

ORIGINAL RESEARCH

## Estimation of seafood byproducts generated by freezing companies in the Souss-Massa Region, Morocco

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**ABSTRACT.** The seafood processing industry generates substantial quantities of byproducts that remain underutilized despite their potential for recovery and further utilization. This study aimed to assess the generation and management of seafood byproducts within the freezing industry of the Souss-Massa region, Morocco. A voluntary semi-structured survey was conducted among 21 of the 39 regional freezing companies, focusing on raw material supply, processing activities, byproduct generation, and management practices. Following post-stratification to the regional frame of 39 freezing companies, the estimated annual processed volume was approximately 70,230 t, generating an estimated 22,504 t of seafood byproducts, corresponding to approximately 32% of the processed raw material. Byproduct generation varied according to species and product type, with *Sardina pilchardus*, *Trachurus trachurus*, *Merluccius merluccius*, and *Loligo vulgaris* contributing the largest estimated quantities. Viscera (29%), heads (28%), and bones and tails (21%) were dominant byproduct fractions, while shells and carapaces, skin, and trimmings accounted for smaller proportions. The companies surveyed reported several management routes, including fishmeal production, animal feed, external management channels, and direct sales. These findings provide a regional inventory of seafood byproduct streams that may be considered for future valorization. Their technical, economic, and environmental feasibility requires further assessment through approaches such as techno-economic assessment (TEA) and life-cycle assessment (LCA).



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**Key words:** Seafood byproducts, freezing industry, valorization, circular economy, material flow analysis.

### Estimación de los subproductos marinos generados por empresas congeladoras en la región de Souss-Massa, Marruecos

**RESUMEN.** La industria de procesamiento de productos del mar genera cantidades considerables de subproductos que permanecen infrautilizados, a pesar de su potencial de recuperación y aprovechamiento posterior. Este estudio tuvo como objetivo evaluar la generación y gestión de subproductos pesqueros en la industria de congelación de la región de Souss-Massa (Marruecos). Se realizó una encuesta voluntaria semiestructurada a 21 de las 39 empresas regionales de congelación, centrándose en el suministro de materia prima, actividades de procesamiento, generación de subproductos y prácticas de gestión. Tras realizar una post-estratificación basada en el universo regional de 39 empresas, se estimó un volumen anual procesado de aproximadamente 70.230 t, generando unas 22.504 t de subproductos pesqueros, lo que equivale a cerca del 32 % de la materia prima procesada. La generación de subproductos varió según la especie y el tipo de producto. *Sardina pilchardus*,

*Trachurus trachurus*, *Merluccius merluccius* y *Loligo vulgaris* fueron las especies que aportaron las mayores cantidades estimadas. Las vísceras (29 %), cabezas (28 %) y espinas y colas (21 %) constituyeron las fracciones predominantes de subproductos, mientras que las conchas y caparazones, piel y recortes representaron proporciones menores. Las empresas encuestadas informaron sobre diversas vías de gestión, incluidas la producción de harina de pescado, alimentación animal, canales de gestión externa y venta directa. Estos resultados proporcionan un inventario regional de los flujos de subproductos pesqueros que podrían considerarse para su futura valorización. Su viabilidad técnica, económica y ambiental requiere una evaluación más exhaustiva mediante enfoques como la evaluación técnico-económica (TEA) y el análisis de ciclo de vida (ACV).

**Palabras clave:** Subproductos de origen marino, industria de la congelación, valorización, economía circular, análisis de flujo de materiales.

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## INTRODUCTION

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Aquatic foods play an important role in global food security, nutrition, and socioeconomic development, particularly in coastal countries. They provide high-quality proteins, essential fatty acids, minerals, and vitamins, and represent an important component of healthy diets (Suresh et al. 2018; Prelicpean et al. 2022). Global fisheries and aquaculture production reached a record level in 2022, while apparent per capita consumption of aquatic animal foods was estimated at 20.7 kg, highlighting the growing importance of aquatic food in global food systems (FAO 2024). This increase has been associated with population growth, changing dietary preferences, and improvements in processing and distribution systems (Cooney et al. 2023). Global fisheries and aquaculture production reached 223.2 million tons in 2022, comprising 185.4 million tons of aquatic animals and 37.8 million tons of algae. Approximately 89% of aquatic animal production was intended for human consumption, while the remaining share was used for non-food purposes (FAO 2024). Despite this production growth, the sector faces increasing pressure on marine resources. In 2021, 62.3% of the assessed marine fish stocks were exploited within biologically sustainable levels, whereas 37.7% were overfished. When weighted by production, 76.9% of global landings originated from biologically sustainable stocks (FAO 2024).

Seafood processing also generates heteroge-

neous material streams, including heads, viscera, bones, skins, trimmings, and shells (Suresh et al. 2018). Their quantity and composition vary according to species, body size, product form, and processing intensity (Venugopal 2021). When these material streams are poorly quantified or managed, opportunities for their recovery as sources of proteins, lipids, collagen, minerals, and other valuable compounds remain limited. Reliable information on their generation and current management is therefore necessary to support appropriate recovery and valorization strategies (Caruso 2015).

In Morocco, the fisheries sector is a major component of the national blue economy. Supported by a coastline extending approximately 3,500 km, the country is among the principal producers and exporters of seafood products in Africa (Nejjari and Elyousfi 2023; Boudad et al. 2025). National fisheries production reached approximately 1.42 million tons in 2023, with a reported value of USD 1.59 billion (DPM 2023a). In the same year, the seafood-processing sector comprised 518 establishments covering freezing, fresh-product packaging, canning, semi-preserving, and fishmeal and fish-oil production, with freezing companies representing the dominant category (DPM 2023b).

The Souss-Massa region occupies a major position in this processing network, accounting for more than 19% of national freezing companies and nearly 40% of all seafood-processing establishments (DPM 2023b). Although these companies contribute to employment and regional economic activity, their processing operations generate substantial streams of seafood byproducts alongside

other waste streams. In this study, seafood byproducts refer to biological fractions generated during processing and are potentially available for further use, whereas other waste streams are considered separately. However, quantitative information on the species-specific generation, composition, management, and recovery of these materials remain limited in Morocco. National and sectoral statistics describe fisheries production, processing activities, and the structure of the Moroccan seafood-processing industry (DPM 2023b), but provide limited information linking individual freezing companies, processed species, byproduct generation, and reported management pathways. Previous national assessments have mainly provided aggregated or subsector-level estimates, whereas international studies have documented seafood byproduct generation and valorization across a range of processing contexts (Erasmus et al. 2021; Venugopal 2021; Cooney et al. 2023). This information gap limits the assessment of potentially available byproduct streams and the development of evidence-based recovery and further-use strategies.

Therefore, this study aimed to estimate the quantities and characterize the composition of seafood byproducts generated by freezing companies in the Souss-Massa region, examine their distribution according to species and processed product, and assess the existing management and recovery practices. The study also sought to identify reported constraints to byproduct valorization and explore respondents' awareness of potential valorization pathways.

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## MATERIALS AND METHODS

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### Study area

The Souss-Massa region is one of Morocco's major seafood processing hubs, with a high concentration of freezing companies located in the Agadir industrial area. According to the Maritime

Fisheries Delegation (DPM 2023b), the regional sampling frame comprised 39 freezing companies processing a wide range of marine resources. These companies generate substantial quantities of seafood byproducts; however, no comprehensive regional database describing byproduct generation, management, and valorization is currently available. To address this gap, 21 of the 39 freezing companies participated in the study. Participating companies were in the main industrial zones of Agadir: (a) Anza, (b) New and Old Port (N.Port), (c) Tassila, and (d) Haliopole (Figure 1).

### Survey design and data collection

Face-to-face interviews were conducted with company representatives, including directors, production managers, quality managers, and health, safety and environment (HSE) officers. The questionnaire was pre-tested in three companies selected from three different industrial zones, to assess its clarity and identify any necessary adjustments. These companies were subsequently re-interviewed using the finalized questionnaire to complete the additional or revised questions. All 39 freezing companies identified in the regional sampling frame were contacted. Twenty-one agreed to participate in the survey and were interviewed, whereas; the remaining 18 companies did not participate.

Data were collected between May and July 2025 in either French or Moroccan Arabic (Darija), depending on the respondent's preference. Interviews lasted approximately 30-50 min. This approach allowed standardized data collection with the flexibility to obtain detailed technical and operational information, particularly where official datasets were unavailable. To ensure confidentiality, all participating companies were anonymized, and the results were presented in aggregated form. The questionnaire consisted of 47 questions organized into six thematic sections covering company characteristics, raw material supply, processing activities, byproduct generation, current management practices, and environmental management.

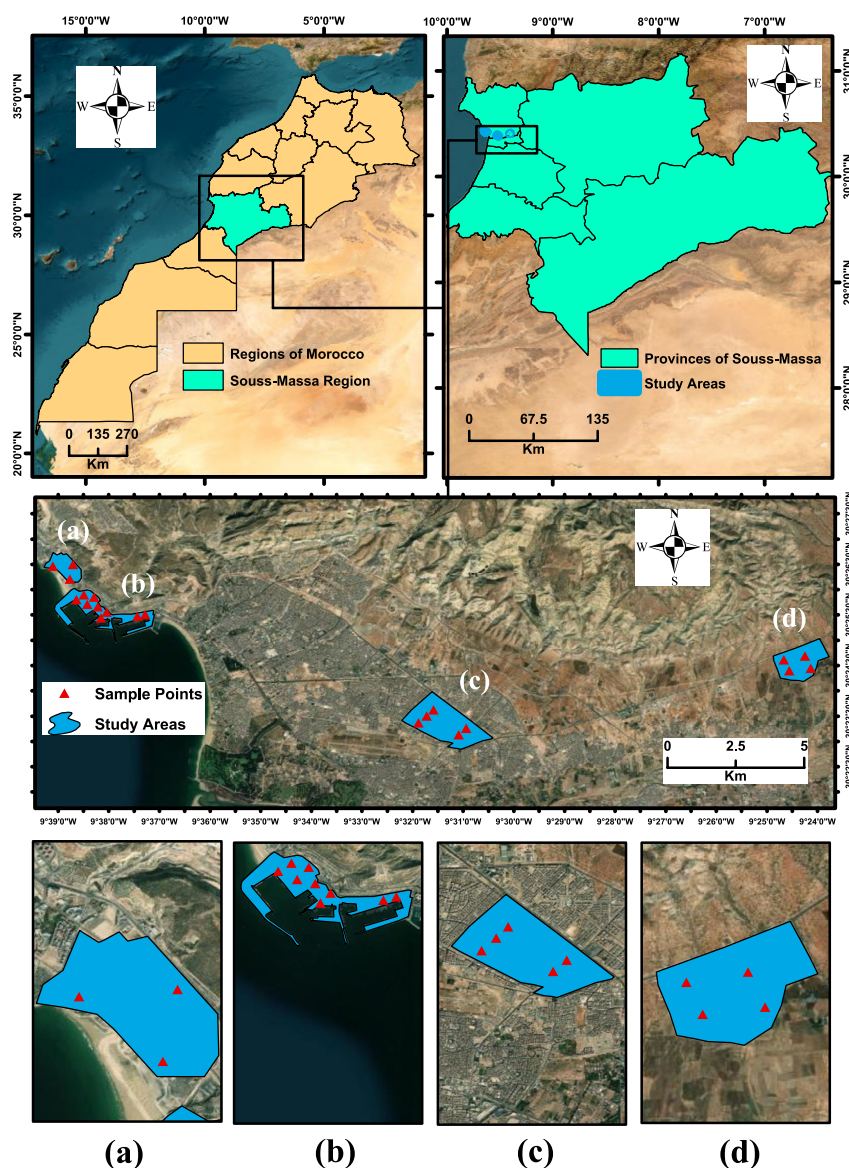


Figure 1. Map of study area; Anza industrial zone (A), New Port and Old Port (N.Port) (B), Tassila industrial zone (C), Haliopole industrial park (D).

The questionnaire was pre-tested in three freezing companies to improve its structure and clarity before the main data collection. Annual processed volumes referred to the 2024-2025 reference period and were recorded in tons.

Before each interview, the objectives of the study were explained to the participants, and oral

informed consent was obtained. The questionnaire covered company characteristics, sources of raw materials, annual processing volumes, processed species, byproduct generation, management practices, and valorization pathways. Missing or unavailable responses were not imputed and were excluded from the corresponding descriptive anal-

yses. To complement survey information, secondary information was obtained from the Maritime Fisheries Delegation (DPM), the National Office of Fisheries (ONP), and Customs authorities. These institutional sources were used to contextualize the information collected during the interviews.

### Estimation of seafood byproduct generation

#### Conversion factors

Quantities of seafood byproducts generated by the surveyed freezing companies were estimated by combining annual processing volumes reported during the interviews with species-specific conversion factors obtained either through in-plant measurements, where feasible, or from FAO sources when direct measurements were unavailable. These conversion factors represented cumulative mass changes across successive processing stages were species-specific. For each species for which conversion factors were directly determined, three independent processing lots were monitored (Table 1). Each lot was weighed before processing and after each successive processing stage. The cumulative conversion factor for species  $s$  at stage  $j$  was calculated as the ratio of the mean initial mass of the three lots to the mean remaining mass after stage  $j$ :

$$CF_{s,j} = \frac{\overline{M_{s,0}}}{\overline{M_{s,j}}}$$

where  $M_{s,0}$  is the mean initial mass of the replicate lots of species  $s$  before processing and  $M_{s,j}$  is the mean mass remaining across the same lots after processing stage  $j$ . Because the same number of replicates lots was used for both means, the ratio of means is mathematically equivalent to the ratio of the total initial mass to the total remaining mass of the monitored lots. This pooled mass-based conversion factor was used because it was subsequently applied to industrial mass flows. Standard errors were calculated from the paired initial and

remaining mass measurements using first-order error propagation, including the covariance between paired measurements:

$$SE = \frac{1}{\sqrt{n}} \sqrt{\frac{S_{M_0}^2}{\overline{M_j}^2} + \frac{S_{M_j}^2 \overline{M_0}^2}{\overline{M_j}^4} - \frac{2 \overline{M_0} S_{M_0, M_j}}{\overline{M_j}^3}}$$

where ( $S_{M_0}^2$  and  $S_{M_j}^2$  are the sample variances of the initial and remaining masses, respectively,  $S_{M_0, M_j}$  is their covariance, and ( $n = 3$ ). Because cumulative conversion factors at successive processing stages were derived from the same replicate lots, their uncertainties were correlated and were not considered independent.

#### Byproduct estimation

Because processing forms varied according to customer requirements, a species-specific set of applicable processing pathways was used for the estimation. The quantity of byproducts generated at each processing stage was estimated as the difference between the remaining masses immediately before and after that stage, using the corresponding cumulative conversion factors according to the following relationship:

$$BP_{i,s,j} = \frac{M_{i,s,0}}{CF_{s,j-1}} - \frac{M_{i,s,j}}{CF_{s,j}}$$

where  $M_{i,s,0}$  denotes the initial processed mass of species  $s$  in company  $i$  and  $CF_{s,j-1}$  and  $CF_{s,j}$  represent the cumulative conversion factors corresponding to the processing stages immediately before and after stage  $j$ , respectively. For the initial unprocessed state,  $CF_{s,0} = 1$

#### Regional estimation and mass-balance assessment

*Post-stratification.* Regional quantitative estimates were obtained using post-stratification by industrial zones rather than direct unweighted extrapolation from the 21 participating companies. Because the

Table 1. Species-specific cumulative conversion factors (CF) according to successive processing stages. Values for directly measured conversion factors are presented as CF  $\pm$  SE. WR: whole round (CF = 1); G: gutted; GH: gutted and headed; GHS: gutted, headed and skinned; B&T: bones and tail; IS: internal structure; Sh: shelling; TR: trimming. NA: not applicable; ND: not determined. *Magallana gigas* is reported as *Crassostrea gigas* in the corresponding source. \*: FAO (2000).

| Species                            | CF-G              | CF-GH             | CF-GHS            | CF B&T            | CF-IS             | CF-Sh | CF-TR             |
|------------------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------|-------------------|
| <i>Merluccius merluccius</i>       | 1.213 $\pm$ 0.010 | 1.502 $\pm$ 0.034 | 1.624 $\pm$ 0.021 | 2.160 $\pm$ 0.067 | NA                | NA    | 2.204 $\pm$ 0.037 |
| <i>Sparus aurata</i>               | 1.103 $\pm$ 0.011 | 1.141 $\pm$ 0.010 | 1.181 $\pm$ 0.001 | 1.420 $\pm$ 0.017 | NA                | NA    | 1.436 $\pm$ 0.023 |
| <i>Argyrosomus regius</i>          | 1.055 $\pm$ 0.013 | 1.142 $\pm$ 0.015 | 1.190 $\pm$ 0.001 | 1.400 $\pm$ 0.006 | NA                | NA    | 1.404 $\pm$ 0.017 |
| <i>Macruronus magellanicus</i>     | 1.072 $\pm$ 0.012 | 1.270 $\pm$ 0.013 | 1.394 $\pm$ 0.016 | 1.680 $\pm$ 0.007 | NA                | NA    | 1.736 $\pm$ 0.021 |
| <i>Pomatomus saltatrix</i>         | 1.115 $\pm$ 0.009 | 1.184 $\pm$ 0.015 | 1.243 $\pm$ 0.009 | 1.570 $\pm$ 0.022 | NA                | NA    | 1.606 $\pm$ 0.016 |
| <i>Mycteroperca rubra</i>          | 1.128 $\pm$ 0.040 | 1.369 $\pm$ 0.031 | 1.428 $\pm$ 0.034 | 1.840 $\pm$ 0.010 | NA                | NA    | 2.005 $\pm$ 0.023 |
| <i>Seriola dumerili</i>            | 1.043 $\pm$ 0.015 | 1.149 $\pm$ 0.003 | 1.186 $\pm$ 0.009 | 1.460 $\pm$ 0.016 | NA                | NA    | 1.479 $\pm$ 0.015 |
| <i>Trachurus trachurus</i>         | 1.115 $\pm$ 0.014 | 1.474 $\pm$ 0.037 | 1.643 $\pm$ 0.053 | 1.800 $\pm$ 0.049 | NA                | NA    | 1.825 $\pm$ 0.009 |
| <i>Sardina pilchardus</i>          | 1.055 $\pm$ 0.012 | 1.184 $\pm$ 0.004 | 1.213 $\pm$ 0.013 | 1.490 $\pm$ 0.019 | NA                | NA    | 1.521 $\pm$ 0.015 |
| <i>Engraulis encrasicolus</i>      | 1.032 $\pm$ 0.006 | 1.546 $\pm$ 0.003 | 1.703 $\pm$ 0.018 | 1.860 $\pm$ 0.013 | NA                | NA    | 1.864 $\pm$ 0.013 |
| <i>Sarda sarda</i>                 | 1.103 $\pm$ 0.026 | 1.307 $\pm$ 0.009 | 1.418 $\pm$ 0.043 | 1.990 $\pm$ 0.009 | NA                | NA    | 2.256 $\pm$ 0.024 |
| <i>Lepidopus caudatus</i>          | 1.090 $\pm$ 0.010 | 1.229 $\pm$ 0.011 | 1.327 $\pm$ 0.019 | 1.510 $\pm$ 0.015 | NA                | NA    | 1.533 $\pm$ 0.017 |
| <i>Octopus vulgaris</i>            | 1.088 $\pm$ 0.089 | 1.128 $\pm$ 0.079 | NA                | NA                | NA                | NA    | 1.135 $\pm$ 0.077 |
| <i>Loligo vulgaris</i>             | 1.155 $\pm$ 0.014 | 1.183 $\pm$ 0.015 | NA                | NA                | 1.227 $\pm$ 0.018 | NA    | 1.234 $\pm$ 0.011 |
| <i>Sepia officinalis</i>           | 1.128 $\pm$ 0.011 | 1.161 $\pm$ 0.011 | NA                | NA                | 1.163 $\pm$ 0.032 | NA    | 1.188 $\pm$ 0.036 |
| <i>Magallana gigas</i> *           | ND                | ND                | ND                | ND                | ND                | 5.33  | ND                |
| <i>Mytilus galloprovincialis</i> * | ND                | ND                | ND                | ND                | ND                | 5     | ND                |
| <i>Parapenaeus longirostris</i> *  | ND                | ND                | ND                | ND                | ND                | 1.05  | ND                |

information available for non-participating companies was limited to their industrial-zone location, respondent-nonrespondent comparisons were restricted to zone distribution (Little 1993; Valliant 1993). For each zone  $k$ , a post-stratification weight  $w_k$  was assigned, where  $N_k$  denotes the number of companies in the regional sampling frame and  $n_k$  the number of surveyed freezing companies (Table 2):

$$w_k = \frac{N_k}{n_k}$$

The reported processing tonnage of each surveyed companies and the estimated species-specific byproduct quantities within each company were extrapolated to the regional level using the corresponding zone-specific post-stratification weight. The regional total was estimated as:

$$T = \sum_k \frac{N_k}{n_k} \sum_{i=1}^{n_k} y_{ki}$$

where  $y_{ki}$  represents either the reported processing tonnage or the estimated byproduct quantity for participating facility  $i$  in zone  $k$ .

#### *Sensitivity analysis*

Because annual processing volumes were reported as point estimates without associated uncertainty

bounds, formal confidence intervals could not be derived. Uncertainty related to extrapolation to the 18 non-participating freezing companies was therefore assessed using a deterministic sensitivity analysis based on the variability observed among participating companies within each industrial zone. For each zone  $k$ , three scenarios were defined for non-participating companies: a lower scenario using the minimum observed processing volume, a base scenario using the mean, and an upper scenario using the maximum. Reported volumes of participating companies remained unchanged. The estimated processed volume for zone  $k$  under scenario  $z$  was calculated as:

$$T_K^z = \sum_{i=1}^{n_k} Y_{ki} + (N_k - n_k)Y_{kz}$$

where  $Y_{ki}$  is the reported processing volume of participating facility  $i$ , and  $Y_{k(z)}$  represents the observed minimum, mean, or maximum processing volume among participating companies in zone  $k$ . Regional estimates were obtained by summing the zone-specific estimates.

The base scenario was mathematically equivalent to the post-stratified estimate. Species composition and conversion factors for the processed raw material were kept constant, while only the assumed processing volume of non-participating companies changed. Additional deterministic sensitivity analyses were conducted separately for spe-

Table 2. Regional sampling frame, participation, and post-stratification weights by industrial zone.

| Industrial zone | Regional frame ( $N_k$ ) | Participating ( $n_k$ ) | Non-participating | Weight ( $N_k/n_k$ ) |
|-----------------|--------------------------|-------------------------|-------------------|----------------------|
| N.Port          | 20                       | 9                       | 11                | 2.222                |
| Anza            | 7                        | 3                       | 4                 | 2.333                |
| Tassila         | 5                        | 5                       | 0                 | 1.000                |
| Haliopole       | 7                        | 4                       | 3                 | 1.750                |
| Total           | 39                       | 21                      | 18                | -                    |

cies composition and conversion factors. Species composition sensitivity was assessed using the lowest- and highest-byproduct-yielding company profiles observed within each zone, while keeping total processed volume and conversion factors unchanged (See Supplemental Material). A local deterministic sensitivity check for conversion factors was performed by varying directly measured cumulative conversion factors as CF-SE, CF, and CF + SE, while factors without reported standard errors were kept constant. This was not considered a full propagation of joint uncertainty. Resulting ranges were interpreted as deterministic sensitivity scenarios rather than statistical confidence intervals (Table 3).

#### *Internal computational consistency check*

Internal computational consistency was assessed for each modeled processing pathway by confirming that the initial processed mass was equal to the final remaining product mass plus the sum of the byproduct fractions removed during successive processing stages:

$$M_{i,s,0} = M_{i,s,Final} + \sum_j BP_{i,s,j}$$

The check was restricted to the modeled solid biological fractions and did not include wastewater, melted ice, packaging, or other non-modeled processing streams

#### **Data processing and analysis**

Survey responses were compiled, organized, and processed using R version 4.5.0. Data processing and graphical analyses were performed using the dplyr (version 1.1.4), tidyr (version 1.3.1), and ggplot2 (version 4.0.3) packages. Descriptive analyses included frequencies, percentages, totals, and graphical summaries. Categorical results were reported as n/N (%), with N corresponding to the number of valid responses for each item, while multiple-response items were analyzed separately. Post-stratification weights were applied only to regional quantitative estimates, whereas descriptive survey results were reported for participating companies without weighting. No inferential statistical tests were applied to estimated byproduct tonnages.

#### **Study limitations**

The quantities reported in this study should be regarded as estimates derived from company-re-

Table 3. Deterministic Sensitivity Analysis of Regional Processed raw material and Seafood byproduct estimates.

| Sensitivity factor            | Scenario | Processed volume (t) | Estimated byproduct (t) | Byproducts/processed volume (%) |
|-------------------------------|----------|----------------------|-------------------------|---------------------------------|
| Processed raw material volume | Lower    | 53,050               | 16,794                  | 31.66                           |
|                               | Base     | 70,230               | 22,504                  | 32.04                           |
|                               | Upper    | 84,659               | 27,294                  | 32.24                           |
| Species composition           | Lower    | 70,230               | 20,080                  | 28.59                           |
|                               | Base     | 70,230               | 22,504                  | 32.04                           |
|                               | Upper    | 70,230               | 25,412                  | 36.18                           |
| Conversion factors            | Lower    | 70,230               | 21,302                  | 30.33                           |
|                               | Base     | 70,230               | 22,504                  | 32.04                           |
|                               | Upper    | 70,230               | 23,603                  | 33.61                           |

ported processing volumes and species-specific conversion factors rather than from direct annual measurements. Destination-specific byproduct tonnages could not be quantified or independently verified because systematic company-level records were generally unavailable.

## RESULTS

### Characteristics of surveyed seafood processing companies

Companies surveyed were characterized based on their years of operation and workforce structure (Table 4). Considerable heterogeneity was observed in both company age and workforce size among the 18 companies with valid responses. Approximately 83% had been operating for more than 15 years, with a mean operating age of approximately 21 years. Workforce size differed markedly among companies, particularly in terms of employment status. The number of seasonal workers ranged from 6 to 110, whereas that of permanent employees ranged from 15 to 141 companies.

### Sources of raw material supply

To better understand the dynamics of byproduct generation in seafood freezing companies operating in the Souss-Massa region, it was necessary to examine their raw material supply patterns.

Most companies obtained their raw materials from seafood traders, while 26% operated their own fishing fleets. However, according to the companies surveyed, locally available volumes were insufficient to meet their requirements, particularly during fishing closure periods. Consequently, some companies relied on imports to supplement local supplies, meet their raw material needs, and maintain production continuity. Raw materials were received in several forms. Fresh fish stored under ice in polystyrene containers was reported by 95% of the companies surveyed. Fresh products were also received in refrigerated boxes or transported in bulk using insulated trucks, with each mode reported by 63% of the companies. In addition, frozen fish in blocks was reported by 68.4% of companies, while cartons and bags were reported by 73.7% and 68.4%, respectively (Figure 2; Table 5). Nevertheless, no formal system was identified for recording or monitoring the quantities of packaging waste generated.

Table 4. Company age and workforce characteristics among surveyed freezing companies with valid responses (N = 18). Note: Workforce values represent the total numbers of seasonal and permanent = workers reported by all companies within each company-age group.

| Company age group (years) | Seasonal workers (total) | Permanent workers (total) | Companies n/N (%) |
|---------------------------|--------------------------|---------------------------|-------------------|
| 0-5                       | 49                       | 97                        | 2/18 (11.1)       |
| 6-10                      | 0                        | 0                         | 0/18 (0.0)        |
| 11-15                     | 16                       | 34                        | 1/18 (5.6)        |
| 16-20                     | 85                       | 33                        | 5/18 (27.8)       |
| 21-25                     | 110                      | 141                       | 5/18 (27.8)       |
| 26-30                     | 42                       | 112                       | 1/18 (5.6)        |
| 31-35                     | 26                       | 57                        | 3/18 (16.7)       |
| 36-45                     | 6                        | 15                        | 1/18 (5.6)        |

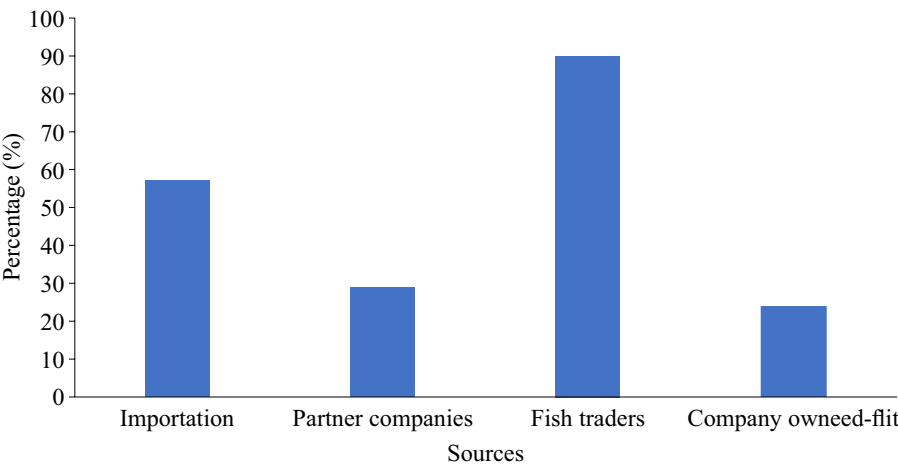


Figure 2. Sources of raw material supply reported by the responding companies (N = 19).

Table 5. Product state Reception mode Proportion n/N (%).

| Product state | Reception mode        | Proportion n/N (%) |
|---------------|-----------------------|--------------------|
| Fresh fish    | Ice-filled containers | (18/19) 95         |
|               | Refrigerated cartons  | (12/19) 63         |
|               | Bulk                  | (12/19) 63         |
| Frozen fish   | Frozen blocks         | (13/19) 68         |
|               | Cartons               | (14/19) 74         |
|               | Bags                  | (13/19) 68         |

Information on the disposal destinations of packaging waste was also not systematically documented.

Respondents identified fishing closure periods, limited coordination among supply-chain actors, and rising energy prices as constraints affecting raw material availability. They also perceived these factors as contributing to higher raw material prices and increased competition among seafood-processing companies.

**Composition and quantification of byproducts**

The estimated byproduct quantities were obtained by combining the processed volumes re-

ported by the surveyed freezing companies with species- and product-specific conversion factors. These factors varied according to both species and processing stage, with whole-round products assigned a reference conversion factor of 1 (Table 1). The post-stratified regional estimate indicated that approximately 70,230 t of seafood was processed during the reference period, generating an estimated 22,504 t of seafood byproducts, corresponding to approximately 32% of the estimated processed mass. Regional estimates showed that viscera and heads represented the two largest byproduct fractions, accounting for approximately 6,530 t (29%) and 6,347 t (28%) of the total estimated byproduct

quantity, respectively. Bones and tails ranked third, representing approximately 4,669 t (21%). Together, these three fractions accounted for nearly 80% of the estimated byproducts. Shells and carapaces, skin, and trimmings accounted for smaller proportions (Table 6).

Species-specific estimates revealed differences in each species contribution to total regional byproduct generation. *Sardina pilchardus* represented the largest contribution (16.3%), followed by *Trachurus trachurus* (12.2%) and *Merluccius merluccius* (10.8%). Cephalopods also contributed substantially, particularly *Loligo vulgaris* (8.0%), *Sepia officinalis* (7.5%) and *Octopus vulgaris* (5.1%) (Table 7; Figure 3). Among demersal fish, *Merluccius merluccius* generated the highest quantity of byproducts, whereas *Sardina pilchardus* and *Trachurus trachurus* predominated among pelagic species. Among cephalopods, *Loligo vulgaris* and *Sepia officinalis* generated the largest quantities, while bivalve byproducts consisted almost entirely of shells. Despite differences among species, viscera, heads, bones and tails remained the predominant byproduct fractions in most fish species (Table 7; Figure 3).

### Sensitivity analysis of regional estimates

The deterministic sensitivity analysis showed that the estimated regional processed volume varied

from 53,050 t under the lower scenario to 84,659 t under the upper scenario, with a base estimate of 70,230 t. The corresponding byproduct estimates were 16,794 t, 22,504 t, and 27,294 t, respectively. When processed volume was held constant, variation in species composition resulted in byproduct estimates ranging from 20,080 to 25,412 t, whereas the local deterministic perturbation of directly measured conversion factors using CF-SE and CF + SE resulted in estimated byproduct quantities ranging from 21,302 to 23,603 t. These values represent deterministic sensitivity scenarios and should not be interpreted as statistical confidence intervals (Table 3).

### Byproduct management practices

The survey included specific questions regarding the implementation of Environmental Management Systems (EMS). Among the 19 companies providing valid responses, 12/19 (63.2%) reported having no plans to implement an EMS, 6/19 (31.6%) were in the process of implementing one, and only 1/19 (5.3%) reported having an operational EMS (Figure 4).

In addition to solid seafood byproducts, the surveyed freezing companies also generated liquid effluents during processing operations. Liquid effluents were considered separately and were not

Table 6. Regional estimated quantities of seafood byproducts by category.

| Byproduct fraction   | Quantity (t) | Percentage (%) |
|----------------------|--------------|----------------|
| Viscera              | 6,530        | 29.0           |
| Heads                | 6,347        | 28.0           |
| Skin                 | 1,767        | 8.0            |
| Bones and tails      | 4,669        | 21.0           |
| Trimmings            | 886          | 4.0            |
| Shells and carapaces | 1,999        | 9.0            |
| Internal structures  | 305          | 1.0            |
| Total                | 22,504       | 100.0          |

Table 7. Post-stratified regional model estimates of seafood byproducts by species for the 2024-2025 reference period. Values are presented as estimated tonnes and percentage of total estimated by-product mass.

| Species                          | Estimated byproducts (t) | Byproduct share (%) |
|----------------------------------|--------------------------|---------------------|
| <i>Merluccius merluccius</i>     | 2,430.5                  | 10.8                |
| <i>Sparus aurata</i>             | 396.1                    | 1.8                 |
| <i>Argyrosomus regius</i>        | 118.9                    | 0.5                 |
| <i>Macruronus magellanicus</i>   | 1,270.1                  | 5.6                 |
| <i>Pomatomus saltatrix</i>       | 15.0                     | 0.1                 |
| <i>Mycteroperca rubra</i>        | 1,004.1                  | 4.5                 |
| <i>Seriola dumerili</i>          | 88.8                     | 0.4                 |
| <i>Trachurus trachurus</i>       | 2,735.4                  | 12.2                |
| <i>Sardina pilchardus</i>        | 3,660.9                  | 16.3                |
| <i>Engraulis encrasicolus</i>    | 1,064.9                  | 4.7                 |
| <i>Sarda sarda</i>               | 1,418.1                  | 6.3                 |
| <i>Lepidopus caudatus</i>        | 1,642.4                  | 7.3                 |
| <i>Octopus vulgaris</i>          | 1,149.4                  | 5.1                 |
| <i>Loligo vulgaris</i>           | 1,810.6                  | 8.0                 |
| <i>Sepia officinalis</i>         | 1,698.6                  | 7.5                 |
| <i>Magallana gigas</i>           | 1,047.8                  | 4.7                 |
| <i>Mytilus galloprovincialis</i> | 950.5                    | 4.2                 |
| <i>Parapenaeus longirostris</i>  | 0.9                      | 0.0                 |

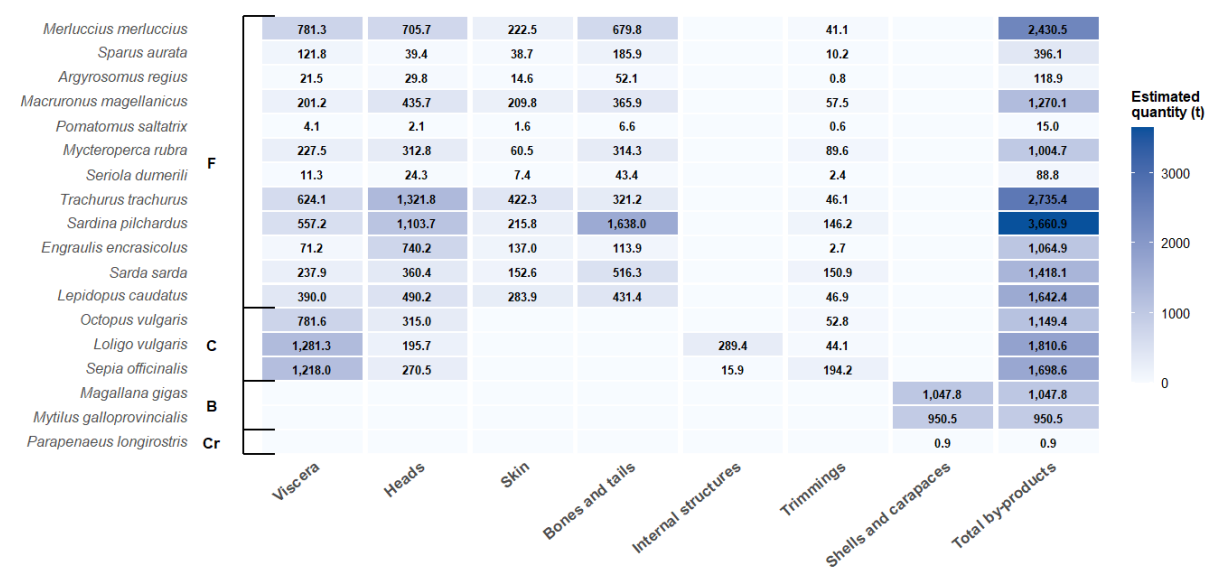


Figure 3. Heatmap of post-stratified regional seafood byproduct estimates (t) by species and fraction. F = fish; C = cephalopods; B = bivalves Cr = crustaceans.

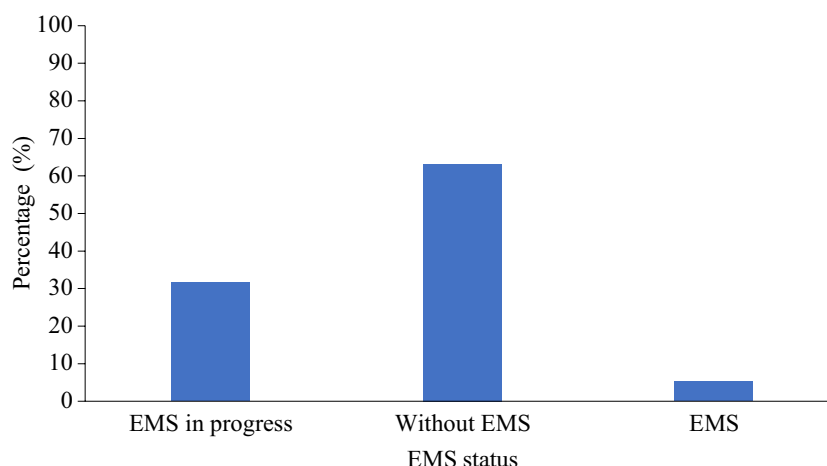


Figure 4. Environmental management system (EMS) status reported by the responding companies (N = 19).

included in the quantitative byproduct estimates. Among the 19 companies providing valid responses, 2/19 (10.5%) reported having a wastewater treatment plant (WWTP), whereas 17/19 (89.5%) reported having no dedicated wastewater treatment system. No formal monitoring system for wastewater discharges was reported in the survey. The survey documented wastewater management practices as reported by participating companies, while discharge events and environmental performance were not independently assessed.

The surveyed companies reported using several external routes for the management or utilization of seafood byproducts. Transfer to external fishmeal producers and animal feed were each reported by 15/19 (78.9%) of the responding companies, while 19/19 (100%) reported disposal to a public landfill, and 4/19 (21.1%) reported direct sales. One facility, 1/19 (5.3%), reported another destination (Figure 5). Companies could report more than one destination; therefore, percentages do not rise to 100%. These categories were not mutually exclusive, as companies could use different routes for different byproduct streams. These percentages represent the proportion of companies reporting each destination rather than the share of byproduct tonnage allocated to each route or the frequency of use of each destination. No on-site valorization was reported,

and destination-specific quantities could not be estimated because systematic records of byproduct flows by destination were unavailable.

Regarding perceived barriers, surveyed companies reported several constraints affecting further seafood byproduct utilization (Figure 6). Financial constraints were reported by 9/19 companies (47.4%), followed by regulatory constraints reported by 8/19 (42.1%), limited technical expertise by 5/19 (26.3%), lack of market outlets by 4/19 (21.1%), and limited availability of qualified personnel by 1/19 (5.3%). Multiple responses were allowed; therefore, percentages do not sum to 100%.

## DISCUSSION

This study provides a regional assessment of seafood byproduct generation and management practices in the freezing industry of the Souss-Massa region, Morocco. The regional quantities should be interpreted as conditional modeled estimates derived from voluntary participation and zone-based post-stratification. Based on annual processing volumes and species-specific conversion factors, the post-stratified regional estimates indicated approximately 22,504 t of seafood byproducts from

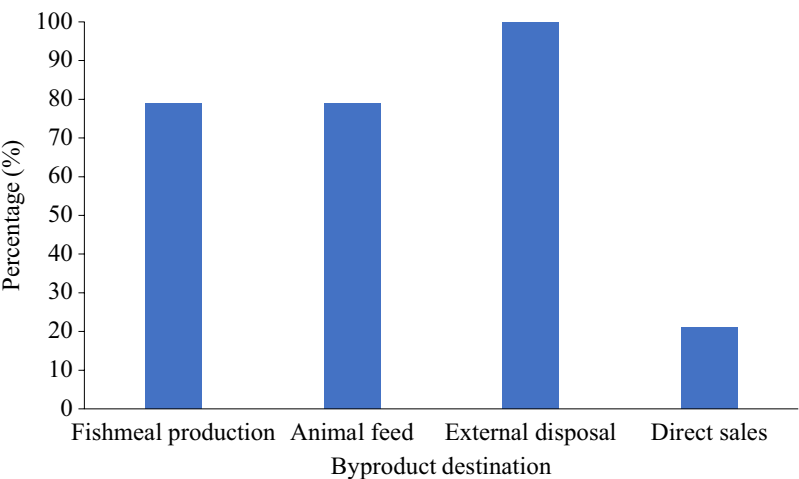


Figure 5. Seafood byproduct destinations reported by the responding companies (N = 19). Multiple responses were allowed; percentages are unweighted, may overlap, and represent neither tonnage allocation nor frequency of use.

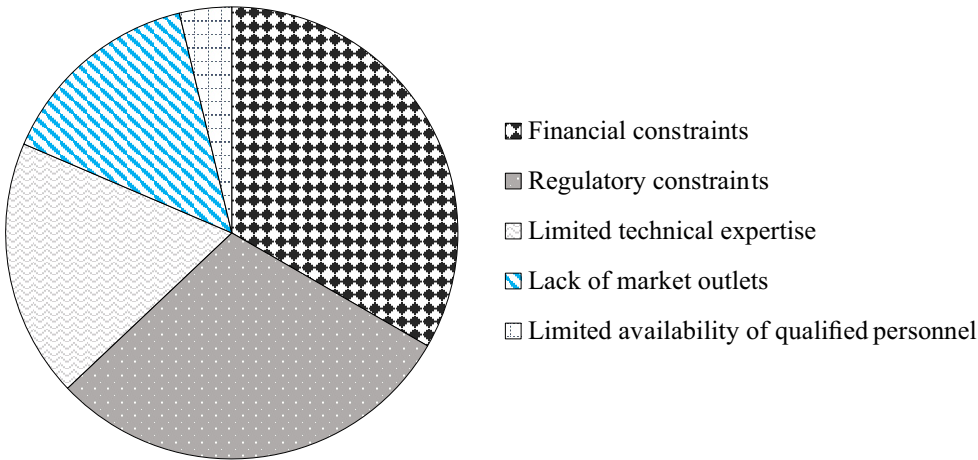


Figure 6. Reported constraints to further seafood byproduct utilization among surveyed freezing companies (N = 19).

an estimated processed biomass of 70,230 t, corresponding to approximately 32% of the estimated processed raw material. These estimates refer only to the modeled solid biological fractions included in the study and should not be interpreted as total facility waste or as verified recoverable material. The deterministic sensitivity analyses further showed that the regional estimate was influenced by assumptions regarding processed raw material volume, species composition, and conversion factors. These deterministic scenarios should not be

interpreted as confidence intervals. These findings provide a quantitative estimate of seafood byproduct generation in the Souss-Massa freezing companies and may contribute to broader resource-efficiency objectives consistent with Sustainable Development Goal 12 (Responsible Consumption and Production).  
The estimated proportion of byproducts (32%) was influenced by the species and processing pathways represented in the companies surveyed. Differences in byproduct generation among sea-

food-processing operations are generally associated with the processed species, processing technology, and final commercial products (Coppola et al. 2021; FAO 2022; Cassol et al. 2025). This variability supports the use of species- and product-specific conversion factors rather than a single generalized factor. Variability in raw material supply may also contribute to temporal changes in species availability and processed volumes.

The composition of byproducts was strongly influenced by the processed species. The predominance of fish-derived byproducts and of viscera, heads, and bones and tails reflects the routine evisceration and heading operations applied before freezing. Comparable distributions have been reported in other seafood-processing industries, where viscera, heads, skeletons, skins, and shells represent major byproduct streams (Nawaz et al. 2020; Erasmus et al. 2021). This information may support the preliminary screening of potential utilization pathways; however, their technical and economic feasibility may also depend on factors such as material quality and preservation, processing yields, logistics, market conditions, regulatory requirements, and costs.

Beyond their quantitative importance, seafood byproducts may provide feedstocks for further utilization of pathways. Numerous studies have reported that fish skins, bones, viscera, scales, and shells are rich in collagen, gelatin, bioactive peptides, omega-3 polyunsaturated fatty acids, minerals, chitin, and chitosan, with potential applications in the food, pharmaceutical, cosmetic, biomedical, and agricultural sectors (Felician et al. 2018; Nikoo et al. 2023; Elhiss et al. 2024; Mkaem and Kaanane 2024). These reported applications indicate potential pathways for further utilization; however, their technical and economic feasibility in the Souss-Massa context was not evaluated in the present study.

Among the identified by-product fractions, the skin of *Mycteroperca rubra* is discussed only as a hypothesis for future screening because it was mechanically separated as a distinct by-product

stream during processing. Fish skin is recognized as a potential marine source of collagen and gelatin, compounds investigated for applications in tissue engineering, wound healing, cosmetics, and nutraceuticals because of their biocompatibility and potentially lower risk of disease transmission compared with mammalian collagen (Ge et al. 2020; Zou et al. 2024). However, no biochemical, safety, recoverable-yield, market, or feasibility data were collected for *M. rubra* in the present study; therefore, its potential for further utilization remains to be evaluated. Despite the potential for further utilization, the surveyed companies reported several conventional routes for the management or utilization of seafood byproducts, including fish meal production, animal feed, disposal to a public landfill, and direct sales. However, destination-specific tonnages were unavailable; therefore, the proportion of total byproduct mass allocated to each route could not be quantified. The frequency with which each route was used was also not quantified. None of the surveyed companies reported industrial-scale extraction of collagen, gelatin, bioactive peptides, marine oils, or other high-value compounds. These findings indicate that such higher-value biorefinery applications were not reported among the surveyed companies, rather than establishing the overall stage of circular-bioeconomy development in the Moroccan seafood-processing sector. Nevertheless, several Moroccan studies have investigated related valorization approaches. Kharroubi et al. (2021) developed wound-dressing materials based on shrimp-shell-derived chitosan, while Aboudamia et al. (2020) extracted chitin and characterized chitosan obtained from *Sardina pilchardus* scales. In a subsequent study, Aboudamia et al. (2022) showed that *Sardina pilchardus* scales contain both organic and inorganic phases and exhibit a porous, fibrous structure, supporting their potential as a source of marine biomaterials. These studies illustrate research activity in this field in Morocco, but the present survey identified no corresponding industrial-scale extraction among the responding companies. Strengthening collabo-

ration between research institutions, seafood-processing companies, and public stakeholders could support future technology transfer and pilot-scale evaluation of these pathways.

Emerging green technologies, including ultrasound-assisted, microwave-assisted, and supercritical fluid extraction, have been investigated as alternative approaches for recovering compounds from biological byproducts (Silotry et al. 2021; Hassoun et al. 2023). However, their applicability to seafood byproduct streams in the Souss-Massa region was not evaluated in the present study. Their technical, economic, and environmental performance would require dedicated characterization, techno-economic assessment (TEA), and life-cycle assessment (LCA), including assessments of extraction yields, energy and solvent use, processing scale, capital and operating costs, and product quality.

Despite these potential pathways, the respondents reported several financial, regulatory, technical, and market-related constraints to further byproduct utilization. Only a small proportion of the surveyed companies implemented an operational environmental management system, reflecting limited reported adoption of formal EMS among respondents rather than providing a direct measure of overall environmental performance. In addition, seafood byproducts are highly perishable and require rapid collection, preservation, and processing to prevent microbial degradation and quality loss (Yusoff et al. 2024). In addition, the literature has identified contaminants such as heavy metals as a potential concern in certain seafood byproducts. Although no chemical measurements were performed in the present study, this highlights the importance of future quality and safety assessments before their use in food or biomedical applications (Honrado et al. 2024; Younis et al. 2024).

Overall, this study indicates that the seafood freezing industry in the Souss-Massa region generates substantial quantities of biological byproducts that may provide feedstocks for further utilization. Further evaluation of these streams will require consideration of regulatory requirements, stronger

collaboration between academia and industry, and technical and economic assessments of candidate utilization pathways. Future studies should complement the present estimates with direct industrial measurements, further validation of conversion factors, biochemical characterization, techno-economic analyses, and life-cycle assessments to evaluate the feasibility and environmental performance of potential seafood byproduct management and utilization strategies within a circular bioeconomy framework.

Although this study provides a regional assessment of seafood byproduct generation and management in Souss-Massa freezing companies, several limitations should be acknowledged. Estimates were based on company-reported processed volumes and species-specific conversion factors because systematic records of byproduct generation and destination were generally unavailable; therefore, the quantities assigned to each management or utilization pathway could not be determined. Moreover, only 21 of the 39 freezing companies in the regional sampling frame participated in the survey, and information available for non-participating companies was limited to their industrial-zone location. Consequently, residual nonresponse bias cannot be excluded despite the use of zone-based post-stratification and sensitivity analysis. The resulting regional quantities should therefore be interpreted as zone-calibrated estimates conditional on the observed respondent profiles and the assumptions applied to non-participating companies. Differences from previous studies may reflect variations in species composition, processing pathways, product forms, industrial scale, and estimation methods. Consistent with FAO guidance, conversion factors may also vary for the same species depending on the processing method applied (FAO 2000). Processing route uncertainty could not be quantified because no standard species-specific route or information on the frequency of alternative routes was available from the survey. The sensitivity ranges reported in this study represent deterministic scenarios rather than

confidence intervals. Nevertheless, the approach may provide a structured framework for estimating regional material flows where direct annual byproduct measurements are unavailable and provides a basis for future monitoring and validation studies.

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## CONCLUSIONS

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This study provides a regional assessment of seafood byproduct generation and management practices in the freezing industry of the Souss-Massa region, based on data collected from 21 participating freezing companies and zone-based post-stratification to the regional frame of 39 companies. By combining reported annual processing volumes with species-specific conversion factors, the study provides an estimate of regional seafood byproduct flows and documents the management practices reported by participating companies.

The post-stratified regional processed volume was estimated at approximately 70,230 t, associated with approximately 22,504 t of seafood byproducts, corresponding to approximately 32% of the estimated processed raw material. The processed raw material sensitivity analysis produced byproduct estimates ranging from approximately 16,794 t under the lower scenario to 27,294 t under the upper scenario, indicating that the regional estimate was sensitive to the assumed processing volumes of non-participating companies. Additional sensitivity analyses also showed that species composition and conversion factors influenced the regional estimate. These ranges represent deterministic scenarios rather than confidence intervals. The results also showed that byproduct composition varied according to the processed species and processing pathways, with viscera and heads among the major estimated fractions.

The companies surveyed reported several management and utilization routes, including fishmeal production, animal feed, disposal to a public land-

fill, and direct sales. These responses indicate the routes used by companies but do not represent destination-specific tonnage shares or frequency of use, because systematic records of these flows were unavailable.

The estimates remain subject to uncertainty related to company-reported processing volumes, extrapolation to non-participating companies, processing pathways, and the conversion factors used. They should therefore be interpreted as conditional on the observed respondent profiles and the assumptions used for non-participating companies. Future studies should prioritize direct industrial measurement of annual byproduct flows, further validation of conversion factors, and improved recording of destination-specific quantities. Biochemical characterization, techno-economic assessment, and life-cycle assessment could subsequently be used to evaluate specific utilization pathways and their technical, economic, and environmental performance.

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### Declaration of interest

The authors declare there are no conflicts of interest related to this study.

### Use of artificial intelligence tools

During the preparation of this manuscript, artificial intelligence tools (ChatGPT, OpenAI, and Per-

plexity) were used to assist with English-language editing, reformulation, and improving clarity and coherence. The data, calculations, research objectives, methodological choices, scientific interpretations, and conclusions were provided, reviewed, and validated by the authors, who retain full responsibility for the scientific content of the study.

### Author contribution

Ez-Zalmtay Youness: writing original draft; conducts surveys; data curation; visualization and conceptualization. Fatima Bellali: supervision; writing, review and editing; methodology; data curation and conceptualization. Maainia Saadani: writing original draft. Meriem Kharroubi: writing, review and editing, supervision; methodology; project administration.

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