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Review

Application of fruit and vegetable processing by-products as ingredients in aquafeed

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Abstract

Aquaculture is the fastest-growing sector in the food industry. To support this growth, approximately 53 million tonnes of aquafeed are produced each year. Traditionally supported by fishmeal and fish oil, the modern aquafeed industry searches actively for novel ingredients of high nutritional value, functionality and high sustainability performance. The adoption of circular production models with the re-introduction of food processing waste in aquafeed is a valuable strategy to improve aquaculture sustainable growth. The waste generated from the fruit and vegetable processing industry (F&V by-products) arises as a source for ingredients of high nutritional and functional value. This review gathers the information available on: (i) the nutritional requirements of the most produced freshwater and marine fish species; (ii) on the production of crops that potentially originate valuable by-products for aquafeed. The nutritional and functional value of such by-products are revised as well as the routes to process and transform these by-products into aquafeed ingredients. More than 100 peer-reviewed papers were analysed to collect information on fish nutrition requirements, nutritional evaluation of F&V by-products, their application in aquafeed, and the processing and transformation methods allowing its use. The by-products of olive oil and wine production hold high potential to replace fish meal and fish oil in aquafeed. On the other hand, the extracts of seeds and peels of several fruits and vegetables can be used as a source of functional compounds to improve fish welfare, even if they must constitute a minor component in the feed formulation. The use of F&V by-products in aquafeed requires efficient processing methods to enhance their nutritional value, eliminate anti-nutritional substances, ensure feed safety, and optimise resource utilisation. Emerging technologies like high-pressure homogenization (HPH) and ultrasound-assisted extraction (UAE) are effective to add value to these by-products. However, constraints related to variable composition, scalability of technologies, regulations, market acceptance, sustainability, and waste management costs still halt their full use as ingredients in aquafeed.

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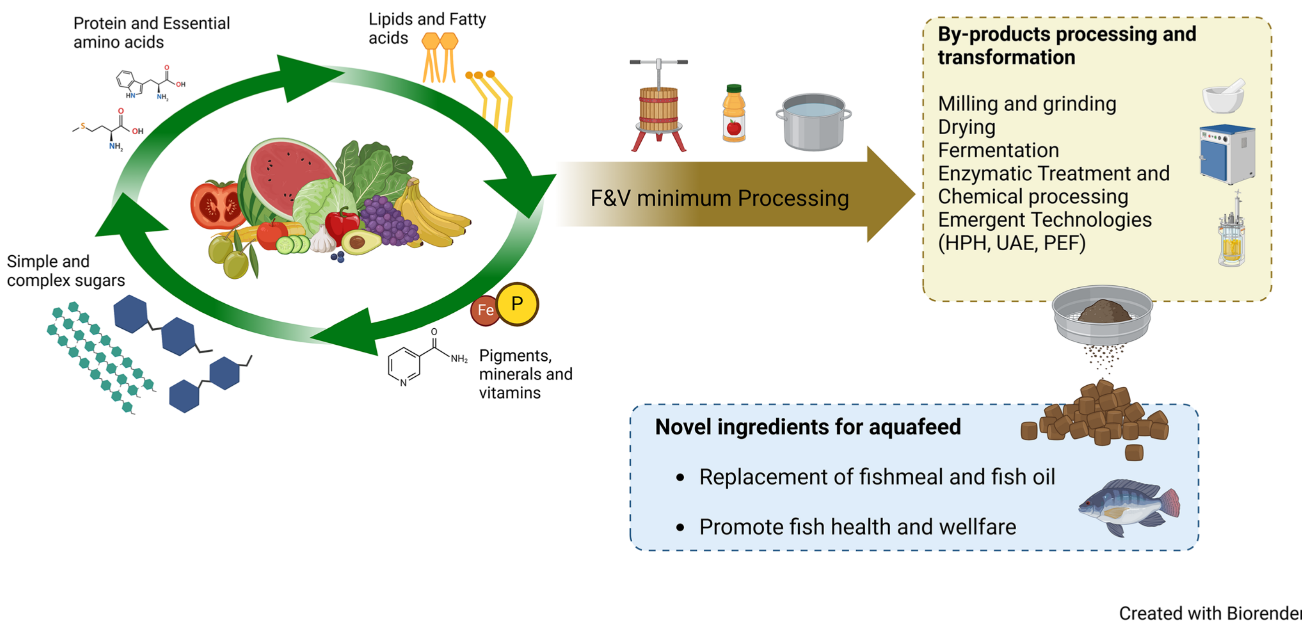
Graphical abstract



Highlights

- Global aquaculture demand for sustainable sources of high-quality ingredients for aquafeed;
- F&V by-products are valuable sources of nutrients and functional molecules;
- Innovative processing and transformation methods are mandatory to increase inclusion rates of F&V by-products;
- Regulatory constraints and technological limitations halt the use of F&V by-products in aquafeed.

Keywords Fish nutrition · Circular economy · Emerging technologies · Functional ingredients · Waste · Add value

1 Introduction

Modern society faces huge challenges to secure healthy food for all. These challenges include overpopulation, climate change, ethical production and responsible consumption of food [31]. The steady growth of the world population requires increasing food production generating large amounts of waste and emissions, increasing vulnerability to climate-related and human health impacts [31]. In this scenario, adopting the circular economy concept has been identified as a power strategy to keep increasing the production of healthy food while reducing the dependence on natural resources. Within the circular economy concept, the waste produced during processing, distribution and consumption can be reduced, reused and recycled [101].

Aquaculture is the fastest-growing food production sector. For the first time in 2022, aquaculture surpassed fisheries, producing today more than 94.4 million tonnes of fish for human consumption [34]. Nowadays, 73% of the world's aquaculture production requires approximately 52.9 million tonnes of aquafeed each year [39] and it is expected to follow the same production trend. Traditionally supported by marine ingredients (fishmeal and fish oil), the aquafeed industry has been progressively sought alternative ingredients that allow sustainable growth of aquaculture. These alternative ingredients should be safe, fair and environmentally and economically sustainable [39].

In 2020, 42 million tonnes of ingredients used in modern aquafeed have a terrestrial origin [39]. The projections for increasing aquaculture production associated with growing concerns regarding the competition for land use, deforestation issues and the intensification of armed conflicts increase the cost of such feedstuff [38]. Most of these plant-derived ingredients are processed to maximize protein concentration, quality, and suitability for use in aquafeed while minimizing anti-nutritive factors [26]. However, they are still unbalanced towards several essential amino acids (EAA) and essential fatty acids (EFA) required for the healthy growth of carnivorous and omnivorous fishes [38]. These issues drive aquaculture nutrition research to identify additional supplements aiming to improve nutritional value and fish health and wellbeing (functionality) [4, 38].

In this context, by-products from fruits and vegetables generated during various stages of food production and processing can serve as a valuable source of essential nutrients [21, 90]. These by-products include a diverse range of organic residues such as rejected pieces, leaves, peels, seeds, and pomaces. Examples include residues from the olive oil and wine industries, as well as from the processing of tomatoes, potatoes, pumpkins, pears, apples, bananas, and brassica vegetables. In recent reviews, several by-products of the agro-industry have been identified and characterized as potential ingredients for aquafeed [22, 64].

However, a thorough analysis of the steps involved in the transformation of waste from major minimum processed F&V into co-products with added value for aquafeed is still missing. In the present review, we crossed the known nutritional requirements of the fish most produced worldwide with the by-products generated for the most important fruits and vegetable crops to achieve such a goal. Being aware that some of these F&V by-products require additional treatment to be incorporated in aquafeed, we also investigate potential treatments to enhance by-products' nutritional value. Finally, we make some considerations about the value chain of such by-products towards the use in modern aquafeed.

2 Bibliographic review methodology

Considering the broad scope of the present review, we started by identifying the fish and F&V crops most produced globally. This identification was made by consultation of the most recent information available in FAO and Eurostat databases and reports. After this initial selection of the boundaries for the systematic review, peer-reviewed papers published preferentially between 2000 and 2023 in scientific journals indexed in the databases Scopus, Web of Science and Mendeley were screened using different selection and exclusion criteria depending on specific sections of this bibliographic review (Table 1), namely: Fish Nutritional Requirements (Sect. 3); Nutritional value and functional properties of selected vegetables and fruits processing by-products (Sect. 5); and Fruits and vegetables by-products processing and transformation (Sect. 6). The section on value chain challenges (Sect. 7) is an opinion section in which the authors critically analyse the challenges identified from waste generation until ingredients incorporation into aquafeed.

3 Fish nutritional requirements

The worldwide fish aquaculture production is dominated by a few freshwater and marine species, mainly carp, the Nile tilapia, catla, Atlantic salmon, milkfish, gilthead seabream, large yellow croaker and the European seabass [34]. All these species share similar nutritional requirements for energy, protein and EAA with some particular differences (Table 2).

Carnivorous species like the Atlantic salmon, croaker, seabream and seabasses require a considerable amount of dietary protein (close to 50% depending on life stage) [53]. Herbivorous fish like the cyprinids (e.g. the common carp *Cyprinus carpio*, the grass carp *Ctenopharyngodon idellus* and the catla *Catla catla*) have a protein requirement close to 40% [54]. In addition to the crude protein content of a diet, its essential amino acid (EAA) profile is crucial for ensuring optimal growth performances. The crude protein requirements can be reduced if a high-quality (balanced EAA:NEAA ratio) protein source is provided [123]. Both freshwater and marine fish share the same ten EAA: Arginine (Arg), Histidine (His), Isoleucine (Ile), Leucine (Leu), Lysine (Lys), Methionine (Met), Phenylalanine (Phe), Threonine (Thr), Tryptophane (Trp), Valine (Val). However specific AA requirements change with the carnivory level of species. Fish of higher trophic level have significantly lower Lysine (Lys), Threonine (Thr) and Phenylalanine (Phe) + Tryptophane (Trp) requirements (%CP) when compared with those of lower trophic level [125].

Lipids are the primary energy source for fish, with a notable difference between freshwater and marine species. Freshwater fish typically require a lipid content of 3–12% dry matter (DM), whereas marine species have higher demands. For instance, the Atlantic salmon require a lipid content ranging between 9 and 30% DM (Table 2). Traditionally, aquafeed relies on fish oil rich in polyunsaturated fatty acids (PUFA), particularly the linoleic (LA, C18:2n-6), and α-linolenic (ALA, C18:3n-3) acids and the n-3 HUFA eicosapentaenoic (EPA, C20:5n-3) and docosahexaenoic (DHA, C22:6n-3) acids. Recently, Castro et al. [11] showed that both marine and freshwater fish can produce endogenously EPA and DHA. However, the efficiency of such biosynthesis

Table 1 Process of papers selection to conducting the bibliographic review on the applications of fruits and vegetable processing by-products as ingredients in aquafeed for the main fish produced

Review section	Sources	Period	Keywords	Exclusion criteria	Papers screened	Papers selected
3. Fish nutritional requirements	FAO website, Scopus, Web of Science and Mendeley	2000–2023*	Nutrition, protein, lipids, energy, essential amino acids, fatty acids, vitamins, minerals	Papers on the nutritional requirements of species other than the selected	50	29
5. Nutritional value and applications of selected fruits and vegetable processing by-products	Scopus, Web of Science and Mendeley	2000–2023	Nutritional composition, banana, broccoli, cauliflower, carrot, pear, potato, pea, pumpkin, grape, tomato, by-products, amino acids, fatty acids, pigments, minerals, vitamins, phenolic content	Studies on F&V by-products that do not match the species or aquafeed application	69	61
6. Fruits and vegetables by-products processing and transformation	Scopus, Web of Science and Mendeley	2015–2023	F&V by-product, process, transform, mill, grid, dry, fermentation, enzymatic treatment, chemical processing, emerging technology, high-pressure homogenization, superfine grinding	F&V by-products for animal feed and human food; papers that discuss classical technologies or processes, such as basic drying or simple mechanical separation techniques, which do not meet the standards of emerging technologies in nutrient retention or bioactive compound preservation	46	23

*Specific nutritional requirements of some fish species were published previously to the revision period. Given the relevance of the information provided these papers were selected

Table 2 Main freshwater and marine fish species produced worldwide and their nutritional requirements

Species	Productio (10^3 tonnes)*	Protein (%DM)*	Lipids (%DM)*	Energy (kcal/g protein)*	EAA (% dietary protein)*	EFA (% Total FA)*	Vitamins (mg/Kg diet)*	Minerals (mg/Kg diet)	Reference
Freshwater species									
Grass carp *Ctenopharyngodon idellus*	6151.6	38.03–38.31	3	5.93	Lys 5.89	LA 1%, ALA 1%, HUFA 0.5%	Vit C 67.17, Vit A IU/Kg, Vit B6 1 mg/Kg, Vit D 1994.80 IU/kg	Se 2.21	[1–9]
Nile tilapia *Oreochromis niloticus*	5002.8	45	12	400 kcal/100 g	Lys 5.12, Arg 4.20, His 1.72; Val 2.80; Leu 3.39; Ile 3.11; Thr 3.75; Trp 1.00; Met 3.21; Phe 5.54	LA and ARA 0.5%	Vit C ~ 125/100 g dry diet Vit B2 5; Vit B6 3; Vit B7 0.06; Vit B9 0.82; Vit K 5.2; Vit B5 10 mg of calcium-pantothenate/kg; Vit A 5.85–6.97 IU/kg; Vit D 374.8 IU/kg; Vit E 42–44 mg/kg of diet and 60–66 mg/kg of diet in 5% and 12% lipid diets, Vit B6 11	Fe 150 -160; Cu 2; Zn 30; Mn 7; Co 1; Se 1; Cr 400 ug/kg	[1, 10, 11, 12, 13, 14, 15, 34]
Common carp *Cyprinus carpio*	4012.7	10–12 g/Kg BW/Day	12% DM	18–20 mg Protein/kJ	Arg 1.6%DM; His 0.8%DM; Lys 2.2%DM; Ile 0.9%DM Leu 1.3%DM; Valine 1.4%DM; Met 1.2%DM; Phe 2.5%DM; Thr 1.5%DM; Trp 0.3%DM	LA and ALA 1%	Vit E 100, Thiamine 0.5 Vit B2 7–14, Vit B6 5–6, Vit B5 30–50, Vit B3 28, Choline 4000, inositol 400, Vit A 10000 IU, Biotin 1 to 10	P 0.6–0.7%; Mg 0.04–0.05%; Zn 15–30; Mn 13; Cu 3; Co 0.1; Fe 150	[1, 16, 33]

Table 2 (continued)

Species	Productio (10^3 tonnes)*	Protein (%DM)*	Lipids (%DM)*	Energy (kcal/g protein)*	EAA (% dietary protein)*	EFA (% Total FA)*	Vitamins (mg/Kg diet)*	Minerals (mg/Kg diet)	Reference
Catla *Catla catla*	4145.1	30	4	3.49	Arg 1.9%DM, His 1.0%DM; Lys 2.5%DM; Ile 0.9%DM; Leu 1.5%DM; Val 1.4%DM; Met 1.4%DM; Phe 1.5%DM; Thr 2.0%DM; Trp 0.4%DM	For broodstock LA 20.8, ARA 3.6, ALA 2.5, EPA 5.2; DHA 2.7	Vit E 98.4 IU/Kg		[1, 16, 17, 18, 19]
Marine Species									
Atlantic salmon *Salmo salar*	2869.4	40–45	24–30	20	Arg 1.6; His 0.7; Ile 0.8; Leu 1.4; Lys 1.8; Met 1; Phe 1.2; Thr 0.8; Try 0.2; Val 1.3	EPA 0.5, DHA 1	Vit A 12300 IU/kg/ BW day, Vit D 2000 IU/Kg; Vit E 100, Vit K 1, Vit B5 20, Vit B3 10, Vit B12 0.2, Choline 1000 mg/kg; Inositol 300, Ascorbic acid 50, Vit B1 6.5, Vit B2 6.5, Vit B6 2 to 8, biotin 0.2 to 0.7, folic acid 2.1	P 0.6%; K 0.7%; Fe 60; Cu 3; Mn 15; Zn 50; Se 0.3	[1, 19, 31, 33]
Milkfish *Chanos chanos*	1196.1	40	9	2740 kcal/Kg diet	Arg 2, His 4.0, Ile 5.1, Leu 4.0, Lys 2.5, Met 2.8–4.2, Phe 4.5, Thr 0.6; Trt 3.6, Val 5.2	ALA 1%, EPA 0.5%, DHA 0.5%	Vit C 1500, Vit E 50	P and Fe are required	[1, 20, 21, 22, 23, 24]

Table 2 (continued)

Species	Productio (10^3 tonnes)*	Protein (%DM)*	Lipids (%DM)*	Energy (kcal/g protein)*	EAA (% dietary protein)*	EFA (% Total FA)*	Vitamins (mg/Kg diet)*	Minerals (mg/Kg diet)	Reference
Gilthead seabream *Sparus aurata*	344.4	40–45	12–25	18 MJ/kg DP/DE ratio 24 g/MJ	Arg 5.4, His 1.7, Ile 2.6, Leu 4.5, Lys 5, Met 2.4, Phe 2.9, Thr 2.8, Trt 0.6, Val 3	PUFA n3 1% DHA 0.6% DHA Ratio EPA:DHA 1	Vit A 2500 IU/Kg, Vit D 2400 IU/Kg, Vit E 50, Vit K 10,, Vit B2 4, Vit B6 3, Vit B5 20, Vit B3 10, Folic acid 1, Vit B12 0.01, Choline 1000 mg/kg; Inositol 300, biotin 0.15, Ascorbic acid 50, thiamine 5 to 10	P 0.65%	[1, 19, 25, 33]
Large yellow croaker *Larimichthys crocea*	257.7	49–52	9	Unknown	His < 1.40%DM, Lys 2.4–2.5% DM			P 0.91%	[1, 26, 27, 28, 29]
European sabass *Dicentrarchus labrax*	293.6	42–48	18–20	19 mg/kJ DP: DE	Lys 4.4; Met 1.8–1.9; Thr 2.3–2.6; Arg 3.9; Trp 0.5–0.7	Total EFA 1%	Vit A 121000 IU/Kg; Vit C 5–200, Vit D3 27600 IU/Kg, Vit E 50, Vit K 10, Vit B1 1, Vit B2 4, Vit B6 3, Vit B5 20, Vit B3 10, Folic acid 1, Vit B12 0.01, Choline 1000, Inositol 300, Biotin 0.15, ascorbic acid 50	P 8	[1, 19, 30, 32]

The information presented included the data available for distinct life cycle stages and is merely indicative. The bibliographic references consulted to build the table are supplied in the supplementary material

*Unit used to represent data, otherwise specific units are provided. Essential Amino Acids (EAA): Arginine (Arg), Histidine (His), Isoleucine (Ile), Leucine (Leu), Lysine (Lys), Methionine (Met), Phenylalanine (Phe), Threonine (Thr), Tryptophane (Trp), Valine (Val); Essential Fatty acids (EFA): n-6 Polyusanturated fatty acids (n-6 PUFA)—Linoleic acid (C18:2n-6, LA), Arachidonic acid (C20:4n-6, ARA)—and n-3 PUFA—α-linolenic acid (C18.3n-3, ALA), Eicosapentaenoic acid (C20:5n-3, EPA) and Docosahexaenoic acid (C22:6n-3, DHA). Minerals: Selenium (Se), Iron (Fe), Copper (Cu), Zinc (Zn), Managenese (Mn), Cobalt (Co), Chromium (Cr), Magnesium (Mg) Phosphorus (P), Potassium (K) is species-dependent [124]. In general, marine fish are unable to synthesize EPA and DHA, while some diadromous fish like Atlantic salmon and herbivorous like the common carp can elongate EPA and DHA through ALA provided by the diet [124]. Additionally, the requirement for EPA is typically higher than that for DHA, and all these FA are considered essential [119].

Both freshwater and marine fish require energy for their metabolic processes and growth. The energy provided is a result of the metabolic oxidation of proteins, lipids and carbohydrates contained therein [51, 94]. In a growing fish, new tissues are built and part of the energy supplied by the diet is firstly used to synthesise structural biomolecules (i.e. proteins, nucleic acids and membrane lipids) and then to produce storage molecules (mainly triglycerides and glycogen). In traditional aquatic nutrition, energy was essentially supplied by fishmeal and fish oil. However, with the inclusion of plant-based ingredients, other energy sources (i.e. starch) are made available, which decreases protein and lipid requirements [110]. The optimal dietary level of carbohydrates is mostly controlled by the ability of fish to digest and assimilate starch [54]. While herbivorous species like the common carp cope well with starch inclusion levels of 45% [54], salmon and seabass have a lower ability to process high amounts of starch [51]. In both cases, transformation processes like cooking and extrusion can improve its digestibility [82].

Vitamins play important roles in fish embryogenesis, skeletal integrity and growth, reproduction, immune system response, vision, fish appetite, and flesh quality [20, 23, 41, 43, 100]. Although vitamin requirements are low, vitamin-deficient diets can result in skin and fin erosion/haemorrhage, clubbed gills and other organ damage, anaemia, cataracts, exophthalmia, erratic swimming, hyperirritability, convulsions and other nervous dysfunctions [74]. Several of these vitamins naturally occur in fishmeal and fish oil as well as in terrestrial ingredients [74]. Carotenoids (such as -carotene, astanxanthin and cataxanthin) complement and sometimes partially replace the metabolic functions of vitamins A, E and C due to their anti-inflammatory properties and strong antioxidant activity. Therefore, the inclusion of carotenoids in aquaculture feeds may result in a reduced need for these vitamins [23, 100].

The role and requirements of minerals and particularly trace elements for the growth and health of fish have been poorly studied. Except for phosphorus (P) and calcium (Ca) which are key elements for osteogenesis, the role of zinc (Zn), selenium (Se), Manganese (Mn) and other trace elements only recently started to be examined. Traditionally considered abundant, phosphorus and calcium sources have been more frequently included in modern aquafeed. Phosphorus requirements are known for the common carp, the Atlantic salmon, the gilthead seabream, the large yellow croaker and the European seabass (Table 2). Zinc is vital for immune function and inflammation regulation in fish, while selenium enhances antioxidant defence mechanisms and immune responses. Magnesium helps maintain immune system integrity and has anti-inflammatory properties, all of which contribute to the overall health of aquaculture fish [62, 122].

Phytogenic molecules like carotenoids, polyphenols, flavonoids some polysaccharides and bioactive peptides improve fish's anti-oxidative and anti-inflammatory response [30]. These molecules are very abundant in several non-conventional terrestrial ingredients like leaves, roots, tubers and fruits [21, 64, 81], and their inclusion in aquafeed has been progressively required due to their beneficial effect on the growth performance and the immune response of fish.

The carotenoids are fat-soluble pigments, commonly found in fruits, vegetables, and certain grains, classified into two functional groups: the xanthophylls that include lutein and zeaxanthin; and the carotenes that include α-carotene, β-carotene and lycopene [108]. Astaxanthin, canthaxanthin, fucoxanthin and β-carotene occur naturally in the diet of fish and have an important role in preventing diseases, reducing inflammation and maintaining good health [63, 67, 77, 79, 80, 97, 107]. Moreover, carotenoids have an important role in fish muscle pigmentation contributing to the fillet colour, contributing to an increase in the attractiveness of aquaculture products among consumers [97]. Feed supplementation with carotenoids is essential for the Atlantic salmon and other salmonids (mainly astaxanthin and cataxanthin) as well for shrimp production. In wild salmonids, carotenoid levels may range from 26 to 39 mg/kg for sockeye salmon (*Oncorhynchus nerka*) to 8–9 mg/kg for chinook salmon (*O. tshawytscha*) and more than 3 mg/kg in rainbow trout (*O. mykiss*) [10, 79].

Considerable work has reinforced the demand for the production and use of natural sources of astaxanthin as a pigment colouring agent that currently covers most world markets [70, 87, 100]. In the European Union, canthaxanthin is currently used alone or together with astaxanthin up to a concentration of 25 mg per kg of feed for salmonids [126]. To obtain organoleptic properties suitable for the commercial market, a minimum concentration of carotenoids (canthaxanthin or astaxanthin) of 8 mg/kg is required for salmonids, with the maximum allowed being 13.7 mg/kg [127].

4 Fruits and vegetables processing by-products availability

In light of the EU's Blue Growth strategy (2021) [19], the aquaculture sector is required to adopt more efficient and sustainable production processes. The introduction of waste produced by terrestrial crops, particularly F&V by-products as nutrient sources represents an opportunity to improve the sustainability of aquafeed production. Fruit and vegetable

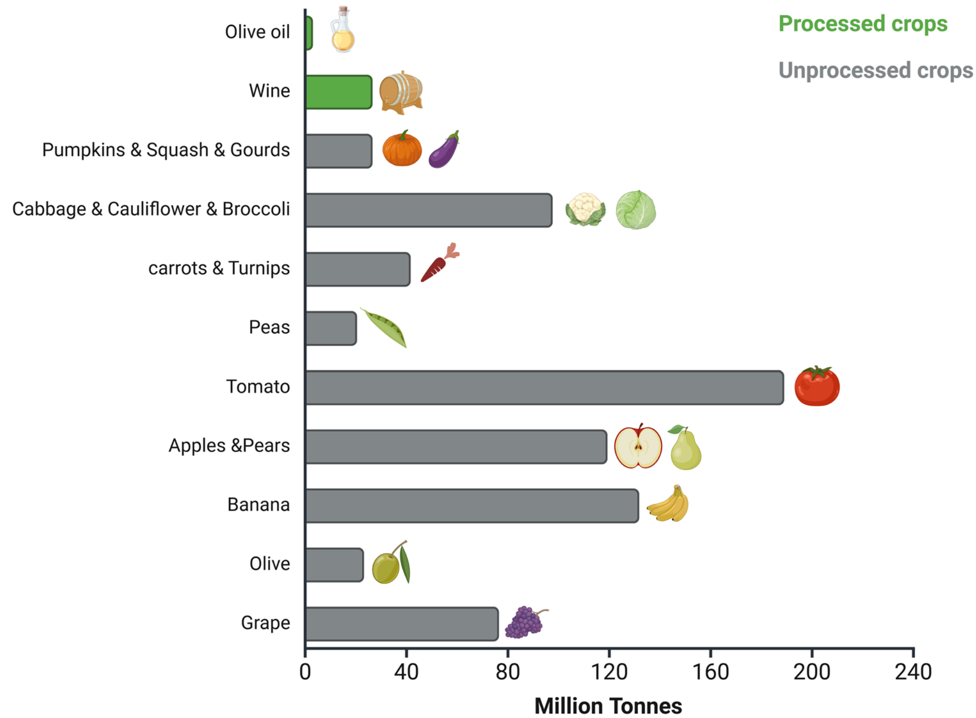


Fig. 1 Global production in 2021 of the main processed and unprocessed crops and processed products (data source: Eurostat, 2024)

by-products are low-cost [22] and constitute an opportunity to adopt circular economy criteria for aquafeed production, increasing the availability of valuable nutrients, reducing its environmental impact on the food production sector and adding value to these by-products.

The global production of primary crops has followed the same trajectory observed in the aquaculture industry. Between 2000 and 2021, there was a remarkable increase of 54% in the production of cereals, sugar crops, vegetables, oils, and fruits [33]. In 2021, vegetables and fruits accounted for 19% and 17% of total annual primary crop production, 1154.6 million tonnes and 909.6 million tonnes, respectively [33]. From those, 189.3 million tonnes of tomatoes and 41.9 million tonnes of carrots, 3.3 million tonnes of olive processing products, 26.9 million tonnes of wine, and 373.8 million tonnes of potatoes [32] were produced. The most widely produced and consumed fresh fruits include bananas (132 million tonnes), apples (93.9 million tonnes), orange fruits (76.3 million tonnes), and grapes (76.7 million tonnes) (Fig. 1). They are also utilized in the food processing industry, resulting in many by-products and waste, for instance, from juice and jam products (Eurostat, 2024), with approximately one-third of fruits were lost as waste during the production and processing stages [128].

5 Nutritional value and aquafeed applications of selected fruit and vegetables by-products

Fruits &Vegetable by-products hold a high nutritional value (Fig. 2). They contain high amounts of simple and complex carbohydrates and high fibre content (mainly in the leaves, peels and pomaces). Fruit pomace is particularly rich in reserve molecules like starch, simple sugars and some lipids, while seeds are interesting sources of polyunsaturated fatty acids (PUFA). Fruits &Vegetables by-products are also important sources of pigments, vitamins, minerals and other compounds of high phytogenic properties (e.g. phenolic acids and flavonoids), immune system enhancers (e.g. organic acids), digestive enzymes, taste and colour enhancers, anti-oxidants and antimicrobial agents (see Table 4 for references).

Some immunomodulatory compounds such as immunoglobulins, lectins, and plant-derived compounds found in the F&V by-products modulate the immune system of aquatic organisms, enhancing their resistance to pathogens and diseases. Additionally, some by-products serve as prebiotics or contain probiotic microorganisms (Fig. 2), promoting the growth of beneficial gut bacteria in fish and enhancing their immune function [106]. It is also worth noting that F&V by-products contain compounds with antimicrobial properties (Fig. 2), which can help control the growth of pathogens in aquaculture systems, indirectly reducing inflammation by preventing infections. Polyphenols found in these by-products

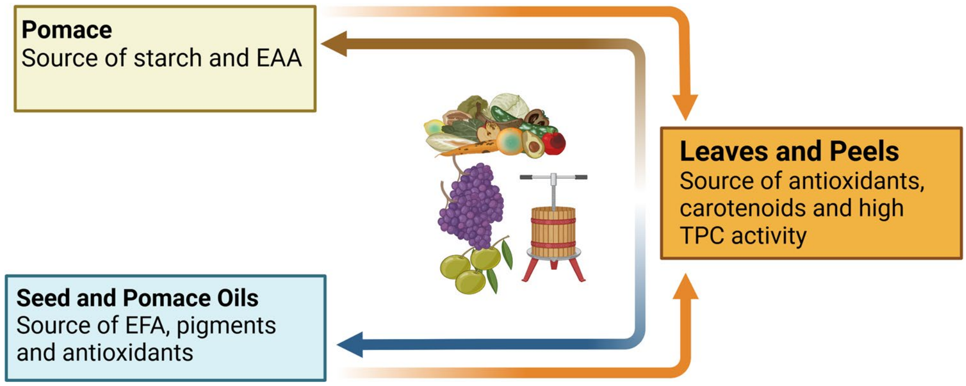


Fig. 2 Replacement and functional properties of different fruit and vegetable by-products (created in BioRender)

possess antimicrobial properties against various fish pathogens. They inhibit the growth of bacteria such as *Aeromonas hydrophila* and *Vibrio* spp., common pathogens in aquaculture, thereby reducing the risk of infection in fish [58].

By-products containing essential oils, such as citrus peels and seed extracts, have demonstrated antimicrobial activity against fish pathogens (Fig. 2). These oils can inhibit the growth of bacteria and fungi, contributing to improved health and disease resistance in aquaculture fish [117]. It should also be added that lectins derived from vegetable by-products have shown antimicrobial activity against a range of fish pathogens, and stimulate the immune system, enhancing the overall health of fish in aquaculture systems [29]. Also, the enzymes extracted from fruit and vegetable by-products, such as lysozyme and proteases, exhibit antimicrobial activity against bacteria and fungi commonly found in aquaculture environments [106]. Incorporating these antimicrobial agents from F&V industry by-products into aquafeed or directly into aquaculture systems can provide a natural and sustainable approach to improving the health and disease resistance of fish in aquaculture.

5.1 Tomato processing by-products

Tomato processing by-products include peels, seeds, some pulp and fibrous parts, usually referred to as tomato bagasse or pomace. After drying, this waste, mainly composed by fibre, still presents interesting amounts of proteins (Table 3). Unsaturated fatty acids are the major lipidic compounds, particularly LA (C18:2n-6), oleic (C18:1n-9) and ALA (C18:3n-3) (Table 3). Concerning essential amino acid content Arg, Leu, Ile and Phe were found in significant amounts [35, 92]. Moreover, tomato by-products contain several valuable compounds, including carotenoids (as lycopene and β-carotene) and phenolic compounds recognised as enhancer functions (Table 4) [18, 92, 116]. Two studies explored dried tomato pomace as an ingredient for the common carp feed [56, 57]. In a study conducted by Keramat et al. [56]. It was observed that replacing a maximum of 10% wheat flour with tomato pomace powder increased the growth performance and feed efficiency while decreasing protein digestibility. Kesbiç et al. (2022) [57] formulated new feeds for common carp by replacing 0.5, 1, 2 and 5% corn starch with dried tomato pomace. The results showed that, the incorporation of this carotenoid-rich byproduct into the diet, improved fish welfare. Nevertheless, such beneficial aspects of tomato pomace must be proved for other species.

5.2 Olive oil industry by-products

The olive oil industry generates considerable amounts of by-products with relevance for aquafeed industry, namely the olive pomace, olive oil pomace, olive mill wastewater and olive leafs [25, 42]. From those, the olive oil pomace seems the most promising as a (partial) replacement of fish oil [89, 114]. The olive pomace is composed, mainly, of carbohydrates (including fibre) followed by protein and fat (Table 3). The olive pomace oil comprises the lipid fraction of this by-product and is especially rich in oleic acid, followed by palmitic, linoleic, and stearic acids [3]. The amino acid profile of olive pomace (Table 3), includes a wide range of EAA, namely, His, Trp, Phe and Val [62, 90]. This residue is also a rich source of vitamin E (containing several tocopherol structures) as well as antioxidant phenolic compounds [3]. The olive pomace oil was successfully used to replace fish oil with inclusion rates up to 8%—in diets for gilthead seabream and rainbow trout showing that besides the good responses regarding growth performance and feed efficiency, the inclusion of such sources of fatty acids, considerably improved the lipid profile of fish fillet, contributing to enhancing the

Table 3 Nutritional characterization of selected fruits and vegetables by-products with potential to be used in aquafeed

Crop	Nutritional Composition (% DM)*	Major Fatty Acids (% Total FA)*	Essential Aminoacids (mg/100 g DM)*	References
Banana	*Fruits* Carbohydrates (97); Protein (1.3–4.4); Lipids (1.7); Crude Fiber (2.9–5.4) Ash (0.4–2.9)	*Fruits* (mg/100 g DM) C16:0 (243); C18:0 (17); C18:1n-9 and n-7 (27 and 40); C18:2n-6 (145); C18:3n-3 (186); C22:6n-3 (8.9)		[1–3]
	Peels Carbohydrates (44.6–77); Protein (9.7–15); Lipids (5.5–7); Crude Fiber (24); Ash (12.8–25)	*Peels* (mg/100 g DM) C16:0 (411); C18:0 (43); C18:1n-9 and n-7 (43 and 9.9); C18:2n-6 (292) C18:3n-3 (185); C22:6n-3 (4.3)	*Peels* (g/100 g protein) Arg (11.1); Leu (11); Phe (9.6); Ile (9.5); Trp (7.4); Lys (7.2); His (4.6); Thr (2.8) Met (2.5) Val (2.0); Tyr (2)	[2, 3]
	Leaves Carbohydrates (60–71); Lipids (21); Protein (15); Ash (10)			[1]
Brocolli	*Leaves* Carbohydrates (46.2–56.4); Protein (21.6–27.5); Lipids (5); Fiber (25.6–32.9); Ash (14.4–18.6)	*Leaves* C16:0 (23.5–26.6); C18:0 (3.9–5.5); C18:1n-7 (9.2); C18:1n-9 (3.2–3.7); C18:2n-6 (13.1–14.4); C18:3n-3 (47.1–51.8)	*Leaves* (mg/g FM) Tyr (35); Leu (4.6); Thr (4.3); Arg (4.1); His (4.05); Ile (3.5); Phe (2.4); Met (1.1)	[4, 5]
	Stalk Carbohydrates (62.7–68.3); Protein (13.7–18.1); Lipids (0.8–1.7); Fiber (35.8); Ash (7.6–9.1)	*Stalk* C16:0 (28.4); C18:0 (3.5); C18:1n-7 (2.2); C18:1n-9 (2.7); C18:2n-6 (15.9); C18:3n-3 (39.2)	*Stalk* (mg/g FM) Tyr (32); Leu (1.2); Thr (2.8); Arg (3.0); His (2.3); Ile (2.3); Phe (2.5); Met (1.2)	[4]
Cauliflower		*Leaves* C16:0 (27.1–27.3); C18:0 (10.1–11.7); C18:1n-9 (3.7–4.2) C18:2n-6 (13.1–14.5); C18:3n-3 (39.8–42.8)		[5]
Carrots	*Discarded carrots* Carbohydrates (67.9); Protein (6.4); Lipids (0.7); Fiber (22.8); Ash (6.1)	*Discarded carrots* C16:0 (15.6); C18:0 (7.4); C16:1n-7 (2.6) C18:1n-9 (12.6); C18:2n-6 (54); C18:3n-3 (6.3)		[6, 7]
Pear	*Rocha pear pomace* (% FM) Humidity (85.2); Frutose (9.4); Glucose (1.8); Protein (1.5); Lipids (0.02); Fiber (3.5)	*Several cultivars* C16:0 (20–29); C18:0 (0.8–3.2); C18:1n-9 (2–13); C18:2 n-6 (54–69); C18:3n-3 (1.1–6.9)	*Several cultivars*(mg/ 100 FM) His (1- 6.5); Thr (1.5—3.1); Val (1–3.8); Met (0.4–1.4); Ile (0.6–2); Phe (0.5–1.2)	[8, 9]
Apple	*Pomace* Carbohydrates (74.4); Proteins (3.42); Fat (0.26); Fiber (8.9); Ash (1.68) (% FM) Total carbohydrates (44.5–57.4); Frutose (44.7); Glucose (18.1–18.3); Protein (2.7–5.3); Lipids (1.1–3.6) Total fiber (4–47)	*Pomace (Several cultivars)* C16:0 (9.2–9.3); C18:0 (9.7–9.9); C18:1n-9 (13.3–13.6); C18:2n-6 (37.9–38.3); C18:3n-3 (3.9–4.0)	*Pomace (Several cultivars)* (mg/ 100 FM) Val (1.1–2.2); Lys (0.25–3.0); Met (1.2–1.9); Ile (1.1–1.9); Leu (0.5–1.7); Phe (0.46–0.66); Thr (0.56–0.7)	[10–12]
	Whole fruit (% FW) Total carbohydrates (13.8); Fructose (5.8–6.0); Glucose (2.4–2.5); Protein (0.24–0.28); Lipids (0.16–0.18) Total fibre (2.1–2.6)			[11]
		Peels (Several cultivars) C16:0 (3.0–3.8); C18:0 (2.5–2.8); C18:1n-9 (3.2–7.6); C18:2n-6 (83.4–85.1); C18:3n-3 (0.4)	*Peels (Several cultivars)* (mg/ 100 FM) Val (1.6–3.1); Lys (1.6–1.8); Met (1.3–1.4); Ile (3.4–4.1); Leu (0.72–1.1); Phe (0.7–0.8); Thr (0.6–0.9)	[12]
Potato	*Peels (Several cultivars)* Carbohydrates (68.7–88.0); Proteins (2.1–17.2); Lipids (0.7–2.6); Ash (1–9)	*Region between the peel and vascular ring of the tuber* C16:0 (10.5–11.0); C18:0 (3.9–4.0); C18:1n-9 (43.9–45); C18:2n-6 (19.5–20.6); C18:3n-3 (11.3–11.5)	*Peels (several cultivars)* (mg/ 100 DM) Val (154–2325); Tyr (62–112); Phe (43–76); Thr (57–84); Met (44–61); Lys (35–64); Ile (50–76); Leu (20–34)	[13–15]

Table 3 (continued)

Crop	Nutritional Composition (% DM)*	Major Fatty Acids (% Total FA)*	Essential Aminoacids (mg/100 g DM)*	References
Pea	*Pods* Carbohydrates (24.3–28); Protein (13.4–14.2); Lipids (1.3–2.1); Fiber (51–59); Ash (4.5–6.6)	*Pods* C16:0 (21–24); C18:0 (4.5–5); C18:1n-9 (3.6–21.8); C18:2n-6 (35–37.2); C18:3n-3 (9.7–29)	*Seeds and Pods* Lys; Leu; Phe; Thr; Met; Trp	[16–18]
Pumpkin	*Peels* Protein (2.0–23.9); Lipids (0.3–6.6); Fiber (13.9–29.6); Ash (0.4–10.7)		*Peels* Arg; Leu; Ile; His; Lys; Phe; Met; Thr; Val	[19]
	Seeds Protein (14–39.8); Lipids (32–58); Fiber (1–24.9); Ash (2.5–5.5)	*Seeds* C16:0 (1.2–20.8); C18:0 (0.16–7.6); C18:1n-9 (15.6–30.8); C18:2n-6 (26.2–81.2)	*Seeds* Lys; Leu; His; Val; Thr; Ile; Met	[19–21]
Grape	*Pomace (several cultivars)* Starch (5.5–21.6); Proteins (8.9–13.0); Lipids (5.3–9.5); Ash (5.3–6.7)		*Pomace (Several cultivars)* Tre (3350–4110); Arg (710–899); Leu (627–725); Phe (588–669); Val (424–467); Ile (359–401); Lys (328–396); His (318–387); Met (3.5–8.3)	[14, 22]
		Seed oil (Several cultivars) C16:0 (6.9–9.6); C18:0 (3.7–6); C18:1n-9 (13.1–18.5); C18:2n-6 (66.7–72.5)		[23]
Tomato	*Seeds* Protein (15.2–38.7); Lipids (4.0–6.4); Fiber (21.6–22.3)	*Seeds* C16:0 (14.8); C18:0 (5.9); C18:1n-9 (15.5–29.7); C18:2n-6 (37.6–72.7)		[24–26]
	Peels Protein (11.7–21.9); Lipids (3.2–6.0); Fiber (44–59.0)			[24]
	Bagasse Protein (16.3–19.4); Lipids (5.8–21.9); Fiber (52.4–59); Ash (2.9–4.2 Sugars (5.2–25.7)	*Bagasse* C16:0 (16.3); C18:0 (5.43); C18:1n-9 (18.5); C18:2n-6 (51.9) C18:3n-3 (3.35)	*Bagasse* Thr (550 mg/100 g); Arg (1460); Tyr (690); Val (540); Phe (610); Ile (690); leu (1070); Lys (880); Met (270)	[24, 27, 28]
Olive	*Pomace* Total carbohydrates (84.9); Protein (7.4); Lipids (5.8); Ash (1.9)	*Pomace* C16:0 (10.4); C18:0 (3.3); C18:1 n-9 (75.2); C18:2 n-6 (8.5)	*Pomace* His (2138); Thr (160); Tyr (373); Val (711); Met (272); Trp (1187); Phe (1103)	[29, 96]

The bibliographic references that support the data provided are supplied in the supplementary material. The bibliographic references consulted to build the table are supplied in the supplementary material

FM Fresh mass, *DM* Dry mass, *FA* Fatty Acid

*Unit used to represent data, otherwise specific units are provided. Essential Fatty acids (EFA): n-6 Polyunsaturated fatty acids (n-6 PUFA)—Linoleic acid (C18:2n-6, LA), Arachidonic acid (C20:4n-6, ARA)—and n-3 PUFA—α-linolenic acid (C18.3n-3, ALA), Eicosapentaenoic acid (C20:5n-3, EPA) and Docosahexaenoic acid (C22:6n-3, DHA). Essential Amino Acids (EAA): Arginine (Arg), Histidine (His), Isoleucine (Ile), Leucine (Leu), Lysine (Lys), Methionine (Met), Phenylalanine (Phe), Threonine (Thr), Tryptophane (Trp), Valine (Val)

Table 4 Carotenoids, minerals, vitamins and phenolic content of the selected fruit and vegetable and by-products with potential to be used in aquafeed

Crop	Carotenoids (mg/ 100 g DW)*	Major mineral (mg/100 g DM)*	Vitamins (mg/100 g DW)*	Phenolic content (GAE mg /100 g DM)	References
Banana	*Fruits* Total carotenoids content (0.25–0.40) β-carotene (0.0294–0.117)	*Fruits* K (308–1005); P (15–29); Ca (4–25); Cu (0.03–0.4) Zn (0.11–0.9); Fe 0(0.19–2.9); Mn (0.12–1.6); Na (6.5); Mg (72)	*Fruits* Vit C (18.4)	*Fruits* TPC (3–90.4)	[1–3, 31]
	Peels Total carotenoids (0.068–0.450) β-carotene (0.049–0.241)	*Peels* K (4.39–4600); P (204–211); Na (32.5–101-115); Ca (59–2011); Fe (2.5–83); Mg (42–95); Cu (5.6–12.4); Mn (1.4–5.7); Zn (2.3–35)	*Peels* Vit A (3.21); Vit E (1.03); Vit B1 (1.79) and Vit B6 (2.93)	*Peels* TPC (7.1–208) (high levels in unripe peels) Quinic acid (most abundant phenolic compound)	[1–3, 31, 32]
		Leaves K (3.8); P (1.8); Ca (1.2); Fe (0.28); Mn (0.26)		*Leaves* TPC (28)	[1]
Brocolli	*Leaves* Total carotenoids (109.5) β-carotene (48.4); Luteín (24.8); Neoxanthin (20.6); Violaxanthin (15.6)	*Leaves* K (18200); Ca (710); P (507); Na (643); Mg (133); Cu (0.021); Zn (2.27); Fe (1.58); Mn (0.70)	*Leaves* Vit E (Total Tocopherols) (15.5) Vit C (292–454)	*Leaves* TPC (534–2850) Total flavonoids (1137–1293 mg CE/100 DM)	[4, 5]
	Stalk Total carotenoids (1.56) Luteín (0.48); Neoxanthin (1.08)	*Stalk* K (13600); Ca (2899); P (342); Na (263); Mg (167); Cu (0.024); Zn (2.33); Fe (4.01); Mn (2.62)	*Stalk* Vit E (total tocopherols) (0.2)	*Stalk* Total flavonoids (206–370 mg CE/100 DM)	[4]
Cauliflower			Leaves Vit C (372—472)	TPC (900–962) Total flavonoids (444–800 mg CE/100 DM)	[5, 8, 33, 61]
Carrots	Pomace Total carotenoids (8.3)	Discard carrots Ca (571); P (214); Fe (71)		Peels TPC (487)	[6, 34, 35]
Pear		*Rocha pear pomace* (mg/100 g FM) K (136); P (12.5); Ca (11.0); S (8.3); Mg (8.1); Na (4.3); Fe (3.1); Cu (0.18); Zn (0.17); B (0.32)	*Rocha pear pomace* (mg/100 g FM) Vit C (30)	*Rocha pear pomace* (mg/100 g FM) TPC (29,35)	[8]
			Peel (Several cultivars) (mg/100 g FM) Vit C* (11.6–22.8) * Sum of AA and DHAA	*Peel (several cultivars)* TPC (123–200.5)	[36]

Table 4 (continued)

Crop	Carotenoids (mg/ 100 g DW)*	Major mineral (mg/100 g DM)*	Vitamins (mg/100 g DW)*	Phenolic content (GAE mg /100 g DM)	References
Apple		*Pomace* (mg/100 g FM) K (398–880); Mg (18.5–333.5); Na (185.3); Ca (55.6–92.7); P (64.9–70.4); Fe (2.9–3.5); Zn (1.4); Cu (0.1); Mn (0.4–0.8)	*Pomace* (mg/100 g FM) Vit C (2–35); Vit E (5.5)	*Pomace* TPC (324)	[10, 11, 37]
		Whole fruit (mg/100 g FM) K (105–109); Mg (4.9–5.1); Na (0.9–1.1); Ca (5.7–6.3); P (10.7–11.3); Fe (0.11–0.13); Cu (0.026–0.028; Mn (0.033–0.037)			[11]
Potato	*Whole tubers* Total carotenoids (0.28–3.62)	*Whole tubers* Fe (3–15.8); Zn (1.3–2.9); Ca (27–109)	*Whole tubers* Vit C (21.8–68.9)	*Whole tubers* TPC (112–1237)	[38]
		Peels (Several cultivars) K (3330–2430); P (454–290); Ca (110–66); Mg (160–119); Fe (15.1–30.8); Zn (1.75–1.37); B (1.12–0.96); Mn (1.01–0.63); Cu (0.84–0.40)		*Peels* TPC (86.3 in aqueous extract—1400 ethanolic extract) Total flavonoids mg CE/100 DM (100 aqueous extract—330 ethanolic extract)	[13, 39]
Pea		*Pods* K (409–1200); Mg (240–507); Ca (130–3043); Na (84–1739); Fe (1.2–10); Zn (0.16–1.6); Cu (0.06–1.1)	*Pods* C (34.7); B1 (0.53–1.61); B2 (0.07–0.4); B9 (0.05)	*Pods* TPC (3200 in methanolic extract) Total Flavonoids (2200 mg QE/100 g methanolic extract)	[16–18]
Pumpkin	*Peels* Total carotenoids (23.7) β-carotene (4.6–11.9)	*Peels* Na (8.96); K (458); Ca (5571–4.58) P (319); Fe (4.05–247); Zn (0.25–42.9); Cu (12.9)	*Peels* Vit C (ascorbic acid at 18.9)	*Peels* TPC (93–519); Total Flavonoids (45 mg CE/100 g)	[19, 40]
	Seeds Total carotenoids (8.2) β-carotene (0.99**)**	*Seeds* Na (1.93); K (388); Fe (6.16); Ca (5.67); Zn (15.21)	*Seeds* Vit E (α-tocopherol at 0.833–12.3)	*Seeds* TPC (225); Total Flavonoids (139 mg CE/100 g)	[19, 40]
Grape		*Pomace* K (1500–2410); Ca (229–372; P (232–325); Mg (97–121); S (102–135); Fe (11.5–14.7); Al (5.1–15.2); Na (3.3–9.9); Zn (0.73–1.5); Mn (1.4–1.9); Cu (0.8–1.3)	*Pomace* Vit E (α-tocopherol at 8.9–15.7); Vit C (261)	*Pomace* TPC (57–65)	[22, 41]

Table 4 (continued)

Crop	Carotenoids (mg/ 100 g DW)*	Major mineral (mg/100 g DM)*	Vitamins (mg/100 g DW)*	Phenolic content (GAE mg /100 g DM)	References
Tomato	*Pomace* Total carotenoids (670–780); Lycopene (51.1); β-carotene (9.56)	*Pomace (peels and seeds)* Ca (132); Mg (211); K (3030); Na (66.6); Fe (5.6); Mn (1.4); Cu (1.2); Zn (6.3); Cr (0.35); B (1.95)		*Pomace* TPC (92–140) Total flavonoids (41.5 mg QE /100 g DM)	[17, 28, 85]
	Peels Lycopene (100–150); β-carotene (31)				[24]
	Seeds Lycopene (20–13); β-carotene (6.3)				[24]
Olive		*Pomace* K (1756–5431); P (159–476); Mg (50–153); Ca (165–132); Na (17)	*Pomace* Vit E (α-tocopherol) (7.64 mg/100 g)	*Pomace* TPC – mainly Hidroxytyrosol (12.96–35.46 mg GAE /g of methanolic extract)	[29, 30]

The bibliographic references that support the data provide in this table are supplied in the supplementary material. The bibliographic references consulted to build the table are supplied in the supplementary material

DM Dry mass, *FM* Fresh mass, *TPC* Total Phenolic Content, *GAE* Galic acid equivalents, *CE* Catechin equivalents, *QE* Quercetin equivalents

*Unit used to represent data, otherwise specific units are provided. Minerals: Selenium (Se), Iron (Fe), Copper (Cu), Zinc (Zn), Managenese (Mn), Cobalt (Co), Chromium (Cr), Magnesium (Mg) Phosphorus (P), Potassium (K) cardioprotective function of fish fillet in human wealth [114]. Nevertheless, it is important to note that the inclusion level of olive oil by-products is restricted to up to 8% due to anti-nutritional effects [42].

5.3 Wine production by-products

Grape pomace, produced by the wine industry, includes the peels, seeds and stems. This by-product has the potential to be used as a feed aquaculture ingredient [98], since it contains high amounts of starch, proteins and lipids (Table 3). Threonine is the most abundant amino acid whereas other EAA namely Arg, Leu, Phe, Tyr, Val, Ile, Lys and His are also present in significant amounts [15]. Grape seeds contain 12–17% of oil, mainly composed by LA (C18:2n-6), C18:1n-9, C16:0 and C18:0 fatty acids (Table 3) [126]. Polyphenols and flavonoids are also abundant in grape by-products [5, 8, 98]. Recently, Quagliardi et al. [98] reviewed the applications of grape by-products in aquafeed, concluding that this group of by-products can be a valuable phytonutrient to be incorporated into diets to enhance fish growth and health. The inclusion of several grape by-products including grape seed extract, grape pomace flour, and grape seed proanthocyanidins were already tested in aquafeed. The inclusion of 15% of dried grape in a reference diet, resulted in an improvement in growth performance, survival and nutritional indices of common carp [73]. The grape seed extract is a particularly interesting supplement. Recently, Mehrinakhi et al. [78] evaluated the effect of grape seed extract on common carp growth, immune response and disease resistance. In this study, were tested four inclusion levels (0, 10, 20 and 30 g/Kg) in a basal diet containing 23% DM of crude protein. The results showed that an inclusion equal to or above 20 g/Kg promoted growth performance, feed efficiency, immune activity and increased fish resistance to pathogenic infections. Grape seeds are rich in proanthocyanidins and polyphenolic compounds with several health-promoting functions, including antioxidant and anti-inflammatory capacity, and enhancement of toxicity resistance [127]. Other studies showed that dietary supplementation with 200 mg/kg or higher content of grape seed proanthocyanidin, resulted in an improvement in growth performance, feed intake, immune response and welfare of Nile tilapia [127, 130]. Additionally, grape seed oil is also a good candidate for partial replacement of fish oil improving the growth performance, antioxidant activity and fatty acid profile of rainbow trout [73]. Nevertheless, this replacement is limited to approximately 50% [129].

5.4 Pumpkin processing by-products

Pumpkin peels and seeds, which are usually discharged during pumpkin processing, still contain valuable nutrients [2, 47, 112]. The peels contain a high percentage of fibre, followed by protein and at lower level by lipids while the seeds contain mainly lipids and proteins (Table 3). Unsaturated FA are the principal constituents of pumpkin seed oil, particularly LA and C18:1n-9 in addition to C16:0 and C18:0. On the other hand, pumpkin peels and seeds contain Val, Leu and Lys in relatively high amounts (Table 3). Pumpkin peels are rich in vitamin C, as well as in β-carotene, minerals (namely P and Fe) and phenolic compounds (Table 4). In seeds, K and Zn are the most abundant minerals, in addition to Fe, Ca, and Na [47]. Pumpkin seeds also contain considerable amounts of tocopherol and phenolic compounds, particularly flavonoids [46, 47]. Recently, Mounes et al. [84] used pumpkin seed cake as a substitute for soybean meal in diets for Nile tilapia, showing that a 40% replacement of soybean meal improved fish growth performance, feed conversion ratio and an enhancement of immune and oxidative responses.

5.5 Pea processing by-products

Peas are recognized as a source of high-quality proteins with a considerable amount of EAA, namely Lys, Leu, Phe, Thr, Met and Trp [60, 88], being frequently used as an alternative plant protein [72]. Pea pods, usually considered waste, still contain proteins in significant amounts in addition to fibre and reserve carbohydrates. Moreover, pea pods have a high-quality lipid fraction (2%) containing high amounts of ALA, LA and oleic acid (C18:1n-9) (Table 3). This by-product is rich in K, Ca and Mg with a ratio of Na/K equal to 0.07 whereas other minerals (Fe, Zn, Cu) appear in minor quantities (Table 4). In a study conducted by Desouky et al. [24] pea peel meal (fibre-free) was used as a substitute for fish meal in 15 and 25% levels in aquafeed for Nile tilapia. The results showed no detrimental effects on fish growth in both diets with an improvement of feed efficiency in the fish fed with the 15% diet. These results indicate that this by-product can be used as a substitute for fish meal.

5.6 Potato processing by-products

Potato peels are a by-product that results from potato processing as well as from potato starch, flour and canning industries [109]. The nutritional composition of this residue depends on potato variety and origin [109] but it is mainly a source of carbohydrates, proteins and a low amount of fat (Table 3). Choi et al. [16] analysed the free AA profile of peels from several potato varieties reporting high amounts of EAA, including Val, Tyr and Phe, Thr, Met, Lys, Ile and Leu. The potato peel lipidic fraction is mainly composed of C18:1n-9, LA, ALA, C16:0 and C18:0 [102] (Table 3). Potato peels are also described as a good source of phenolic compounds with antioxidant and antimicrobial properties [16, 109] as well as minerals like K, P, Ca, Mg and Fe [120]. Potato protein concentrate (PPC) produced by protein precipitation from potato juice has been indicated as a promising candidate as a vegetable source of protein for aquafeed. However, some studies using PPC resulted in severe appetite loss, even at dietary levels as low as 5%, as a result of the presence of bitter-flavoured glycoalkaloids [103]. Before being used as a protein source, such ingredients require a pre-treatment to eliminate anti-nutritional components as tested for the Atlantic salmon [103].

5.7 Apple and pear processing by-products

Apple and pear pomaces, generated by the fruit processing and juice industry, include peels, seeds, stems and pomace. Apple and pear pomace hold high levels of carbohydrates (including sugars and fibre) and low levels of protein and fat (Table 3). Despite the low content of lipids, both apple and pear pomace have an interesting profile of EFA, particularly LA, C18:1n-9 and ALA [14, 69]. Minerals found in pear pomace include by decreasing order K, P, Ca, Mg, Na and Fe [69] (Table 4). In comparison, apple pomace contains higher amounts of K, Mg, Na; Ca, P and still holds trace quantities of Fe, Zn, Cu and Mn [115]. Moreover, vitamin C was found in similar quantities in apple and pear pomaces, but phenolic compounds and vit E are more abundant in apple pomaces [69, 115] (Table 4). Pectin a carbohydrate present in fruit peels is a good candidate for dietary supplements. Feed supplementation with 2–4% of apple peel-derived pectin for common carp resulted in an improvement of growth performance, feed utilisation, immune and oxidative response indicating that there is a potential functional role of apple by-products as an aquafeed supplement [45].

5.8 Brassica vegetables processing by-products

Brassica vegetables such as cauliflower and broccoli are recognized for their nutritional value and are among the most consumed vegetables in the world [7, 122]. Florets are usually preferred for human consumption while other parts, such as stalks and leaves, constituting approximately 60–75% of production, are wasted during harvesting [132]. However, these parts also have a valuable nutritional composition. Leaves are composed by carbohydrates, proteins, fiber and inorganic compounds (Table 3). They contain several EAA, mainly Tyr and in minor quantities Leu, Thr, Arg, His, Ile, Phe and Met. Concerning FA, broccoli and cauliflower stand out for their high ALA content, followed by C16:0, C18:2 n-6, C18:0 and C18:1 [7, 65]. Potassium, Ca and P constitute the major macro-elements in broccoli leaves and stalk whereas Fe, Mn and Zn are the more relevant micro-elements (Table 4). Moreover, both broccoli and cauliflower are rich in vitamin C in addition to other antioxidant compounds [7, 65, 76]. Brassica by-products are, most probably, the F&V by-products most used in substitution of soybean meal and fish oil. Lakwani et al. [61] pointed out that *Brassica* sp. supplement of 1–2% increases the intestinal immunity in rainbow trout. Few studies indicate that there is a potential use of cabbage leaves and broccoli as replacements for cereals meal [50, 95]. Oke et al. [86] tested the effect of dried cabbage leaves inclusion in feed for Nile tilapia fingerlings. Diets with 34% DM crude protein were formulated by replacing corn meal with dried leaf powder and fed to Nile tilapia fingerlings. Fingerlings grow better with the 0.5% inclusion level, indicating a constraint regarding the inclusion of such ingredients, due to anti-nutritional factors like oxalate. Kadhim et al. (2002) [50] overcome this issue by conducting an aqueous extraction of any anti-nutritional substances in broccoli. After the aqueous extraction of broccoli, the extract was incorporated in isonitrogenous and isocaloric diets with the replacement of 1, 2 and 3% of the wheat brain. Results showed that fish fed a 2% broccoli extract showed better growth performance.

5.9 Banana processing by-products

Banana by-products such as damaged or overripe fruits, peels, pseudo-stems, leaves, and blossoms are rich in several nutrients such as carbohydrates, protein, dietary fiber and vitamins [59]. Peels and leaves contain a considerable amount of lipids and proteins whereas fruits are rich in carbohydrates (Table 3). The EAA present in banana peels include Arg, Leu, Phe, Ile, Trp, Lys, His, Thr, Met and Val, Banana peels are also an interesting source of n-3 PUFA, namely ALA and DHA in addition to other unsaturated FA, particularly LA and C18:1n-9 [1, 44, 59, 83]. Banana byproducts contain a wide range of phytochemicals including phenolic compounds [59, 113, 131], carotenoids [113], vitamin C, vitamin E and vitamin B complex [59]. Potassium is the major mineral in banana by-products in addition to P, Ca and Mn (Table 4). The banana peel was used to supplement diets for Nile tilapia [128] with promising results regarding growth performance, feeding efficiency and nutrient digestibility. In the study conducted by Yossa et al. [119], dietary inclusion of 30% banana peel improved the growth performance, feed utilisation and several condition indices however, it reduced the digestibility indices of crude protein and gross energy in Nile Tilapia.

Despite not representing an high production at the global level, other crops arise as important waste producers. This is the case of carrot production. After the harvest, the carrots without the quality standards and the requirements of size and shape imposed by the market, are usually discarded. This by-product is particularly rich in β-carotene [118], a highly valued carotenoid as a supplement for fish feed. Other examples are by-products from citrus [22] and jackfruit [13] among others.

6 Fruits and vegetables by-products processing and transformation

In this section, we delve into the processing methods employed to transform F&V by-products into viable aquafeed ingredients. The use of F&V by-products as functional ingredients for aquafeed requires efficient processing methods to enhance their nutritional value, eliminate anti-nutritional substances, ensure feed safety, and optimise resource utilisation [71]. Key processing methods such as grinding and milling, drying, extrusion, fermentation, enzymatic treatment, and chemical processing offer unique advantages to improve by-products' nutritional value and safety.

By elucidating the intricacies of processing methods, challenges, and value chain considerations associated with F&V by-products, this section aims to provide valuable insights for stakeholders involved in the development and implementation of sustainable aquafeed solutions.

6.1 Milling and grinding

Milling and grinding are mechanical processes employed to reduce F&V by-products into smaller particles, facilitating their handling and incorporation into aquafeed formulations. Various methods such as hammer, ball, roller, and attrition mills can be used to reduce different matrices in powder. The choice of equipment depends on factors like hardness, moisture content, and desired particle size of the F&V by-products. It's worth noting that grinding may decrease the particle size of F&V by-products and alter their physicochemical properties, particularly dietary fibre, which plays a significant role in their functional properties [36].

Superfine grinding, a new food processing technology, produces powders with exceptional properties such as high solubility, dispersion, adsorption, and chemical reactivity [27, 68].

6.2 Drying

Drying is a fundamental method employed to reduce the moisture content of F&V by-products, making them suitable for long-term storage and incorporation into aquafeed formulations. Drying significantly prevents the activity of microorganisms and enzymes, thereby extending the shelf-life of F&V by-products. Additionally, it facilitates the management and distribution of these by-products, enabling the creation of multiple value-added functional ingredients for use in the food sector [85].

Drying involves the removal of moisture from F&V by-products through evaporation, typically achieved by exposing the material to heat and airflow. Various drying techniques are employed depending on factors such as the type of by-product, desired moisture content, and economic feasibility. Common drying methods include air drying, sun drying, freeze drying, and mechanical drying (e.g., rotary dryers, and fluidized bed dryers).

However, the effectiveness of drying is not without its complexities. The combination of drying temperature and time can impact the stability of various molecular classes, such as phenolic compounds and pigments. Prolonged exposure to high temperatures can lead to the reduction of phenolic activity due to polymerization or oxidation reactions when exposed to air. Conversely, excessively slow drying processes conducted at temperatures conducive to microbial growth and spoilage may fail to preserve the fresh pâté's characteristic phenolic profile [12, 53].

The optimal drying method and conditions for by-products vary depending on their unique characteristics and intended applications. While some may benefit from gentle drying methods like freeze-drying to preserve bioactive compounds, others may require conventional drying methods like oven drying or air drying to effectively remove moisture. Factors such as moisture content, chemical composition, and end-use must be considered when selecting the appropriate drying strategy [6, 48, 121]. By tailoring the drying process to the specific needs of each by-product, it is possible to maximize the retention of bioactive compounds, maintain product quality, and unlock their potential for re-use or valorization in various industries.

6.3 Fermentation

The biotechnological process of fermentation is predominantly driven by the indigenous microorganisms naturally present in raw food materials. Initially, the goal was to extend the shelf life of food items, particularly fruit and vegetable-based products, enabling long-term storage at ambient temperatures by enhancing the microbial stability of food matrices. Recent discoveries have unveiled that food fermentation not only extends to nutritional and health advantages, enriching foods with vitamins, promoting prebiotic/probiotic effects, and enhancing digestibility but also contributes to heightened food safety through its allelopathic activity against harmful bacteria and fungi contaminants [66] with evident advantages in being applied to F&V by-products.

Recent examples of fermentation-based valorization strategies include the bioconversion of various by-products, the improvement of the nutritional value of food matrices, or the isolation of biologically active ingredients for functional food formulation (Table 5). Moreover, fermentation strategies utilizing various types of bacteria, yeasts, and moulds have been explored to enhance properties or increase compound production. This involves increasing the efficiency of producing a specific compound or product through fermentation. Examples include enhancing the output of vitamins, amino acids, or other valuable chemicals (Table 5).

A diverse range of microorganisms has been selected for by-product valorization (Table 5). This includes lactic acid bacteria (LAB) and other bacteria species and fungi. Each type of microorganism brings unique metabolic capabilities and fermentation pathways, allowing the production of a wide array of compounds from different substrates like green tomato, apple and grape pomace, tomato and carrot pulp, olive cake and potato silage (Table 5).

In response to the rising global interest and demand for fermented products, coupled with heightened awareness of food safety, there arose a need for standardization in the production process. This requires industrial control over production procedures, including the implementation of starter cultures and the regulation of fermentation protocols on an industrial scale [37]. The starter cultures enable a more precise control of the physico-chemical conditions of the entire fermentation process and obtain predictable safety and organoleptic features.

Fermentation plays a crucial role in improving the nutritional quality of various foods through several mechanisms, one of which is the reduction of anti-nutrients. Anti-nutrients are compounds that interfere with the absorption of nutrients in the body, thereby reducing their bioavailability [91, 111]. For instance, phytic acid is an anti-nutrient commonly found in grains, seeds, and legumes. During fermentation, microorganisms metabolize sugars and produce organic acids, which in turn lower the pH of the environment. This acidic environment promotes enzymatic degradation, leading to a reduction in the concentration of phytic acid complexes. These complexes often bind to essential minerals such as iron, zinc, and calcium, rendering them unavailable for absorption in the digestive tract. By decreasing the levels of phytic acid, fermentation increases the availability of soluble minerals in the fermented food. This enhancement in mineral bioavailability is critical for ensuring adequate nutrient intake and preventing deficiencies. Improved mineral absorption contributes to overall health and well-being, supporting various physiological functions such as bone health, immune function, and energy metabolism.

Table 5 Fermentation processes used for bioconversion of fruits and vegetables by-products

F&V By-product	Microorganism	Process Conditions	Products/Outcomes	Target Benefits
Tomato Green Waste [1]	Lactobacillus spp. (LAB)	Anaerobic fermentation; 37 °C, pH 4–5	Increased lycopene bioavailability; probiotic enrichment	Enhanced antioxidant activity in aquafeeds
Apple Pomace [2]	Saccharomyces cerevisiae, LAB	Co-fermentation; 30 °C	Alcohols, esters, phenolic enhancement	Improved palatability and fish gut health
Grape Pomace [3]	Aspergillus niger	Solid-state fermentation; 30 °C, high humidity	Polyphenols, enzymes (cellulase, pectinase)	Anti-inflammatory properties for aquafeeds
Melon/Tomato/Carrots [4]	Bacillus subtilis, LAB	Liquid fermentation; moderate aeration, pH controlled	Vitamin enrichment, microbial biomass	Enhanced fish immunity and growth
Olive Cake [5]	Trichoderma reesei	Solid-state fermentation; optimal moisture content	Enzymes, phenolic compounds	Increased digestibility and antioxidant potential
Potato Silage [6]	Lactobacillus plantarum	Anaerobic storage; low oxygen, pH drop	Lactic acid, improved protein digestibility	Long-term storage for protein-rich aquafeeds

The bibliographic references consulted to build such a table are supplied in the supplementary material using the numeric reference provided in brackets

Furthermore, fermentation can improve protein availability and digestibility. Microorganisms involved in the fermentation process produce enzymes that break down proteins into smaller peptides and amino acids, making them easier to digest and absorb. This increased protein digestibility ensures that the body can utilize the protein efficiently for tissue repair, muscle growth, and other physiological processes [91].

6.4 Enzymatic treatment and chemical processing

Enzymatic and chemical treatments are widely used in the processing F&V by-products, improving their suitability as aquafeed ingredients. Both methods play critical roles in enhancing nutrient availability, reducing anti-nutritional factors, and improving feed quality, although they differ in their mechanisms, advantages, and challenges.

The enzymatic treatment involves the use of biological catalysts such as cellulases, proteases, and phytases. For example, cellulases are effective in hydrolyzing cellulose in fibrous by-products, making energy-rich polysaccharides more accessible to aquatic organisms [28]. Proteases, on the other hand, degrade proteins into amino acids and peptides, improving the nutritional value and digestibility of protein-rich by-products such as tomato pomace and pea pods [57]. Phytases are used to hydrolyze phytic acid into inositol and inorganic phosphorous, decreasing the chelating effect of this anti-nutritional and consequently mineral bioavailability, which is vital for fish growth and skeletal health [17, 22].

One of the primary advantages of enzymatic treatments is their ability to operate under mild conditions, preserving sensitive bioactive compounds such as polyphenols, carotenoids, and vitamins. For instance, the enzymatic hydrolysis of olive pomace has been shown to retain high levels of vitamin E and phenolic compounds, both of which contribute to the antioxidant properties of the final product [3]. However, enzymatic treatments are highly process-specific, requiring precise control over reaction conditions such as pH, temperature, and enzyme concentrations. Furthermore, their high cost remains a challenge for large-scale applications, especially in low-margin aquafeed formulations. The substrate heterogeneity also hinders the enzymatic processing of F&V by-products [38].

Chemical processing, on the other hand, offers an alternative approach to improving the quality of F&V by-products for aquafeed. This method often involves using acids, alkalis, or other chemical agents to modify the structure of by-product components. Acid hydrolysis, for instance, enhances the solubility of proteins and carbohydrates, making them more digestible and suitable for aquatic species [12]. Similarly, alkaline treatments are effective in breaking down lignin in fibrous materials, improving fibre digestibility and energy availability [27]. Chemical methods are generally more cost-effective than enzymatic treatments, making them suitable for large-scale applications. However, the aggressive nature of chemical treatments can lead to the degradation of sensitive nutrients. For example, high acidity or alkalinity can oxidize phenolic compounds and carotenoids, reducing their antioxidant efficacy [8]. The environmental impact of chemical residues creates challenges, requiring strict waste management. Residual chemicals in treated by-products can also threaten feed safety, making it essential to follow regulations when using them in aquafeed [40].

Both enzymatic and chemical treatments have their unique strengths and limitations. Enzymatic methods excel in preserving nutrient integrity but face scalability and cost barriers. In contrast, chemical treatments offer cost efficiency and versatility but may compromise nutrient quality and environmental sustainability. Studies suggest that a combined or sequential application of these methods could maximize their benefits while mitigating their respective challenges. For instance, enzymatic pre-treatment followed by chemical processing can enhance nutrient recovery while reducing environmental impacts, providing a promising pathway for the sustainable utilization of F&V by-products in aquafeed [75, 96].

6.5 Emerging technologies

Emerging technologies have revolutionized the processing and transformation of F&V by-products, providing innovative solutions to enhance their utilization as aquafeed ingredients. These technologies focus on optimizing nutrient retention, improving functional properties, and addressing sustainability challenges.

One of the most promising advancements is high-pressure homogenization (HPH), which involves mechanically disrupting plant cells to release intracellular compounds such as proteins, polyphenols, and pigments. Studies on tomato peels have demonstrated that HPH significantly improves the bioavailability of lycopene, a carotenoid with antioxidant properties critical for fish health [9, 49]. This technique also enhances the rheological properties of processed residues, making them easier to incorporate into feed formulations. Furthermore, HPH's reliance on water as a medium makes it an eco-friendly alternative compared to chemical processing methods. Another groundbreaking method is superfine grinding, which reduces the particle size of F&V by-products to micro or nano levels. This technique improves the solubility, dispersion, and bioavailability of nutrients, enhancing their effectiveness in aquafeed. For example, superfine grinding of carrot and pumpkin peels increased their antioxidant activity due to the higher surface area available for enzymatic digestion and nutrient release [27]. Moreover, the powders produced through this method exhibit better physical properties, such as improved flowability, which is advantageous in feed manufacturing.

Ultrasound-assisted extraction (UAE) is another innovative approach that uses high-frequency sound waves to facilitate the release of valuable compounds from F&V by-products. This technique is particularly effective in extracting polyphenols, carotenoids, and essential oils from materials such as citrus peels and grape pomace. UAE not only enhances the yield of bioactive compounds but also operates under mild conditions, preserving heat-sensitive nutrients like vitamin C and flavonoids [105]. The non-thermal nature of UAE makes it suitable for processing ingredients intended for high-value aquafeeds, such as those targeting premium fish species like Atlantic salmon.

Pulsed electric field (PEF) technology is gaining attention for its potential to improve nutrient recovery from F&V by-products [93]. PEF works by applying short bursts of high-voltage electricity to cells, disrupting their membranes and facilitating the extraction of intracellular nutrients. Recent research has shown that PEF-treated citrus fruits and peel Increased yield of juice by 25% for oranges, 37% for pomelos and 59% for lemon, improved extraction of polyphenols to 50% [52]. Pulsed electric field is particularly advantageous for its ability to operate at low temperatures, minimizing nutrient loss while reducing energy consumption.

While these technologies hold great promise, their application is not without challenges. High initial costs, the need for specialized equipment, and the variability in by-product composition can limit widespread adoption. However, advances in process optimization and the integration of multiple technologies are paving the way for their broader implementation. For instance, combining HPH with fermentation has been shown to synergistically improve the release of bioactive compounds while enhancing the microbial stability of the product [66]. Emerging technologies are shaping the future of sustainable aquafeed production by enabling the efficient and environmentally friendly use of F&V by-products. Continued research and development in this field will further unlock the potential of these innovations, driving progress in both aquaculture and circular economy practices.

Figure 3 summarises the key processing methods, their advantages and challenges for each discussed processing and transformation method.

7 Value chain challenges

Using F&V by-products as fish meal and fish oil replacement or as bioactive ingredients presents a promising avenue for sustainable aquafeed formulation. Yet it is accompanied by distinct processing challenges and considerations throughout the value chain.

The adoption of a circular economy production model represents a fundamental shift in how we approach food production and consumption. This approach focuses on the reuse and repurposing of materials to extend their lifecycle and generate additional value for the waste produced. In agriculture, this approach holds particular significance as agro-industrial by-products stand out as valuable raw materials with diverse potential applications across various industries including aquafeed [86, 104]. Moreover, agro-industry waste disposal holds a high cost for the companies, leading them towards recycling and repurposing by-products to curtail environmental impact and trim operational expenses.

It is essential to define the F&V by-products value chain followed to incorporate these as ingredients for aquafeed. However, this value chain faces several challenges. These include supply chain management, regulatory compliance, market acceptance, sustainability, waste management costs and stakeholder collaboration. All these challenges play pivotal roles in maximizing the efficiency and sustainability of F&V by-products for aquafeed and other feeding industries. Another important challenge is the lack of awareness about the potential of agro-industrial by-products. To address this, investment in research and new technologies is needed to turn these by-products into valuable food sources,

Additionally, the sheer volume of by-products generated poses logistical and environmental quandaries. Fruits and vegetable processing waste is produced from edible sources in different conditions, different materials and components of the processing lines with different priorities on cleaning and disinfection, originating frequently a biomass bulk from different sources. With the cuts, enzymes are in contact with substracts, and the decay is very fast from a a couple of hours to a few days. Due to that, and to not compromise the ends, a strong logistic or stabilizing process must be in place, close to processors. Implementing efficient strategies for waste management, like biorefinery approaches [55] is imperative to avert environmental degradation and mitigate potential hazards linked with large-scale disposal. Addressing these challenges demands collaborative efforts among industry, researchers and policymakers. Governments, in particular,

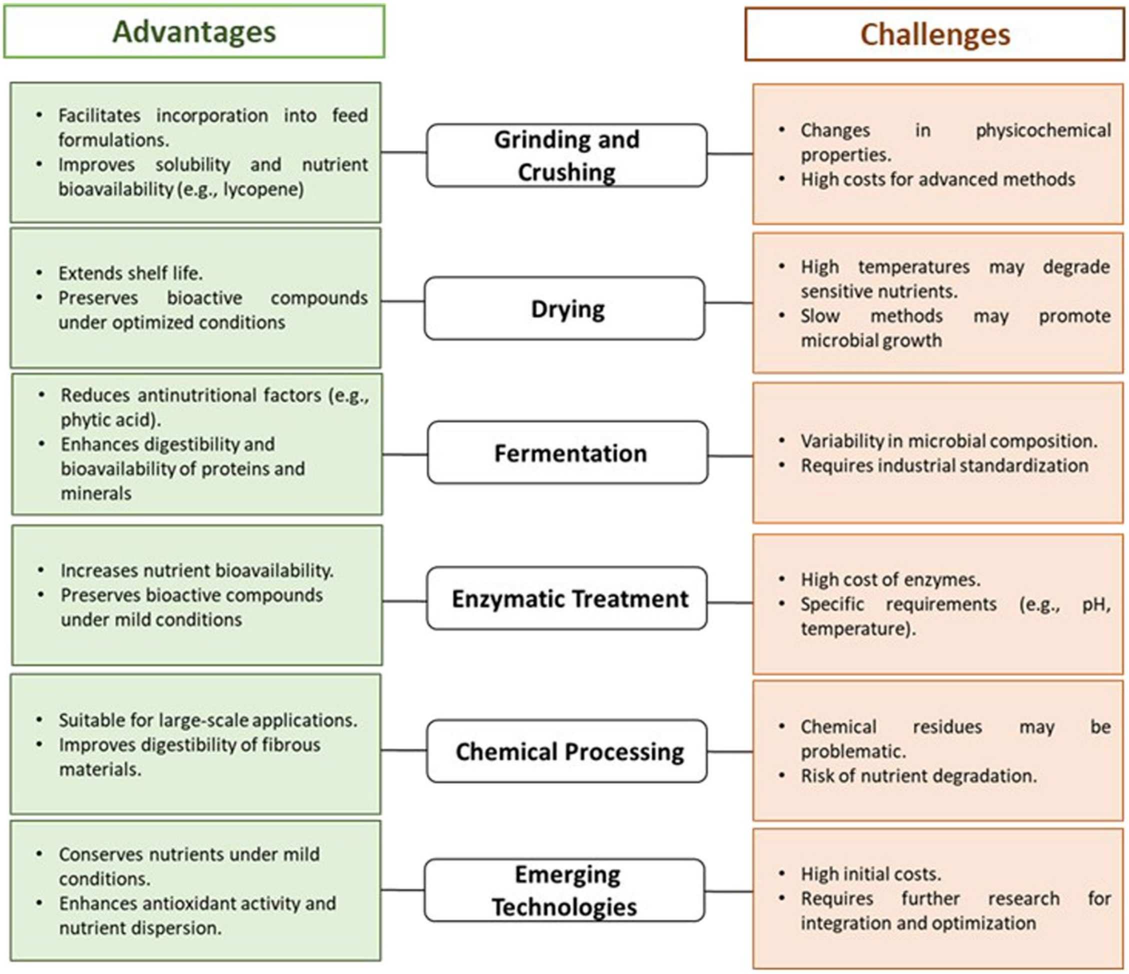


Fig. 3 Advantages and challenges of processing methods that can be used to valorize fruit and vegetable by-products to be incorporated in aquafeed

play a pivotal role by encouraging sustainable practices and enacting legislation that promotes the responsible use of by-products to curb water and environmental pollution. Researchers, shoulder a critical responsibility in this endeavour by delving into innovative treatment methods to enhance the recovery of valuable materials from by-products. Tailored protocols and statistical approaches can optimize the procurement, transformation, and recovery processes, ensuring maximal value extraction, the development of innovative processes as nutrients up-cycle including the use of insects as vector to produce high quality protein, or the use of single-cell protein production through waste fermentation. Both technologies contribute to minimize negative environmental impacts of waste production.

On another perspective, regulatory considerations are pivotal in the utilization of agro-food by-products in animal feed and particularly in aquafeed. These regulations, which vary across regions and countries, mandate compliance with safety standards and regulations concerning feed additives, contaminants, and labelling. Such regulations establish safety thresholds for feed ingredients, encompassing maximum allowable levels of contaminants such as heavy metals, pesticides, mycotoxins, and pathogens. Compliance with these standards is essential for ensuring the safety and quality of animal feed, thus safeguarding both animal and human health. Additionally, regulatory authorities often oversee the usage of feed additives, including vitamins, minerals, antibiotics, and growth promoters. Approval processes for these additives are diverse, necessitating manufacturers to ensure adherence to regulatory requirements and approved usage levels [129].

Market dynamics exert a significant influence on the utilization of F&V by-products as feed ingredients. Considerations such as availability and cost-effectiveness are shaped by market fluctuations and seasonal variations in supply. The seasonal ebb and flow of by-product availability, dictated by factors like crop harvest cycles and weather conditions, impacts pricing strategies and feed formulation. Moreover, the economic viability of by-products hinges on factors such as availability, processing costs, transportation expenses, and competing demands from alternative sectors. Shifts in market demand and pricing dynamics for alternative uses, such as bioenergy production or human consumption, engender competition for limited resources. This competition can, in turn, influence the availability and cost of by-products for animal feed, thereby shaping feed formulation and pricing decisions [99].

Navigating the intricate landscape of regulatory requirements and market dynamics is imperative for feed manufacturers and producers. Doing so ensures compliance, upholds feed quality and safety standards, and enables informed decisions about ingredient sourcing and formulation. Collaboration among industry stakeholders, regulatory bodies, and research institutions is pivotal in addressing these challenges and fostering the sustainable utilization of agro-food by-products in animal feed production.

8 Conclusion and future perspectives

To grow healthy, modern society relies on increasing aquaculture production. Aquaculture fish is rich in high-quality protein, liposoluble vitamins, n-3 EFA, like EPA and DHA, and minerals like Ca and P, essential to prevent osteoporosis, cardiovascular, degenerative and skin diseases. In a world under a blue transformation, aquaculture production arises as the food production sector with the lowest environmental impact. However, the intensification of fed aquaculture brings several challenges, being the production of nutritionally efficient, fair, economically and environmentally sustainable aquafeed among the most important.

This study underscores the potential of F&V by-products as cost-effective and sustainable ingredients for aquafeed formulations. By-products such as peels, pomace, and seeds are rich in nutrients and bioactive compounds that can enhance fish health and growth performance while reducing feed costs and environmental impacts.

In this context, F&V by-products arise as potential ingredients for aquafeed. These by-products are energetic (high in reserve sugars) and rich in functional molecules like pigments, vitamins, minerals, anti-oxidant and anti-inflammatory compounds, essential for fish growth and health. However, their low content in EAA and EFA, the presence of anti-nutritional factors, and potential contamination with phytochemicals and microorganisms are barriers to their valorization by the feed industry.

The introduction of F&V by-products in aquafeed requires efficient processing and transformation methods. Emerging processing technologies like high-pressure processing and ultrasound-assisted extraction have proven effective in preserving the nutritional integrity of these by-products, making them suitable for incorporation into aquafeeds. These and other classical methods like milling, grinding and milling have advantages and disadvantages depending on the matrix and processing objective (Fig. 3), and can be applied together as a biorefinery approach. Fundamentally, all these methodologies constitute opportunities to foster the F&V by-products value chain.

However, challenges such as variability in by-product composition, scalability of technologies, regulatory constraints, market acceptance, sustainability, and waste management costs must be addressed to unlock their full potential.

At the moment, the maturity of the feed industry to develop a value chain and use F&V by-products as co-products is very low. Nevertheless, the concerns with waste generation, with the proportional increase of production costs and sales, have been in the minds of producers for a long time. The vegetable&V production industry has come a long road of progress, choosing the best varieties, adapting crops and using the best harvest practices to reduce waste. In the processing plants, many improvements were made, to hold the increasing of waste in the lines and tru the lines. Add value to the by-products generated in the fruit and vegetable processing industry by transforming and up-cycling their nutritional value into aquafeed is an opportunity to improve the sustainability track of both industries.

Future research should focus on scaling up the application of advanced technologies such as high-pressure processing, pulsed electric fields, and supercritical fluid extraction for industrial use. These methods could enhance nutrient bioavailability and reduce environmental footprints, aligning with the principles of the circular economy. Further, developing cost-effective and energy-efficient processing technologies will be pivotal in making these by-products viable alternatives to conventional feed ingredients.

Moreover, in-depth investigations into the long-term effects of by-products on fish health, growth performance, and product quality are essential to validate their efficacy and safety. Genomics and metabolomics approaches could also be employed to understand the interactions between bioactive compounds in by-products and fish metabolism. Finally, fostering collaborations between academia, industry, and policymakers will be crucial in establishing robust guidelines for the inclusion of these by-products in aquafeed, ensuring regulatory compliance and market acceptance.

This review highlights the need for continued research and development to optimize the processing, formulation, and application of F&V by-products in aquaculture. Moving forward, integrating these by-products into aquafeed formulations not only supports the sustainable growth of the aquaculture sector but also contributes to reducing food waste and advancing global food security.

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Declarations

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