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Valorization of Underutilized Plant and Fishery Byproducts for Sustainable Food Systems and Biodiversity Conservation: A Comprehensive Review

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Abstract

Food processing and fish handling generate very large quantities of plant residues (peels, seeds, pomace, bran, stems) and fishery wastes (heads, frames, skin, scales, viscera, shells), which are still discarded, landfilled or used at low value in many regions. These streams are not waste in a nutritional sense: they contain dietary fibre, polyphenols, carotenoids, proteins, bioactive peptides, omega-3 fatty acids, collagen, chitin and minerals. This review critically examines the composition of underutilized plant and fishery byproducts, the extraction and bioconversion technologies used to recover value from them (conventional solvent extraction, ultrasound- and microwave-assisted extraction, supercritical fluid extraction, enzymatic hydrolysis, fermentation and membrane processing), and the products that result, including functional foods, protein hydrolysates, edible coatings, biopolymers and nutraceuticals. We further discuss how byproduct valorization contributes to biodiversity conservation by reducing pressure on wild resources, lowering pollution loads on terrestrial and aquatic ecosystems, and promoting neglected and underutilized species within circular bioeconomy models. Technical, safety, economic and regulatory barriers are analysed, and research priorities are proposed, including integrated biorefineries, green extraction, life cycle assessment and context-specific models for developing economies such as India.

Keywords: valorization; food processing byproducts; fishery waste; bioactive compounds; circular bioeconomy; biodiversity conservation; sustainable food systems

1. Introduction

The global food system faces a double challenge: producing nutritious food for a growing population while reducing its environmental footprint. An estimated one third of food produced for human consumption is lost or wasted along the supply chain, and fruits, vegetables, roots and tubers show some of the highest loss rates (Gustavsson et al., 2011). Food processing contributes a large share of this burden because peeling, pressing, juicing, filleting and shelling inevitably generate residues. When these residues are dumped, they decompose and release greenhouse gases, contaminate soil and water, and represent a loss of nutrients and embedded resources such as water, land and energy.

Fisheries and aquaculture add a second major stream. Global production of aquatic animals and algae exceeded 200 million tonnes in 2020, and aquatic foods are an important source of protein and micronutrients for billions of people (FAO, 2022). A substantial proportion of every fish or shellfish, which varies with species and processing method, is removed during processing as heads, frames, skin, viscera, scales or shells. Historically these materials were converted into low-value fishmeal or discarded, with local pollution and odour problems near processing centres (Caruso, 2015; Yan and Chen, 2015).

Research over the past two decades shows that these byproducts are rich reservoirs of molecules with technological and health-promoting properties (Galanakis, 2012; Kim and Mendis, 2006; Ben-Othman et al., 2020). Valorization, the conversion of low-value residues into higher-value products, is therefore central to circular bioeconomy strategies (Kardung et al., 2021; Mirabella et al., 2014).

The link with biodiversity is less often discussed but equally important. Roughly one third of assessed marine fish stocks are fished at biologically unsustainable levels (FAO, 2022), and agricultural intensification relies on a narrow set of crop species. Making full use of what is already harvested reduces the need for additional extraction, while valorizing neglected and

underutilized species (NUS) can widen the food base, strengthen local livelihoods and give farmers an economic reason to conserve genetic diversity (Padulosi et al., 2013; Hunter et al., 2019; Mabhaudhi et al., 2019).

Despite many reviews on either plant or fishery byproducts, few treat the two together or connect valorization explicitly to conservation outcomes. This review addresses that gap. Its objectives are to (i) summarise the composition and bioactive potential of underutilized plant and fishery byproducts, (ii) compare valorization technologies, (iii) describe application areas, (iv) analyse the contribution to biodiversity conservation and sustainable development, and (v) identify challenges and future directions.

2. Review methodology

This review followed a structured narrative approach. Literature was searched in Scopus, Web of Science and Google Scholar using combinations of the term's valorization, valorisation, byproduct, by-product, food waste, fish waste, fishery discards, bioactive compounds, protein hydrolysate, chitin, collagen, edible coating, circular economy and biodiversity. [Insert dates of search and number of records identified.] Peer-reviewed articles, reviews and authoritative reports (for example FAO and UN documents) published in English were included. [Insert inclusion and exclusion criteria, number of records screened and number finally included; a PRISMA-style flow diagram may be added as Figure 1.] Priority was given to studies reporting composition, extraction conditions, bioactivity or application trials, and to recent work on sustainability assessment.

3. Underutilized plant byproducts

3.1 Sources and generation

Plant byproducts arise at every stage from harvest to industrial processing. Typical examples include fruit peels and seeds from juice, pulp and jam industries, pomace from pressing, cereal bran and husk from milling, and leaves, stems and trimmings from vegetable handling. Many are seasonal, geographically concentrated and highly perishable because of high moisture, which limits their use unless they are stabilised quickly (Sagar et al., 2018; Majerska et al., 2019).

3.2 Composition and bioactive potential

Peels, seeds and pomace often contain higher concentrations of phenolic compounds, carotenoids and fibre than the edible pulp. Mango peel, for example, has been shown to contain substantial phenolics and carotenoids with antioxidant activity (Ajila et al., 2007). Citrus processing residues are a source of dietary fibre with good water- and oil-holding capacity (Marín et al., 2007), and winery byproducts such as grape pomace and seeds are rich in flavonoids, stilbenes and proanthocyanidins with reported antioxidant, anti-inflammatory and cardioprotective effects (Teixeira et al., 2014). Phenolic compounds as a class are associated with antioxidant activity and a range of health effects (Shahidi and Ambigaipalan, 2015).

Table 1. Representative plant byproducts, key constituents and potential uses

Byproduct	Main constituents	Potential applications
Mango peel and kernel	Polyphenols, carotenoids, fibre, kernel fat	Natural antioxidants, fibre-enriched bakery, functional ingredients
Citrus peel and pulp	Pectin, flavonoids, essential oils, fibre	Gelling agents, dietary fibre, flavouring, preservatives
Grape pomace and seeds	Proanthocyanidins, anthocyanins, fibre, seed oil	Nutraceuticals, natural colourants, functional foods
Cereal bran and husk	Arabinoxylans, phytic acid, B vitamins, silica	Fibre ingredients, prebiotics, biocomposites
Vegetable trimmings and leaves	Fibre, minerals, chlorophyll, phenolics	Powders, extracts, feed, compost

Note: compositions vary widely with cultivar, maturity and processing; see cited reviews for quantitative ranges.

3.3 Link to underutilized species

Neglected and underutilized crops, including many local millets, wild fruits and traditional leafy vegetables, are often adapted to marginal environments and nutritionally dense, yet commercially overlooked (Padulosi et al., 2013; Hunter et al., 2019). Their processing residues have received even less attention. Including them in valorization research can create value chains that reward the cultivation of diverse species, an important point for in situ conservation of agrobiodiversity.

4. Underutilized fishery byproducts

4.1 Sources and generation

Fish and shellfish processing generates heads, frames, trimmings, skin, scales, viscera, blood and shells. The proportion varies widely by species and by whether the product is sold whole, filleted or canned. Canning residues from sardine and mackerel, for instance, have been reviewed as sources of oils, proteins, collagen and minerals (Ferraro et al., 2013). Crustacean processing yields shells rich in chitin, proteins, pigments and calcium (Kandra et al., 2012; Yan and Chen, 2015).

4.2 Composition and bioactive potential

Fishery byproducts can contain high-quality protein, omega-3 long-chain polyunsaturated fatty acids, collagen and gelatin, calcium and other minerals, enzymes, and chitin and its derivatives (Kim and Mendis, 2006; Caruso, 2015). Fish protein hydrolysates produced by enzymatic treatment have shown antioxidant, antihypertensive and other bioactive properties as well as good functional behaviour in foods (Kristinsson and Rasco, 2000; Chalamaiah et al., 2012). Collagen and gelatin from skin, scales and bones are alternatives to mammalian sources, relevant for cultural, religious and disease-risk reasons (Gómez-Guillén et al., 2011). Chitin and chitosan from crustacean shells have been widely studied for antimicrobial, film-forming and chelating properties (Hamed et al., 2016).

Table 2. Representative fishery byproducts, key constituents and potential uses

Byproduct	Main constituents	Potential applications
Heads, frames, trimmings	Protein, lipids, calcium, phosphorus	Protein hydrolysates, bone-derived minerals, fish sauces, feed
Skin and scales	Collagen, gelatin	Gelatin, collagen peptides, edible films, biomedical materials
Viscera	Lipids, digestive enzymes	Fish oil, proteases and lipases, silage
Crustacean shells	Chitin, protein, astaxanthin, calcium carbonate	Chitosan, carotenoid pigments, edible coatings, water treatment
Canning residues	Oils, protein, minerals	Omega-3 concentrates, hydrolysates, mineral supplements

Note: values depend on species, season and processing method.

5. Valorization technologies

5.1 Pre-treatment and stabilisation

Because byproducts are perishable, rapid stabilisation by chilling, freezing, drying, acidification or ensiling is the first step. Drying and milling convert wet residues into powders that can be stored and incorporated into foods, but drying conditions must be selected to limit loss of heat-sensitive bioactives (Majerska et al., 2019; Sagar et al., 2018).

5.2 Extraction of bioactives

Conventional solvent extraction is simple and widely used but consumes large volumes of solvent, time and energy. Emerging technologies aim to improve yield and selectivity while reducing environmental impact (Galanakis, 2012). Ultrasound-assisted extraction improves mass transfer through cavitation and has been applied to a range of food and natural products

(Chemat et al., 2017). Microwave-assisted extraction, pressurised liquid extraction, pulsed electric fields and supercritical CO2 extraction offer further options, particularly for lipids and thermolabile compounds. Selection depends on target compound, matrix, cost and scale.

5.3 Enzymatic and biological processing

Enzymatic hydrolysis with proteases is the most common route to fish protein hydrolysates and bioactive peptides; degree of hydrolysis, enzyme type and conditions determine functional and bioactive properties (Kristinsson and Rasco, 2000; Chalamaiah et al., 2012). Carbohydrases and pectinases improve release of phenolics and fibre from plant residues. Solid-state and submerged fermentation can convert residues into enzymes, organic acids, single-cell protein and other products, while also enhancing nutritional quality (Pandey et al., 2000; Ravindran and Jaiswal, 2016). Biological chitin extraction by lactic acid bacteria fermentation or enzymes is being explored as a lower-impact alternative to harsh chemical demineralisation and deproteinisation (Hamed et al., 2016; Yan and Chen, 2015).

5.4 Separation, concentration and drying

Membrane filtration (ultrafiltration, nanofiltration) fractionates hydrolysates and extracts by molecular weight and removes salts and solvents. Spray drying, freeze drying and encapsulation then stabilise and protect bioactives for use in foods.

Table 3. Comparison of selected valorization technologies

Technology	Advantages	Limitations
Conventional solvent extraction	Simple, low equipment cost	High solvent use, long time, possible degradation
Ultrasound-assisted extraction	Shorter time, better yield, scalable	Equipment cost, possible radical formation
Supercritical CO_2 extraction	Solvent-free, good for lipids	High capital cost, limited for polar compounds
Enzymatic hydrolysis	Mild conditions, bioactive peptides	Enzyme cost, bitterness, process control
Fermentation	Low energy, value-added metabolites	Strain and substrate dependence, contamination risk
Membrane separation	Selective fractionation, mild	Fouling, membrane cost

5.5 Integrated biorefinery concept

Rather than targeting a single compound, a biorefinery fractionates a residue in a cascade, for example recovering oil first, then protein, then minerals, with the remainder going to feed, fertiliser or energy. Cascading use increases total value and reduces residual waste, and is consistent with circular bioeconomy principles (Kardung et al., 2021; Ravindran and Jaiswal, 2016).

6. Applications of valorized products

6.1 Functional foods and ingredients

Fibre-rich powders from peels, pomace and bran can be added to bakery, dairy and meat products to improve nutritional value and texture, although high levels may affect colour, taste and sensory acceptance (Majerska et al., 2019; Marín et al., 2007). Fish protein hydrolysates and collagen peptides serve as protein fortifiers and bioactive ingredients in beverages, sports nutrition and clinical foods (Chalamaiah et al., 2012).

6.2 Natural preservatives, edible films and coatings

Plant extracts rich in phenolics and chitosan from crustacean shells can act as antimicrobial and antioxidant agents in edible coatings that extend the shelf life of fresh produce and perishable foods (Dhall, 2013; Hamed et al., 2016). Gelatin- and collagen-based films from fish skin offer biodegradable packaging alternatives (Gómez-Guillén et al., 2011). These applications directly reduce post-harvest losses, creating a feedback loop in which valorization of byproducts helps prevent further waste.

6.3 Nutraceuticals and pharmaceuticals

Polyphenols, carotenoids, omega-3 fatty acids, chitooligosaccharides and bioactive peptides from byproducts have been investigated for antioxidant, anti-inflammatory, antihypertensive and other effects (Shahidi and Ambigaipalan, 2015; Kim and Mendis, 2006; Teixeira et al., 2014). Most evidence still comes from in vitro and animal studies, and well-designed human trials remain limited.

6.4 Feed, fertiliser, energy and materials

Residues unsuitable for human food can be converted into animal and aquaculture feed, compost, biochar, biogas or bioethanol. Chitin, cellulose and lignin fractions are used in biomaterials and water treatment (Kumar et al., 2017; Ravindran and Jaiswal, 2016).

7. Contribution to biodiversity conservation and sustainable development

7.1 Reducing pressure on natural resources

Using byproducts fully increases the nutrition obtained from each tonne of crop or catch, which can reduce the need for expanding agricultural land and fishing effort. With roughly one third of assessed fish stocks overexploited (FAO, 2022), maximising the value of landed fish is an important complement to stock management. Diets and production systems that waste less and diversify more are consistently linked with lower environmental impact (Tilman and Clark, 2014; Willett et al., 2019).

7.2 Lowering pollution loads

Disposal of fish waste and fruit and vegetable residues contribute to eutrophication, oxygen depletion and greenhouse gas emissions. Diverting them to valorization lowers organic loads on rivers, coastal waters and soils, protecting aquatic and terrestrial habitats (Mirabella et al., 2014; Caruso, 2015).

7.3 Promoting neglected species and agrobiodiversity

Building value chains around neglected and underutilized plants and under-exploited fish species creates market demand that rewards diversity. This supports on-farm conservation of local varieties, improves dietary diversity and builds climate resilience (Padulosi et al., 2013; Hunter et al., 2019; Mabhaudhi et al., 2019). Care is needed to avoid overexploitation of newly popular species, so that valorization is coupled with sustainable harvest and traceability.

7.4 Alignment with the Sustainable Development Goals

Byproduct valorization contributes to SDG 2 (zero hunger), SDG 3 (health and well-being), SDG 9 (industry and innovation), SDG 12 (responsible consumption and production), SDG 13 (climate action), SDG 14 (life below water) and SDG 15 (life on land) (United Nations, 2015).

8. Challenges and limitations

Technical: Heterogeneous and seasonal feedstocks, rapid spoilage, and difficulty in standardising products complicate processing. Scaling laboratory methods to industrial operations is often limited by cost and equipment availability (Galanakis, 2012; Ravindran and Jaiswal, 2016).

Safety: Byproducts may concentrate undesirable substances, including pesticide residues, heavy metals, microbial contaminants, histamine and allergens such as fish and shellfish proteins. Traceability, hygiene during collection and rigorous quality testing are essential before products enter food chains.

Economic and logistic: Collection, cold chain and transport from dispersed small processors can be more expensive than disposal, particularly where waste regulation is weak. Without clear business cases, valorization remains a laboratory exercise.

Regulatory and consumer-related: Novel ingredients from byproducts need safety assessment and clear regulatory status under national food laws. Consumers may perceive byproduct-derived foods negatively, so communication and labelling matter.

Evidence gaps: Many health claims rest on in vitro data; bioavailability, dose and long-term safety of byproduct-derived compounds need human studies. Life cycle assessment and techno-economic analysis are missing for most valorization routes.

9. Future perspectives

1. **Green and hybrid extraction:** combining ultrasound, enzymes, deep eutectic solvents and supercritical fluids to reduce solvent and energy use.
2. **Integrated biorefineries:** cascading recovery that treats plant and fishery residues from the same region together, for example in coastal agro-processing clusters.
3. **Life cycle and techno-economic assessment:** to show whether valorization routes truly reduce environmental impact and are commercially viable.
4. **Digital tools:** sensors, modelling and machine learning for process optimisation, traceability and quality control.
5. **Human clinical evidence:** well-designed trials for byproduct-derived nutraceuticals and functional ingredients.
6. **Conservation-linked value chains:** certification and benefit-sharing for products derived from neglected species and from sustainably managed fisheries.
7. **Context-specific models for India and other developing economies:** India has large horticultural, cereal and fisheries sectors, and decentralised, low-cost valorization units linked to cooperatives, farmer-producer organisations and fishing communities could convert disposal problems into rural income. [Authors may add India-specific statistics and policy references here.]

10. Conclusion

Underutilized plant and fishery byproducts represent an under-tapped resource of fibre, antioxidants, proteins, lipids, collagen and chitin. Advances in green extraction, enzymatic and microbial processing and biorefinery design now make it possible to convert these streams into functional foods, natural preservatives, biopolymers and nutraceuticals. Beyond waste reduction, valorization supports biodiversity conservation by easing pressure on wild and cultivated resources, reducing pollution and rewarding diversity in production systems. Realising this potential requires attention to safety, economics, regulation and evidence, and closer collaboration between food technologists, botanists, zoologists, economists and policy makers.

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