as sub-indicators: global warming (GW); ozone formation, terrestrial ecosystems (OFE); terrestrial acidification (TA); freshwater ecotoxicity (FET); marine ecotoxicity (MET); terrestrial ecotoxicity (TET); freshwater eutrophication (FEP); marine eutrophication (MEP); land use (LU); mineral resource scarcity (MRS); fossil resource scarcity (FRS) and water consumption (WC). They were selected because they represent the most critical life-cycle environmental issues related to milk production (EDA, 2018).

*(B) Society*

All social aspects of the UNEP LCA methodological sheets should be considered whenever possible. For the specific case study of the 50 Galician dairy farms, certain social aspects have been neglected based on the accessibility of information. In this sense, most of the subcategories covering "working" stakeholders have not been considered, such as fair salary, working hours or forced labor. This is because all farms are certified with the "Galega 100 %" quality label, which in addition to guaranteeing the origin of milk from Galician dairy farms, also entails another series of requirements, such as animal

health and welfare, in addition to restrictive food safety conditions (Xunta de Galicia, 2011). Moreover, these are located in the same geographical region and are part of the same agri-food cooperative. Consequently, it is expected that the farms studied are managed with the same worker policy and follow very similar processes. As this chapter only covers the production process stage, the stakeholder categories "society", "value chain actors", "consumer" and "children" are outside the scope of this assessment. Consequently, sub-indicators have been proposed to convey the particularities of the social aspects of the system under study considering the two most commonly used stakeholder categories in S-LCA: "local community" and "worker" (Tragnone et al., 2022):

- Supporting the local economy (part of the "local community" stakeholder category): As explained above, to meet animal feed requirements, farmers must purchase feed from external suppliers (e.g., other regions). Therefore, this indicator represents the relationship between workers and the local community, more precisely in terms of evidence of a connection between primary buyers (farmers) and local employment. This indicator has been estimated taking into account the distances from supply centers to farms as well as the amount of feed purchased externally, as shorter distance and less feed purchased is an indication not only of less environmental impact and nutritional safety for the cows, but also of supporting the local economy as well as fostering the creation of closer working relationships between workers and the community.

- Health and safety (part of the "worker" stakeholder category): six indicators of the ReCiPe Midpoint 2016 method have been chosen, that is stratospheric ozone depletion (SOD); ionizing radiation (IR); ozone formation, human health (OFH); fine particulate matter formation (FPM); human carcinogenic toxicity (HTC) and human non-carcinogenic toxicity (HTN).

*(C) Economy*

To assess the economic aspect of dairy farms through a LCC, it is common to consider profitability as the difference between total costs and revenue from sales of milk and any other co-products obtained (meat) (Chen and Holden, 2018). Unfortunately, information in terms of cost was not available for the specific case of the 50 farms. Consequently, two indicators can be used:

- Revenues from raw milk: gross profit earned through milk production from dairy cows.

- Revenues from meat: gross profit obtained through meat production from slaughtered cows.

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### 8.3.2. Step II: Calculation of indicators

#### 8.3.2.1. *Data collection*

For data collection, the information for the 50 dairy farms is related to the 2020 annual milk production campaign (January to December) through surveys fulfilled by farmers. All farms are located in Galicia, most of them in the provinces of Lugo (31 farms) and La Coruña (17 farms), while two farms are located on the border between Galicia and the Principality of Asturias. All of them are integrated within AGACA, which is a group that seeks to promote the competitiveness of the different livestock and agricultural activities in Galicia through leadership strategies and advice on farm management. Production activity is based almost exclusively on raw milk production, although once dairy cows have reached the end of their productive life, they are sold to slaughterhouses for extra economic benefits in the form of meat. On average, these farms have been in operation for 12 years and a herd of 156 cows consisting of 36 heifers, 105 dairy cows and 15 dry cows. Likewise, more than 12,000 L of milk per cow are produced on average by every dairy farm in one year. On the other hand, each farm sends an average of 25 cows to slaughterhouses annually, which is equivalent to producing 7,500 kg of meat, being replaced by heifers beginning their first lactation.

The premises of the farm (average area of 51 ha) were cultivated for cow feed. The maize silage and grass silage are harvested using farm machinery. In addition, 12 farms have grazing fields where cows can feed depending on the availability of grass. However, these are not sufficient to meet the demand for feed and additional feed has to be purchased from external suppliers. For fertilization of crop fields, cow manure is collected and used as organic fertilizer in pits built with reinforced concrete walls and floors and a fiber cement cover to prevent rainwater infiltration. These pits have a storage capacity equivalent to the manure produced for four months, so they are usually emptied three times a year, coinciding with the planting seasons for maize (April) or pasture (October), although synthetic fertilizers and chemical pesticides are still necessary to achieve optimum production levels.

To maintain good levels of milk production, each farm allocates a daily ration for the dairy cows, in addition to the amount of drinking water. In addition to the above, other inputs necessary for cow welfare during milking activities were considered in the information collected: cow bedding (which can be straw, sand, wood chips or carbonate), nipple liners (silicone) and udder disinfectant (iodine). Information was collected on the inputs necessary for the proper operation of the farms: cleaning agents used in the cowshed (detergents, paper and different disinfectant solutions), water, energy requirements (electricity, butane and refrigerant gas), together with other consumables (plastics from containers and silos). The water used on the farms comes from two different sources: internal (well water) or external (mains water), being suitable for drinking, cleaning or hygienic use. Finally, all the information related to the waste flows generated during the raw milk production activity in terms of plastic from the material used for silage that can no longer be reused and from the containers of the chemical pesticides

used, as well as paper, cardboard, glass and solid waste transferred to the expert waste managers was also compiled. Wastewater from cleaning the milking parlor and farmers, in addition to milk residues caused by infectious disorders (mastitis), is pumped to a slurry pit.

8.3.2.2. *Circularity indicators*

The following are the procedures to be followed in calculating the C sub-indicators:

*(A) Minimize external resource input*

- Feed autonomy: The percentage (%) of the annual amount of feed obtained from crops (kg) compared to the total amount required to meet the nutritional needs of cows per year (kg of total feed, summed from feed produced by crops together with that from external suppliers) should be considered. For its estimation, **Equation 8.6** was used.

$$\text{Feed autonomy}_X\ (\%) = \frac{CF_X}{CF_X + ES_X} \cdot 100,\ \forall\ X \qquad \textbf{Eq 8.6}$$

Where:

| | |
|---|---|
| X | dairy farm evaluated, X = {1, …, 50}. |
| $CF_x$ | amount of feed provided by crop fields (t) of farm X. |
| $ES_x$ | amount of feed purchased by external suppliers (t) of farm X. |

- Water autonomy: A distinction should be made between the sources of water present on the farm: own (well water) or external (mains water). In our specific case study, the crop fields in the 50 farms are only supplied with rainwater. Consequently, the water used in the sample of dairy farms evaluated is suitable for up to three different uses: cleaning, drinking or hygiene. In this way, a percentage comparison can be made by considering the ratio of water availability from on-farm sources (i.e., well water) versus off-farm sources (i.e., mains water). For its estimation, see **Equation 8.7**.

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$$\text{Water autonomy}_X\ (\%) = \frac{WW_X}{W_X} \cdot 100 = \frac{D_{WW_X} + C_{WW_X} + H_{WW_X}}{WW_X + (D_{MW_X} + C_{MW_X} + H_{MW_X})} \cdot 100, \forall\ X \qquad \textbf{Eq 8.7}$$

Where:

X dairy farm evaluated, X = {1, …, 50}.

$Dww_X$ availability or disability for supplying well water for drinking uses of farm X, $D_{WW_X}$ = {0 (no), 1 (yes)}.

$Cww_X$ availability or disability for supplying well water for cleaning uses of farm X, $C_{WW_X}$ = {0 (no), 1 (yes)}.

$Hww_X$ availability or disability for supplying well water for hygienic uses of farm X, $H_{WW_X}$ = {0 (no), 1 (yes)}.

$WW_X$ availability of well water for drinking ($D_{WW_X}$), cleaning ($C_{WW_X}$) or hygienic ($H_{WW_X}$) uses of farm X, WW = {0, …, 3}.

$Dmw_X$ availability or disability for supplying mains water for drinking uses of farm X, $D_{WW_X}$ = {0 (no), 1 (yes)}.

$Cmw_X$ availability or disability for supplying mains water for cleaning uses of farm X, $C_{WW_X}$ = {0 (no), 1 (yes)}.

$Hmw_X$ availability or disability for supplying mains water for hygienic uses of farm X, $H_{WW_X}$ = {0 (no), 1 (yes)}.

$W_X$ availability or disability for supplying any type of water (well water or mains water) for any type of use (drinking, cleaning of hygienic) of farm X, TW = {0, …, 6}.

- Fertilization autonomy: For its estimation, the percentage (%) of the annual apport of organic fertilizers (cow manure) used on crops in relation to the total amount required to meet the nutritional needs of the fields (sum of organic and synthetic fertilizers) should be considered. To compare organic and synthetic fertilizers, a common unit was chosen for both: kg of N, since although each synthetic fertilizer has different compositions in terms of N, P and K, N was the most predominant element among the fertilizers used in the dairy farms analyzed. **Equation 8.8** was used for its estimation.

$$\text{Fertilization autonomy}_X\ (\%) = \frac{OF_X}{OF_X + SF_X} \cdot 100, \forall\ X \qquad \textbf{Eq 8.8}$$

Where:

X dairy farm evaluated, X = {1, …, 50}.

$OF_X$ amount of organic fertilizer (kg N) in the form of manure from cows employed in the crop fields of farm X.

$SF_X$ amount of synthetic fertilizer (kg N) purchased by external suppliers employed in the crop fields of farm X.

*(B) Optimize production-consumption system*

- Machinery yield: The ratio ($kg \cdot L^{-1}$) of the annual amount of feed obtained from the crops (kg) in relation to the amount of fuel (L) used by the agricultural machinery fleet per year can be considered. For its estimation, **Equation 8.9** was used.

$$\text{Machinery yield}_X \left(\text{kg food} \cdot \text{L fuel}^{-1}\right) = \frac{CF_X}{FM_X}, \forall X \qquad \textbf{Eq 8.9}$$

Where:

X dairy farm evaluated, X = {1, …, 50}.

$CF_X$ amount of food provided by crop fields (t) of farm X.

$FM_X$ amount of fuel (L) employed by the agricultural machinery fleet in the crop fields of farm X.

- Crop yield: The ratio ($kg \cdot ha^{-1}$) of the annual amount of feed obtained from the crops (kg) compared to the field territory (ha) can be used (see **Equation 8.10**).

$$\text{Crop yield}_X \left(\text{kg food} \cdot \text{ha}^{-1}\right) = \frac{CF_X}{EX_X}, \forall X \qquad \textbf{Eq 8.10}$$

Where:

X dairy farm evaluated, X = {1, …, 50}.

$CF_X$ amount of food provided by crop fields (t) of farm X.

$EX_X$ extension of the crop fields (ha) of farm X.

- Cow yield: It can be used the daily ratio of the amount of raw milk produced by the dairy cows (L raw milk·(cow·$day^{-1}$)) to the amount of feed provided for the dairy cows (kg feed·(cow·$day^{-1}$)). **Equation 8.11** was used for its calculation.

$$\text{Cow yield}_X \left(\text{L raw milk} \cdot \text{kg feed}^{-1}\right) = \frac{MO_X}{FI_X}, \forall X \qquad \textbf{Eq 8.11}$$

Where:

X dairy farm evaluated, X = {1, …, 50}.

$MO_X$ daily raw milk output by each dairy cow (L raw milk·(cow·$day^{-1}$)) of farm X.

$FI_X$ daily feed input by each dairy cow (kg feed·(cow·$day^{-1}$)) of farm X.

*(C) Maximize waste prevention*

- Solid waste prevention: Consideration should be given to preventing the amount of solid waste (kg of waste) in relation to the amount of raw milk produced (L raw milk). For its estimation, **Equation 8.12** was used.

$$\text{Solid waste prevention}_X \left(\text{L raw milk} \cdot \text{kg waste}^{-1}\right) = \frac{RM_X}{SD_X}, \forall X \qquad \textbf{Eq 8.12}$$

Where:

| | |
|---|---|
| X | dairy farm evaluated, X = {1, …, 50}. |
| $RM_X$ | total amount of raw milk produced by the dairy cows (L raw milk) of farm X. |
| $SD_X$ | total amount of solid waste (kg) of farm X. |

- Wastewater prevention: The amount of wastewater (L wastewater) should be considered in relation to the amount of raw milk produced (L raw milk). (See **Equation 8.13**).

$$\text{Wastewater prevention}_X \left(\text{L raw milk} \cdot \text{m}^3 \text{ wastewater}^{-1}\right) = \frac{RM_X}{SW_X}, \forall X \qquad \textbf{Eq 8.13}$$

Where:

| | |
|---|---|
| X | dairy farm evaluated, X = {1, …, 50}. |
| $RM_X$ | total amount of raw milk produced by the dairy cows (L raw milk) of farm X. |
| $SW_X$ | total amount of wastewater ($m^3$) of farm X. |

- Milk waste prevention: The amount of food waste (L milk waste due to mastitis) in relation to the amount of raw milk produced (L raw milk) should be considered. **Equation 8.14** was used for its estimation.

$$\text{Milk waste prevention}_X (\%) = \frac{MW_X}{TM_X} \cdot 100, \forall X \qquad \textbf{Eq 8.14}$$

Where:

| | |
|---|---|
| X | dairy farm evaluated, X = {1, …, 50}. |
| $MW_X$ | amount of milk waste (L) caused by mastitis of farm X. |
| $TM_X$ | total amount of milk produced (L): raw milk and milk waste of farm X. |

8.3.2.3. *Sustainability indicators*

*(A) Environment*

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An attributional LCA has been proposed to calculate the sub-indicators of the environmental performance of the raw milk production processes in 50 Galician dairy farms. For this purpose, the SB of the dairy farms can be defined following a "cradle-to-farm gate" approach, as reflected in **Figure 8.3**.

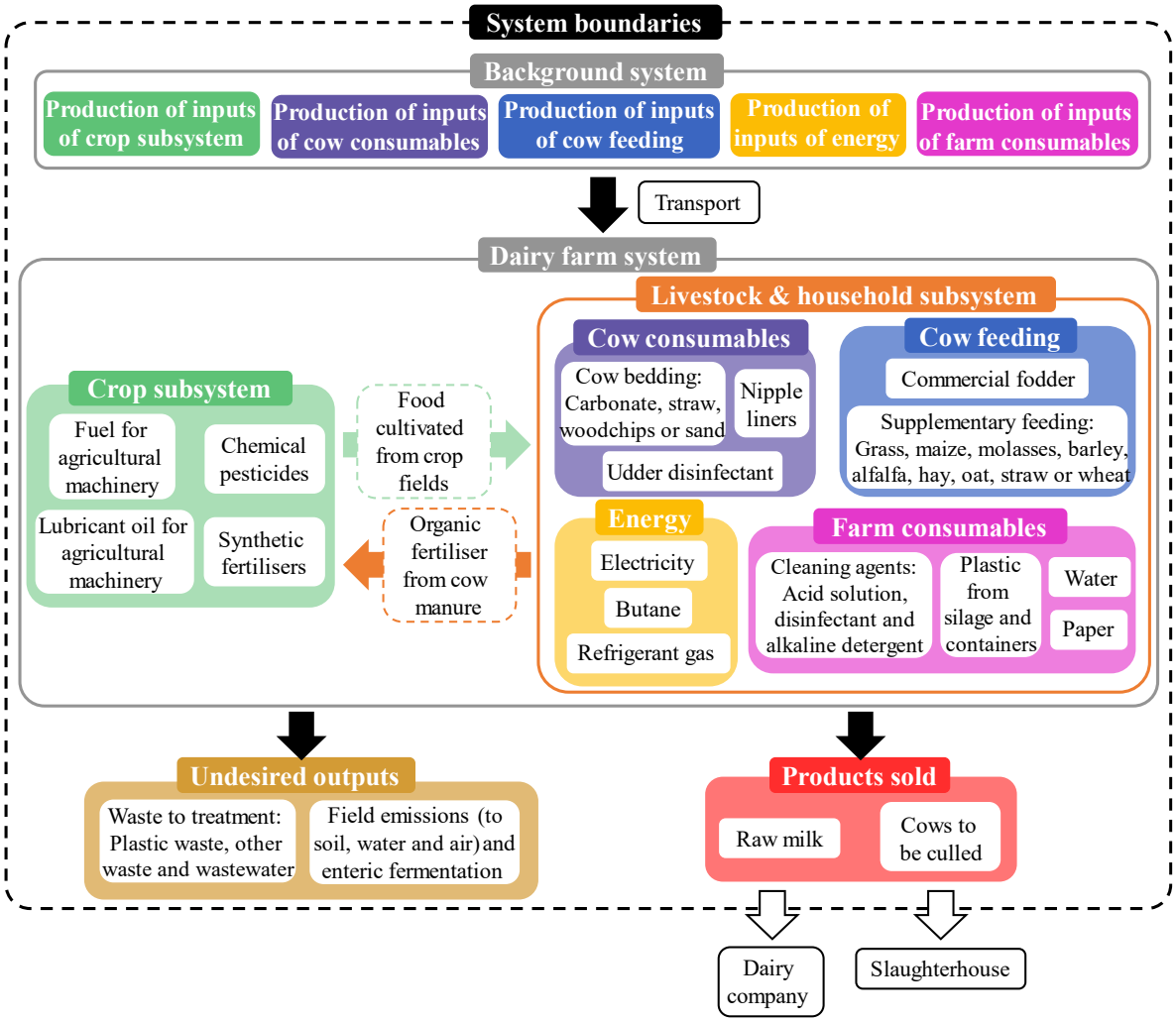



**Figure 8.3**. Boundaries of the dairy farm system, from the production of the inputs in the background system up to the production of outputs along with other undesirable products.

In line with the International Dairy Federation (IDF, 2015), the FU selected to estimate the impacts should be 1 kg of Fat- and Protein-Corrected Milk (FPCM), estimated using **Equation 8.15**. This FU was selected for two main reasons: (1) it allows determining the energy content of milk, avoiding variations among breeds or feeding patterns, and (2) it constitutes the most predominant FU among the studies available in the literature, which facilitates the comparison of the results obtained (Mancilla-Leytón et al., 2021).

$$FPCM = MP \cdot (0.1226 \cdot F + 0.0776 \cdot P + 0.2534) \quad \textbf{Eq 8.15}$$

Where:

FPCM fat- and protein-corrected milk produced by year ($kg \cdot year^{-1}$).

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MP annual milk production ($kg \cdot year^{-1}$).

F milk fat content (4 %).

P milk protein content (3.3 %).

Reliable primary data were collected by the 50 dairy farms in relation to an annual productive campaign. However, since the farm outputs are both raw milk and meat, it was necessary to perform an allocation procedure for the corresponding environmental burdens. Therefore, a biophysical allocation between raw milk and meat was performed as shown in **Equations 8.16-8.18**, this method being the most commonly used in LCA modelling of dairy farm systems (Kyttä et al., 2022).

$$MMR = \frac{LWAS}{FPCM} \quad \textbf{Eq 8.16}$$

$$AF_{milk} = 1 - 6.04 \cdot MMR \quad \textbf{Eq 8.17}$$

$$AF_{meat} = 1 - AF_{milk} \quad \textbf{Eq 8.18}$$

Where:

MMR meat to milk ratio.

LWAS live weight of animal sold by year ($kg \cdot year^{-1}$).

$AF_{milk}$ allocation factor of milk.

$AF_{meat}$ allocation factor of meat.

In addition, the following assumptions have been necessary during the impact assessment calculations in the modelling phase of the LCA:

i) Direct emissions of GHGs to air from agricultural practices (soil and manure management) and from livestock (enteric fermentation) were estimated using the recommendations of the IPCC (IPCC, 2019b): (i) $CH_4$ from enteric fermentation and manure management, (ii) $N_2O$ from manure and soil management (manure application to soil).

ii) Direct emissions from the combustion of fuels (normally diesel or natural gas) were modelled using the updated EMEP/EEA air pollutant emissions inventory guidebook (EMEP/EEA, 2019b).

iii) Indirect emissions of ammonia ($NH_3$) and nitrate ($NO_3^-$) from manure and soil management ($N_2O$) were calculated according to IPPC guidelines (IPCC, 2019), while distribution factors of 90 % and 10 % were applied to ammonia and nitrate, respectively (Denier Van Der Gon & Bleeker, 2005).

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iv) Direct emissions from synthetic fertilizers application were assessed as: (i) phosphate ($PO_4^{3-}$) to groundwater by leaching and to surface water by run-off;

(ii) phosphorus (P) from water erosion (i.e. removal of soil by water) to surface water; and (iii) heavy metals (Cd, Cu, Zn, Pb, Ni, Cr) to ground and surface water and through soil erosion (Nemecek et al., 2019).

v) The distribution of the active ingredients from the chemical pesticides applied was calculated using the PestLCI Consensus model (Fantke et al., 2017), which allows to differentiate among the three compartments: soil, water and air.

To illustrate the life cycle inventory of the farms, the average result of the 50 farms studied can be consulted in **Table 8.1**.

**Table 8.1**. Average life cycle inventory of the 50 dairy farms (data relative to 1 year of milk production, 2020 campaign).

| | | | |
|---|---|---|---|
| **Inputs from nature & technosphere** | | | |
| **Crop** | | **Farm consumables** | |
| Fuel (kg) | 9,040.3 | Acid solution (kg) | 231.8 |
| Lubricant oil (kg) | 149.2 | Disinfectant (kg) | 310.9 |
| Chemical pesticides (kg) | 106.2 | Alkaline detergent (kg) | 584.5 |
| Synthetic fertilizers (kg) | 35,016.8 | Plastic from silage (kg) | 452.4 |
| **Cow consumables** | | Plastic containers (kg) | 138.1 |
| Cow bedding (carbonate, straw, woodchips or sand) (t) | 332.2 | Paper (kg) | 155.2 |
| Nipple shields (kg) | 8.5 | Water ($m^3$) | 4,290.5 |
| Iodine sealant (L) | 358.8 | **Energy** | |
| **Cow feeding** | | | 41,740.2 |
| | | Electricity (kWh) | 2.0 |
| Commercial fodder (kg) | 378,855.3 | Butane (kg) | 52.0 |
| Supplementary feeding (kg) | 277,440.7 | Refrigerant gas (kg) | 0.18 |
| **Outputs to nature** | | | |
| **Emissions to air** | | **Emissions to water** | |
| $CH_4$ (enteric fermentation) (kg) | 15,833.1 | $NO_3^-$ (manure management) (kg) | 562.2 |
| $CH_4$ (manure management) (kg) | 4,817.8 | $NO_3^-$ (soil management) (kg) | 729.2 |
| $N_2O$ (manure management) (kg) | 44.2 | $PO_4^{3-}$ (to groundwater by leaching) (kg) | 5.6 |
| $NH_3$ (manure management) (kg) | 5,060.1 | $PO_4^{3-}$ (to surface water by run-off) (kg) | 14.5 |
| $N_2O$ (soil management) (kg) | 740.0 | P (to surface water by water erosion) (kg) | 2.5 |
| $NH_3$ (soil management) (kg) | 1,799.5 | Heavy metals (kg) | 4.1 |
| Active ingredient (chemical pesticide) (kg) | 1.1 | Active ingredient (chemical pesticide) (kg) | 0.01 |
| **Emissions to soil** | | **Emissions to soil** | |
| Heavy metals (kg) | 0.96 | Active ingredient (chemical pesticide) (kg) | 10.9 |
| **Outputs to technosphere** | | | |
| **Products** | | **Waste to treatment** | |
| Raw milk (kg FPCM) | 348,227.3 | Plastic waste (kg) | 599.4 |
| Meat (kg) | 7,514.3 | Other solid waste (kg) | 543.1 |
| | | Wastewater ($m^3$) | 924.4 |

For this specific case study, the ReCiPe 2016 hierarchist Midpoint (v1.06) World (2010) method was used for the impact assessment (Huijbregts et al., 2017). In this chapter, the background processes were modelled using the Ecoinvent database v3.8 (Moreno Ruiz et al., 2021), while the SimaPro software v9.4 was considered to carry out the modeling and calculation procedures.

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*(B) Society*

The procedures to carry out the calculation of the social indicators are shown below.

- Support to the local economy can be calculated through the sum of the products of the distances (in km) from the destination (dairy farm) to the origins (supply centers) by the amount of feed purchased (in t), depending on the type of feed. Therefore, this indicator may vary according to the different types of feed required (maize, grass, alfalfa, straw, oat, molasses, commercial fodder or others). On the other hand, the distance from the centers which supply the commercial fodder has been assumed to be, on average, 40 km for all the farms according to the information provided by AGACA. For its estimation, see **Equation 8.19**.

$$\text{Local economy support}_{XY}\ (t \cdot km) = \sum_{Y=a}^{h} F_{XY} \cdot D_{XY},\ \forall\ XY \qquad \textbf{Eq 8.19}$$

Where:

X dairy farm evaluated, X = {1, …, 50}.

Y different types of feed supplied: maize (a), grass (b), alfalfa (c), straw (d), others (e), oat (f), molasses (g) or commercial fodder (h), Y = {a, …., h}.

$F_{XY}$ amount of feed provided by the supplying center (t) according to the type of feed (Y) of farm X.

$D_{XY}$ distance from the supplying center (km) according to the type of feed (Y) of farm X.

- Health and safety indicators (HTN, HTC, SOD, IR, OFH and FPM) can be calculated following the same procedure previously described for the environmental indicators.

*(C) Economy*

The economic indicators were calculated from data on the average annual selling price of raw milk (in € per liter of raw milk produced) and meat (in € per kg of meat sold) for each farm. The "revenues from raw milk" sub-indicator was calculated using total annual revenue from milk sales divided by the number of dairy cows, while the "revenues from meat" sub-indicator was estimated using total annual revenue from meat sales divided by the number of cows slaughtered. For their estimations, see **Equations 8.20** and **8.21**.

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$$RMi_X\ (€ \cdot \text{dairy cow}^{-1}) = \frac{SPMi_X\ (€ \cdot \text{L raw milk}^{-1}) \cdot \text{Annual raw milk production (L)}}{\text{Dairy cows}},\ \forall\ X \qquad \textbf{Eq 8.20}$$

$$RMe_X\ (€ \cdot \text{culled cow}^{-1}) = \frac{SPMe_X\ (€ \cdot \text{kg meat}^{-1}) \cdot \text{Annual meat production (kg)}}{\text{Culled cows}},\ \forall\ X \qquad \textbf{Eq 8.21}$$

Where:

X dairy farm evaluated, X = {1, …, 50}.

$RMi_X$ revenues from raw milk ($€ \cdot \text{dairy cow}^{-1}$) of farm X.

$RMe_X$ revenues from meat ($€ \cdot \text{culled cow}^{-1}$) of farm X.

$SPMi_X$ selling price from raw milk ($€ \cdot L^{-1}$) of farm X.

$SPMe_X$ selling price from meat ($€ \cdot L^{-1}$) of farm X.

### 8.3.3. Step III: Integration of indicators

The integration of the indicators into the CDFi for each dairy farm should be performed in three consecutive phases: (i) normalization, applying **Equation 8.1** to the circular and economic sub-indicators; and **Equation 8.2** to the environmental and social sub-indicators, since they are directly and inversely proportional to the CDFi, respectively, (ii) weighting, following a perspective of equality among all the indicators considered (see **Table 8.2**), and (iii) aggregation into the CDFi by applying **Equation 8.3-8.5**.

**Table 8.2**. Weighting factors assigned to each type of indicator and (sub)indicator. Indicators: minimize external resource input (MI), optimize production-consumption system (PC), maximize waste prevention (WP), environmental (EN), social (SO) or economic (EC) according to the perspective followed.

| **Aspect** | Circularity | | | Sustainability | | |
|---|---|---|---|---|---|---|
| **Weighting factor applied to each aspect** | 50 | | | 50 | | |
| **Indicator** | MI | PC | WP | EN | SO | EC |
| **Weighting factor applied to each indicator** | 16.67 | 16.67 | 16.67 | 16.67 | 16.67 | 16.67 |
| **Number of sub-indicators (C / S)** | 3 | 3 | 3 | 12 | 7 | 2 |
| **Weighting factor applied to each sub-indicator (Wc / Ws)** | 5.557 | 5.557 | 5.557 | 1.389 | 2.381 | 8.335 |

### 8.3.4. Step IV: Interpretation of results

Grouping farms according to the results could help with the analysis. In this specific case study, the 50 farms were classified into 5 different groups (A, B, C, D or E) composed of the same number of farms according to their CDFi. Therefore, the 10 farms at the top of the ranking were assigned with the letter A and so forth to the farms with the lowest score (group E). After that grouping, a detailed analysis of each group should be

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conducted, including the hot spots of the main sources of impacts and possible C improvements.

## 8.4. Circularity and sustainability of dairy farms

### 8.4.1. Composite Dairy Farm index (CDFi)

Each CDFi of the 50 dairy farms is shown in **Figure 8.4**. Given the CDFi results, it is possible to verify that the high homogeneity of the farms stands out. As can be observed, most of the results of the composite index vary between the range of 40-60 points, with the minimum for farm 10 (CDFi 36 points) and the maximum for farm 21 (CDFi 64 points). This homogeneity can be explained by two main reasons: i) the farms are in the same geographical region; and ii) they are covered by the same agri-food cooperative. Therefore, the combined action of these factors leads to a similarity not only in the production processes of raw milk and fodders for cow feed, but also in terms of waste management systems and selling prices established for raw milk and meat. The above confirms that the analyzed indicators are indeed influenced by the same factors (e.g., geographical boundaries, legislation at regional level and internal regulation of the agri-food cooperative), leading to the average value of 51 (standard deviation ±7.4) points.

Therefore, none of the farms achieved a high overall score, since the maximum value of the CDFi is 100 points. The low scores could be attributed to a high number of indicators evaluated (30), making it unlikely that a farm will score well on all of them. However, a variety of indicators is needed when assessing complex concepts such as C or S, while constraints in terms of funding, time and data availability require a range of indicators that are sufficiently meaningful to be understood by stakeholders (Tanzer and Rechberger, 2020). A more detailed interpretation of the CDFi values in terms of C and S shows that the latter has a higher contribution to CDFi (average 29 points) compared to C (average 22 points).

### 8.4.2. Ranking by groups

The sample of 50 farms was subdivided into five groups composed of ten farms each (groups A, B, C, D and E) according to the CDFi results. This subdivision was made to carry out a more detailed evaluation in identifying trends or particularities among the groups of farms (**Figure 8.5**). As mentioned earlier, the low variability in the CDFi of the assessed farms (**Figure 8.4**) is also observed when divided into groups (**Figure 8.5**). This low variability can be seen, for example, in the small difference of only 21 points between the best group (group A with 61 points on average) and the worst (group E with 40 points on average). Furthermore, the variability between groups follows the same trend, with an average of 6 additional points when moving from one group to another, with the only exception of groups C and D, with only a 3 points difference.

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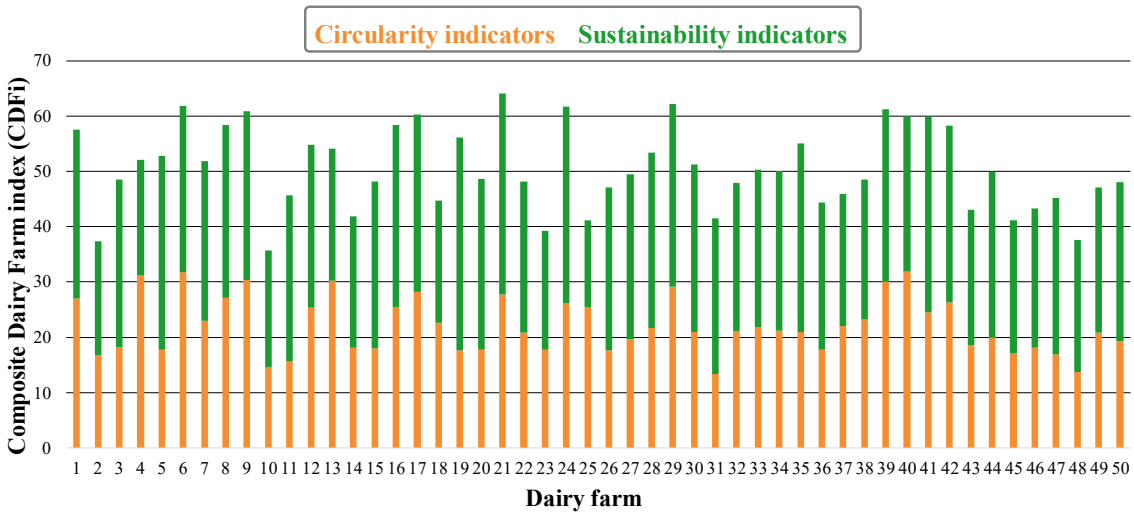



**Figure 8.4**. Composite Dairy Farm index (CDFi) of the 50 dairy farms, being represented in accordance with the contribution of circularity indicators and sustainability indicators.

A more in-depth analysis of the C indicators shows that the variability among groups regarding the "minimize external resource input" indicator is considerably higher (contribution to CDFi from 7 to 12 points) compared to "optimize production-consumption system" and "maximize waste prevention" (with minimum scores of 5 and 6 and maximum scores of 9 and 8, respectively). These results show "minimize external resource input" indicator has the largest differences, with the additional sum of at least 1 or 2 points each time a group is compared to its higher one. Likewise, in the "optimize production-consumption system" indicator there is a difference of 3 points between groups A and B, while the CDFi for the other groups remains constant with average values fluctuating between 5 and 6 points. Conversely, "maximize waste prevention" is the C indicator where the smallest variation is visualized, starting with a value of 8 points for group A, dropping one point in group B, until reaching group C, where the scores remain fixed at 6 points.

Concerning the S indicators, "environment" and "society" are those with the highest values for each of the 5 differentiated groups, with practically identical values, ranging from 9 to 12 points for the worst (group E) and the best group (group A), respectively. Likewise, although the variance by group is not remarkable for these indicators, ranging from 11 to 12 points for groups A, B and C, it is worth noting that this is where the greatest difference between the lowest scoring groups occurs (mean values of 11 and 9 points for groups D and E, respectively). In contrast, "economy" indicators have relatively low values for all groups, ranging from 5 to 8 points.

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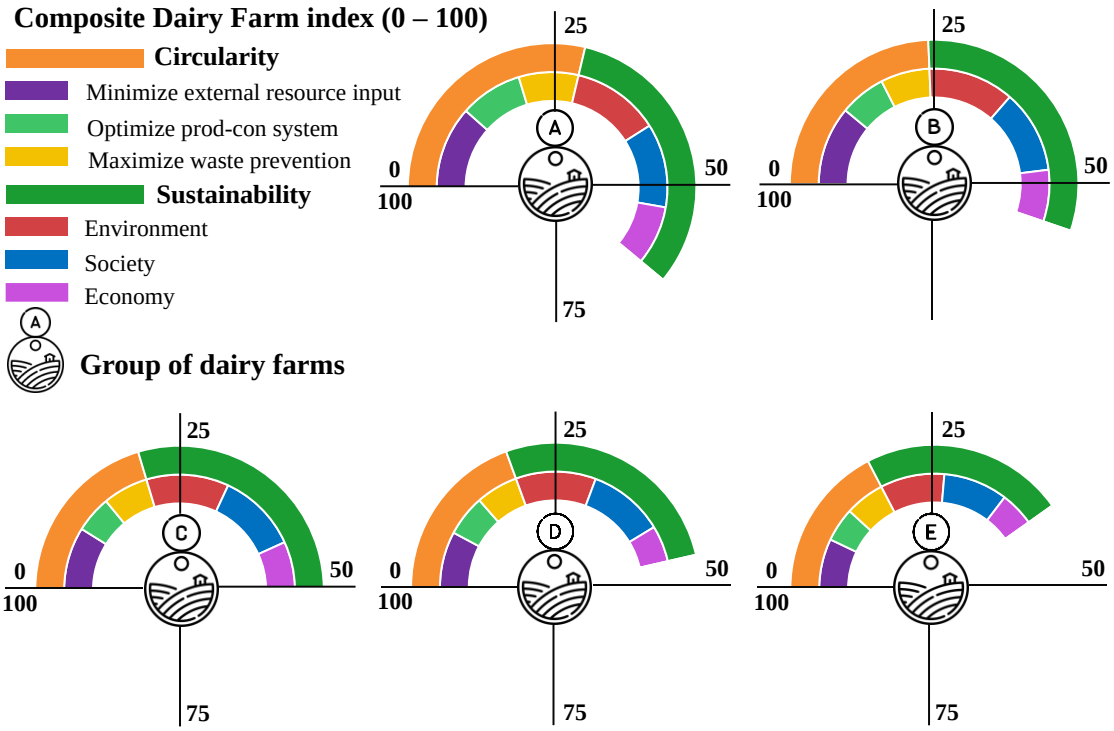



**Figure 8.5**. Average Composite Dairy Farm index (CDFi) divided by aspect (circularity and sustainability) and subdivided indicator for the 5 groups (A, B, C, D and E) within the 50 dairy farms.

Given the results obtained for each indicator, it can be said that "minimize external resource input", "environment" and "society" are the most influential in terms of the total score obtained, although it is the indicator of C that gives rise to the greatest differences in the points recorded among the groups. On the other hand, "optimize production-consumption system" is a key indicator for a dairy farm to be classified in the best group (group A), as this is where the biggest inter-group difference occurs between groups A (9 points) and B (6 points). Environmental and social indicators turn out to be the most relevant to classify the worst groups, with differences of up to 3 points between groups D (11 points) and E (9 points). Therefore, for this case study, "maximize waste prevention" and "economy" indicators were detected as the least significant for the CDFi.

### 8.4.3. Identification of hot spots

"Minimize external resource input" has the highest score and variability within the C indicators of the groups shown in **Figure 8.5**. Therefore, it was analyzed more closely which sub-indicator has the greatest influence on this indicator. All sub-indicators have a convergence between 0 and 6 points in the CDFi, with the averages for the farms being 4, 2 and 3 points for "feed, water and fertilization autonomies", respectively. Thus, it can be concluded that having feed autonomy was the most influential C sub-indicator for the assessed dairy farms. On top of that, the application of the LCA methodology to calculate the environmental and some social S sub-indicators enables the identification of the exact sources of impact given the categories collected in the LCI (see **Table 8.1**). This can be

consulted in terms of their average relative contributions of the 50 dairy farms in **Figure 8.6** considering the following categories: field emissions and enteric fermentation, cow consumables, energy, waste to treatment, farm consumables, cow feeding, and crop, divided by sub-indicator.

As observed in **Figure 8.6**, the field emissions and enteric fermentation and the cow feeding account for almost the total contribution of four sub-indicators (GW, SOD, FPM and TA), with values above 90 %. These results are related to the emissions ($CH_4$, $N_2O$ and $NH_3$) from agricultural practices (manure management and its application in the soil) and the enteric fermentation by ruminants during the digestion of the food (Krzyzaniak et al., 2020). Likewise, cow feeding turns out to be a hot spot with contributions often exceeding 70 % for 11 sub-indicators (OFH, OFE, FEP, MEP, FET, MET, HTN, LU, MRS, FRS and WC). These results are not surprising, as feed-related impacts have been shown to be an important factor in the environmental implications of livestock farming, with a strong correlation with the LU indicator due to the use of large areas of cropland to feed cows (Carvalho et al., 2022).

On the other hand, three indicators (IR, TET and HTC) show different trends. In the case of IR, more than half of the total impact is associated with the energy (i.e. electricity, butane and refrigerant gas), which could be related with the generation of electricity from nuclear power plants (35 % of the Spanish energy supply during 2019-2021 was provided by nuclear plants (AIB, 2022). Crop cultivation contributes more than 70 % to the TET impact due to the fraction of pesticides remaining in the soil. Finally, in the case of HTC, the contributions of cow feeding (47 %) and crop cultivation (38 %) are relatively similar and are mainly associated with the use of pesticides and synthetic fertilizers (Mostafalou and Abdollahi, 2017).

Regarding the social sub-indicators, the sub-indicator of support to the local economy turned out to be the one with the highest contribution to the CDFi compared to the others (SOD, IR, OFH, FPM, HTC and HTN). In addition, this sub-indicator shows to have great disparity among the farms. In this sense, the five farms with the highest value (farms 4, 13, 14, 25 and 40) have an average of more than 171,000 t·km per year, while the rest of the dairy farms barely exceed 27,000 t·km per year, which is translated into general positive values for almost all the farms in terms of CDFi. To reverse this situation, it should be necessary to reduce dependence on food from external sources, apart from betting on local suppliers to meet the food shortage. Finally, since the main source of income of the farms is milk production, the economic indicator of revenues from raw milk prevails over revenues from meat.

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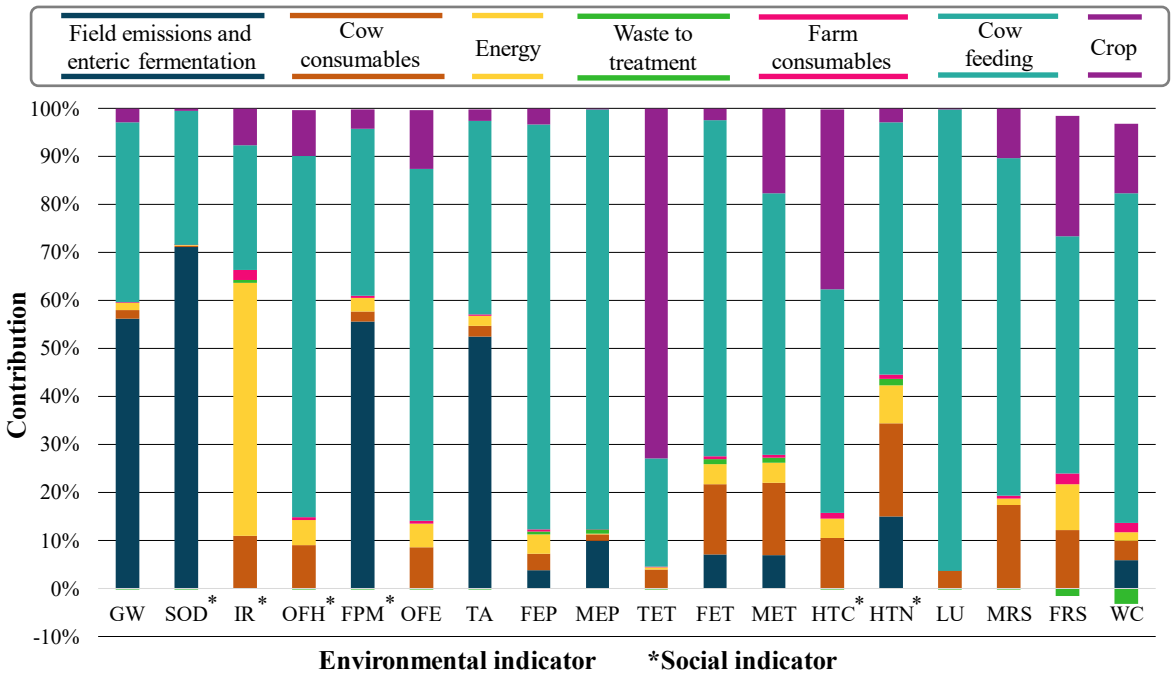



**Figure 8.6**. Relative contributions of the life cycle assessment sub-indicators divided by category on average for the 50 dairy farms. GW: global warming; OFE: ozone formation, terrestrial ecosystems; TA: terrestrial acidification; FET: freshwater ecotoxicity; MET: marine ecotoxicity; TET: terrestrial ecotoxicity; FEP: freshwater eutrophication; MEP: marine eutrophication; LU: land use; MRS: mineral resource scarcity; FRS: fossil resource scarcity; WC: water consumption; HTN: human non-carcinogenic toxicity; HTC: human carcinogenic toxicity; SOD: stratospheric ozone depletion; IR: ionizing radiation; OFH: ozone formation, human health; FPM: fine particulate matter formation.

## 8.5. Conclusions

CC is one of the most prominent problems facing modern society. The food industry (particularly agriculture and livestock farming sectors) is both one of the main contributions but also suffers from this global threat. However, other environmental impacts, economic costs and social development must be considered when addressing CC. Therefore, the concepts of sustainability (S) and circularity (C) have emerged to guide and promote sustainable development. S and C approaches have been included in international initiatives and policies, and methodologies and frameworks for standardization have been developed. However, these two concepts, although interrelated, are today considered separately, resulting in a deterioration of how they can promote synergies. To fill this gap, a novel framework for the integration of CIrcularity and SUstainability indicators (CISU) is proposed to jointly assess both C and S levels in any sector. This same framework has been adapted to evaluate dairy farms (integration of CIrcularity and SUstainability indicators in DAiry Sector - CISUDASE) and has been implemented in 50 farms from Galicia (a region in NW Spain). CISUDASE framework evaluates the production process of dairy farms through a single value in which a multi-criteria perspective is brought together, allowing a clear and easy interpretation for stakeholders (farmers, dairy companies and consumers). Moreover, it can also enable

green policies and measures, including stricter restrictions for high-impact tasks in the dairy sector.

The results after applying the CISUDASE framework to calculate the Composite Dairy Farm index (CDFi, ranging from 0 to 100), showed a relative homogeneity among the dairy farms evaluated. This level of homogeneity is attributed to similarities in their production models (all farms belong to the same agri-food cooperative) and to being located in the same geographical region. The farms obtained relatively low values (51 points on average), showing significant room for improvement, particularly from a C perspective. In this regard, "minimize external resource input" is the most influential indicator for the C result, with the "feed autonomy" sub-indicator being the most important contributor. As far as S is concerned, the environmental sub-indicators of "freshwater ecotoxicity", "marine eutrophication" and "land use" have a higher contribution to the CDFi, standing out mostly from “cow feeding” rate. On the other hand, regarding the social sub-indicators, "local economy support" and "ozone formation, human health" have the most significant contributions. Finally, between the two economic sub-indicators, "revenues from raw milk" is the most influential as raw milk is the main product produced by dairy farms.

The analysis carried out in this paper shows that cattle feeding management is vital to achieve a milk production system that is circular and sustainable. To this end, minimizing dependence on external resource input in terms of cow feeding was found to be a key aspect for C. In addition, the use of own-produced fodder on the farm and proper management of crop fields has high implications for S. However, some aspects should be re-evaluated, such as whether S should prevail over C (or vice versa) or the normalization and weighting factors used for the integration of indicators and sub-indicators (i.e., MCDA) into a single value. In addition, it is vital to include consensus on how to measure C in different sectors or products and to establish specific indicators. On the other hand, although great efforts have been made to quantify environmental impacts considering the LCA methodology, there is usually a lack of information in the literature for more reliable economic (LCC) and social (S-LCA) indicators used for S assessments.

Finally, the CISU framework allows the integration of C and S indicators for the case of a company or product (i.e., micro level), to obtain a single value that is easily interpretable to facilitate communication among stakeholders. However, in future iterations it should be modified to overcome three main shortcomings: (i) integration of other important aspects that are interrelated with C and S (e.g., industrial symbiosis), (ii) applicability at other levels (i.e., meso level: district or supply chain), as well as (iii) its scalability so that it can be adapted to the contextual situation of each case study.

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# Chapter 9

*Conclusions*

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The food industry is considered one of the main pillars of the Spanish economy, and Galicia is one of its main international exponents, with the fishing and dairy industries standing out. However, all these benefits are overshadowed by the environmental impacts caused by the current system of food production and consumption. For this reason, the consumption model must opt for more sustainable food patterns based on the promotion of certain aspects such as prioritizing a balanced and healthy diet accompanied by regular sport, the protection of culinary heritage (for example, the Mediterranean diet), the commitment to seasonal and local foods, among others. To this end, practical guides and food pyramids adapted to the national context have already been drawn up.

With regard to the food production model, in the process of quantifying and monitoring the environmental impacts derived from food, the concept of LCT is crucial, considering all the damage that encompasses the entire value chain (i.e., from the manufacture of raw materials to the management of the waste produced). In this sense, LCA is the most widely used and standardized methodological tool at the international level. In fact, LCA has been used to support environmental accounting, monitoring and decision-making in many food companies. Consequently, it has a high potential to be considered for the creation of environmental policies or initiatives. However, given the complexity and variability of food systems, LCA is not without certain shortcomings in its analysis. Hence, through a literature search, a number of shortcomings were detected, such as a lack of knowledge of the positive impacts in terms of nutritional provision, socio-economic performance, ecosystem services or circularity.

On the other hand, communication of impacts among stakeholders is another important point. In this aspect, labels stand out in the food industry, assuming that they are an easy communication channel between producers and consumers. However, those currently available on the market address separately the nutritional profile of food (i.e., nutrition and health labels) and environmental performance (i.e., eco-labels). Therefore, a major gap was identified in the separate consideration of nutritional and environmental indicators, for which composite indicators are potential candidates in addressing both perspectives. Therefore, with the commitment of achieving a more sustainable food production and consumption system, it is recommended to use the LCA toolbox together with other holistic methodologies and communication channels.

It is from the above that the three main lines of action of this thesis were established: (i) the creation of new analytical perspectives that broaden the focus of environmental studies conducted so far in the food industry, (ii) the development of methodological frameworks to propose policies based on holistic approaches, and (iii) the proposal of composite indicators and ecolabels to improve communication channels between actors in the food industry. Furthermore, to show their applicability in real case studies, a selection was made of the seafood and dairy sectors in the context of the Spanish region of Galicia.

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A framework for the development of a composite indicator based on the WEF nexus concept was proposed, considering indicators related to water and energy

consumption, food supply through the assessment of the nutritional profile and CC as an external driver. In addition, an eco-label was designed to represent this nexus. This was applied to a range of seafood products from the European Atlantic region with the aim of benchmarking the sample. Both the composite indicator (called the WEF nexus index: WEFni) and its presentation as an eco-label proved to be a useful way of assessing and communicating the environmental impact and nutritional benefits of seafood products at the same time, easily understandable through a single indicator that varies as a percentage within a color scale. A further step was taken to better represent the FU of seafood production systems by considering edible and caloric content. This allows a direct and useful comparison between different fishing gears and types of processing and aquaculture.

Similarly, WEFni was adapted for application to the dairy sector to assess several dairy farms. This required a reconsideration of the nutritional footprint of production performance (due to the lack of data on the nutritional profile of the milk produced on each farm), which also happens to be an important aspect as it is closely related to ensuring food security. This allowed a comparison to be made between the 100 farms analyzed in Galicia, to classify them into groups according to their WEFni value and to evaluate the potential of a series of improvement strategies.

A new framework was also developed to obtain another composite percentage indicator, this time based on the close relationship between the concepts of sustainability and circularity. The CISU framework was therefore proposed and applied to 50 Galician dairy farms to demonstrate its applicability. The sustainable and circular yields of the dairy farms analyzed showed relatively low values, which may be related to a certain homogeneity in the sample analyzed. However, practices can be identified on the better performing farms that can be replicated on the poorer performing farms to improve the circular and sustainable profile at the cooperative level.

Therefore, both the frameworks based on the WEF nexus concept and the one integrating circularity and sustainability (i.e., CISU) started with the objective of assessing a set of closely related concepts and presenting them through a single percentage value as a composite indicator. These have proven to be useful for benchmarking between the case studies analyzed, as well as for communicating the results in an attractive way in the case of seafood through the WEF nexus ecolabel. However, all of them have a number of shortcomings. Among the main drawbacks is the lack of standardization in the processes involved in the selection, normalization, weighting and integration of indicators to represent the single value, which need to be revised in subsequent iterations. However, its versatility in terms of its application to other economic sectors (food or non-food) opens the door to its reproducibility and constant refinement.

Following with the commitment of create more holistic assessment frameworks, the CF concept has been extended to the case of the fishing industry, proposing a methodology that analyses all carbon flows from the production, processing and consumption of fish. This was applied to the specific case of one specimen, with the

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addition of the novelty of blue carbon flux, understood as an indirect ecosystem service in terms of carbon sequestration through the remineralization of carbon contained in the body of fish of a certain size once they die naturally and reach the seabed. In addition, several improvements have been proposed to balance negative carbon fluxes with positive ones. Therefore, the holistic definition of the carbon cycle of fisheries allows for a transition to more holistic strategies for a net carbon neutral food industry. However, the methodology for calculating this ecosystem service needs to be improved by using more up-to-date and specific data for the case study evaluated, to improve its representativeness. Likewise, the procedure followed to propose the theoretical framework can serve as a basis for establishing other methodologies based on the valuation of ecosystem services while following a life cycle perspective.

Lastly, a methodological framework has been proposed in which the sustainability of the production of OCPM in Galicia has been analyzed in a holistic way. For this purpose, the PEF methodology was followed for the environmental dimension, while the economic dimension was assessed through Monetary Evaluation Methods in terms of economic damage due to environmental impacts. With regard to the social aspect, an analysis was carried out both on the consumer side, through the evolution of the demand for canned seafood products, and on the producer side, through the certifications that the product under study had. The results obtained with the OCPM were not very promising compared to the standard (i.e., non-organic) version. Furthermore, improving the energy mix by relying on renewable sources has been shown to have a better environmental and economic performance compared to circular strategies based on improving the percentage recycling rates of packaging. On a social level, it was found that the product could take advantage of the local artisanal practices it has undertaken as a sign of the producer company to obtain some form of certification beyond environmental certification to appeal to a wider audience. Therefore, although the way of assessing the economic and social dimensions of the product has been useful to draw certain conclusions, its standardization and harmonization with the environmental pillar is essential to obtain more reliable and comparable results with other types of products.

In the form of a take-home message, in this thesis a series of methodological frameworks have been developed focusing on the LCA methodology and applied to the dairy and seafood industries in a Galician and Spanish context, based on several shortcomings that have been identified. These have led to a notable advance in LCT when integrated with other key concepts in the food industry, such as the WEF nexus or the CE, from a purely environmental vision to a broader one that includes multiple aspects such as society, economy, ecosystem services or nutrition. Likewise, this conceptual change turns out to be an important contribution to the scientific literature for LCA practitioners. In addition, the composite indicators have also been approached from a certification point of view, proposing a label design that integrates the benefits of nutrition labels with eco-labels, while opting for an attractive and easy-to-understand design. In this way, it is possible to solve the problem that although the methodological procedure becomes more complicated in the analysis phase due to the integration of several concepts, this does not

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represent a disadvantage in terms of being applied by producers and understood by consumers, maintaining an aura of commitment to sustainability by all stakeholders in the food industry. From these outcomes, it can be said that this thesis represents a step forward in aligning the food industry with sustainable development. It is now time to pave the way for the harmonization of sustainable holistic food systems analysis methods based on a life cycle approach. To this end, the reproducibility of the methodological procedures proposed through future iterations and refinements is of paramount importance. From here, the objective to be achieved will be the materialization in actions promoted by more holistic policies that lead to strategies towards a more sustainable food production and consumption system.

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# Appendix I

*Articles published used in this thesis*

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## Methodological guidelines for the calculation of a Water-Energy-Food nexus index for seafood products

Eduardo Entrena-Barbero[1], Sandra Ceballos-Santos[6], Antonio Cortés[1], Xavier Esteve-Llorens[1], María Teresa Moreira[1], Pedro Villanueva-Rey[2], Diego Quiñoy[2], Cheila Almeida[3], António Marques[3-4], Paula Quinteiro[5], Ana Cláudia Dias[5], Jara Laso[6], Israel Ruiz-Salmón[6], María Margallo[6], Rubén Aldaco[6*], Gumersindo Feijoo[1]

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Journal quality scores

The impact factor of this journal is 9.8 (2022 Journal Citation Reports), and a CiteScore of 16.8 (Scopus, 2022). Ranking 26 out of 274 in Environmental Sciences (Q1, D1), based on JCR 2022.

Author contribution

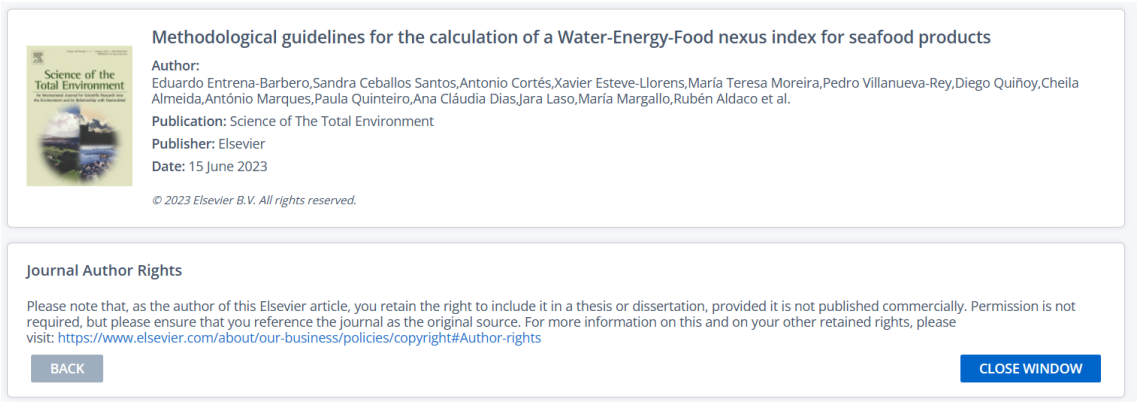
Eduardo Entrena-Barbero performed the investigation, methodology definition, formal analysis, writing-original draft and editing of the research article.

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**Chapter 4** is based on this publication.

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# Water-Energy-Food nexus index proposal as a sustainability criterion on dairy farms

Eduardo Entrena-Barbero[1*], Ricardo Rebolledo-Leiva[1], Leonardo Vásquez-Ibarra[2], Mario Fernández[3], Gumersindo Feijoo[1], Sara González-García[1], María Teresa Moreira[1]

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Journal

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Author contribution

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**Water-Energy-Food nexus index proposal as a sustainability criterion on dairy farms**

**Author:**
Eduardo Entrena-Barbero,Ricardo Rebolledo-Leiva,Leonardo Vásquez-Ibarra,Mario Fernández,Gumersindo Feijoo,Sara González-García,María Teresa Moreira

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## Blue carbon accounting as metrics to be taken into account towards the target of GHG emissions mitigation in fisheries

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Journal

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Author contribution

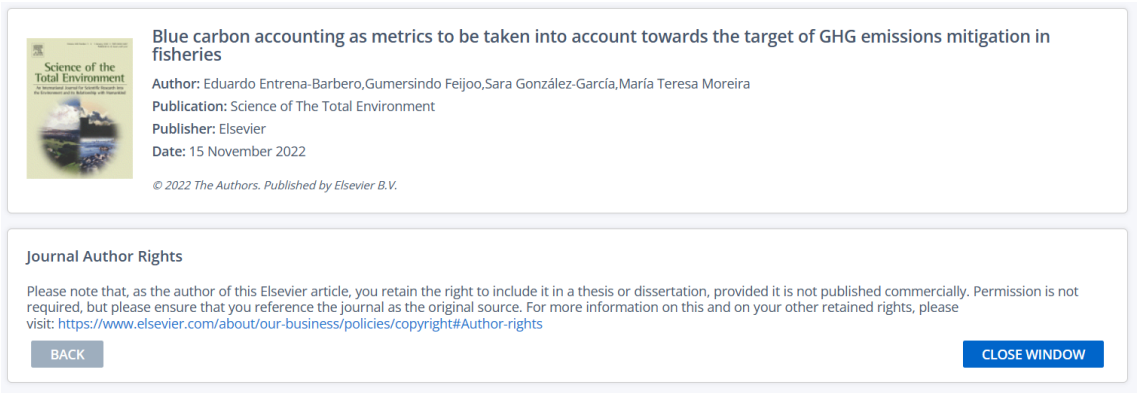
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## Addressing environmental and economic impacts in the sustainable production profile of organic canned pickled mussels

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**Chapter 7** is based on this publication.

## Integrating circularity as an essential pillar of dairy farms sustainability

Eduardo Entrena-Barbero[1*], Raphael Ricardo Zepon Tarpani[2], Mario Fernández[3], María Teresa Moreira[1], Alejandro Gallego-Schmid[2*].

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Journal

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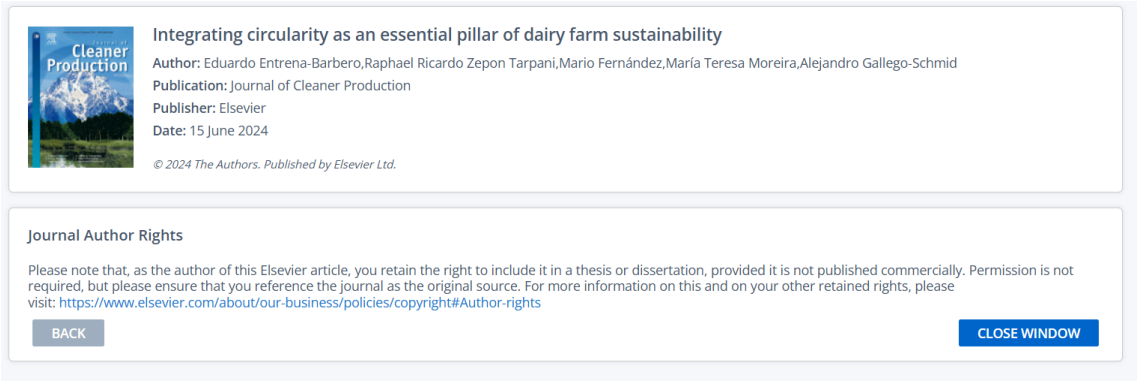
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Eduardo Entrena-Barbero performed the investigation, methodology definition, formal analysis, writing-original draft and editing of the research article.

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Galicia is a benchmark for quality and excellence in the food industry at the European level. However, it should not be forgotten that food production systems have a significant impact on the environment. In this regard, the Life Cycle Assessment is a useful tool. Therefore, the main objective of this thesis is to promote a more sustainable model of food production and consumption based on the improvement of several limitations that have been identified. A series of novel frameworks have been proposed and applied to a series of Galician case studies of the fisheries and dairy sectors. From the results, it is now time to harmonize, through future iterations and refinements, sustainable holistic food systems analysis methodologies based on a life cycle approach.