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RESEARCH ARTICLE

Energy and Environmental Performance of Nile Tilapia Processing Methods for a Circular Economy in the Fish Industry

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Abstract

The protein supply from fisheries has increased worldwide despite of a restricted use of sustainability metrics. Even though most studies focus on fish production, the processing and distribution stages influence significantly the performance indicators of the final products. This work evaluated the energy and environmental performance over the life cycle of Nile tilapia processed in methods for eviscerated, steak and fillet cuts and delivered to the retail market. The assessed categories were area occupation, water consumption, energy demand, global warming, acidification and eutrophication. The assessed categories' values were the lowest in the eviscerated cut, which increased 73-85% in steak and 111-130% in fillet. Even though the Nile tilapia production stage accounted for the highest contribution in the evaluated categories (81% to 99%), the distribution stage showed potential to increase the base scenario category values by up to 81 % in the sensitivity analysis of transport distance and mode. The allocation procedures are sensitive parameters for co-products. In this regard, the consumption of eviscerated fish was identified as a strategy to promote the circular economy of the food supply in a preventive manner.

Keywords Aquaculture · Processed Nile tilapia · Fish cut methods · Life Cycle Assessment (LCA) · Water-Energy-Food (WEF) Nexus

Highlights

- Energy and environmental performance of Nile tilapia cuts were assessed
- The fish production stage had the greatest impact on the final product
- Eviscerated fish performed favorably compared to steak and fillet cuts
- Transport distance and mode was relevant in the assessed indicators
- The allocation procedure was highly sensitive for the evaluated products

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1. Introduction

Animal protein from fisheries plays an essential role in human nutrition. The global consumption of animal protein from fish increased 3.1% on annual average between 1961 and 2017, while that of other protein sources grew 2.1% (FAO 2020). Aquatic animal foods provided 15% of animal proteins and 6% of all proteins in 2021 (FAO 2024a). In this regard, fish consumption per capita worldwide increased from 9 kg in 1961 to 20 kg in 2022 (FAO 2024a). Capture and aquaculture fisheries production reached 223.2 million tonnes, which represented USD 472 billion market in 2022 (FAO, 2024a). While the catch from fisheries has stabilized since the 1980s, the amount of fish from aquaculture has increased and accounted for 51% of total fish production in 2022, being essential to ensure that the global supply of fish keeps up with demand (FAO 2024b). This trend will likely continue during following years, as the production of fish from aquaculture is expected to increase by 10% till 2032, having a positive impact on the global food security (FAO, 2024b).

Fish production in Brazil reached 1359 000 tonnes, being 65% from aquaculture in 2024 (Brasil-MPA 2025). In this fish farming sector, Brazil produced 579 080 tonnes of tilapia in 2024, representing 65% of the national production (PEIXE BR, 2025). Regarding consumption, tilapia was the animal protein that grew the most in the last decade, rising from 1.47 kg/year to 2.8 kg/year per capita (PEIXE BR, 2025). On the global stage, Brazil is the fourth largest producer of tilapia, behind China, Indonesia, and Egypt, reinforcing this fish species' importance in the country (WEF, 2022; PEIXE BR, 2025). However, the expansion of aquaculture with conventional techniques has amplified its environmental impacts. Additionally, fish processing generates up to 75% losses of the entire organism in mass basis (Ling Wen Xia et al. 2024). These concerns have led to the proposal of guidelines for sustainable aquaculture (FAO 2025) and circular economy (Van Ewijk et al. 2023).

The fish supply chain is comprised by the stages of fish production, processing and distribution stages. Those stages are composed of farms, factories, warehouses, supermarkets and street markets before reaching the final consumer. Processing is key to add value to fish as it increases the shelf life of the final product and its market value. Tilapia fillet is the main processed product, surpassing whole gutted fish, steaks, and semi-finished products. However, the environmental performance of animal-based food production and animal co-product processing has a lack of attention compared to animal production (Germond et al. 2024). In this regard, evaluating fish processing methods' energy and environmental performance is essential to identify critical points and potential improvements in tilapia-based supply chain.

The question to be tackled in this research is which fish cut shows the largest energy and environmental burdens in the tilapia-based supply chain, supporting circular economy strategies in the fish industry. In this context, this study aimed to evaluate Life Cycle Assessment (LCA) indicators of processing methods for eviscerated, steak and fillet cuts of Nile tilapia and its distribution to the retail market. Co-products of the processing stage are typically used for fish meal and oil production. The assessment conducted a sensitivity analysis for the allocation procedure of products and co-products in the processing stage and for the transport distance and mode in the distribution stage. Thus, this assessment allows identifying critical points in the evaluated variables to support energy and environmental improvements. The main novelty of this assessment lies in the evaluation of the energy and environmental performance of different Nile tilapia cuts supply in the Brazilian context. Besides fulfilling the literature gaps in LCA of the Brazilian tilapia industry, the authors believe that the results of this study could be useful for this important and growing industry worldwide.

This research is structured as follows: this first section contextualize the growing fish industry with the key role of tilapia aquaculture, followed by the research question. The second section brings a theoretical foundation for LCA and circular economy in the fish industry, highlighting the lack of studies for fish farming downstream processes (i.e. processing and distribution). The third section explains the methods and data used in the evaluated scenarios of Nile tilapia cuts, along with the sensitivity analyzes conducted. The fourth section describes the results for the energy and environmental performance in the assessed indicators. The fifth section discusses the implications of these results compared to the consulted literature, covers challenges and opportunities for the fish industry circularity, and points research limitations and future work. At last, the sixth section summarizes the main conclusions and recommendations.

2. Theoretical framing

LCA is a widely used tool to assess the environmental burdens over stages of a product system (Van Ewijk et al. 2023). More specifically, it can be used to evaluate the energy and environmental performance of animal protein production (McLaren et al. 2021). On the other hand, circular economy promotes waste reduction, resource efficiency and environmental regeneration (Osei et al. 2025). In this regard, LCA supports the circular economy strategies in the fish industry (Hublin et al. 2024), diagnosing the main resource demands, waste generation and pollution sources. The environmental impact of a food product can vary up to 50 times among different producers (Poore and Nemecek 2018). Therefore, the decision-making for sustainable production and consumption must be supported by the assessment of the environmental burden of the fish products coming from each supplier.

Most fish LCA studies consider the upstream supply chain (up to the farm gate), but lack the assessment of the downstream chain (processes up to the retail market) as shown in a review of 59 LCA studies about seafood over 20 years (Ruiz-Salmón et al. 2021). Literature on the post-farming stages in fish LCA for processing and distribution are scarce (Abdou et al. 2017). In this context, transportation has been identified as one of the main factors contributing to the environmental impact of fish products (Bohnes and Laurent 2019), which depends on the energy source, distance and mode (Harini et al. 2025). Also, allocation procedure can influence significantly the environmental burdens of fish processing products and co-products (Dominguez Aldama et al. 2023). Therefore, these gaps were covered in this study for Nile tilapia cuts supply chain.

3. Material and methods

3.1. Scope definition

The attributional LCA was used in this study based on ISO-14040/44 standards (ISO 2006) to assess the energy and environmental performance of processed and distributed Nile tilapia of 1200 g per fish in different cuts. A declared unit of mass of distributed product was used in this study to support consumer decision-making instead of a functional unit due to differences in product composition for each Nile tilapia cut. The reference flow is 1 t (tonne) of processed and distributed fish in eviscerated (TE), steak (TS) and fillet (TF) cuts. The extent of the product system was from the farm to the retail market gate, which covered the Nile tilapia production, processing and distribution stages in the evaluated scenarios (Figure 1).

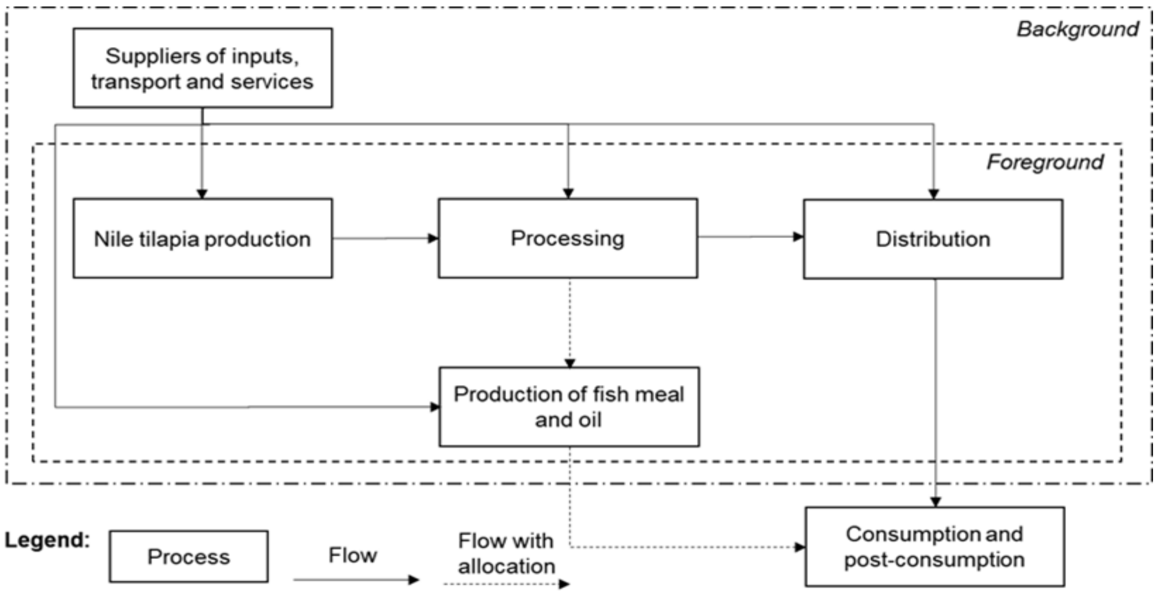

Figure 1. Product system of processed and distributed Nile tilapia. (The fish co-product downstream processing to produce fish meal and oil was disregarded in the base scenario of the main product (eviscerated, steak and fillet cuts)).

3.2. Life cycle inventory

The foreground inventory for the production stage was obtained from a previous work (Petroski et al. 2024), which represented a tilapia farm in Redenção da Serra-SP, Brazil, while that for the processing stage was obtained from a questionnaire applied to the fish processing unit of Lago Dourado Aquaculture (12° 30' 31" S and 39° 8' 46" W) in Cabaceiras do Paraguaçu-BA, Brazil, in 2019. Even though the collected data for Nile tilapia production and processing were from different places, it was assumed that these stages are located in the same place due to common practices in the fish industry. The distribution stage was estimated to cover the transportation and freezing. The foreground inventory of the Nile tilapia production stage covers the processes for producing fingerlings, rearing juvenile fish in a cage, fattening adult fish in a cage and harvesting adult Nile tilapia. The annual production of harvested Nile tilapia on the farm was 2 700 t from 2016 to 2017 (Petroski et al. 2024).

The foreground inventory of the Nile tilapia processing stage covers the processes for reception of live fish, purification, desensitization, bleeding, classification, washing, cutting to produce eviscerated, steak and fillet cuts and freezing (Table 1). The Nile tilapia filleting yield depends on fish weight, body composition, sex, anatomical characteristics (head:trunk ratio), filleting method, operator skill and process mechanization level. The fillet yield in relation to the fish gross weight (the term 'weight' in this article refers to a mass unit) varies from 28% to 33% with an average of 31%. In comparison, the remaining parts of the fish weight are 36% in head and viscera, 8% in skin, 22% in bones and 3% in feces (Pereira and da Costa 2012). Thus, a 76% mass yield was considered in eviscerated cut (whole fish with skin and scales), 41% in steak and 33% in fillet (de Souza et al. 2005) for the main product, while the remaining fish mass was considered co-products. These Nile tilapia processing co-products were used in fish meal and oil production, which are high-value ingredients for fish, swine, dog and cat feed production. The process subdivision allocation procedure (cutoff criteria) was used to consider the total energy and environmental burden for the main product. Furthermore, the infrastructure, electricity, water, transport, ice and wastewater parameters were estimated in the processing stage proportionally to the mass of harvested Nile tilapia input.

Table 1. Foreground inventory of the Nile tilapia processing and distribution stages for 1 t of cut fish per type.

Parameter	Unit	Nile tilapia cut		
		Eviscerated	Steak	Fillet
Processing				
Input				
Infrastructure	p	1.1×10^{-6}	2.1×10^{-6}	2.6×10^{-6}
Electricity	kWh	0.1	0.2	0.3
Potable water	m^3	2.8	5.3	7.2
Harvested Nile tilapia	t	1.3	2.4	3.0
Transport, pick-up truck [a]	t.km	39	73	90
Ice [b]	t	1.3	2.4	3.0
Output				
Processed Nile tilapia	t	1.0	1.0	1.0
Co-products of Nile tilapia	t	0.3	1.4	2.0
Wastewater, treatment	m^3	4.1	7.7	10
Distribution				
Input				
Processed Nile tilapia	t	1.0	1.0	1.0
Transport, refrigerated truck [c]	t. km	500	500	500
Electricity [d]	kWh	459	459	459
Infrastructure	p	1.7×10^{-6}	1.7×10^{-6}	1.7×10^{-6}
Output				
Processed and distributed Nile tilapia	t	1.0	1.0	1.0

Evaluated scenarios for processed and distributed Nile tilapia (each with 1 200 g at harvesting) per cut type: eviscerated (TE); steak (TS); and fillet (TF). Piece (p). [a] The transport distance was 10 km, which transported only ice one way of the trip and the harvested Nile tilapia and ice on the way back, totaling 20 km traveled distance (round trip); [b] 1 m^3 of potable water and 5 kWh per Mg of ice were considered; [c] The refrigerated transport distance was 250 km, which resulted in a traveled distance (round trip) of 500 km; [d] Two freezers of 0.5 m^3 each over 4-6 months.

The road transport with ice for the harvested fish was from the fish farm to the slaughterhouse, while the refrigerated road transport was from the slaughterhouse to the retail market. The foreground inventory of the Nile tilapia distribution stage covers the processes for refrigerated transport of Nile tilapia cuts (final product), freezer infrastructure for product storage and freezer electricity (Table 1). This study did not consider product packaging due to its potential negligible contribution to the environmental impacts (Bremenkamp et al. 2024).

The fish processing co-product was utilized in fish meal and oil production. At this stage, the reference flow was 1 tonne of Nile tilapia co-product input to produce two products: fish meal and fish oil. The foreground inventory of fish meal and fish oil production (Table 2) was obtained from the same questionnaire filled in by a production technician in 2019 (personal communication). The production of fish meal and fish oil uses the same process before separating the solid and liquid phases, which results in the production of fish meal and fish oil, respectively. The allocation procedure by process subdivision was disregarded in this stage as in Fréon et al. (2017). Each tonne of co-product input is converted into 0.13 tonne of fish meal and 0.09 tonne of fish oil. Therefore, the mass allocation procedure for energy and environmental burdens was done in this stage, resulting in a mass allocation factor of 59% for fish meal and 41% for fish oil.

Table 2. Foreground inventory of fish meal and fish oil production stage for 1 t of Nile tilapia co-products to be processed.

Parameter	Unit	Fish meal and oil
Input		
Infrastructure	p	0.63
Electricity	kWh	0.05
Water, groundwater	m^3	0.16
Co-products of Nile tilapia	t	1.0
Transport, refrigerated truck [a]	t. km	20
Antioxidant	t	0.001
Heat, wood burned	MJ	5 234
Output		
Evaporated water	m^3	0.74
Fish meal	t	0.13
Fish oil	t	0.09
Wastewater, treatment	m^3	0.31

Piece (p). [a] The refrigerated transport distance was 10 km, which resulted in a traveled distance (round trip) of 20 km.

The foreground inventory of the evaluated stages comprises operation phase data primarily obtained from the producer. These were complemented with a theoretical estimation, while those for the construction and maintenance phases of the infrastructure were obtained from similar processes in the ecoinvent™ database. The background inventory of the Nile tilapia product system covered the supply chain of material and energy inputs, transport, infrastructure, and waste management (Table S.1 and Table S.2 of the Supporting Information). The databases used in the background inventory were ecoinvent™ version 3.6 (Moreno-Ruiz et al. 2019) and Agri-footprint® version 5.0 (Van Paassen et al. 2019).

3.3. Evaluated categories

The foreground inventory was inserted into the SimaPro® software, version 9.1.1.7, to assess the environmental aspects and impacts of the processed and distributed Nile tilapia. The evaluated categories, units and methods were area occupation in m^2.year with the Selected LCI Results version 1.04 (Frischknecht et al. 2007), water consumption in m^3 with the ReCiPe 2016 midpoint – Hierarchist version 1.1 (Huijbregts et al. 2017), energy demand in MJ with the Cumulative Energy Demand (CED) version 1.11 (Frischknecht and Jungbluth 2003), global warming in kg CO_2eq with the IPCC 2013 – GWP 100 years version 1.03 (IPCC 2013), acidification in kg SO_2eq and eutrophication in kg PO_2^{3-}eq with the CML-IA baseline version 3.06 (Bruijn et al. 2002).

The environmental burden assessment for food products typically cover area occupation, water consumption, energy demand, global warming, acidification and eutrophication categories (Hala et al. 2024).

Area occupation consists of the areas used in different processes such as the supply chain of fish feed, fingerling and juvenile production, cage in the dam lake for Nile tilapia production, slaughterhouse for fish processing, fish meal and oil factory, and the retail market. Water consumption represents the water uptake with no return to the original water body, such as the water evaporated in the supply chain processes (i.e. irrigated agriculture and input manufacturing), cages in the water body, and the fish meal and oil processing in a factory. The energy demand covered the primary energy used and incorporated into the supply chain of inputs and services from varied sources and efficiencies. Furthermore, the IPCC, CML and ReCiPe methods are used to assess global warming, acidification and eutrophication in fish LCA studies (Ruiz-Salmón et al. 2021). Therefore, this study covered the most used assessment methods in the consulted literature.

3.4. Sensitivity analysis

Two sensitivity analyses were conducted in this study. One sensitivity analysis was defined for the Nile tilapia fillet distribution stage to consider different distances and transport modes. The following distances and transport modes, respectively, in the distribution stage of TF were evaluated: 250 km road transport (TF-RT250km – base scenario), 2 500 km road transport (TF-RT-2500km), 10 000 km maritime transport (TF-MT-10000-km), 20 000 km maritime transport (T12000g-F-MT-20000km), 8 000 km air transport (TF-AT-8000km), 16 000 km air transport (TF-AT-16000km). An additional road transport of 50 km was considered in the maritime and air transport scenarios. Furthermore, the distance traveled was twice the transport distance to represent a round trip.

Another sensitivity analysis was defined to identify the influence of the allocation procedure, considering the mass allocation (MA), economic allocation (EA) and cutoff criteria (CC) (process subdivision) on the energy and environmental burdens of the evaluated scenarios. The allocation factors were applied in the foreground inventories for fish processing and fish meal and oil production stages to partition the energy and environmental burdens among the products of each stage. The allocation factors for products and co-products, respectively, of the processing stage were: 76% and 24% in TE, 41% and 59% in TS, and 33% and 67% in TF in MA; 100% and 0% in TE, 99% and 1% in TS, and 99% and 1% in TF in EA; and 100% and 0% in TE, TS and TF in CC. The allocation factors for fish meal and fish oil of the meal and oil production stage were: 59% and 41% in MA; and 32% and 68% in EA, respectively. The energy and environmental burdens were allocated to the main product and co-products as a function of the mass in MA and the price in EA. In contrast, the entire energy and environmental burden was allocated only to the main product in CC.

4. Results

4.1. Evaluated categories

The energy and environmental performance of processed and distributed Nile tilapia in eviscerated, steak, and fillet cuts are shown in Figure 2. Area occupation increased by 130% from TE to TF (Figure 2a). The largest contribution in the area used was the production stage of Nile tilapia, which was 99% in the evaluated scenarios. Water consumption increased by 111% from TE to TF (Figure 2c). The production stage of Nile tilapia was responsible for the highest water consumption with 81-88% in the evaluated scenarios. Energy demand increased by 123% from TE to TF (Figure 2e). The production stage of Nile tilapia accounted for 90-93% of the energy demand in the evaluated scenarios.

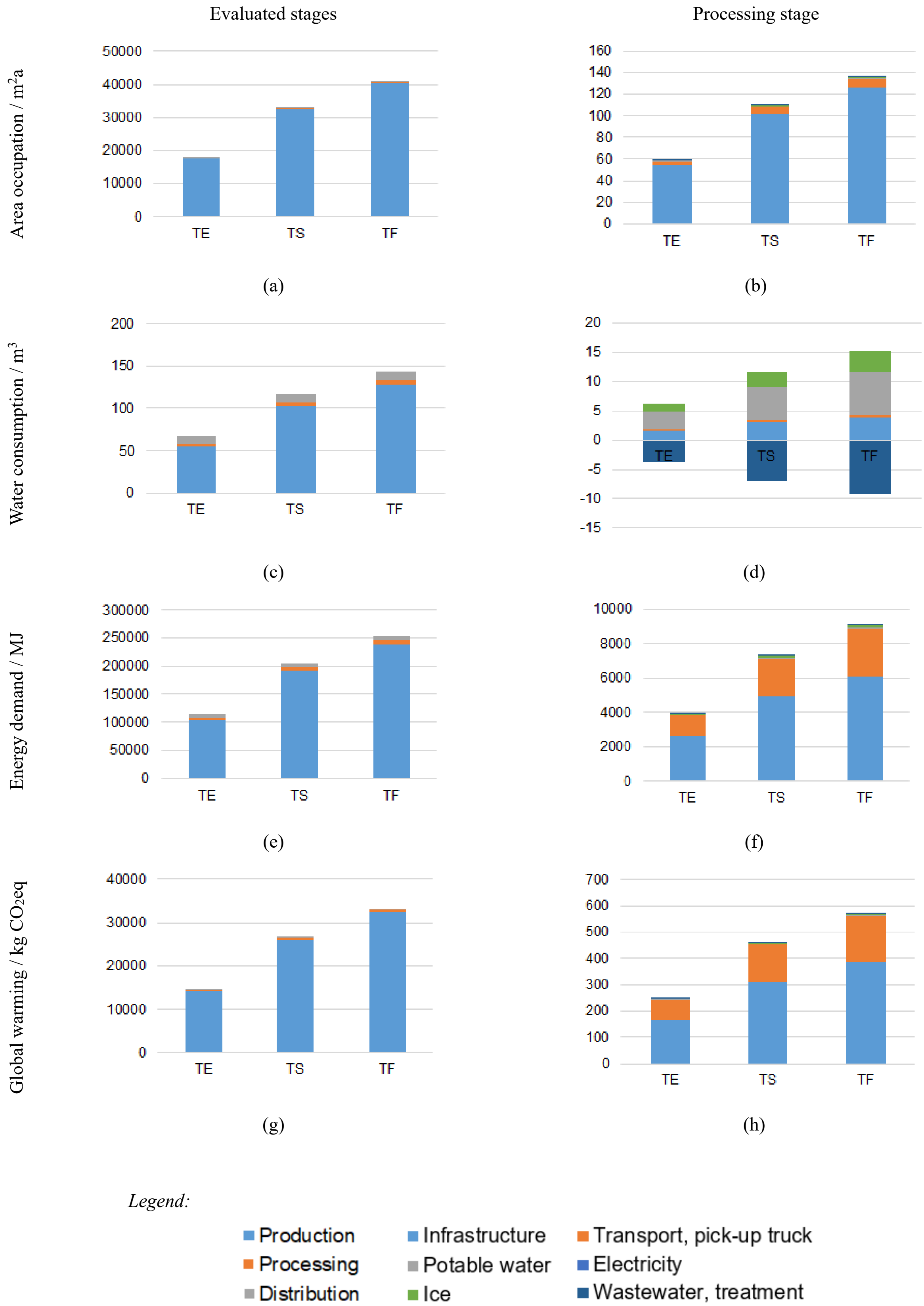

Figure 2. Performance comparison and contribution for 1 t of Nile tilapia processed and distributed per cut type in the evaluated categories. (Evaluated scenarios for processed and distributed Nile tilapia (each with 1 200 g at harvesting) per cut type: eviscerated (TE); steak (TS); and fillet (TF))

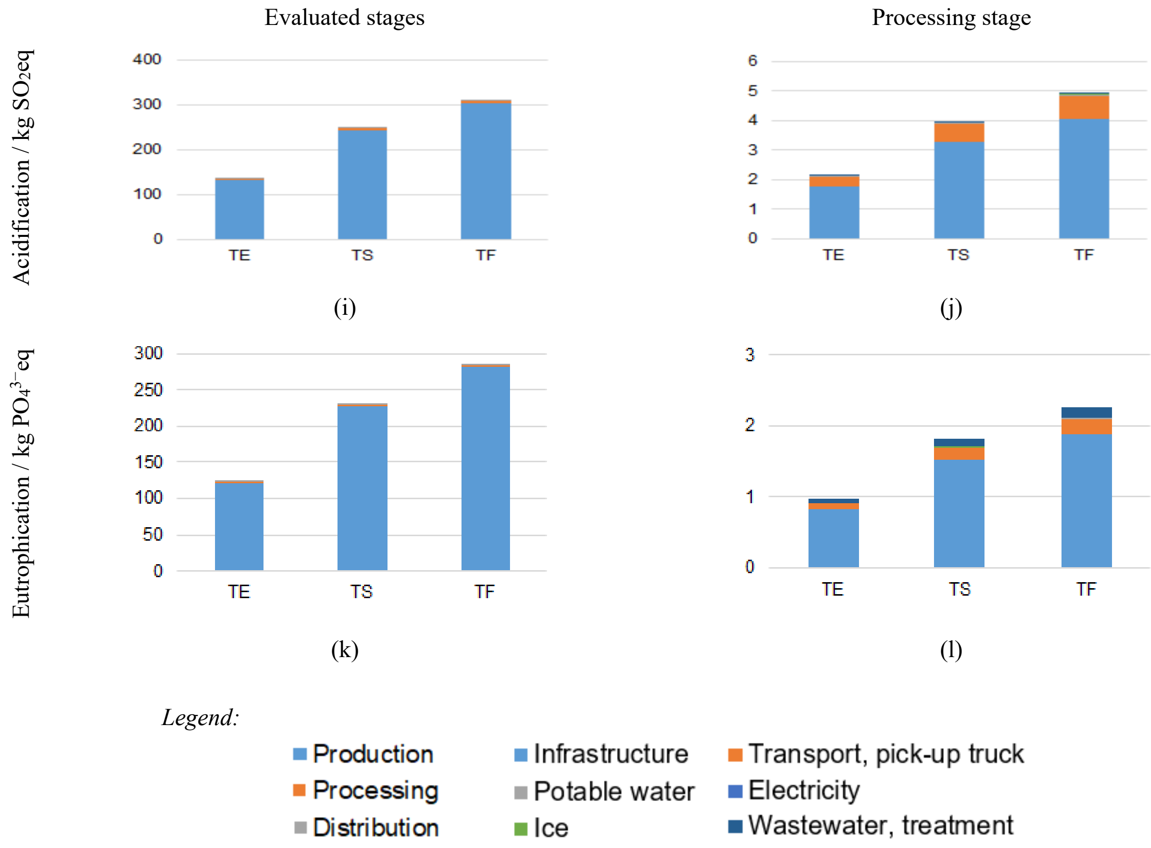

Figure 2 (cont.). Performance comparison and contribution for 1 t of Nile tilapia processed and distributed per cut type in the evaluated categories. (Evaluated scenarios for processed and distributed Nile tilapia (each with 1 200 g at harvesting) per cut type: eviscerated (TE); steak (TS); and fillet (TF))

Global warming increased by 127% from TE to TF (Figure 2g). Nile tilapia's production stage was responsible for 96-97% of this in the evaluated scenarios. Acidification increased by 129% from TE to TF (Figure 2i); the production stage of Nile tilapia was also responsible for 97% in the evaluated scenarios. Eutrophication increased by 130% from TE to TF (Figure 2k); again, it was the production stage of Nile tilapia that was accountable for 98-99% in the evaluated scenarios.

The comparison and contribution analysis of the Nile tilapia processing stage for different cuts (eviscerated, steak and fillet) were presented to identify the critical energy and environmental performance points. Area occupation increased by 130% from TE to TF and infrastructure accounted for 92-93% of this (Figure 2b). Water consumption increased by 134% from TE to TF (Figure 2d). In the processing stage, this was the potable water. However, the water returned to the water body from the wastewater processing stage is regarded as a credit. Energy demand increased by 131% from TE to TF (Figure 2f) and infrastructure was responsible for 66-67% of this in the evaluated scenarios.

Global warming, acidification and eutrophication increased by 131% each from TE to TF (Figure 2h, Figure 2j and Figure 2l, respectively). The largest contribution was infrastructure with 66-67% in global warming, 82% in acidification and 83% in eutrophication in the evaluated scenarios. However, it is worth mentioning that the generic inventory *Chemical factory, organics {GLO}| market for | Cut-off, S* of the ecoinvent™ database was used for infrastructure to cover the absence of local data, which has a high uncertainty level (Table S.1 of the Supporting Information).

4.2. Sensitivity analysis

The sensitivity analysis of the distribution stage was considered for different transport distances and modes (Figure 3). The area used in the base scenario was slightly changed in the sensitivity analysis scenarios (Figure 3a). The water consumption increased by 2% in TF-RT-2500km and 4% in TF-AT-16000km compared to the base scenario (Figure 3b). The energy demand of the base scenario increased by 11% in the TF-RT-2500km, 40% in the TF-AT-8000km and 81% in the TF-AT-16000km (Figure 3c). Global warming increased by 6% in TF-RT-2500km, 20% in TF-AT-8000km and 41% in TF-AT-16000km compared to the base scenario (Figure 3d). The acidification increased by 3% in TF-MT-20000km, 8% in TF-AT-8000km and 17% in TF-AT-16000km (Figure 3e). The eutrophication increased by 1% in TF-AT-8000km and 3% in TF-AT-16000km (Figure 3f). The values for energy demand and global warming categories showed the largest increases in the transport sensitivity analysis of the distribution stage in TF.

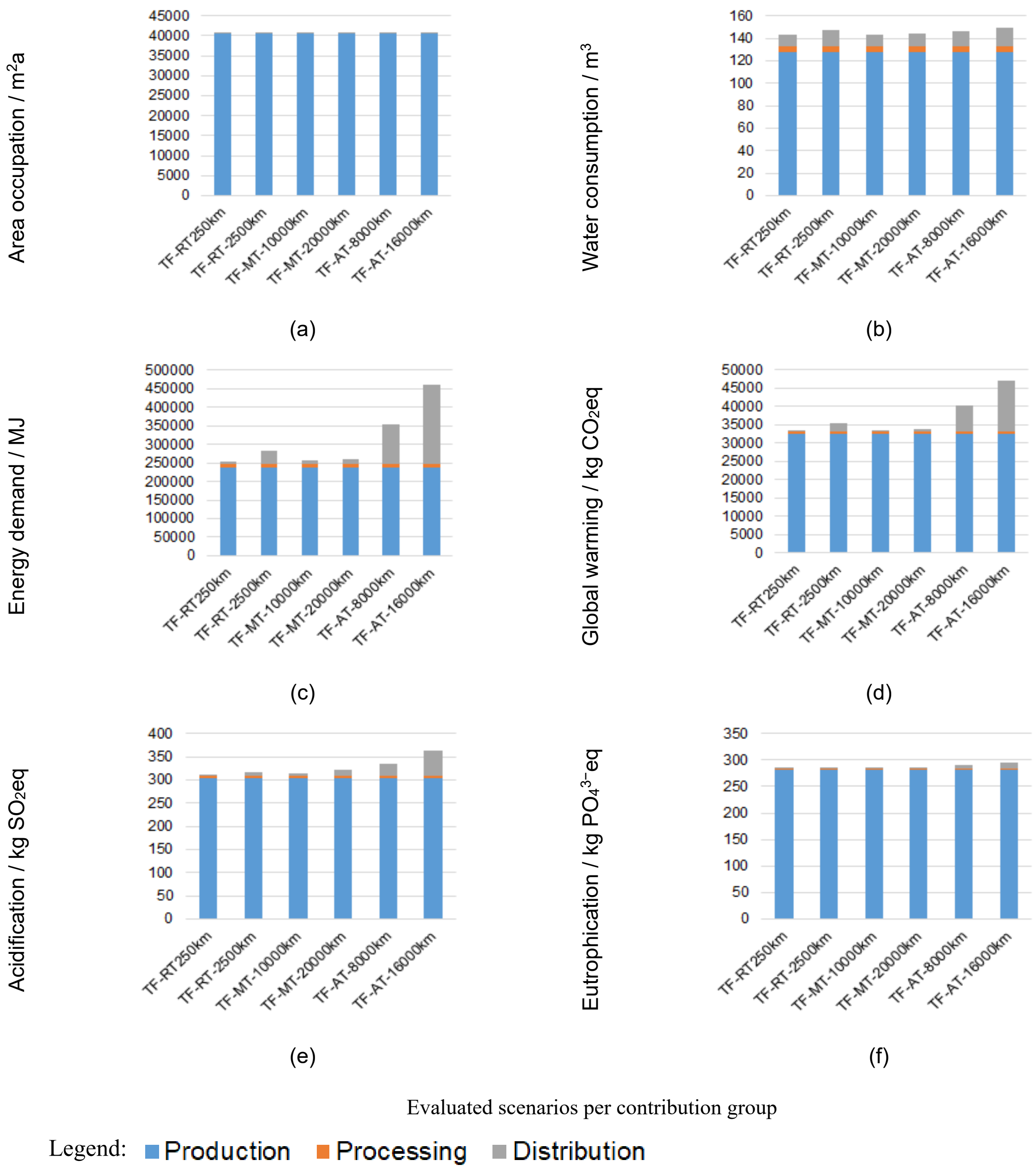

Figure 3. Sensitivity analysis of the performance comparison and contribution for 1 t of processed and distributed Nile tilapia in fillet (TF) in the evaluated categories with different transport distances and modes in the distribution stage.

(Sensitivity analysis scenarios: 250 km road transport (TF-RT-250km – base scenario), 2 500 km road transport (TF-RT-2500km), 10 000 km maritime transport (TF-MT-10000km), 20 000 km maritime transport (TF-MT-20000km), 8 000 km air transport (TF-AT-8000km), 16 000 km air transport (TF-AT-16000km). An additional road transport of 50 km was considered in the maritime and air transport scenarios.)

The sensitivity analysis of the allocation procedure is presented in Table S.3 of the Supporting Information. The energy and environmental burdens of the Nile tilapia cuts were higher in the cut-off criteria (base scenario), in which the entire energy and environmental burden was allocated to the main product, followed by economic allocation and mass allocation. However, the energy and environmental burdens of fish meal and fish oil were smaller with the cut-off criteria allocation procedure, in which no energy and environmental burdens were included in the co-products, followed by the economic allocation and mass allocation. Furthermore, fish meal's energy and environmental burdens decreased with the change from mass allocation to economic allocation due to the higher fish oil unitary price, which is 3 times that of the fish meal. Therefore, the allocation procedure significantly influenced the energy and environmental performance of the fish-based products in the evaluated scenarios.

5. Discussion

5.1. Energy and environmental performance

The processing stage yield of Nile tilapia cuts was 76% for eviscerated fish, 41% for steaks and 33% for fillets, the latter near the range for tilapia fillet 28%-32% in Brazil (Nunes et al. 2023). Tilapia fillet showed high energy and environmental burden in the analyzed categories. The reason for that is the low utilization of the whole fish in the fish processing into fillets, which generated more losses compared to eviscerated fish. Given this, fish processing factories should implement adequate technology to increase their product yield, promoting the circular bioeconomy and environmental protection. For instance, fish co-products can be used in industrial production of different products with applications in aquaculture, agriculture, food, cosmetics, chemical, biomedical and pharmaceutical industries (Sarkar et al. 2023). It was found that the production stage of Nile tilapia was responsible for the most significative contributions in all evaluated categories (Figure 3). Tilapia production in pond was inventoried considering infrastructure, water, fertilizer, feed, electricity and phosphorus and inert nitrogen emissions for Latin America and Rest of World regions (Avadí and Vázquez-Rowe, 2019). The ED and GW ranged 68 000-85 000 MJ and 3 600-5 400 kg CO_2eq, respectively, per tonne of harvested fish, which are comparable to those considered in this study (78 000 MJ and 10 000 kg CO_2eq) using the same software and methods. According to Pelletier and Tyedmers (2010), the environmental impacts of tilapia were higher in the production than in the processing and distribution stages. That is congruent with the results reported in this work. To mitigate these impacts, it is proposed that improving performance in the evaluated categories might include the use of ingredients from cleaner sources in the feed production and efficiency increase in the feed consumption. These practices were also indicated by Petroski et al. (2024).

The energy demand of frozen tilapia fillet produced in earth ponds in Indonesia from cradle to the factory gate showed that aquaculture and processing stages contributed 70% and 23%, respectively, and the feed contributed 92% in the aquaculture stage (Pelletier and Tyedmers 2010). These energy demand contribution values differ from the results of this work, in which the production and processing stages accounted for 91-94% and 3-4%, respectively. Regarding the lack of tilapia LCA literature, the discussion was expanded for the broader context of fisheries. In this regard, Farmery et al. (2015) reported that shrimp processing accounted for the largest contribution in water consumption, 16 m^3/t of shrimp which represented 76% of the total, while shrimp capturing contributed only 10% for the water consumption. In this work, the water consumption of the processing stage was 10 m^3/t of tilapia fillet, equivalent to only 4% of the water consumption, while the production of Nile tilapia represented 81-89%. This shows the high contribution variation in the upstream processes of the processing stage in water consumption for comparing fishery capture and farming. In fish processing, it is important to emphasize that one of the critical points is the cleaning of the refrigerator, which contributes up to 40% of the total water consumption. Improved water efficiency practices, such as cleaning with scrapers and compressed air, and pre-immersion of equipment in cleaning solutions to increase contact time for hygienization, along with monitoring water use, updating equipment's, process-line automation and water recycling can significantly reduce this consumption (Murali et al. 2021).

In the distribution stage of the processed Nile tilapia, the sensitivity analysis indicated long-distance air transportation as the most environmentally impactful, followed by road transport; sea transport had the smallest impact, in line with the findings of Pelletier and Tyedmers (2007). Farmery et al. (2015) found that the global warming for the transport of tiger prawns (shrimps) exported from Australia to Japan was 13 600 kg CO_2eq/t shrimp by air and 330 kg CO_2eq kg/t shrimp by sea freight. In contrast, the global warning of the product sold in Australia was 19 kg CO_2eq/t shrimp for 100 km and 770 kg CO_2eq/t shrimp for 4 000 km transport by refrigerated truck for retail. In this regard, the use of high-load means of transport, cleaner energy sources (i.e. electric vehicles, hybrids and biofuels), and emission regulations are required to reduce global warming in the fish distribution stage.

The conversion rates of co-products into fish meal and fish oil vary according to the fish biometrics (body condition score) and environmental conditions. Fréon et al. (2017) estimated the conversion ratios of 4.2:1 for fish meal and 21:1 for fish oil. In our study, those conversion rates were at 7.6:1 and 11:1, respectively. These conversion rates become more relevant when the main energy source comes from fossil fuels for cooking, drying and evaporation (Fréon et al. 2017) and the upstream environmental burdens are allocated at the processing stage for fish co-products (Table S.3 of the Supporting Information).

The sensitivity analysis of the allocation approaches showed a variation of 2.5 times between the extreme values of the evaluated categories for fish meal and fish oil, for which the allocation factors were 84% and 16% in the mass basis, 34% and 66% in the gross energy content basis and 50% and 50% in the economic basis, respectively, according to Fréon et al. (2017). Mass allocation, which results in the same energy and environmental burdens for fish meal and fish oil when expressed by the reference flow (e.g. 1 tonne of product), appears to be less realistic as fish oil production requires the harvesting and processing of five times the quantity of fish meal. The allocation factors of fish meal and fish oil production in this study were 59% and 41% respectively in the mass basis and 32% and 68% in the economic basis. However, the economic allocation factor is more likely to vary due to market price changes than to the mass allocation factors.

5.2. Fish industry circularity

Aquaculture has improved in feed efficiency and fish nutrition over the last two decades (Naylor et al. 2021), although fish waste generation and pollution should be reduced to promote the circular economy in this industry. The fillets are the most traded Nile tilapia cuts globally, but they are also the ones that generate the largest volume of waste. Waste prevention should be prioritized by achieving a higher fillet yield, above 35% of live weight (Bergman et al. 2020). Diversifying processing methods and encouraging the consumption of this fish formats such as steak and eviscerated cuts is another strategy to increase the environmental sustainability of the tilapia industry.

Waste generated by fish processing, especially for fillet cut, should be managed to increase its value based on circular economy strategies. The underused tilapia biomaterials can be converted into food and other products: heads and bones can be used in food fortification products (e.g. fish cakes, sausages and bread); skin can be processed into clothing and leather artefacts; gelatin from fish skin can be developed into edible films and coating; collagen from fish scales and bones has application in cosmetics and pharmaceuticals; viscera can be converted into silage and hydrolysates, which are sources of peptides and enzymes; any remaining parts can be transformed into products for animal consumption, fuel or fertilizer (Peñarubia et al. 2023). Methods like fermentation, anaerobic digestion, enzymatic hydrolysis, and thermal processing are key drivers for the fish industry circular economy (Olagoke-Komolafe and Oyeboade, 2025).

Even though the sustainability pressure on the aquaculture industry improved the governance, technology, siting, and management in many cases (Naylor et al. 2021), the widespread adoption of these technologies is limited by infrastructural and regulatory deficiencies, lack of technical expertise, and market engagement and investment (Olagoke-Komolafe and Oyeboade, 2025). Therefore, the involvement of all stakeholders in the governance of the fish industry is crucial to take advantage of the opportunities for circular economy and sustainability in the aquaculture sector.

5.3. Research limitations and future work

This work focused on fish processing and distribution. Fish packaging was disregarded, although it can be relevant for aluminum, tinplate, and glass compared to plastic and paper (Almeida et al. 2022). The downstream processes such as fish products and co-products consumption and post-consumption stages should be covered in full product system evaluation. The allocation procedures for multifunctional processes can be further explored, such as system expansion and energy allocation for fish and co-products processing (Dominguez Aldama et al. 2023). In addition, complete inventories and emerging assessment methods support the evaluation of more categories such as human toxicity and biodiversity loss. Furthermore, economic and social indicators should be considered in a broader sustainability assessment of the fish industry (Garlock et al. 2024).

6. Conclusion

Eviscerated Nile tilapia has the lowest burden in area used, water consumed, energy demand, global warming, acidification and eutrophication categories compared to tilapia steak. In contrast, while tilapia fillet had the highest energy and environmental burdens. The production stage in aquaculture is responsible for most of this, especially due to feed production and consumption. Therefore, any energy and environmental improvement in the fish industry should consider identifying and implementing a feed supply from clean sources and use efficiency standards to reduce the energy and environmental burdens in tilapia farming.

The sensitivity analysis for transport in the distribution stage was considered to identify markets' energy and environmental performance over longer distances in different transport modes. It was found that the area occupation was kept the same, while the remaining categories varied by 2%-81% in the evaluated scenarios. The scenario with a 16 000 km distance (round trip) in air transport significantly impacted water consumption, energy demand, global warming, acidification and eutrophication compared to the base scenario with 250 km distance in road transport. Therefore, the production and consumption of eviscerated Nile tilapia distributed by sea is a strategy that can reduce the energy and environmental burdens of the tilapia-based food supply.

The upstream fishery resource demand is driven by the lower fish processing yield. In this regard, a circular economy approach policy for producing higher added value co-products is required to enhance the sustainability of this growing industry. In addition, there should be incentives to produce and process fish in places closer to the consumer market. This will help to reduce the energy and environmental burdens in the distribution stage. For such, fish industry governance by stakeholders' involvement is fundamental for implementing technology and management practices to promote more circular and sustainable supply chains.

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Authors' Contributions LPSP: designed the questionnaires for producers and the company, performed data interpretation and Life Cycle Assessment (LCA) calculations, drafted the initial manuscript, and contributed to its revision. DLM: interpreted the LCA data and contributed to the writing of both the initial and final manuscript versions. TFI: contributed to the manuscript final version writing and revision. ASS: contributed to the manuscript final version writing and revision. LVOV: supervised the project, inferred LCA data applied to aquaculture, and contributed to the writing and revision of the manuscript.

Data Availability The corresponding author's data supporting this study's findings are available upon reasonable request.

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Declarations

Competing Interests The authors declare that they have no competing interests.

Ethics Approval This study did not require ethical approval as it did not involve live animals or human participants. Data were obtained from secondary sources and industry questionnaires. The research focused solely on the energy and environmental performance of Nile tilapia processing using Life Cycle Assessment (LCA).

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