Applying a water-energy-food nexus approach to seafood products from the European Atlantic area

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Abstract

By 2050, food production's environmental impacts are projected to double without intervention. Crucial changes in dietary habits are needed, and seafood can be pivotal. The focus in calculating burdens using life cycle assessment (LCA) indicators has shifted towards exploring interconnections within the Water-Energy-Food (WEF) nexus. Addressing this evolution, this manuscript has applied an innovative methodology to calculate a WEF nexus index (WEFni). This index seamlessly integrates both environmental and nutritional profiles across diverse case studies involving fisheries, aquaculture, and processing production systems in the European Atlantic area. The results showed that when it comes to fishing, purse seine fishing obtained the highest score (99%). For the aquaculture activities, seafood (>73%) obtained better results than fish farming. About processing treatments, freezing (>79%) has lower environmental loads than canning. In addition, a sensitivity analysis was carried out according to a caloric- and edible-based functional unit as well as the modification of the weighting factors assigned to each footprint, in which important variations were reported in the WEFni of most case studies. Consequently, although the methodological guidelines supporting the WEFni have great potential to serve as an ecolabeling tool, certain aspects need to be re-evaluated. On the other hand, it could be interesting to include the potential biodiversity loss, as well as other socioeconomic indicators, with the purpose of considering a more sustainability criteria. Finally, the contribution of this paper to the food industry literature is of paramount importance, as it represents a first step towards holistic assessments and easy-to-understand ecolabelling processes that can promote sustainable production and consumption.

Keywords

Fisheries; Aquaculture; Life cycle assessment; Environmental footprints; Nutritional index; Ecolabel.

Highlights

- A joint analysis of environmental burdens and nutritional profiles was carried out.
- The functional unit and weighting factors were modified in a sensitivity analysis.
- WEFni revealed: purse seine high score, shellfish outperformed fish farming, and freezing had lower burdens.
- The procedure followed has potential applicability to other products.
- Further indicators are needed if a holistic analysis of sustainability is to be made.

Acronyms

CC	Climate change
CF	Carbon footprint
CI	Caloric intake
EF	Energy footprint
EoL	End of life
EP	Edible portion
FU	Functional unit
FU$_{ce}$	Caloric- and edible-based functional unit
HORECA	Hotels, restaurants and catering
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NF	Nutritional Footprint
PEF	Product environmental footprint
PEFCR	Product environmental footprint category rules
RSI	Reference seafood intake
SM	Supplementary material
WEF	Water-Energy-Food
WEFni	Water-Energy-Food nexus index

WF Water footprint

1. Introduction

The food sector integrates a variety of activities such as agriculture, livestock, fisheries, aquaculture, processing and distribution. Over time, food production has shifted towards intensive systems characterised by higher yields to meet an intense food demand (Cucurachi et al., 2019). This has also meant that the food system is related to multiple environmental impacts, such as nutrient pollution (generating acidification or eutrophication from the use of fertilisers), greenhouse gases (GHGs) emissions, land use, as well as water scarcity (Clark et al., 2019). At the same time, food production activities are being affected by climate change (CC). This fact is particularly significant in the case of agriculture, aquaculture and fisheries due to the loss of fertile lands, redistribution of habitats or increasingly frequent extreme weather events (Barange et al., 2018). It has been observed that CC impacts are unevenly distributed depending on the economic activity or social stratum affected. For instance, model projections concluded that fisheries would be more harmed in terms of production level compared to agricultural activities, apart from the fact that the population of lower socio-economic status would experience these changes with greater severity (Cinner et al., 2022).

A combination of measures need to be implemented considering that both the demographic and income levels in most countries will raise and the food system will almost double its environmental impacts by 2050, if the combined action of a number of measures is not carried out, including a shift towards a less meat-based diet, the application of technological breakthroughs, and a reduction of food loss and waste (Springmann et al., 2018). Therefore, food system transformation is key to achieve food security, strengthen the management of natural resources, while providing food in a sustainable manner to cope with CC consequences (Bogard et al., 2019). In this regard, blue foods (i.e., animal, plants and algae harvested or farmed from freshwater and marine environments) (Crona et al., 2023), are presented as potential candidates for nourishing humankind at low environmental burdens on ecosystems (Gephart et al., 2021). In addition, seafood products stand out due to their excellent nutritional profiles, being rich in essential fatty acids (e.g. n-3), proteins (e.g. essential aminoacids), some micronutrients (e.g. Fe, Ca, Zn, Se, I), and vitamins (e.g., A, C, D, E) (Golden et al., 2021). Thus, the consumption of seafood products contributes to a healthy diet and offers a unique perspective to address the global health “triple burden” issue of malnutrition: obesity, undernutrition, and micronutrient deficiencies (Obiero et al., 2019).

Seafood products have also an important socio-economic relevance, being greatly present in the diet of the European Atlantic region (i.e. Spain, Portugal, France, Ireland and United Kingdom), with an average intake of 38.9 kg per capita, a significant higher consumption compared to the European Union (EU) average (23.3 kg per capita) (EUMOFA, 2023). In terms of production, the Atlantic area is recognised as one of the main exporters at the European level, reaching manufacturing levels of 2.6 million tonnes of seafood in 2018 (Laso et al., 2022). These figures are expected to raise over time, since it is estimated that global seafood production (from fisheries and aquaculture) will reach 202 million tons by 2030 and aquaculture production will overtake capture fisheries by 2027 (FAO, 2022).

In view of the environmental challenges that the seafood sector faces and its importance in a socio-economic context, it needs a cross-sectional change to become a more resilient food source. To achieve this goal, the life cycle assessment (LCA) methodology emerges as an accepted analytical framework for assessing environmental impacts related to food production, and proposing mitigation strategies (Ruiz-Salmón et al., 2021a). The application of the LCA methodology to seafood products has generated a great deal of interest in recent years, with about 90% of the LCA studies published in the last decade being reported (Ruiz-Salmón et al., 2021b). Based on the LCA concept, a specific guide for estimating the environmental footprint of marine fish products has been developed recently (Marine Fish PEFCR, 2022). This is related to the initiative of the Product Environmental Footprint (PEF) led by the European Commission (European Commission, 2013), which recommends the use of a set of indicators to create a single market of green products (European Commission, 2018).

However, the use of environmental indicators that focus on a single problem in an individual way hampers the goal of achieving an integrated resource management (Purwanto et al., 2021). This is because such indicators often overlook synergies and trade-offs between water demand, energy requirements, and food provision (Cansino-Loeza et al., 2022). Likewise, the feedback loop between these drivers of water, energy and food scarcity, which constitutes a triple nexus, promotes a situation of competition for an increasingly limited number of basic resources in many regions of the world (Fernández-Ríos et al., 2021). To highlight this issue, the Water-Energy-Food (WEF) nexus concept was developed, providing a tool to balance these elements through a holistic approach (Simpson and Jewitt, 2019). More specifically, for the seafood sector, the WEF nexus index (WEFni) was proposed by Entrena-Barbero et al. (2023a) following an integrative perspective, aggregating a set of indicators in a single value and reflecting different issues related to the seafood sector as a whole.

As a driver for raising awareness of such composite indexes, ecolabels are useful means of communication between producers and consumers (Giacomarra et al., 2021) that are increasingly concerned about sustainable consumption and production (Sigurdsson et al., 2022). Despite decades of academic research and practice using ecolabels as a way of sustainability signalling, over 60% of consumers still find sustainable food choices difficult to identify (International Food Information Council, 2020). This is due to, among other reasons, the large number of ecolabels available in the market (more than 400 worldwide, being 50 applicable to seafood products) and the lack of a robust regulatory framework (Ecolabel Index, 2023). Therefore, a flood of over-information is occurring in an attempt to advise consumers. However, only scientifically based ecolabels and recommendations can generate consumer confidence and security by enabling 'green' and conscious choices when buying seafood products. In this view, the application of the WEFni in the form of an ecolabel will constitute a reliable ecolabelling scheme to promote an environmental sustainability throughout the seafood value chain and to raise awareness on this index.

In this context, the novelty and main goal of this study was to use for the first time the methodological guidelines for the estimation of the WEFni elaborated by Entrena-Barbero et al. (2023a) to a series of case studies in the European Atlantic area to analyse trends and hotspots of both the single indicators (carbon footprint (CF), water footprint (WF), energy footprint (EF), nutritional footprint (NF)), as well as the composite index proposed (i.e. WEFni). After this, strengths and weaknesses of the WEFni methodology were identified with the aim of proposing improvements in further iterations. Along with the main goal, a secondary objective was defined: to carry out a sensitivity analysis of the results obtained by varying certain methodological aspects of the method, in particular the functional unit (FU) and weighting factors. These guidelines were configured within the framework of the NEPTUNUS project (Laso et al., 2022) and their application allows benchmarking seafood products. The study will contribute to the development of a useful framework for the estimation of the environmental, energy and nutritional profiles of seafood products from fisheries or aquaculture production systems, or which have undergone a type of processing.

2. Methodology

The main features of the methodological procedure followed in this paper are summarised in **Figure 1**. The methodological guidelines to calculate the WEFni are described in **Section 2.1**, while the sensitivity analysis is presented in **Section 2.2**.

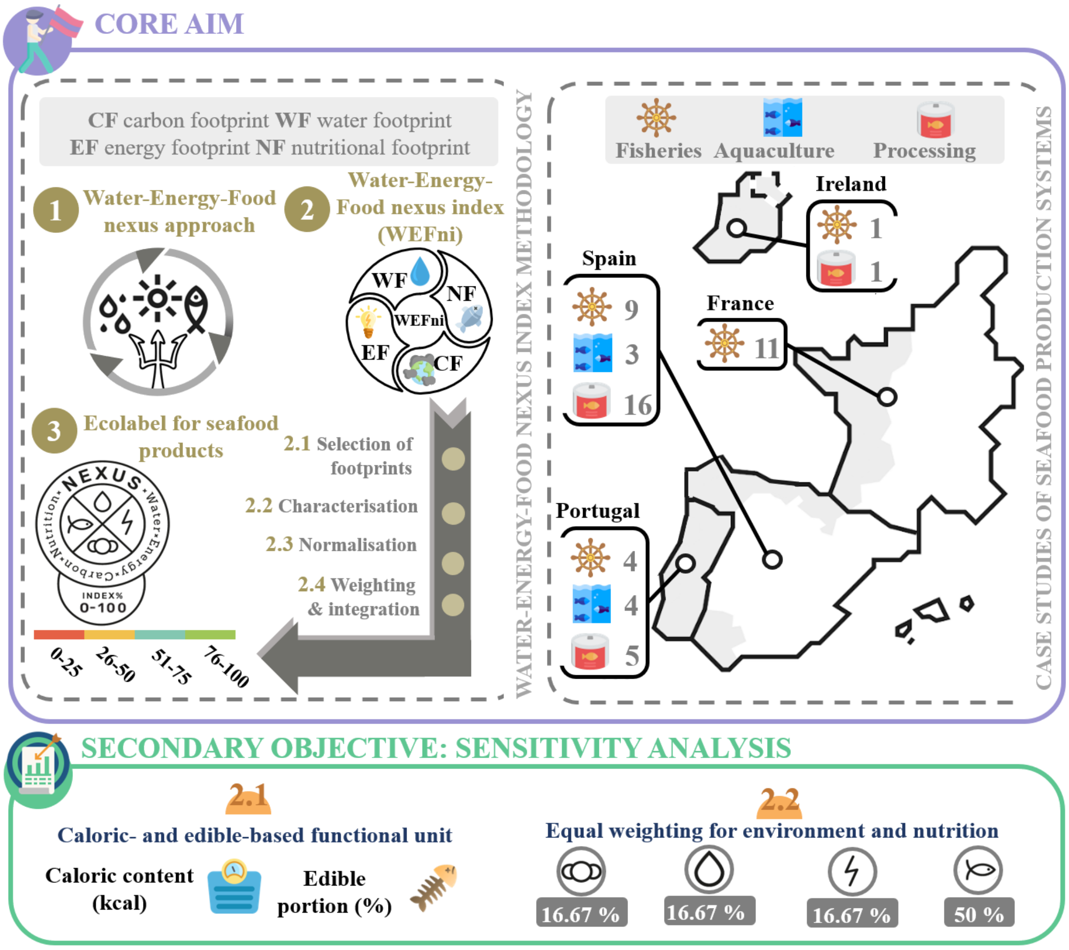

Figure 1. Main features of the methodological procedure.

2.1. Water-Energy-Food nexus index methodological guidelines

The WEFni methodological guidelines, proposed by Entrena-Barbero et al. (2023a), and underpinned by the international standards ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), proposes a common roadmap for the elaboration of LCA studies applied to seafood products, establishing aspects such as FU, system boundaries, allocation rules for multi-functional systems, minimum life cycle inventory (LCI) data required or end of life (EoL) modelling, among others. They also select the life cycle impact assessment (LCIA) methods used to estimate the following environmental footprints: CF, WF and EF. Moreover, they also propose a nutritional footprint in the form of a modified Nutrient Rich Food (NRF) index for the specific case of seafood products, having considered 12 nutrients to promote and 2 nutrients to limit (NRF12.2). Finally, they propose a process of normalisation (from 0 to 1) and weighting (25% for each footprint) to integrate the four indicators into a dimensionless single value (i.e., the WEFni), which varies from

0 to 100. The final value was represented in the form of front-of-pack ecolabel to enable a communication logo that can be applied by producers and perceived by consumers. The main aspects of the methodology are summarised in **Table 1**.

Table 1. Main features of the Water-Energy-Food nexus index methodology.

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)
Characterisation	Global Warming Potential~~s~~ 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 (using Lower Heating Values) (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 normalisation and weighting of the three impact categories)	MJ	Dimensionless
Normalisation	Reverse linear normalisation of a sample from 0 (highest value of the footprint) to 1 (lowest value of the footprint) (see Equation 5 in Entrena-Barbero et al. (2023a))			Linear normalisation of a sample from 0 (lowest value of the footprint) to 1 (highest value of the footprint) (see Equation 6 in Entrena-Barbero et al. (2023a))
Weighting factors	25 %	25 %	25 %	25 %
Integration	Sum of the four weighted values: Water-Energy-Food nexus index (0 – 100)			

The methodology was applied by NEPTUNUS project partners to a series of case studies that can be divided into three different systems: fisheries, aquaculture and processing. Up to 34 studies were conducted regarding fisheries, addressing several fishing gears (e.g., trawls, purse seine, pole and line); 7 case studies were assessed with respect to aquaculture; and 22 seafood case studies were related to processing (e.g., freezing, salting, canning and smoking). All case studies were from the European Atlantic area, more precisely in the following countries: France (Cloâtre, 2018), Ireland, Portugal and Spain. The timeframe under study was between 2011 and 2019. Given the extraordinary circumstances that occurred in 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 in the results obtained (Ruiz-Salmón et al., 2021a). The particularities of each case study can be consulted in more detail in the Supplementary Material (SM), in **Tables SM1-SM3** for the fisheries, aquaculture and processing systems, respectively. Following the WEFni guidelines, the FU was set as 1 kg of seafood, either landed at the port, produced at the farming site, or delivered at the factory gate including the associated packaging material of processed seafood products (Entrena-Barbero et al., 2023b).

Once the methodological guidelines were applied to the case studies of seafood products, these were grouped according to fishing gear, type of aquaculture (fish or shellfish) and processing (e.g., salted, smoked, etc.) for the fisheries, aquaculture and processing systems with the purpose of identifying trends. In addition, an analysis of the results obtained was performed for both the single indicators (CF, WF, EF and NF) and the composite index (WEFni). Finally, the strengths and weaknesses of the WEFni methodological guide were discussed.

2.2. Sensitivity analysis

With the purpose of carrying out a sensitivity analysis of the results obtained, the methodological choices for the estimation of the WEFni, based in Entrena-Barbero et al. (2023a), were modified for two key factors in LCA studies: on the one hand, the FU and, on the other hand, the weighting process as detailed in **Section 2.2.1** and **Section 2.2.2**, respectively. 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.

2.2.1. Functional unit

According to the WEFni guide, a mass-based FU was selected for the assessment of seafood products due to three main reasons: (i) to avoid the common regional differences in price over time (Costello et al., 2020); (ii) it has been the most widely used FU in the seafood LCA literature during the last decade (Ruiz-Salmón et al., 2021b), which facilitates comparisons with other studies; and (iii) it allows for easy and accessible calculations, promoting reproducibility.

Despite the foregoing, a portion of mass, in this case 1 kg, does not fully represent the nourish characteristics of food (Weidema and Stylianou, 2020). Thus, to improve the results, it turns out to be 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 the content of digestible proteins (Sonesson et al., 2017), (ii) multiple nutrients in the form of composite indicators (e.g., the NRF), or (iii) diet contexts (McAuliffe et al., 2020).

Notwithstanding, during the calculation of the WEFni, the nutritional profile was covered by integrating a specific NF for seafood products (i.e., NRF12.2). Therefore, in this case it was decided to opt for estimating the satiating capacity of seafood products through a caloric- and edible-based FU, named as FU_{ce}. To do this, **Equation 1** was applied, considering the values of the caloric intake (CI) of each specimen. Moreover, since it is not plausible to make comparisons between species with very different edible portions (EPs), e.g., hake and mussel, this factor was also taken into consideration.

Likewise, the FU_{ce} was relativised 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 and the results obtained for each case study can be consulted in **Table SM4**. On the one hand, case studies having more than one species as target were disregarded, since conducting averages of both CI and EP would lead to obtain an unrepresentative FU_{ce} 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.

$$\mathrm{FU_{ce}} = \frac{\mathrm{RSI}}{\mathrm{CI} \cdot \mathrm{EP}} \tag{1}$$

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})

2.2.2. Weighting process

Considering the methodological guidelines of WEFni, the default weighting process carried out was proposed by Andreas et al. (2020), performing a combination of two weighting techniques usually considered in LCA studies. On one hand, panel weighting, which is conducted under the opinion of a group of people, which in this case was the NEPTUNUS project consortium. Partners of the NEPTUNUS project considered to perform a sensitivity analysis giving equal importance to the protection of the environment and to the promotion of nutrition: a weighting factor of 50% for the environmental footprints (with equal weight of 16.67% for CF, WF and EF), as well as a weighting factor of 50% for NF. On the other hand, binary weighting, which considers null or equal weights (i.e., weighting factors of 25% for CF, WF, EF and NF). This was decided under the premise of facilitating the aggregation into a single value (i.e., WEFni) to promote its application and acceptance by producers and consumers, respectively. In addition, none of the 4 individual indicators selected were prioritized to show a first simple approximation of what it would mean to follow a benchmarking process based on the WEF nexus concept.

3. Results and discussion

The results obtained from the case studies after implementing the methodological guidelines are presented according to the values of the single indicators: CF, WF, EF and NF (**Section 3.1**), as well as for the composite indicator: the WEFni (**Section 3.2**). Later, the sensitivity analysis is conducted in **Section 3.3**, to conclude with a discussion of strengths and weaknesses of the approached methodology (**Section 3.4**).

3.1. Individual footprints

With the aim of conducting the interpretation and discussion of the four individual footprints comprising the WEFni (i.e., CF, WF, WF, and NF), the results are presented in a normalised form (from 0 to 1) in **Figure 2**. The normalisation process was carried out using **Equations 5** and **6** shown in the study by Entrena-Barbero et al. (2023a), taking the maximum and minimum values of the results of each footprint of the whole sample as a reference. Thus, while the seafood product with the lowest environmental footprint in terms of CF, WF or EF was assigned a score of 1, the other seafood products were decreasing their scores proportionally, considering the cases with the maximum environmental footprints with a normalised value of 0. Conversely, since the NF should be as high as possible, the seafood product with the highest and lowest values will become scores of 1 and 0, respectively. In addition, these values have been grouped according to the averages of fishing gears (**Section 3.1.1**), type of aquaculture **(Section 3.1.2**) or processing systems (**Section 3.1.3**), respectively. For a more detailed information, the values obtained for the four individual indicators in each case study are shown in **Tables SM5-SM7**.

3.1.1. Fishing systems

In view of **Figure 2A**, up to eight fishing gears integrate the 34 fisheries case studies analysed, being the most numerous purse seine, trawls, and artisanal fisheries with 12, 8 and 7 cases, respectively, while others only included 1 or 2 case studies (pole and line, pots and traps, dredge, trammel net and longline).

In terms of environmental footprints (CF, WF and EF), the top three fishing gears with the lowest environmental burdens (and thus had the largest individual normalised scores) were purse seine, artisanal fisheries, and dredge. In contrast, the highest environmental burdens (i.e., the lowest normalised scores) were reported for longline and pots and traps. Regarding the CF, the average values without normalisation ranged between 0.56 and 3.33 kg CO_2 eq. per kg of landed fish for purse seiners and longlines respectively. Between these two limit values, the following fishing gears are ranked in order of highest to lowest impact: pots and traps (with 3.08 kg CO_2 eq.), trammel net and trawls (with similar values of 2.17 and 2.01 kg CO_2 eq., respectively) and dredge and artisanal fisheries, which reached a similar position at around 0.80 kg CO_2 eq. on average. It should be noted that the average trawl aggregation includes both pelagic and bottom trawlers, with CF values ranging from 0.38 kg CO_2 eq. for the former, to 3.31 kg CO_2 eq. for the latter. Further analysis of the factors contributing to the total CF indicated that the major hotspot was, in most cases, the use of fuel during fishing.

To contrast the results, the most representative samples — trawl and purse seine case studies — were compared with the existing literature. A recent study by Sandison et al. (2021) examined the environmental performance of Scottish pelagic fisheries by applying the LCA methodology with a similar scope and using 1 kg of whole mixed pelagic fish as the FU. The sample consisted of eleven trawlers, three of which combined trawl and purse seine gears. The authors reported an average CF of 0.45 kg CO_2 eq. per FU. However, they analysed inter-vessel and inter-annual comparisons and observed CF fluctuations ranging from a minimum of 0.28 kg CO_2 eq. to a maximum of 0.74 kg CO_2 eq., and a value of 0.23 kg CO_2 eq. to 0.29 kg CO_2 eq. for each scenario, respectively. The results found in this study for pelagic trawlers were in line with the Scottish fleet average (Sandison et al. 2021). On the other hand, the average CF obtained for purse seine (0.56 kg CO_2 eq.) is in line with the value reported in a study of the Galician (Spain) purse seine fleet (30 vessels), which accounted 0.79 kg CO_2 eq. (Vázquez-Rowe et al., 2010).

On average terms, WF results showed a similar trend to the CF, moving in a range from 7.02 to 37.45 µPt per kg of landed fish, being purse seine and longline the fishing gears with the lowest and highest values, respectively. A recent study by Ceballos-Santos et al. (2023) obtained a WF of 11.98 µPt for the Cantabrian purse seine fleet here evaluated. This value was the aggregation of the individual indicators (water use: $6.23 \cdot 10^{-2}$ m^3 eq., freshwater eutrophication: $7.38 \cdot 10^{-6}$ kg P eq., and marine eutrophication: $7.93 \cdot 10^{-3}$ kg N eq.). Ceballos-Santos et al. (2023) also analysed the environmental impacts in depth, revealing that the main contributor to the WF was diesel production and combustion, which accounted for 99% of the overall marine eutrophication indicator (this marker contributed 95% to the clustering of water footprint indicators). The same occurred for the longline, in which the marine diesel necessary for the fishing of sardines used as bait entailed practically all burdens in WF terms. Likewise, the longlining value was followed by trammel nets (30.53 µPt) and trawls (28.85 µPt), whereas pots and traps showed and intermediate footprint of 21.6 µPt. On the other side, artisanal fisheries and dredges presented similar average values of 10.85 and 10.81 µPt, respectively. These values come from the normalisation and weighting of the results of three impact categories related to both freshwater consumption (water use) and water degradation (freshwater eutrophication and marine eutrophication) hindering the comparison with reference values reported in literature.

With regard to the non-normalised EF results, they were between 8.45 MJ for purse seine and 49.78 MJ for pots and traps, per kg of landed fish, following the pattern observed for CF and WF. The values of the latter were followed closely by longline (41.17 MJ), while trammel net recorded more distant results (33.4 MJ). Behind of these results were the obtained by trawls (30.02 MJ) and pole and line (26.15 MJ), while dredge and artisanal fisheries showed EFs of 11.54 MJ and 9.79 MJ, respectively. Once again, it was noted that the energy required for the production and combustion of diesel was responsible for most environmental loads encompassed in the EF.

Against this backdrop it is interesting to examine how footprints vary according to how seafood is produced, i.e., the same species captured using different fishing gears. For instance, Atlantic mackerel *(Scomber scombrus)* is the target species of French and Galician trawlers, Cantabrian purse seiners, as well as artisanal fisheries fleets. In such case, the highest footprint values were obtained by Galician trawlers, with a CF of 1.33 kg CO_2 eq., a WF of 16.17 µPt and an EF of 17.83 MJ per kg of Atlantic mackerel captured. For the case of French trawlers, despite being the same kind of gear, the footprint values were around half: 0.52 kg CO_2 eq., 6.93 µPt and 7.79 MJ per FU. Regarding Cantabrian purse seiners, the lowest footprint values were registered: 0.11 kg CO_2 eq., 0.34 µPt and 1.59 MJ 9 per kg of Atlantic mackerel captured, while the use of artisanal fisheries presented intermediate values between those obtained by trawlers and seiners: 0.82 kg CO_2 eq., 13.16 µPt and 1.73 MJ. Another example is the fishing of albacore tuna (*Thunnus alalunga*) by French trawlers, Cantabrian seiners and artisanal fisheries. For this case, the trawling gear also presented the highest footprint values, with a CF value of 4.25 kg CO_2 eq., 58.18 µPt and 65.36 MJ per kg of albacore tuna captured. In contrast, artisanal fisheries fleet had the lowest CF and EF values: 0.13 kg CO_2 eq. and 0.26 MJ, respectively, while purse seiners obtained the lowest WF: 0.74 µPt. These results are in line with the well-documented literature that points out that purse seine fleets targeting inshore fish stand out as one of the fishing gears that generate the least environmental burdens since they are coastal and low fuel-consuming fisheries (Vázquez-Rowe et al., 2010). In contrast, several studies around the world have found that trawlers are the fleet group with the highest fuel consumption per kg of fish, partly because of the long distance they travel to the fishing grounds (Jafarzadeh et al., 2016; Sandison et al., 2021). In fact, bottom trawling was found to be up to five times less efficient than purse seining in some cases (Hognes et al., 2012; Schau et al., 2009).

Regarding the NF scores, it is important to take into consideration that the nutritional assessment depends only on the species of seafood captured and not on the fishing gear used. Consequently, for the fishery scenario, around 25 species were assessed using the dimensionless NRF12.2 index, involving from top predators as tuna (e.g., *Thunnus alalunga*) to small pelagic as sardine (*Sardina pilchardus*), along with cephalopods (e.g., *Octopus vulgaris* and *Sepiida*) and bivalves (e.g., *Pecten maximus*). The NF values ranged between 115 and 361, being ~~Chub~~ chub mackerel (*Scomber japonicus*) and the mix of sea bass (*Dicentrarchus labrax*) and gilthead seabream (*Sparus aurata*) the species with the highest and lowest NF values, respectively. No large contrasts were identified between pelagic and demersal species which reached an average NRF12.2 index of 234 and 213, respectively. Cephalopods accomplished the highest mean score (271) and bivalves the lowest with 187 points. The low NRF12.2 value for the latter is due to the absence of omega-3 content, one of the most valuable nutrients to be promoted in seafood, coupled with a high amount of saturated fat (0.23 g per 100 g), one of the nutrients to be limited in the applied model. These outcomes are quite different from Koehn et al. (2022), who used a modified version of the nutrient richness index developed by Drewnowski (2009), demonstrating that small pelagic fish rated highest than bivalves and cephalopods. In this line, Bianchi et al. (2022) found large variability within species groups in terms of nutrient density scores, but suggested that wild salmonids and small pelagic performed the best.

3.1.2. Aquaculture systems

The results from aquaculture systems (**Figure 2B**) were divided into four fish and three shellfish case studies. Globally, shellfish aquaculture achieved higher normalised scores (almost double) for all individual footprints, meaning lower environmental impacts than farmed fish. In terms of CF, the results per FU ranged from 0.08 for oysters (*Crassostrea gigas* and *Crassostrea angulata*) to 10.30 kg CO_2 eq. for gilthead seabream (*Sparus aurata*), with ten times higher average values for shellfish (0.55 kg CO_2 eq.) compared to fish aquaculture (5.21 kg CO_2 eq.). For the WF this deviation increased, with averages values of 2.16 µPt for shellfish and 54.66 µPt for fish species. As for the EF, the same differences recorded in the CF occurred, with average values for shellfish and fish of 10.00 and 104.35 MJ per FU, respectively, being the maximum for the farming of gilthead seabream (211 MJ). These wide ranges in terms of minimum and maximum values for the environmental indicators could be related to the type of aquaculture implemented in the case studies analysed. For example, those based on intensive aquaculture need a more controlled production process in terms of environmental conditions, external feed or existence of an artificial flow of water that need to be pumped, which translates into higher CF, WF and EF. Therefore, given the particularity of each case study depending on the location and species assessed, it is difficult to make equivalent comparisons. Finally, the nutritional quality of aquaculture products calculated through the NF showed punctuations from 194 for gilthead seabream to 314 for rainbow trout (*Oncorhynchus mykiss*), with shellfish and fish species obtaining a similar average NF of 229.04 and 232.49, respectively. These findings were consistent with those of Gephart and Golden (2022). These authors ranked a sample of aquaculture groups according to the total environmental and nutrient scores, showing that bivalves performed best, followed by silver and bighead carp, trout, and salmon. However, they notified significant heterogeneity in both environmental performance and nutrient content performance, with almost all blue food groups scoring best in at least one metric, leading to possible trade-offs in the assessment of the double bottom line in aquaculture.

3.1.3. Processing systems

With the focus on the 22 case studies of processed products analysed (**Figure 2C**), these were grouped into different processing techniques: freezing (5 case studies); canning in glass jar (4), aluminium (7) and tinplate (3); and smoking, gutting, and salting, with one case study for each type. In addition, different scenarios related to the incorporation of diverse oils and other additives were assessed for canning processes (see **Tables SM1-SM3** for further information). In view of **Figure 2C**, smoked, gutted and frozen products highlighted for reaching upper normalised scores, thus related to having lower footprints. The smoked product got the lowest average CF per FU, with 1.10 kg CO_2 eq., followed by the gutted product (1.61 kg CO_2 eq.) and frozen products (2.77 kg CO_2 eq.). The same ranking was observed for WF, with results of 7.30, 23.69 and 30.69 µPt, for smoked, gutted and frozen items, respectively. In contrast, the gutted product achieved an EF score (18.61 MJ) ten points lower than smoking (28.55 MJ). On the opposite side, canned goods showed the worst performance, with tinplate canned products showing higher averages in CF per FU (10.19 kg CO_2 eq.), WF (278.54 µPt) and EF (282.92 MJ). Then, products canned in aluminium and glass jars followed behind tinplate case studies with CFs of 8.42 and 5.71 kg CO_2 eq., respectively. In terms of WF 229.67 and 127.33 µPt were obtained for products canned in aluminium and glass jar, respectively. As for the EF, canning in aluminium reached an impact (193.51 MJ) almost two times above canning in glass jars (98.13 MJ). Finally, the average salting results were intermediate (CF: 4.94 kg CO_2 eq.; WF: 48.75 µPt; EF: 74.41 MJ). Comparing the most abundant type of processing in the sample, canning, with existing studies it was found that the average CF was in the range of values reported for mussels canned in tinplate, with 4.32 kg CO_2 eq. per kg. (Iribarren et al., 2010) and tuna canned in tinplate, with 8.4 kg CO_2 eq. per kg (Avadí et al., 2015). If a more in-depth analysis is carried out, the stage of seafood production (i.e., fishing or farming) usually has a significant contribution to the environmental burdens. Therefore, if for example a comparison is carried out between frozen cod and sardine, results can vary greatly because

On the nutrition side, NF values for all case studies were within the range of 101-306 with smoked and canned in aluminium products having the lowest and highest averages (185.40 and 262.14, respectively). The nutritional difference between case studies with the same fish species was due to the rest of ingredients used and their proportion to elaborate the final product.

In summary, after analysing the individual footprints of each group per sector, it can be concluded that, although some trends have been identified, it would be necessary to include a larger and more diverse sample in future iterations to enable cross-system comparisons to obtain more plausible results for the Atlantic area. On the other hand, a more detailed study of hotspots has not been carried out due to the lack of equality in the resolution of results for the whole sample and confidentiality issues related to the inventories. Limitations in terms of availability and representativeness of the data used in each case study could have changed the results to a significant extent. Likewise, it should not be overlooked that the main objective of the study is not to identify hotspots of each case study, but rather to systematically quantify the impacts of case studies of marine systems in the European Atlantic area.

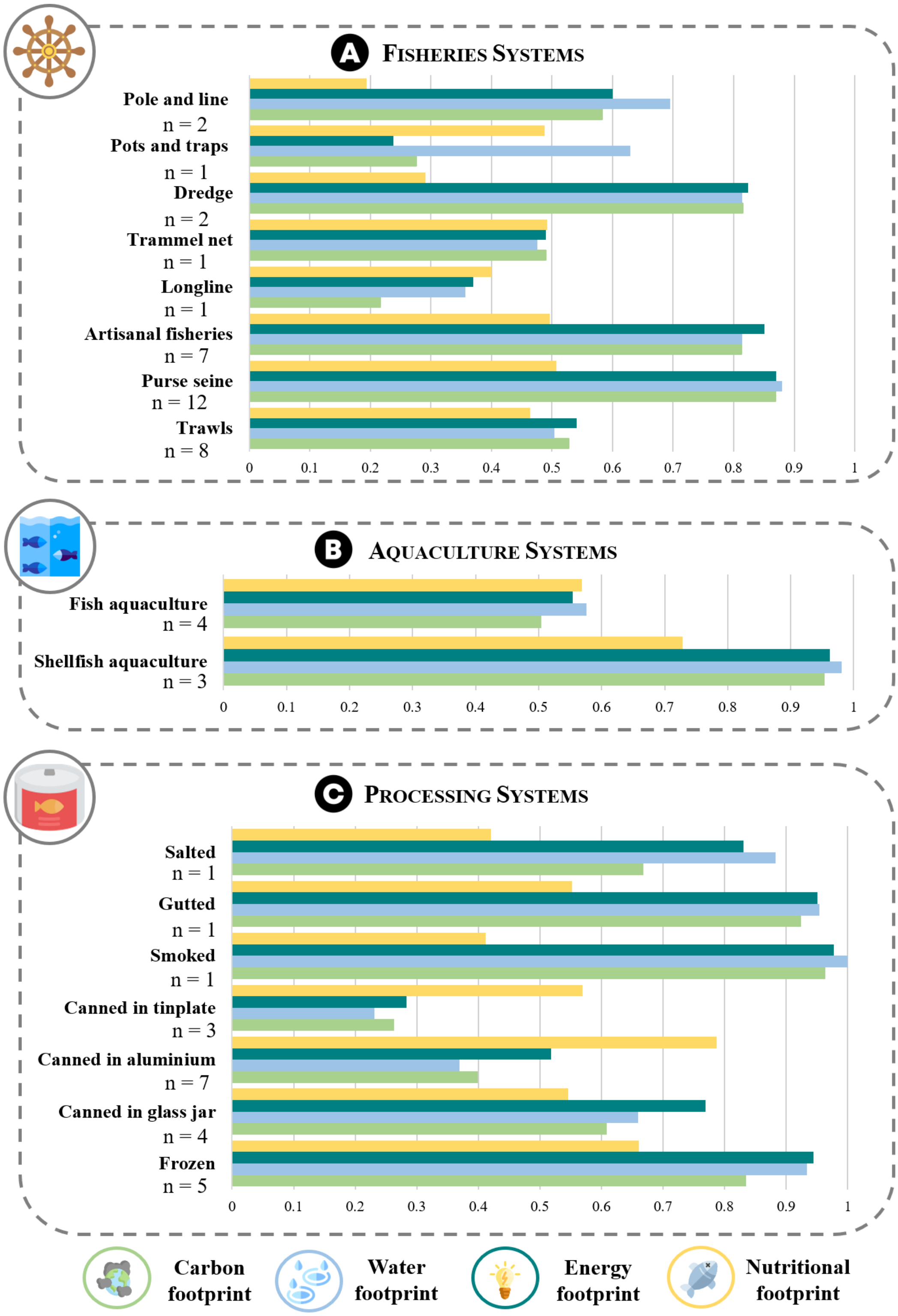

Figure 2. Individual indicators (i.e., carbon, water, energy and nutritional footprints) for each system assessed: (A) fisheries, (B) aquaculture and (C) processing. The results are presented normalised and averaged for the different groups within each system. The lowest value in terms of carbon, water and energy footprints is assigned a score of 1, while the remaining products decrease in proportion, considering 0 as the highest footprint. Conversely, for the nutritional footprint the higher the better, so the highest and lowest values are assigned with scores of 1 and 0, respectively.

3.2. Composite indicator

The four individual footprints shown above (i.e., CF, WF, EF, NF) were aggregated into a single value (i.e., the WEFni), as shown in **Figure 3**, for each case study, according to the type of system: fisheries (**Figure 3A**), aquaculture (**Figure 3B**), and processing (**Figure 3C**).

For the fisheries systems (**Figure 3A**), the list was mainly headed by species captured using purse seine and artisanal fisheries. At the top was the case of chub mackerel purse seine with 99 out of 100 points. Behind this case were cuttlefish captured through artisanal fisheries and horse mackerel captured through purse seiners, being scored with a WEFni of 94 points. A further 12 case studies exceeded 75 points (thus being green coloured), including not only different species landed with the abovementioned fishing gears, but also the trawl fishery for Atlantic mackerel (82 points). Shown as blue bars (varying the WEFni from 51 to 75 points), up to seven case studies have an average value of approximately 70, being mainly represented by purse seiners and trawlers, while pole and line catches of tuna are below 60. Subsequently, with scores between 26 and 50 points (yellow coloured) were 12 case studies comprising different types of fishing gears (trammel net, longline, pots and traps, etc.) and species, such as common sole, saithe or octopus. Finally, at the bottom (25 or less points and red coloured) there were two cases: octopus captured with artisanal fisheries (19 points), and the albacore trawl fishery (9 points). When a detailed comparison of fishing gears was carried out by setting mean WEFni values, purse seiners scored the highest (69 points), followed by artisanal fisheries (66 points), dredges (64 points) and trammel nets (56 points). Pole and line, trawls, and pots and traps obtained lower values, with 48, 45 and 32 points, respectively, while longline showed the worst WEFni performance (27 points).

When it came to the aquaculture products (**Figure 3B**), shellfish were found to score best, with mussels reaching 88 points, followed by Pacific and Portuguese oysters, which scored 78 points. In fact, this oyster mix performed slightly better than the one composed of European flat and Pacific oysters, which reached 73 points, having a similar performance to farming of rainbow trout and sea bass. At the end, with the lowest points, 25 and 24, were gilthead seabream and turbot, respectively. The results for the WEFni showed the same trend as those found from the individual footprints. Even though normalisation among case studies, it was difficult to draw clear conclusions, despite some trends emerged showing a better performance of bivalves when compared to fish farming.

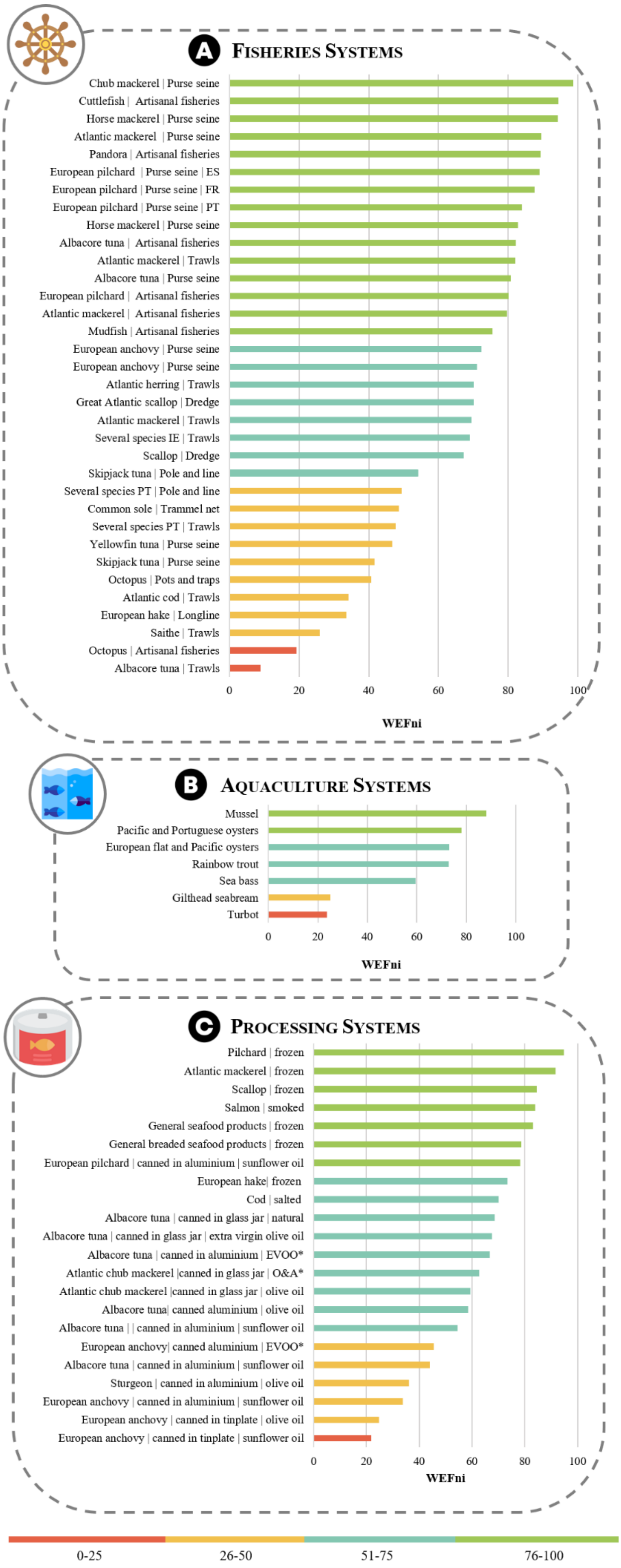
A
FISHERIES SYSTEMS
Chub mackerel | Purse seine
Cuttlefish | Artisanal fisheries
Horse mackerel | Purse seine
Atlantic mackerel | Purse seine
Pandora | Artisanal fisheries
European pilchard | Purse seine | ES
European pilchard | Purse seine | FR
European pilchard | Purse seine | PT
Horse mackerel | Purse seine
Albacore tuna | Artisanal fisheries
Atlantic mackerel | Trawls
Albacore tuna | Purse seine
European pilchard | Artisanal fisheries
Atlantic mackerel | Artisanal fisheries
Mudfish | Artisanal fisheries
European anchovy | Purse seine
European anchovy | Purse seine
Atlantic herring | Trawls
Great Atlantic scallop | Dredge
Atlantic mackerel | Trawls
Several species IE | Trawls
Scallop | Dredge
Skipjack tuna | Pole and line
Several species PT | Pole and line
Common sole | Trammel net
Several species PT | Trawls
Yellowfin tuna | Purse seine
Skipjack tuna | Purse seine
Octopus | Pots and traps
Atlantic cod | Trawls
European hake | Longline
Saithe | Trawls
Octopus | Artisanal fisheries
Albacore tuna | Trawls
0
20
40
60
80
100
WEFni
B
AQUACULTURE SYSTEMS
Mussel
Pacific and Portuguese oysters
European flat and Pacific oysters
Rainbow trout
Sea bass
Gilthead seabream
Turbot
0
20
40
60
80
100
WEFni
C
PROCESSING SYSTEMS
Pilchard | frozen
Atlantic mackerel | frozen
Scallop | frozen
Salmon | smoked
General seafood products | frozen
General breaded seafood products | frozen
European pilchard | canned in aluminium | sunflower oil
European hake| frozen
Cod | salted
Albacore tuna | canned in glass jar | natural
Albacore tuna | canned in glass jar | extra virgin olive oil
Albacore tuna | canned in aluminium | EVOO*
Atlantic chub mackerel |canned in glass jar | O&A*
Atlantic chub mackerel |canned in glass jar | olive oil
Albacore tuna| canned aluminium | olive oil
Albacore tuna | | canned in aluminium | sunflower oil
European anchovy| canned aluminium | EVOO*
Albacore tuna | canned in aluminium | sunflower oil
Sturgeon | canned in aluminium | olive oil
European anchovy | canned in aluminium | sunflower oil
European anchovy | canned in tinplate | olive oil
European anchovy | canned in tinplate | sunflower oil
0
20
40
60
80
100
WEFni
0-25
26-50
51-75
76-100

Figure 3. Water-Energy-Food nexus index (WEFni) results for each case study aggregated by system type: (A) fisheries, (B) aquaculture, and (C) processing. *For fisheries systems: this purse seine case study for the European anchovy is landed in a non-European port. For processing systems: EVOO denotes Extra Virgin Olive Oil and O&A denotes Olives and Almonds as additive.

With regard to case studies of activities belonging to the seafood processing industry (**Figure 3C**), 5 frozen products were found with a score above 76 points, with pilchard freezing showing the best performance (95 points). The other case studies concerned species ranging from salmon or scallops to breaded products and frozen seafood in general. The smoked salmon scenario also reached a high score (84 points). In addition, a canning scenario entered this top position, with 78 points for European pilchard with sunflower oil canned in aluminium. In the intermediate values, between 26 and 75 scores, most canned products were scored, covering a variety of species, additives and packaging formats. In addition, the cases of frozen European hake (73) and salted cod (70) were also scored in intermediate levels. Among the different canning scenarios, albacore tuna and Atlantic chub mackerel in glass jars achieved better scores, with natural products (i.e., without additives) followed by those with extra virgin olive oil (less refined than olive oil or sunflower oil) scoring the highest WEFni. On the other hand, European anchovy canned in tinplate with olive oil scored the worst with only 22 marks. These outcomes may suggest that the use of glass jar packaging for canned products results in a lower environmental burden when compared with aluminium and tinplate cans, thus suggesting that the type of packaging material can improve the environmental performance of these preserved products (Almeida et al., 2022). The ranking of canned scenarios revealed clearer conclusions using the composite indicator compared with the individual footprints.

3.3. Sensitivity analysis

The WEFni obtained for the different case studies after carrying out the sensitivity analysis applied to the FU, the weighting process and the consideration of both approaches are compiled in **Figure 4**, classified in fisheries (A), aquaculture (B), or processing (C) systems. Moreover, given the large number of case studies to which sensitivity analysis was applied (58), it was decided to group them in a similar way as shown in **Figure 2**. Notwithstanding, the individual results for each case study have been compiled in **Tables SM8-SM10**.

Regarding the fishing systems (**Figure 4A**), when the sensitivity analysis was conducted in relation to the FU, it was observed that all fishing gears, except trawls and purse seines, 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 caloric intake and its edible portion (i.e., CC and EP, respectively). 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 (see **Table SM4**). Conversely, more than 90 g of catches were required per person per day to satisfy the RSI through pots and traps (octopus) and trammel net (common sole) thus leading to the largest reductions in terms of WEFni.

Similar results were reported when the weighting process was modified. In this case, the NF associated with each species turns out to be now the key factor in increasing or decreasing the

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 situation (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 the ones with the highest NFs (see **Table SM5**), 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 of the whole sample of fisheries systems: around 230. On the opposite side were the low NF of European hake (213.61) and skipjack tuna (210.32), which implied that longline (minus 54 points) and pole and line (minus 50 points) revealed the greatest reductions in terms of WEFni.

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 most disadvantaged groups with 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 has slipped from second place to the bottom of the ranking.

Concerning aquaculture systems (**Figure 4B**), after conducting the sensitivity analysis for the two groups, fish and shellfish aquaculture, few differences were identified. The FU_{ce} of the fish aquaculture group has on average 81.49 g of catches 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 improving its WEFni by 3 points, while shellfish aquaculture decreased 8 points. Moreover, the sensitivity analysis compromising the weighting process implies reductions in both groups, 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 analysed, i.e., oyster and mussel, with NF equal to 210.00 and 267.12, respectively. When the two approaches were addressed together, it became clear that fish aquaculture was catching up shellfish aquaculture, with 15 points separating them in terms of WEFni. Lastly, according to the ranking, although both groups tend to reduce their differences no change in positions occurred, with fish aquaculture remaining in first place and shellfish aquaculture in second.

In relation to processing systems (**Figure 4C**), 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 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 canning (1 point) and freezing (5 points) process systems. Conversely, for salting, gutted and smoking processes, this variation implied a reduction of at least 10 points, 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 analysed, with further reductions in the WEFni for salting (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 and salted products were the worst WEFni performers.

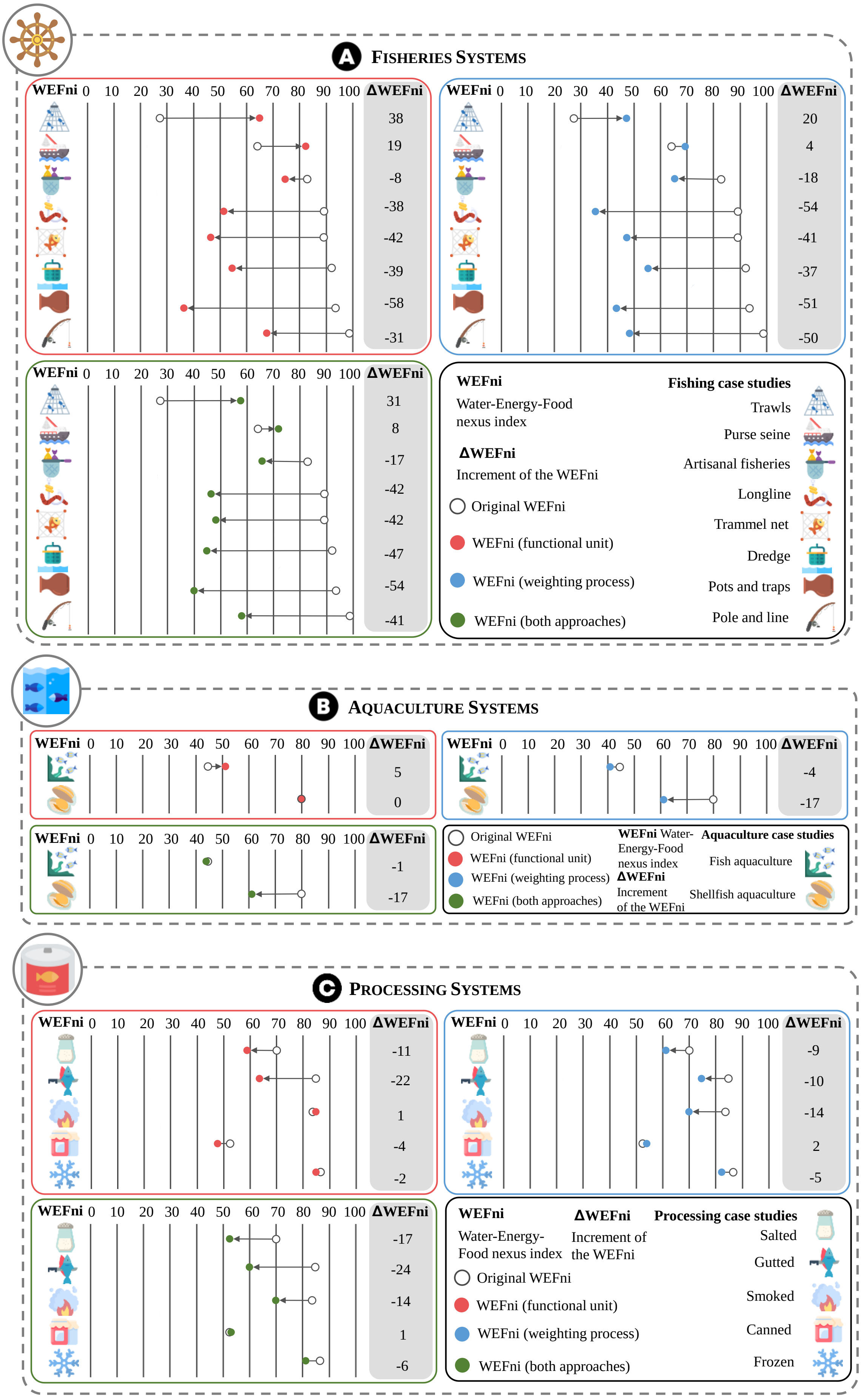
A FISHERIES SYSTEMS
WEFni 0 10 20 30 40 50 60 70 80 90 100 ΔWEFni
38
19
-8
-38
-42
-39
-58
-31
WEFni 0 10 20 30 40 50 60 70 80 90 100 ΔWEFni
20
4
-18
-54
-41
-37
-51
-50
WEFni 0 10 20 30 40 50 60 70 80 90 100 ΔWEFni
31
8
-17
-42
-42
-47
-54
-41
WEFni
Water-Energy-Food nexus index
ΔWEFni
Increment of the WEFni
Original WEFni
WEFni (functional unit)
WEFni (weighting process)
WEFni (both approaches)
Fishing case studies
Trawls
Purse seine
Artisanal fisheries
Longline
Trammel net
Dredge
Pots and traps
Pole and line
B AQUACULTURE SYSTEMS
WEFni 0 10 20 30 40 50 60 70 80 90 100 ΔWEFni
5
0
WEFni 0 10 20 30 40 50 60 70 80 90 100 ΔWEFni
-4
-17
WEFni 0 10 20 30 40 50 60 70 80 90 100 ΔWEFni
-1
-17
Original WEFni
WEFni (functional unit)
WEFni (weighting process)
WEFni (both approaches)
WEFni Water-Energy-Food nexus index
ΔWEFni Increment of the WEFni
Aquaculture case studies
Fish aquaculture
Shellfish aquaculture
C PROCESSING SYSTEMS
WEFni 0 10 20 30 40 50 60 70 80 90 100 ΔWEFni
-11
-22
1
-4
-2
WEFni 0 10 20 30 40 50 60 70 80 90 100 ΔWEFni
-9
-10
-14
2
-5
WEFni 0 10 20 30 40 50 60 70 80 90 100 ΔWEFni
-17
-24
-14
1
-6
WEFni
Water-Energy-Food nexus index
ΔWEFni
Increment of the WEFni
Original WEFni
WEFni (functional unit)
WEFni (weighting process)
WEFni (both approaches)
Processing case studies
Salted
Gutted
Smoked
Canned
Frozen

Figure 4. Water-Energy-Food nexus index results of the sensitivity analysis for each case study divided by system: (A) fisheries, (B) aquaculture, and (C) processing. White dots represent the original WEFni obtained in the base case; red line and dots show the results of the sensitivity analysis performed by varying the FU; line and dots in blue show the results of the sensitivity analysis carried out varying the weighting factors; and line and dots in green show the results for the sensitivity analysis carried out with both approaches jointly.

3.4. Strengths and weaknesses of the WEFni methodological guide

The methodological guidelines applied in this work allowed to assess the environmental impacts and nutritional profiles of a sample of seafood species from the European Atlantic area through a composite index: the WEFni. In addition, this information can be represented as a percentage in the form of a front-end ecolabel to be implemented in seafood products packaging. For that, a design proposal was suggested by Entrena-Barbero et al. (2023a) with the goal to facilitate the communication between producers and consumers. However, while the ecolabel can be a useful tool to consumers that wish to make more sustainable purchases, the representation of results through a single value can mask the main hotspots of the single indicators that compose the WEFni for a more aware or expert audience. In this regard, methodological transparency is key. Further developments in the WEFni ecolabel could include the provision of more detailed information through online channels (e.g., by using a QR code) about the outcomes and methodological procedures of the four individual footprints. In this regard, it is important to bear in mind that the aims and limitations of composite indicators should be presented alongside where the scores come from, what do they mean and what are the limits of their usefulness or interpretability (Barclay et al., 2019).

Since the WEFni methodology implemented in the seafood sector can be applied also to different food products, this should be adapted to the particularities of each foodstuff. In this regard, one of the main aspects to be modified would be the "food" pillar within the WEF nexus (i.e., NF). To do this, the NRF12.2 index used for the seafood products could be modified by adding or disregarding certain nutrients to better assess the nutritional profile of products under evaluation. However, it is also possible that certain aspects of the food pillar may be approached from the point of view of ensuring food security in terms of productivity. This perspective was addressed in the case of a WEFni proposal applied to dairy farms, where a milk yield indicator was considered (Entrena-Barbero et al., 2023c). Likewise, it is important to take into consideration that the population is not exclusively nourished by seafood products purchased at points of sale (supermarket, groceries, etc.). Therefore, this WEF nexus thinking should be extended to different food items that are consumed, as well as in other forms of food consumption such as those out-of-home: meals and menus related to the HORECA (Hotels, restaurants and catering) channel.

To address the WEF nexus perspective, there are numerous methodologies to represent in both a qualitative and quantitative manner depending on the objective. Among them, concept maps or causal loop diagrams can be considered to represent at abstract level the interconnections within a WEF nexus system, while other modelling can be applied in the case of quantitative results, such as agent-based and input-output modelling (Sušnik et al., 2022). In this paper an LCA was followed, which stands out from other methodologies for the holistic quantification of environmental burdens related to the interrelationships of the nexus by considering the resources consumed throughout the life cycle of a product (Mannan et al., 2018).

Notwithstanding, the choice of approaching an LCA has in turn certain limitations related with methodological assumptions. Some are related with the management of by-catch from fisheries.

While some case studies considered them as co-products and used mass allocation procedures to assign the corresponding environmental loads to them, others treated these as waste (output) without clarifying their fate, which should be noted as a limitation when making comparisons and interpreting results. In terms of data limitation, gaps related to non-available specific inputs were filled by using the best available generic or extrapolated data from feasible sources. The geographical and temporal coverage is also considered to generate some deviations in the general guidelines, for instance certain hypotheses or modelling assumptions could be considered obsolete. This again signals that the proposed guidelines should be kept up to date. Another key aspect is the FU selected. Being 1 kg of seafood captured does not address the nutritional quality of seafood products (FAO, 2021). The study of how the nutritional characteristics could modify the results obtained has been addressed through a sensitivity analysis in which the CC, as well as EP of each species were integrated under the basis of an RSI.

As regards environmental impact assessment, although global warming (CF), water scarcity (WF) and energy requirements (EF) have important interrelations with food security, some other impact categories have been left out of the scope of the study. For the case of seafood products, it is relevant to include the ecological status of fishing grounds and its associated biodiversity loss. In this concern, new LCA impact categories have been proposed as, for example, one that quantifies ecosystem quality for fisheries based on several key aspects such as relative biomass, growth rate and biotic resource depletion (Hélias et al., 2023). In addition, it would also be interesting to include the impact associated to plastic leakage along the supply chain of seafood, that occur during fishing activities (fishing gear loss), transportation (tyre particle loss) and processing and end-of-life (plastic packaging loss) (Loubet et al., 2022). Such integration would enable to discriminate different fishing methods associated with various fishing gear loss, different packaging or end-of-life options for fishing gear and packaging (Schneider et al., 2023).

Lastly, to broaden the focus of the WEFni towards a sustainability point of view, as it only considers the environmental pillar, the addition of socio-economic indicators would be important. Examples of the above that apply to the seafood sector include human and labour rights, economic viability, and ethics criteria (e.g., animal welfare). Some are already included in certification schemes such as Friends of the Sea, Naturland Sustainable Capture Fishery of Marine, and Aquaculture Stewardship Council (International Trade Centre, 2023).

4. Conclusions

In the current climate emergency situation, reducing the environmental impacts of food production systems is key to reach climate goals and ensure global food security. Therefore, a good option would be to modify dietary patterns by opting for foods with low environmental burdens and high nutritional profiles, such as blue food. To facilitate this task, many ecolabels exist on the market for seafood products, but most focus on a simple environmental indicator and it is crucial to consider multiple interrelations. For this purpose, the WEFni methodology was applied to a series of case studies in the European Atlantic area. From the results obtained, it can be concluded that the WEFni makes each case study more easily interpretable, as they are influenced by numerous particularities such as fishing gear, target species, location or processing technique. In addition, general trends were found to allow the identification of fisheries, aquaculture or seafood processing practices that can be more recommendable from a WEF nexus perspective.

The results of the sensitivity analysis carried out showed that the WEFni was considerably modified, implying a reclassification of the fishing gear groups, as well as for the processing types, while for aquaculture systems, some improvement was identified for fish farming compared to shellfish farming. This therefore suggests that, on the one hand, a re-evaluation of the chosen mass FU may be necessary, as the FU_{ce} has led to a better definition of the true function of seafood production systems: to meet the recommended daily personal demand (i.e., the RSI), 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 equitable weighting of the individual indicators could also be reconsidered when obtaining a WEFni.

The outcomes provided in this paper may serve to apply the WEFni methodology to other case studies, thus expanding LCA studies on seafood products. Besides, In addition, with appropriate modifications that address the particularities of each sector, the WEFni ecolabel could be extended to other food products and distribution channels.

Acknowledgements

This research was supported by the EAPA_576/2018 NEPTUNUS project, supported by Interreg Atlantic area. Some authors belong to CRETUS and the Galician Competitive Research Group (GRC) ED431C 2021/37, co-founded by Xunta de Galicia and FEDER (EU). E.E.B. is funded by Xunta de Galicia PhD Grant (ED481A-2021/164). A.C.D. and P.Q. acknowledge FCT/MCTES for the financial support to CESAM (UIDB/50017/2020 + UIDP/50017/2020 + LA/P/0094/2020), through national funds, and to the research contracts CEECIND/02174/2017 and CEECIND/00143/2017, respectively.

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914