

Article

Valorization of Fishery and Aquaculture Wastes in Madeira Archipelago: Addressing Challenges and Opportunities

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Abstract

Fish processing generates substantial quantities of by-products, creating important management and valorization challenges, particularly in insular regions. This study provides a first-order quantification of fishery and aquaculture wastes in the Madeira archipelago. The methodology combined a feed-based mass-balance model, targeted data collection, stakeholder analysis, and valorization assessment. Organic matter (OM) released from marine cage aquaculture was estimated at approximately 851.6 t yr^{−1} (dry weight), while fish by-products from processing activities in factories and retail stores generated approximately 938 t yr^{−1} (wet weight). These waste streams differ substantially in their physical characteristics and management pathways, with aquaculture producing diffuse environmental discharges and processing activities generating concentrated and potentially recoverable residues. Structured stakeholder interviews identified limited scale and insufficient raw materials, logistics and labor as the main factors affecting valorization initiatives. A comparative multi-criteria assessment further evaluated potential valorization strategies based on environmental performance and economic viability. Despite the generation of organic residues, the results suggest that effective valorization is constrained less by total waste generation than by biomass fragmentation, logistical limitations, and restricted economies of scale, emphasizing the need for integrated circular management approaches. A combined approach, integrating farm usage of decaying OM from cage systems and locally supported valorization strategies is required to transition towards a more resource-efficient production system.

Keywords: fish by-products; value chain; decaying organic matter; by-product valorization; circular economy; Madeira archipelago



Academic Editor: Tim Gray

Received: 10 June 2026

Revised: 15 July 2026

Accepted: 21 July 2026

Published: 24 July 2026

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1. Introduction

Global production of aquatic food products (including algae) was 223.2 million tons in 2022, keeping its growth in response to two phenomena driving market demand: a continuous rise in population and improving incomes [1]. Fishery landings have maintained constant figures since the mid-1990s; thus, increases in fish production have been made at the expense of aquaculture. Over 70% of the total fish caught undergoes processing before reaching consumers [2], generating substantial quantities of fish by-products of up to 80% of the raw material depending on the species and processing method [3–5] (Figure 1).

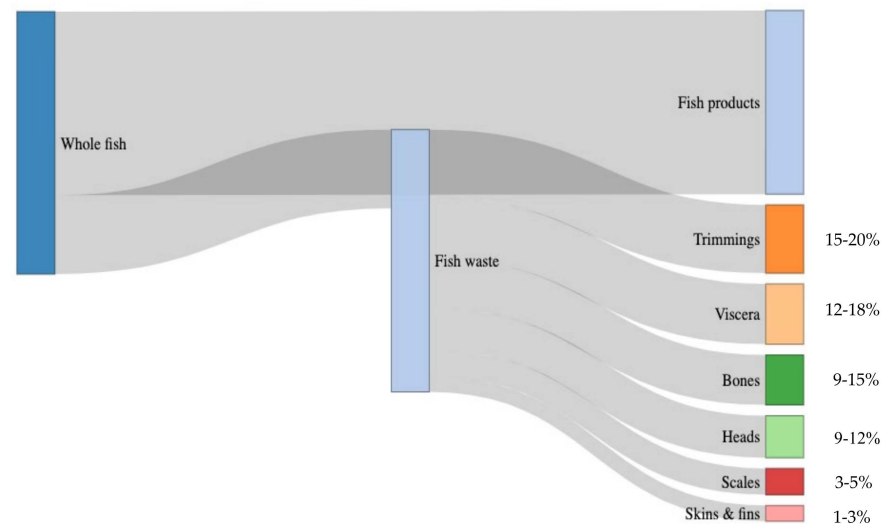


Figure 1. Relative proportions of fish by-products (%) generated during fish processing. The proportion of each fraction varies according to species, processing method, and final product type. Data compiled from published ranges [6–11].

Within this study, we conceptualize the primary independent variables—species and processing methods—as primary determinants of both the quantity and composition of the generated by-product fractions. The entire process—from capture and on-board handling to landing, transportation, transformation, and manufacturing—is inherently difficult [2,12,13]. Advanced equipment, technologies, and streamlined procedures across the industry are necessary to maintain by-product quality and perform its transformation [4,14,15].

Moreover, each by-product possesses distinct characteristics that render it suitable for specific applications. Framing this within the principles of a circular economy, this study views by-products not as waste, but as valuable feedstock for alternative production systems. This shift transforms the economic model from large-scale “mass exploration” to produce composting, energy, fishmeal and oil for animal feeds, to “low-volume exploration” for specialized, high-value items for the pharmaceutical, cosmetics, food and nutraceutical industries [16,17]. Furthermore, valorization fosters job creation and stimulates economic development, particularly benefiting coastal communities reliant on fishing and aquaculture for their livelihoods [18].

Effective waste management is a critical challenge for small insular regions like Madeira (Eastern North Atlantic), exacerbated by its peripheral location, limited land availability, and a fluctuating population due to tourism [19–22]. Addressing these challenges requires specific strategies tailored to insular contexts, which often grapple with logistical constraints including limited land area for processing facilities, logistical complexities due to geographical isolation and dispersed waste sources, a smaller scale of operations leading to less consistent waste volumes, and sometimes a lack of specialized technical expertise [23].

Madeira’s fishing sector is mainly concentrated on pelagic migratory tuna (*Thunnus* spp.) and skipjack species (*Katsuwonus pelamis*), and the deepwater black scabbardfish (*Aphanopus* spp.), which together account for more than 80% of catches and revenue [24]. In addition, the aquaculture industry has expanded over the past 30 years, primarily focusing on offshore production of gilthead seabream, *Sparus aurata* [25].

Central to local and export markets, these species generate by-products. Tuna is sold fresh, frozen, or processed (loins, belly, steaks, dry salted skipjack), black scabbardfish mainly as filets and frozen boneless cuts, and seabream mostly whole or eviscerated/fileted.

Although current by-product volumes are moderate, projected aquaculture growth highlights the need for circular, sustainable processing to reduce waste and recover value.

Understanding and optimizing the management and valorization of fishery and aquaculture wastes in the Madeiran context is not merely an environmental imperative but also a strategic economic opportunity. However, no integrated baseline assessment has yet distinguished between diffuse aquaculture-derived organic matter and recoverable terrestrial fish by-products in Madeira, nor examined how these streams interact with stakeholder perceptions, regular management, and feasible valorization pathways. Consequently, this study aims to evaluate and characterize the types and volumes of fishery and aquaculture wastes generated across the archipelago. Furthermore, it discusses sustainable waste management strategies within the context of a circular economy and micro-logistics challenges, ultimately identifying new economic opportunities and proposing the development of value-added products. To achieve this, the study adopts a dual-stream framework distinguishing between diffuse marine emissions and concentrated terrestrial residues, thereby enabling integrated assessment of management constraints and valorization pathways.

2. Materials and Methods

2.1. Study Area

The Madeira archipelago is an autonomous region of Portugal in the northeastern Atlantic, located about 900 km southwest of mainland Portugal and 600 km west of the African coast (Figure 2). Considered a biodiversity hotspot [25], it comprises the Madeira, Porto Santo, Desertas, and Selvagens Islands. Madeira and Porto Santo islands are the only populated islands, while the Desertas and Selvagens Islands are uninhabited protected areas legally classified as Nature Reserves and included in the Natura 2000 network as both Special Areas of Conservation (ZEC/SACs) and Special Protection Areas (ZPE/SPAs) [26]. The archipelago has approximately 250,000 inhabitants [22,25], mainly concentrated along Madeira's southern coast (including the capital, Funchal), and tourism represents one of its main economic activities, accounting for about 28.8% of regional GDP [27].

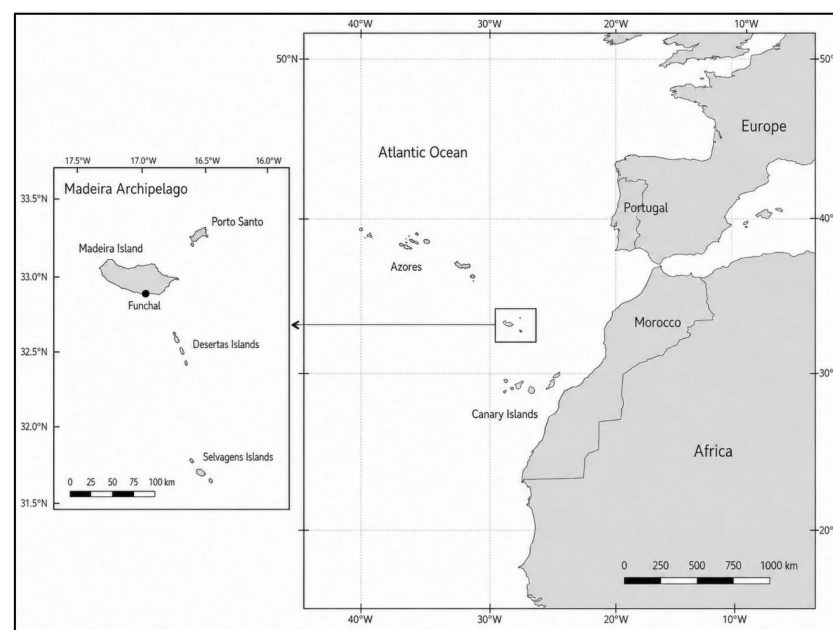


Figure 2. Map of the study area, showing its geographic location in the Northeast Atlantic and its relative position to mainland Europe and Northwest Africa.

2.2. Literature Review and Statistical Data Collection

To gather baseline information, a structured bibliographic review was conducted using Google Scholar, Scopus and Web of Science. The review was designed as a structured narrative search rather than a systematic review or meta-analysis, since its purpose was to support baseline quantification and contextual interpretation. The search workflow followed three sequential steps: (i) the identification of peer-reviewed and gray literature using predefined search terms; (ii) screening of titles, abstracts and keywords for thematic relevance; and (iii) full-text assessment of documents addressing fish by-products, aquaculture organic matter discharge, valorization of fish by-products, circular economy strategies, waste-to-energy, nutrient recovery, integrated multi-trophic aquaculture (IMTA), or waste management in insular regions. Local newspapers were also consulted for regional contextual information (search made in the *Jornal da Madeira* and *Diário de Notícias* on 20 November 2025). The final search equation was adapted to the syntax of each database and combined the following terms: (“fish waste” OR “fish by-product” OR “seafood by-product” OR “fisheries waste” OR “aquaculture waste” OR “organic matter discharge”) AND (“valorization” OR “valorisation” OR “circular economy” OR “waste management” OR “nutrient recovery” OR “waste-to-energy” OR “biogas” OR “integrated multi-trophic aquaculture” OR “IMTA” OR “mass balance model”) AND (“island*” OR “insular” OR “small island*” OR “Madeira” OR “Macaronesia”).

Furthermore, a targeted search was performed on official fisheries and aquaculture statistics from the Regional Directorate of Statistics of Madeira (DREM), Madeira Government, covering the 2022–2024 period. These data were subsequently compiled and analyzed to quantify regional fishery and aquaculture production trends.

2.3. Fish By-Product Quantification and Stakeholder Assessment

To quantify fish processing waste, a targeted data collection approach was adopted due to the lack of aggregated regional statistics. The sampling frame included major fish processing facilities ($n = 6$) and supermarket chains with fresh fish sales ($n = 2$), encompassing numerous stores in the archipelago ($n = 30$). Small-scale retailers and fishmongers were excluded due to their comparatively limited contribution and lack of systematic reporting. The identity of companies providing primary data was kept confidential under non-disclosure agreements.

To complement the quantitative assessment, stakeholder perceptions regarding fish waste management and valorization constraints were collected through structured interviews conducted via email. Interviews involved directors and CEOs from four companies representing the principal solid waste management operators in the Madeira archipelago, including entities responsible for handling fish by-products. All identified operators were contacted, and all provided responses, resulting in four company-level interviews/responses ($n = 4$; corresponding to 100% coverage of the identified fish by-product management firms in Madeira). Therefore, the consultation covered the full population of licensed operators identified for this activity in the region.

All stakeholders were asked the same set of predefined questions to ensure consistency and comparability between responses. Initial contact and clarifications were conducted in person, by telephone or by email, depending on respondent availability. However, to ensure traceability and documentary evidence, the corresponding answers of the enquiry were provided in writing via email. The interview protocol consisted of five open-ended questions addressing: (i) whether the company collects and/or processes fish by-products; (ii) the main factors affecting fish by-product management in Madeira; (iii) the existence of additional valorization pathways, such as fishmeal, oil extraction, organic fertilizers or biofuels; (iv) the perceived feasibility of establishing a dedicated regional valorization unit;

and (v) possible measures to improve the current management framework. Contributors were informed of the purpose of the consultation, and no personal, sensitive, confidential, or individually identifiable information was included in the manuscript. All information is presented in aggregated or non-identifiable form. To improve procedural transparency and reproducibility, the quantitative data used in the analyses are summarized in Supplementary Table S1, while the structured stakeholder interview protocol is provided in Supplementary Table S2.

Responses were subsequently converted into ordinal scores ranging from 0 (none) to 4 (high), reflecting the perceived relevance or importance attributed to each factor by stakeholders. The scoring system was based on the frequency of convergence between operators: when the same issue or constraint was identified by all four stakeholders, the factor received the maximum score of 4; factors identified by three, two, or one stakeholders received scores of 3, 2, and 1, respectively. This aggregation approach enabled semi-quantitative comparison of stakeholder perceptions by translating recurrent qualitative responses into comparable ordinal values [28]. Results were represented using a radar chart.

2.4. Estimation of Organic Matter Production from Aquaculture and Sensitivity Analysis

Organic matter (OM) production from aquaculture was estimated by a simplified feed-based mass-balance approach following the framework of Lupatsch and Kissil [29]. In contrast to full nutrient budget models [30], the present approach focuses on total organic matter outputs due to the absence of detailed feed composition data. Feed input was partitioned into retained biomass, uneaten feed, and fecal losses, with OM calculated as the sum of uneaten feed and feces. OM outputs were calculated as follows:

$$OM = F \cdot [u + (1 - u)(1 - ADC_{DM})] \quad (1)$$

where F is feed input, u is the uneaten feed fraction, and ADC_{DM} is the dry matter digestibility. All values are expressed annually as dry weight.

Farm-specific inputs, including annual feed supply and mean feed conversion ratio (FCR), were obtained from aquaculture operators in Madeira and represent average production conditions over the last three years. Data were provided by Ilhapeixe, S.A. (Rui Gonçalves, *pers. comm.*) and Marismar, Lda. (Silvestre França, *pers. comm.*). The reported FCR values therefore reflect real commercial farming conditions. Following Findlay and Watling [31], Vassallo et al. [32] and Ballester-Moltó et al. [33], uneaten feed was assumed to be 3% (range: 2–5%), and dry matter digestibility (ADC_{DM}), which varies depending on feed formulation and ingredient quality, with higher values associated with highly digestible extruded diets [34,35], was set at 70% (range: 65–75%), consistent with commercial seabream diets. A sensitivity analysis was performed by varying u (2–5%) and ADC_{DM} (65–75%), while keeping other parameters constant [36].

3. Results

3.1. Fishery and Aquaculture Production in Madeira

Between 2022 and 2024, total fish production in Madeira averaged 5761 tons year^{−1}, generating approximately EUR 25.1 million year^{−1} (Table 1). Commercial fisheries accounted for about 75% of total production (4310 tons year^{−1}), while aquaculture contributed approximately 25% (1451 tons year^{−1}). Tuna and black scabbardfish dominated fishery landings (~90%), whereas marine aquaculture production consisted entirely of gilthead seabream [24]. Total production decreased from 6308 tons in 2022 to 4879 tons in 2024, while total revenue remained relatively stable.

Table 1. Total fish production and revenue between 2022 and 2024 in Madeira archipelago [24].

Year	Production (Tons)		Total Production (Tons)	Total Revenue (Millions of Euros)
	Fisheries	Aquaculture		
2022	4711	1597	6308	23,998,344 €
2023	4702	1395	6097	26,165,731 €
2024	3517	1362	4879	25,187,421 €
Mean	4310	1451	5761	25,117,116 €

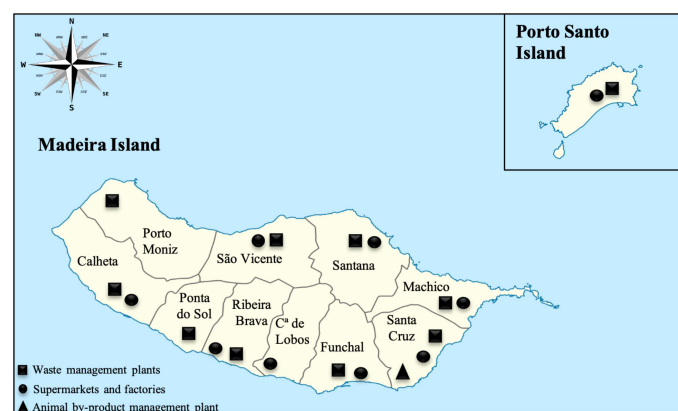
3.2. Fish By-Product Generation and Spatial Distribution

Total fish waste production averaged 938 tons year^{−1} over the study period, corresponding to a mean waste ratio of 16.6% relative to total fishery landings (Table 2). Annual waste increased from 837 tons in 2022 to 1.001 tons in 2024, despite declining total production. Aquaculture-derived processing waste was limited (1.7% of production) in the only vertically integrated operation. For the remaining production, waste was aggregated at processing facilities without source differentiation.

Table 2. Total fish production (including commercial fisheries and the aquaculture sector), fish waste production, and waste ratio in Madeira archipelago between 2022 and 2024 [24].

Year	Total Production (Tons)	Fish Waste (Tons; Wet Weight)	Waste Ratio (Fish Waste/Total Production)
2022	6308	837	13.3%
2023	6097	977	16.0%
2024	4879	1001	20.5%
Mean	5761	938	16.6%

Madeira's seafood processing sector is dominated by three major firms, concentrated along the south-southeast coast near the commercial harbors of Funchal and Caniçal and the airport in Santa Cruz. In parallel, regional waste is managed through Waste Processing and Transfer Plants (WPTPs) operated by ARM—Águas e Resíduos da Madeira, S.A., municipalities, and licensed private entities, where waste is sorted, packed, and directed to treatment pathways (Figure 3). Undifferentiated waste is ultimately sent to the Solid Waste Treatment Plant (SWTP), operated by ARM, for incineration with energy recovery, supplying approximately 5% of regional electricity production, with residual ashes disposed of in landfill [37].

**Figure 3.** Spatial representation of fish waste generation sources and waste management infrastructure in Madeira archipelago.

Figures 4 and 5 provide a detailed disaggregation of the data and illustrate the relationship between total fish production (5761 tons/year on average) in the archipelago and the corresponding amount of fish waste generated over the same period (938 tons/year). The seafood industry contributes substantially more than supermarkets (64% vs. 36%). While total production has declined over time (−22.7%), fish waste has increased (+19.6%).

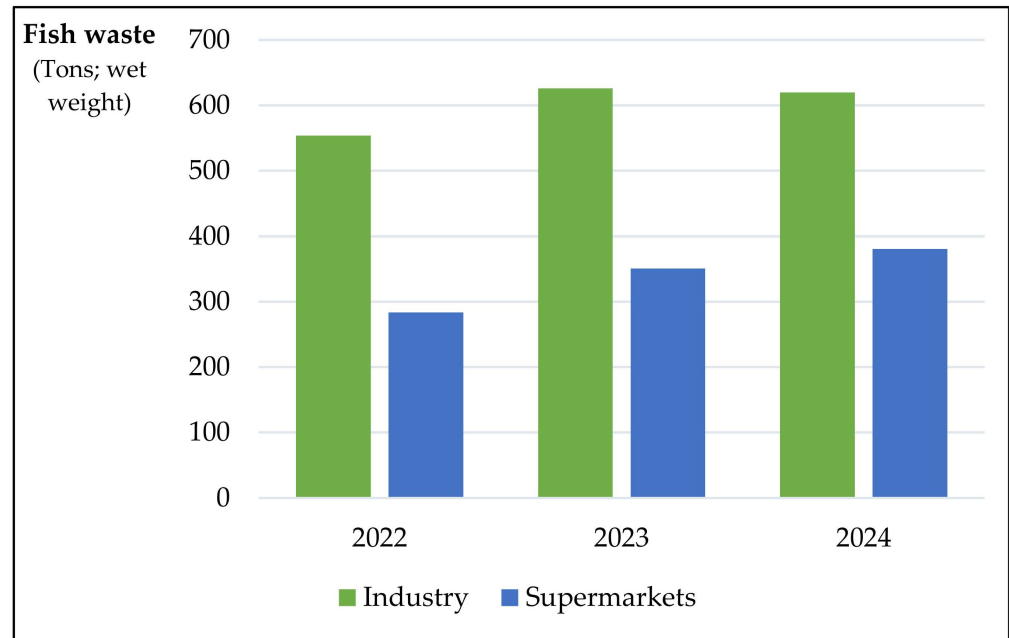


Figure 4. Production of fish waste (wet weight) from the 2022–2024 period in Madeira archipelago according to its origin: seafood industry and supermarkets.

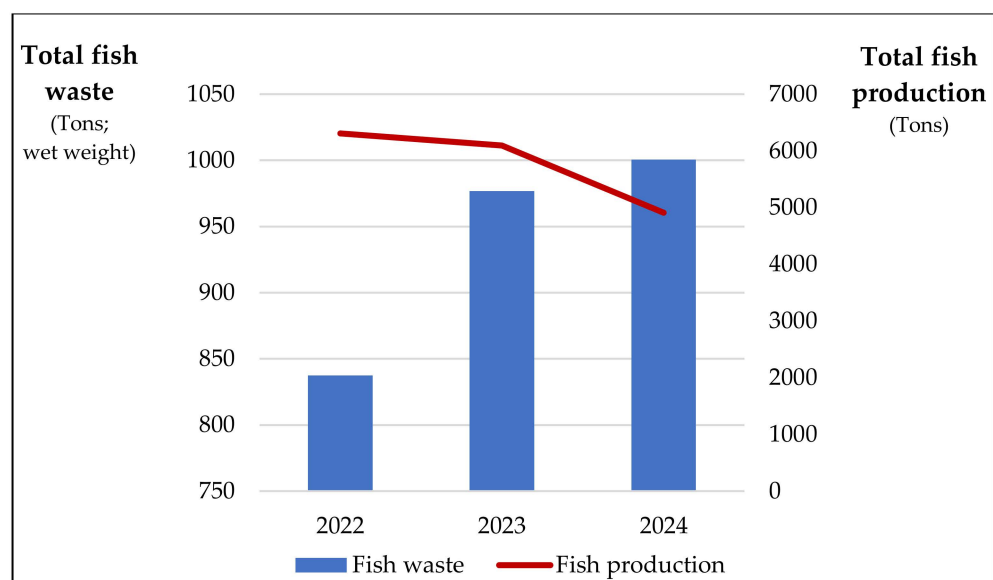


Figure 5. Total fish production and resultant by-products (wet weight) in the Madeira archipelago during the 2022–2024 period.

3.3. Organic Matter Production from Aquaculture

Using farm-reported feed inputs (2653 t yr^{-1}) and a mean FCR of 1.93, the estimated organic matter released to the environment was $8.516 \times 10^5 \text{ kg yr}^{-1}$ (dry weight). Of this total, approximately 9% corresponds to uneaten feed ($7.959 \times 10^4 \text{ kg yr}^{-1}$) and 91% to fecal material ($7.72 \times 10^5 \text{ kg yr}^{-1}$), as shown in Figure 6.

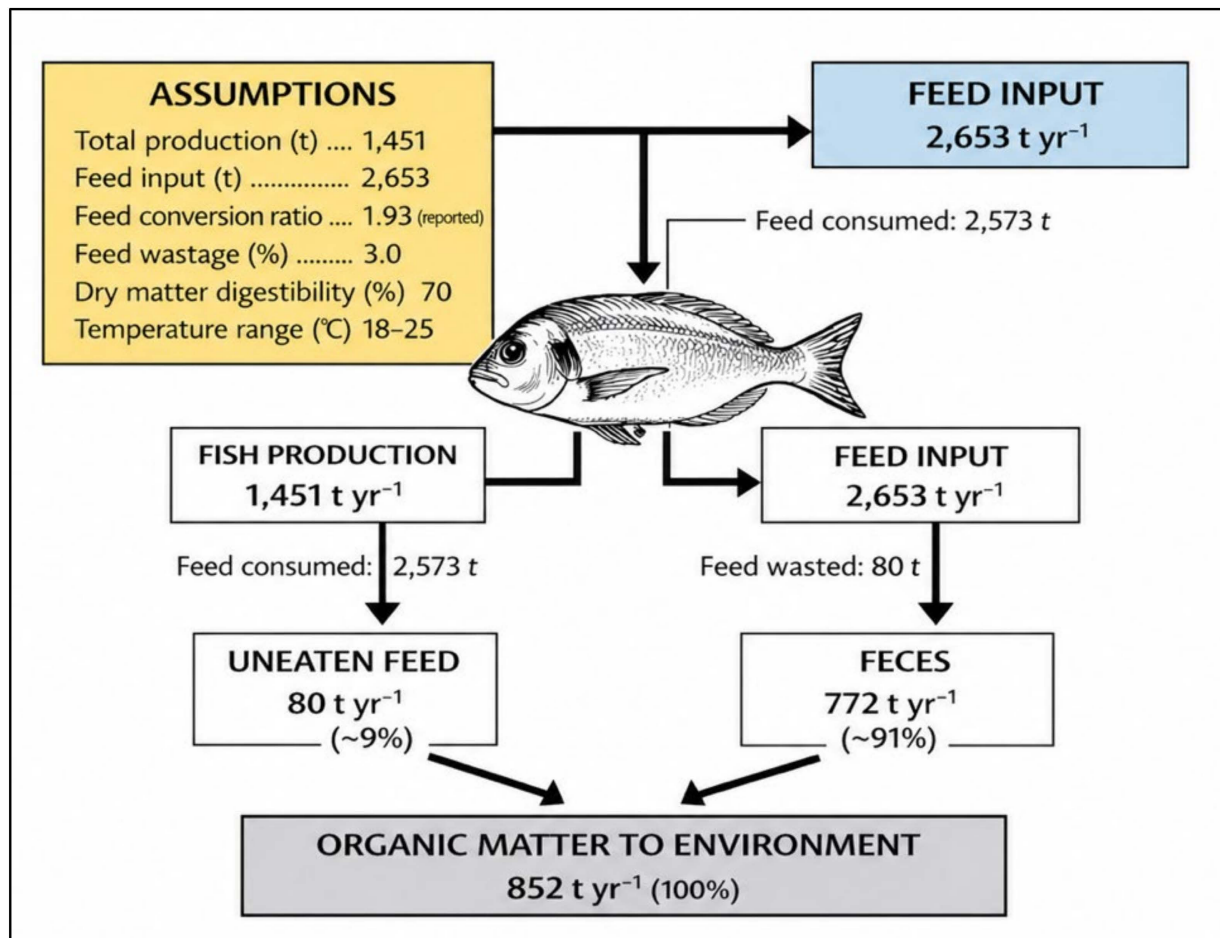


Figure 6. Mass-balance model of organic matter (OM, dry weight) produced by seabream fish farms in Madeira Island. Feed input and conversion ratio data were provided by local fish farming companies. Some represented values are rounded.

Table 3 exhibits sensitivity analysis of organic matter, with estimates ranging from 0.69×10^6 to 0.95×10^6 kg yr⁻¹, depending on assumed feeding losses and digestibility. The base scenario yielded 0.899×10^6 kg yr⁻¹ ($u = 0.03$; $ADC_{DM} = 0.70$), falling within the mid-range of model outcomes.

Table 3. Sensitivity analysis of organic matter estimates (dry weight).

Uneaten Feed (u)	$ADC_{DM} = 0.65$	$ADC_{DM} = 0.70$	$ADC_{DM} = 0.75$
0.02	0.92×10^6 kg	0.80×10^6 kg	0.69×10^6 kg
0.03	0.93×10^6 kg	0.85×10^6 kg	0.70×10^6 kg
0.05	0.95×10^6 kg	0.88×10^6 kg	0.73×10^6 kg

3.4. Stakeholder Perceptions on Fish By-Product Management

The radar chart in Figure 7 summarizes stakeholder perceptions regarding key factors influencing fish by-product management in Madeira. The highest scores with a unanimous response were associated with constraints related to a lack of scale and insufficient raw materials. Other management factors such as specialized labor, economic feasibility, logistics, and collection ranked second with three positive responses. Lastly, treatment, energy recovery, waste export and policy/strategy ranked third with just one positive response.

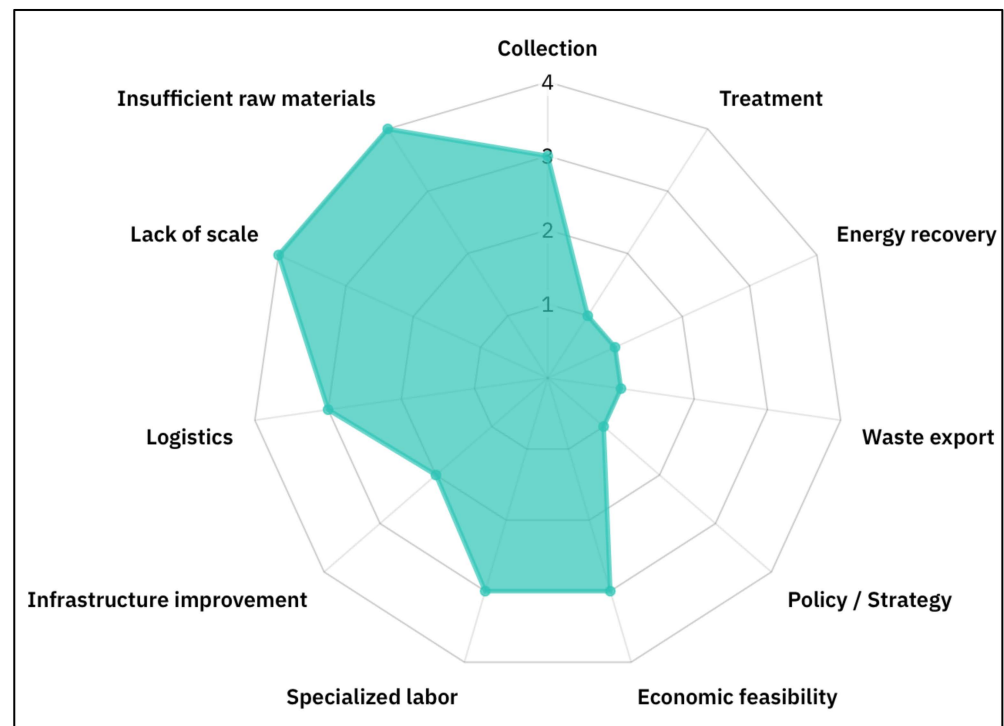


Figure 7. Perceived stakeholder (n = 4) importance of factors influencing fish by-product management and valorization pathways in the Madeira archipelago.

4. Discussion

4.1. Organic Waste Generated by Madeira's Fisheries and Aquaculture Activities

The present study provides a first-order quantification of organic waste associated with fish production and processing activities in Madeira, distinguishing between organic matter released directly into the environment by offshore fish farms and fish by-products generated within the value chain. Aquaculture systems were estimated to release approximately 851.6 t yr^{-1} of organic matter (dry weight) to the marine environment, corresponding to roughly 32% of total feed input. This reflects the combined influence of feed digestibility and production efficiency, with the relatively high FCR (1.93) contributing to increased waste outputs. The mean FCR observed in Madeira is higher than values commonly reported under optimized gilthead seabream production conditions, where FCRs below 1.6 have been documented [38], and falls within values frequently reported for well-managed Mediterranean cage farms, typically ranging between 1.7 and 2.2 [39].

Because floating cages represent an open production system, they are subject to natural hydrodynamic conditions that can transport uneaten feed and waste particles away from the site. Consequently, cage-based systems are generally more prone to feed losses than more controlled aquaculture operations [40]. In Madeira, offshore fish farms are situated along the south coast, typically several hundred meters from shore. Here, steep bathymetry provides rapid access to suitable depths while maintaining logistical proximity to essential land-based infrastructure [41]. Although these sites benefit from favorable oceanographic conditions and protection from prevailing northeast trade winds [42], they remain vulnerable to episodic extreme weather events from southern quadrants, such as storm Oscar which impacted Madeira in 2023 [43]. Offshore cage damage and fish escape episodes have been documented in Madeira [44]. Such disturbances may have temporarily reduced feeding efficiency, increased feed losses, and lowered biomass retention, thereby contributing to elevated FCR values. Accordingly, the reported FCR should be interpreted

as representative of real commercial production conditions rather than optimal farming performance, with direct implications for organic matter discharge.

In addition to environmental exposure, feeding practices also play a critical role in determining feed losses and overall production efficiency. Feeding regime—including ration size, feeding frequency, timing, and delivery methods—is directly related to feed utilization and the FCR [40]. In commercial gilthead seabream farming, feeding management commonly shifts with fish growth stage, with younger fish often managed under more controlled hand feeding practices before transitioning to automated delivery systems during grow-out. Transitional feeding periods between pellet sizes are also implemented to accommodate heterogeneous size classes and optimize feed acceptance. Pellet size is known to influence feeding behavior, digestibility, and feed waste in gilthead seabream [33], while chewing and pellet ejection may further increase losses during feeding [45].

4.2. Fish By-Products and Characteristics of Organic Matter Streams

In parallel to aquaculture-derived decaying organic matter, fish processing activities generate solid organic residues, including trimmings, viscera, heads, and other by-products [11], which arise from both wild-caught and farmed fish handled in supermarkets and processing facilities, and are calculated at approximately 938 t yr^{−1} (wet weight) for Madeira. These residues are generated at discrete locations, facilitating collection and valorization. As such, they represent a concentrated and potentially recoverable biomass stream, widely recognized as a valuable resource [4,12,46].

These waste streams differ in both their physical characteristics and management pathways. Aquaculture-derived organic matter is predominantly particulate and settles in the vicinity of cage systems, directly influencing benthic conditions [30]. In contrast, fish by-products are generated within the terrestrial system, where their recovery potential depends on effective logistics, infrastructure, and coordination [23,47]. This distinction is particularly relevant in island systems, where spatial constraints and fragmented infrastructure can limit efficient waste handling.

However, the terrestrial fish waste stream is not homogeneous. Fish processing facilities account for the largest share of generated residues (approximately 64%), largely due to industrial-scale transformation of large pelagic species, particularly tuna, which generate substantial amounts of by-products [5,16,48]. In contrast, supermarkets contribute approximately 36% of total fish waste generation and include the single largest individual by-product generator identified in this study. This highlights the substantial contribution of retail operations to regional fish waste production, previously pointed out by Caldeira et al. [49], Greggio et al. [50] and O'Donnell et al. [51]. Unlike factory-derived residues, supermarket waste is strongly influenced by perishability, prolonged display time in fish counters, and food safety compliance, which lead to the disposal of fish that is no longer suitable for sale [48,51,52]. The high contribution from retail outlets, therefore, reflects not only processing losses but also post-distribution wastage associated with direct consumer markets.

Consumer perceptions play a non-trivial role in this process: consumers often associate “never-frozen” fish with superior freshness, healthiness, and taste [53]. While this perception may hold for fish consumed immediately after catch in coastal settings, it is not necessarily valid for most commercially distributed fish. Proper handling and rapid freezing post-capture often yield fish quality comparable or superior to conventional iced storage. Research indicates that the combination of vacuum sealing and freezing is particularly effective at maintaining a product’s nutritional and sensory profile throughout the supply chain [51]. Nevertheless, retail environments often prioritize “fresh-on-ice” presentation to meet consumer expectations. As a result, products may be discarded earlier to maintain visual and perceived freshness standards, thereby increasing waste generation. The high

contribution from retail outlets therefore likely reflects not only processing losses but also post-distribution wastage associated with direct consumer markets and demand-driven quality perceptions. A potential mitigation pathway, as stated by O'Donnell et al. [51] and Neff et al. [53], includes shifting consumer preferences toward high-quality frozen fish, which could reduce unnecessary discard and improve overall supply chain efficiency.

Our results show that although total fish production in Madeira has declined in recent years, by-product generation has increased. The total by-products generated by the industry, at 600 tons/year, are significantly higher than the 175 tons/year previously estimated for Madeira and less than a third reported for the Azores Archipelago (Portugal), where a robust tuna canning industry exists [54]. This apparent mismatch may be explained by external sourcing. A substantial fraction of Madeira's fishery production is associated with variable resources, particularly tuna [24,25]. Moreover, local fish factories process imported fish, while supermarkets increasingly commercialize imported wild and farmed fish species, reflecting the globalization and diversification of seafood supply chains [1,48]. Consequently, fish waste generation within the archipelago is influenced not only by local production, but also by imported biomass entering regional processing and retail chains. By contrast, the by-products generated by processing aquaculture fish produced in Madeira appear negligible, contributing only an estimated 1–2% of total fish waste. This reflects the limited scale of local onshore processing associated with aquaculture operations, since the sector's primary waste output remains the organic matter released directly to the marine environment [29,30].

4.3. Spatial Organization and Fish By-Product Management Factors

Spatial organization further influences fish by-product management pathways. Madeira's seafood processing sector is concentrated along the south and southeast coast, located near the commercial harbors of Funchal and Caniçal and the airport in Santa Cruz, facilitating both product distribution and raw material supply [25]. In parallel, regional waste infrastructure includes waste management plants distributed across the archipelago, where waste is received, sorted, and directed to treatment pathways, with non-recyclable fractions sent for incineration with energy recovery [37]. This infrastructure provides a logistical foundation for future valorization initiatives, although its current configuration may not be specifically adapted for dedicated fish by-product recovery. Internal heterogeneity within fish waste streams contributes to biomass fragmentation—a challenge well-documented in previous studies [12,23,47]. This seems to represent the primary driver of stakeholder concerns regarding economies of scale, raw material consistency, and collection logistics.

Our findings indicate that lack of scale and insufficient raw materials are perceived as major factors in dealing with fishery by-product residues, reflecting the limited volumes generated inland. In addition, intermediate scores for logistics and economic feasibility further indicate that, while opportunities exist, their implementation depends on overcoming infrastructural and organizational barriers. Lower scores associated with treatment capacity, energy recovery, and policy strategy indicate a low extent of implementation, highlighting the current limitations in local processing capabilities and reinforcing the view that existing systems are not yet adapted to efficiently convert fish by-products into value-added products. Although total waste is 938 t yr^{-1} (wet weight), its spatial fragmentation and temporal variability likely reduce effective aggregation, supporting stakeholder perceptions of insufficient scale. These results do not directly quantify waste but rather highlight the operational and structural conditions under which waste is currently managed in Madeira. Similar observations have been previously reported [10,12,55], stating that the volume and steadiness of raw material supply are key in sustaining a valorization process. As such, stakeholder insights complement the quantitative estimates by identifying the key

factors affecting implementation and are consistent with the limited integration of circular economy practices.

Overall, the results indicate that the organic waste produced by the fishing and aquaculture industries is characterized by a dual structure: diffuse environmental discharges from offshore fish farms and value chain fish by-products. These define the operational conditions under which effective waste management and valorization strategies must be developed.

4.4. Strategies to Enhance Waste Management and Promote Valorization

The magnitude of organic waste generated highlights a clear opportunity where waste streams are re-integrated as valuable resources. In the context of Madeira, this is particularly relevant given the insular nature of the region and the limited capacity for waste disposal. Following the assessment of organic waste streams from the fishery and aquaculture sectors, several realistic strategies have been identified to enhance management and promote valorization. The following analysis explores the environmental and economic implications of each approach.

4.4.1. Strategy 1: Waste-to-Energy (Biodiesel and Biogas)

This strategy focuses on converting organic discards, such as offal, into renewable energy. From an environmental perspective, this approach significantly mitigates climate change by reducing reliance on imported fossil fuels and lowering greenhouse gas emissions through the production of carbon-neutral biofuels. Furthermore, it provides a robust solution for waste volume reduction, which is critical for an island like Madeira where landfill space is finite, by diverting organic matter from landfills. This strategy also prevents issues such as leachate contamination and methane leaks from uncontrolled decomposition [56,57].

Economically, waste-to-energy enhances energy security and provides a stable, local power source that shields the island from volatile global fuel prices. The production of biogas also yields a nutrient-rich digestate that can be sold as biofertilizer, fostering a circular economy. However, these benefits are countered by high capital investment costs and the technical complexity of building and maintaining specialized reactors. There is a significant risk regarding feedstock consistency; if the supply of fish waste is too dispersed or irregular, as in the case of Madeira, the facility may become economically unviable or inefficient. Additionally, there is an “opportunity cost” to consider, as converting high-quality organic matter into low-value energy may be less profitable than extracting specialized compounds for the pharmaceutical or cosmetic industries.

4.4.2. Strategy 2: Nutrient Recovery

Nutrient recovery emphasizes the capture and reuse of organic matter to create agricultural inputs or integrated farming systems. Fish-based fertilizers typically contain high concentrations of essential macronutrients, such as N, P, and Ca, often in quantities that align with or exceed the agronomic demands of crop plants [46]. Some of the most important macronutrients required by the main crops in Madeira Island are N, K, P, Ca, Mg and S [58–60].

Environmentally, this strategy is highly effective at preventing nutrient runoff—specifically nitrogen and phosphorus—from entering coastal waters, thereby reducing the risk of harmful algal blooms and hypoxia. Techniques like integrated multi-trophic aquaculture (IMTA) promote farming species like seaweed and shellfish in the vicinity of fed fish farms to naturally filter the water from excess nutrients, while contributing to aquaculture species diversification and farmers’ profitability [61]. Since Madeira’s current fish farming model is based on the monoculture of *Sparus aurata* [25], transitioning to IMTA systems would likely improve environmental health, economic viability, and public perception of aquaculture activities. On the other hand, composting returns vital micronutrients to the soil, improving its structure and reducing the need for synthetic fertilizers. Economically, nutrient recovery

is often more accessible for small-scale operations because methods like composting require lower initial capital than energy plants.

Despite these advantages, this strategy faces logistical hurdles in collecting waste from dispersed fish processors and supermarkets, which can lead to high transport costs and potential odor issues, if not managed swiftly. Market acceptance is another challenge regarding fish compost, as local farmers may require education or certification to trust the quality and standardization of fish-based fertilizers [46,58]. Furthermore, in Madeira, a small island, the land required for large-scale composting and the ocean space needed for IMTA can create competition with other vital sectors like tourism or navigation.

4.4.3. Strategy 3: Bio-Product Valorization

This strategy involves a tiered approach to waste utilization, ranging from the extraction of high-value compounds to the processing of bulk secondary products. At the high-value end, it focuses on isolating compounds such as collagen, omega-3 fatty acids, and enzymes for use in the food, medical, and cosmetic sectors [2,4,15,17,48]. Economically, this represents the highest potential for revenue, transforming what was once waste into premium specialty products with access to global nutraceutical markets [62]. Concurrently, fractions of the biomass that are unsuitable for high-purity extraction can be redirected toward the production of fish meal and animal feeds.

Environmentally, bio-product and feed valorization represent the ultimate form of the circular economy, ensuring that every fraction of the harvested biomass is utilized to its maximum potential and minimizing the total environmental footprint of the sector. Transforming processing by-products into animal feed directly replaces the need for virgin marine or terrestrial feed inputs, reducing pressure on wild fish stocks and agricultural land.

However, the barriers to entry for the highest-value streams are substantial. The extraction of bioactive compounds requires massive upfront investment in laboratory-grade infrastructure and a highly specialized workforce that may be scarce in isolated regions. Despite capabilities at the local university, Madeira lacks this type of infrastructure and technical expertise [63]. While fish meal and feed production require less sophisticated technology and lower capital expenditure, they still demand consistent volumes of raw material to remain economically viable. This vulnerability is illustrated by the closure of a fish meal plant in Madeira adjacent to a tuna cannery; according to the facility's operator, operations became unsustainable due to a shortage of raw materials, high acquisition costs, and elevated stevedoring fees [64].

Additionally, the entire industry is governed by stringent international regulatory and quality control standards. High-value biomolecules must comply with costly medical or cosmetic frameworks (e.g., Food and Drug Administration, Good Manufacturing Practice, European Food Safety Authority), while animal feed production must adhere to strict safety regulations regarding contaminant levels and biosecurity to prevent disease transmission. Logistically, all raw materials must be preserved with extreme care, often requiring immediate refrigeration or freezing to prevent spoilage and to maintain either the integrity of the bioactive compounds or the nutritional value of the feed, adding a layer of cost and energy consumption to the collection process [10,52].

4.4.4. Strategy 4: Towards a Biorefinery Cascade Concept

So far, this study has selected strategies as distinct pathways to enhance fish waste management and promote waste valorization. By adopting a circular approach, these strategies are not mutually exclusive but rather complementary. Therefore, the most sustainable resolution is likely to adopt an integrated biorefinery cascade concept, essential for maximizing the economic, ecological, and social impacts of bio-based industries [62]. By

combining the production of high-added-value chemicals with energy or nutrient recovery to create more integrated farming systems, it is expected that the inherent potential of fish-derived biomass will be utilized more effectively.

The adoption of this model depends on advancements in the technology of a range of processes, on technical performance and cost-effectiveness, and, ultimately, the availability of sustainable biomass [65]. As the supply of local waste biomass is limited and cannot satisfy all market demands simultaneously, the implementation of such a system in Madeira must be preceded by rigorous techno-economic assessments. Such early stage evaluations are critical to ensure that the chosen technological configuration is not only biologically viable, but also commercially scalable and resource-efficient [62,66].

5. Conclusions

This study provides a baseline quantitative assessment of fishery and aquaculture wastes in Madeira. The results highlight a structurally dual system, characterized by diffuse OM marine discharges and spatially concentrated but fragmented terrestrial residues. The findings indicate that the primary constraint to effective valorization is not the total volume of waste generated, but its spatial distribution, temporal variability, and limited aggregation capacity, which restrict economies of scale and complicate the logistics in an insular context.

Among the selected strategies to enhance fish waste management and promote valorization, nutrient recovery approaches, such as composting and IMTA systems, emerge as the most immediately applicable technical solutions, with direct environmental benefits. However, an integrated biorefinery cascade model is usually the most effective strategy for optimizing the fish waste stream. While this model offers superior economic and social benefits, its adoption is strictly dependent on favorable results from forthcoming techno-economic and environmental assessments.

Although this is a baseline assessment, some methodological limitations should be acknowledged. Firstly, the estimation of aquaculture-derived organic matter was based on a simplified feed-based mass-balance approach, due to the absence of a detailed feed analytical composition. Secondly, the quantification of terrestrial fish by-products relied on the main formal generating nodes with systematic records, namely major processing operators and supermarkets. Informal waste streams were not included. In addition, although encompassing all of them, the small number of stakeholders was limited by the small size of the regional economy. As a result, the stakeholder analysis should be interpreted as a semi-quantitative indication of sectoral perceptions.

Despite these limitations, this study provides the foundation for future initiatives, such as (i) systematic assessment of organic waste streams, (ii) testing of IMTA-based mitigation approaches, (iii) pilot-scale valorization strategies, (iv) integration of fish by-products management indicators into regional statistics, and (v) opportunities for private investment, by identifying key elements for circular economy implementation in Madeira.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18157547/s1>, Table S1: Summary of the quantitative data gathered for this study; Table S2: Structured interview protocol used for stakeholder consultation with licensed fish by-product management operators in the Madeira Archipelago.

Author Contributions: Conceptualization, C.A.P.A. and C.G.; methodology, C.A.P.A. and C.G.; investigation, C.G.; data collection, C.G.; formal analysis, C.A.P.A. and C.G.; software, C.G.; writing—original draft preparation, C.A.P.A. and C.G.; writing—review and editing, C.A.P.A., C.G. and S.C.; supervision, C.A.P.A. and S.C.; project administration, S.C.; funding acquisition, S.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work had the support and was executed under the scope of project AQUAFISH0.0 (EAPA_0062/2022), co-financed by the Interreg Atlantic Area Program 2021–2027 (ERDF), under the European Territorial Cooperation (ETC) objective of the EU Cohesion Policy.

Institutional Review Board Statement: Ethical review and approval were waived for this study by the Institutional Committee due to GDPR (Regulation (EU) 2016/679) and Portuguese Law No. 58/2019, as the dataset excluded personal, sensitive, or identifiable participant-level data. The study did not involve clinical trials, patients, vulnerable groups, or health-related interventions. Consequently, it falls outside the scope of EU regulations (EU No 536/2014, EU 2017/745) and Portuguese laws (Law No. 21/2014, Decree-Law No. 80/2018) that mandate ethics committee approval.

Informed Consent Statement: Verbal informed consent and/or written authorization by email was obtained from the participants. Verbal consent was obtained rather than written because participants provided information voluntarily, were aware of the purpose of the consultation, and no personal, sensitive, or confidential information was included in the manuscript. The reported information was used only in aggregated or non-identifiable form.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors gratefully acknowledge Silvestre França, Rui Gonçalves, and Mirandolina Freitas for their valuable support, technical insights, and assistance in data collection, which significantly contributed to this study. The authors also acknowledge the contribution of Aldina Maltez regarding insights given in fish by-product management in Madeira. In addition, the authors also recognize the representatives of Madeira's waste management sector for their time and valuable contributions through interviews and personal communications, as well as the fish processing factories and supermarkets that provided operational data and information upon request. During the preparation of this manuscript, the authors used ChatGPT-5 (OpenAI) as an auxiliary tool for language improvement, figure refinement, and structural organization. All outputs were critically reviewed, revised and validated by the authors, who take full responsibility for the final content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

OM	Organic Matter
IMTA	Integrated Multi-Trophic Aquaculture
FCR	Feed Conversion Ratio
ARM	Águas e Resíduos da Madeira
DREM	Direção Regional de Estatística da Madeira
ADC _{DM}	Dry Matter Digestibility

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