

# Aquaculture Waste Valorization: A Quantitative Review of Fish Processing Waste, Bioactive Compounds and Value-Added Products

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**Abstract** – The rapid expansion of aquaculture and fish processing has increased the generation of nutrient-rich processing by-products, creating both an environmental challenge and an opportunity for circular bioeconomy development. Global aquaculture production of aquatic animals exceeded 100 million tonnes in 2024, while total global fisheries and aquaculture production reached approximately 235 million tonnes, highlighting the increasing volume of biomass entering aquatic-food value chains. Fish processing can generate approximately 30–70% of the original fish biomass as side streams, including heads, viscera, skin, bones, frames, fins and scales. These materials contain proteins, collagen, gelatin, peptides, lipids, omega-3 fatty acids, minerals and other bioactive compounds that can be recovered through extraction, hydrolysis, fermentation and biorefinery approaches. Tilapia processing provides a representative example: fillets generally constitute only 30–33% of whole-fish weight, leaving approximately 67–70% as processing by-products. Quantitative evidence demonstrates substantial recovery potential. Fish scales and bones can contain approximately 30–40% organic collagen matrix and 60–70% hydroxyapatite, while recent extraction approaches have reported collagen yields of up to 25–35%. Experimental studies have reported collagen yields ranging from less than 1% to more than 50%, depending on species, tissue, pretreatment and extraction method. Fish-processing lipids also represent an important source of omega-3 fatty acids, with EPA and DHA frequently detected at biologically relevant proportions in viscera, liver, heads and frames. This review quantitatively examines the magnitude of fish-processing waste, composition of major by-products, recovery of collagen, protein hydrolysates and omega-3 lipids, and their conversion into food, nutraceutical, pharmaceutical, cosmetic, biomedical, agricultural and biomaterial products. The review further evaluates technological limitations, economic considerations and future directions for integrated zero-waste aquaculture and fish-processing systems.

**Keywords** – Aquaculture waste; Fish processing by-products, Omega-3 fatty acids; Bioactive peptides; Circular bioeconomy; Value-added products

## I. INTRODUCTION

Aquaculture has become a major component of global aquatic-food production. According to the FAO's *State of World Fisheries and Aquaculture 2026*, global fisheries and aquaculture production reached approximately 235 million tonnes in 2024, including about 195 million tonnes of aquatic animals. Aquaculture production of aquatic animals exceeded 100 million tonnes for the first time, with a farm-gate value of approximately USD 371 billion.

This expansion has increased the availability of fish for human consumption and processing. However, only a fraction of the whole fish becomes the primary edible product. Depending on species, processing technology and product type, approximately 30–70% of the original biomass may remain as processing side streams.

These materials are often described as waste, although many are actually nutrient-rich biological resources. Heads, frames and trimmings contain proteins and minerals; skin and scales are valuable sources of collagen and gelatin; viscera and liver contain lipids and enzymes; and bones and scales contain substantial mineral fractions, particularly hydroxyapatite.

Consequently, fish-processing residues can be viewed as secondary raw materials rather than waste.

The transition from disposal to valorization is particularly important within a circular bioeconomy because it can simultaneously:

- reduce organic waste,
- recover valuable nutrients,
- generate additional revenue,
- reduce pressure on conventional raw materials,
- create new food and non-food products, and
- improve resource efficiency.

Recent reviews emphasize that fish by-products can provide collagen, gelatin, peptides, omega-3 fatty acids, antioxidants, enzymes, hydroxyapatite and other biomolecules with applications across food, pharmaceutical, cosmetic, biomedical and agricultural sectors.

### Objectives of the Review

This review aims to:

- Quantify the major categories of fish-processing waste.
- Examine the nutritional and biochemical composition of major by-products.

- Compare reported collagen and biomaterial extraction yields.
- Evaluate protein hydrolysates and bioactive peptide potential.
- Assess omega-3 fatty acid recovery from fish-processing residues.
- Summarize major value-added products and their applications.
- Identify technological and economic barriers to commercial valorization.
- Develop an integrated framework for sustainable fish-waste biorefinery.

## II. REVIEW METHODOLOGY

The review focuses on quantitative evidence reported in peer-reviewed literature and authoritative fisheries reports.

### Major indicators considered

- percentage of fish-processing waste,
- percentage contribution of individual by-products,
- protein content,
- lipid content,
- mineral content,
- collagen yield,
- gelatin yield,
- hydroxyapatite yield,
- omega-3 content,
- EPA and DHA concentration,
- extraction efficiency,
- processing time,
- antioxidant activity,
- and potential value-added applications.

Particular emphasis was placed on recent reviews and experimental studies published between 2021 and 2026, supplemented by foundational studies where numerical data were particularly useful.

### Magnitude and Composition of Fish-Processing Waste

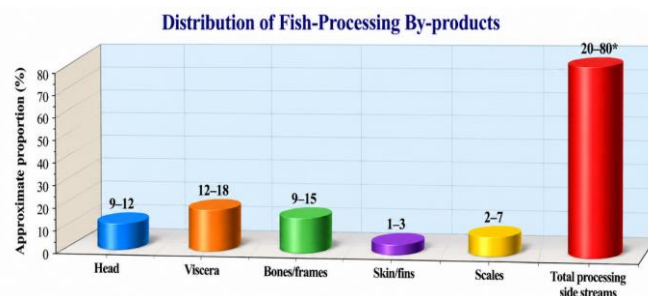
Fish processing generates several major side streams.

Table 1. Major fish-processing by-products and approximate proportion of whole-fish biomass

| By-product                    | Approximate proportion (%) | Major recoverable components           |
|-------------------------------|----------------------------|----------------------------------------|
| Head                          | 9–12                       | Protein, lipids, minerals, collagen    |
| Viscera                       | 12–18                      | Lipids, enzymes, proteins, peptides    |
| Bones/frames                  | 9–15                       | Collagen, minerals, hydroxyapatite     |
| Skin/fins                     | 1–3                        | Collagen, gelatin, proteins            |
| Scales                        | 2–7                        | Collagen, hydroxyapatite               |
| Total processing side streams | 20–80*                     | Proteins, lipids, minerals, bioactives |

\*Reported range varies considerably according to species and processing method.

For filleted tilapia, the edible fillet represents approximately 30–33% of the whole fish, leaving around 67–70% as heads, bones, skin, viscera and other residues. This provides an important quantitative rationale for valorization.



For example:

1 tonne of whole tilapia → approximately 300–330 kg fillet + approximately 670–700 kg processing by-products. Rather than treating the latter fraction as disposal material, an integrated biorefinery could recover several product streams from it.

### Distribution of Major Bioactive Components

Fish-processing residues contain several classes of valuable compounds.

Table 2. Major compounds recoverable from fish-processing by-products

| Component       | Typical source               | Approximate quantitative range                       | Major application        |
|-----------------|------------------------------|------------------------------------------------------|--------------------------|
| Protein         | Heads, frames, viscera, skin | 15–60%                                               | Food, hydrolysates       |
| Lipids          | Viscera, liver, heads        | 20–60% in lipid-rich tissues                         | Fish oil, nutraceuticals |
| Collagen matrix | Scales/bones                 | 30–40% organic matrix                                | Biomaterials, cosmetics  |
| Hydroxyapatite  | Bones/scales                 | 60–70% mineral fraction in scales/bones              | Biomedical, dental       |
| EPA             | Viscera, liver, frames       | ~3–15% of total fatty acids in many reported systems | Nutraceuticals           |
| DHA             | Viscera, liver, trimming     | ~5–33% of total fatty acids in reported systems      | Nutraceuticals           |

|                    |                      |                   |                               |
|--------------------|----------------------|-------------------|-------------------------------|
| Gelatin            | Skin                 | Variable          | Food films, coatings          |
| Bioactive peptides | Protein-rich tissues | Process-dependent | Functional foods              |
| Enzymes            | Viscera              | Species-dependent | Food/industrial biotechnology |

Protein and lipid values vary considerably among species and tissues, so the ranges should be regarded as literature ranges rather than universal composition values.

### III. COLLAGEN RECOVERY FROM FISH BY-PRODUCTS

#### 1. Fish scales and bones as collagen resources

Collagen is one of the most extensively investigated products from fish-processing residues.

Recent evidence indicates that fish scales and bones typically contain approximately 30–40% organic collagen matrix, together with approximately 60–70% hydroxyapatite minerals.

The exact recovery depends strongly on:

- species,
- tissue,
- mineral removal,
- acid concentration,
- enzyme treatment,
- temperature,
- extraction duration,
- solid-to-liquid ratio, and
- purification method.

A study comparing six fish species reported substantial differences in collagen recovery from scales.

Table 3. Collagen yields from selected fish scales

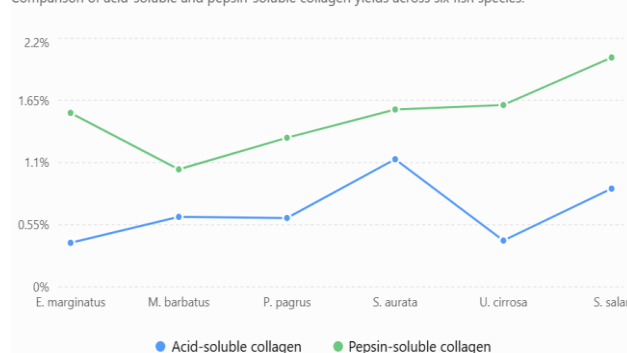
| Fish species                  | Acid-soluble collagen (%) | Pepsin-soluble collagen (%) |
|-------------------------------|---------------------------|-----------------------------|
| <i>Epinephelus marginatus</i> | 0.39 ± 0.02               | 1.54 ± 0.06                 |
| <i>Mullus barbatus</i>        | 0.62 ± 0.06               | 1.04 ± 0.04                 |
| <i>Pagrus pagrus</i>          | 0.61 ± 0.05               | 1.32 ± 0.06                 |
| <i>Sparus aurata</i>          | 1.13 ± 0.06               | 1.57 ± 0.06                 |
| <i>Umbrina cirrosa</i>        | 0.41 ± 0.02               | 1.61 ± 0.07                 |
| <i>Salmo salar</i>            | 0.87 ± 0.02               | 2.03 ± 0.10                 |

Values are expressed on a dry-weight basis.

However, other extraction strategies can produce considerably higher yields. A study of fish scales reported collagen yields of **37.5–50.9% on a dry-weight basis** for selected species following decalcification and pepsin digestion.

Collagen Yield from Selected Fish Species

Comparison of acid-soluble and pepsin-soluble collagen yields across six fish species.



This large variation demonstrates an important point for quantitative review: collagen yield cannot be compared directly unless the basis of calculation and extraction method are standardized.

### IV. HYDROXYAPATITE RECOVERY

Fish scales and bones are also important sources of calcium phosphate biomaterials.

Hydroxyapatite has applications in:

- bone regeneration,
- dental materials,
- tissue engineering,
- drug delivery,
- adsorption,
- and biomedical coatings.

Recent work using fish scales reported a hydroxyapatite recovery efficiency of 25.8%, while literature values for fish bones have been reported around 56–60% for catfish, tilapia, sea bass and tuna.

Table 4. Reported hydroxyapatite recovery from fish by-products

| Source                     | Hydroxyapatite yield/recovery (%) |
|----------------------------|-----------------------------------|
| Fish scales – recent study | 25.8                              |
| <i>Labeo rohita</i> scales | 24.3                              |
| Catfish bones              | 56.9–59.99                        |
| Tilapia bones              | 56.5–59.2                         |
| Sea bass bones             | 56.7–59.6                         |
| Tuna bones                 | 56.2–59.3                         |

The substantially higher yield from bones compared with scales reflects their higher mineral content.

#### Protein Hydrolysates and Bioactive Peptides

Fish-processing residues contain proteins that can be converted into hydrolysates and bioactive peptides through:

- enzymatic hydrolysis,
- fermentation,
- acid hydrolysis,
- alkaline hydrolysis,

- ultrasound-assisted hydrolysis, and
- membrane-based fractionation.

Protein hydrolysates have attracted attention because peptides generated during hydrolysis may possess:

- antioxidant activity,
- ACE-inhibitory activity,
- antimicrobial activity,
- antidiabetic potential,
- anti-inflammatory activity, and
- metal-chelating activity.

Reviews published in recent years identify fish frames, skin, scales and viscera as important sources of bioactive protein fractions.

A major advantage of enzymatic hydrolysis is that it can transform relatively low-value protein material into fractions with greater functional value.

### Recovery of Omega-3 Fatty Acids

#### Fish-processing lipids as a source of EPA and DHA

Viscera, liver, heads and trimming fractions can contain significant quantities of recoverable lipids.

A quantitative review of aquaculture and food by-products reports substantial EPA and DHA concentrations in different fish tissues. For example, cod viscera contained approximately 7.4–13.3% EPA, while DHA ranged from 8.5–22.0% depending on the material examined. Haddock viscera contained approximately 7.7–15.7% EPA and 10.3–20.2% DHA.

Trout processing by-products provide another example. EPA and DHA in oil from spines, heads and viscera were approximately:

- **Spines:** 8.7% EPA and 7.3% DHA
- **Heads:** 7.9% EPA and 6.3% DHA
- **Viscera:** 6.4% EPA and 6.0% DHA.

Table 5. EPA and DHA in selected fish-processing by-products

| Species/by-product | EPA (%)  | DHA (%)   |
|--------------------|----------|-----------|
| Trout spines       | 8.7      | 7.3       |
| Trout heads        | 7.9      | 6.3       |
| Trout viscera      | 6.4      | 6.0       |
| Cod viscera        | 7.4–13.3 | 8.5–22.0  |
| Haddock viscera    | 7.7–15.7 | 10.3–20.2 |
| Saithe viscera     | 5.0–10.2 | 5.9–21.9  |

These values demonstrate the potential of fish-processing residues as alternative sources of omega-3 fatty acids.

### Value-Added Products from Aquaculture Waste

The most important aspect of valorization is conversion of by-products into commercially useful products.

Table 6. Fish-processing by-products and potential value-added products

| By-product        | Major recovered compound | Value-added product        | Application              |
|-------------------|--------------------------|----------------------------|--------------------------|
| Skin              | Collagen/gelatin         | Films, coatings, cosmetics | Food/packaging/cosmetics |
| Scales            | Collagen                 | Collagen peptides          | Nutraceuticals           |
| Scales            | Hydroxyapatite           | Biomaterial                | Bone/dental applications |
| Bones             | Collagen/minerals        | Hydroxyapatite             | Biomedical               |
| Viscera           | Lipids                   | Omega-3 oil                | Nutraceuticals           |
| Viscera           | Enzymes                  | Enzyme preparations        | Food/biotechnology       |
| Heads             | Protein/minerals         | Fish protein ingredients   | Food                     |
| Frames            | Protein                  | Protein hydrolysates       | Functional foods         |
| Trimmings         | Protein                  | Fish mince/hydrolysates    | Food                     |
| Skin              | Collagen                 | Edible films               | Food packaging           |
| Viscera           | Lipids                   | Biodiesel                  | Bioenergy                |
| Remaining biomass | Nitrogen/minerals        | Fertilizer                 | Agriculture              |

Fish skin has been investigated for gelatin, edible films and coatings; collagen from scales and bones has applications in cosmetics and pharmaceutical materials; and viscera can be converted into oil, silage and hydrolysates.

### Food Applications

Fish-processing by-products can be incorporated into food products after appropriate processing and safety validation. Potential products include:

- fish protein powder,
- protein hydrolysates,
- fortified bakery products,
- fish cakes,
- sausages,
- soups,
- crackers,
- functional beverages,
- collagen-enriched foods,
- gelatin-based products, and
- calcium-rich food ingredients.

Tilapia processing by-products, for example, have been investigated for incorporation into fish cakes, sausages and bread.

Fish gelatin can additionally be incorporated into edible films and coatings, providing an alternative to some conventional packaging materials.

### Agricultural Applications

Fish-processing residues can also be converted into agricultural products.

Potential applications include:

- organic fertilizer,
- nitrogen fertilizer,
- fish silage,
- protein-rich feed ingredients,
- mineral supplements,
- soil amendments, and
- plant-growth-promoting formulations.

One experimental study demonstrated that metabolites released from enzymatically treated fish scales could be used as a nitrogen source for plant growth.

This provides a useful example of cascade utilization, in which a single waste stream can generate multiple products before the remaining fraction is returned to agriculture.

### Environmental Benefits of Valorization

The environmental argument for fish-waste valorization is closely linked to the biochemical nature of the material.

Uncontrolled disposal of fish residues can increase:

- biological oxygen demand,
- ammonia,
- sulfide,
- odor,
- microbial growth,
- methane generation,
- and nutrient loading.

## V. CONCLUSION

Fish-processing residues represent a substantial but underutilized resource within the expanding aquaculture and aquatic-food economy. Global aquaculture production of aquatic animals exceeded 100 million tonnes in 2024, while global fisheries and aquaculture production reached approximately 235 million tonnes. Processing can leave approximately 30–70% of fish biomass as side streams, creating a major opportunity for resource recovery.

The quantitative evidence demonstrates that these residues contain several commercially important compounds. Fish scales and bones can contain approximately 30–40% organic collagen matrix, while their mineral fraction can reach 60–70%. Reported collagen extraction yields vary widely according to species and processing conditions, while hydroxyapatite recovery from fish bones can approach 56–60% in some systems. Fish-processing lipids are also significant sources of EPA and DHA, with several by-products demonstrating substantial omega-3 proportions.

The evidence therefore supports a transition from conventional waste disposal → low-value utilization → high-value cascade valorization.

The most promising future model is an integrated fish-waste biorefinery, in which protein, collagen, gelatin, peptides, omega-3 lipids, hydroxyapatite and minerals are

sequentially recovered before the remaining biomass is directed toward feed, fertilizer or bioenergy. Such systems could reduce environmental burdens while generating additional economic value and supporting circular production.

However, laboratory-scale extraction yields cannot automatically be translated into commercial profitability. Future studies must combine yield, purity, bioactivity, processing cost, energy consumption, water use, environmental impact, regulatory compliance and market value. The development of standardized quantitative indicators and pilot-scale validation will be essential for transforming fish-waste valorization from a promising research concept into a commercially viable component of sustainable aquaculture.

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