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RECOVERY OF BIOACTIVE COMPOUNDS FROM SELECTED INDUSTRIAL PLANT WASTES AND BY-PRODUCTS-CASE STUDIES ON: TOMATO PROCESSING RESIDUES, OLIVE WASHING WATERS AND SEA BUCKTHORN BY-PRODUCTS

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Abstract

Industrial processing of plant raw materials generates significant amounts of solid and liquid residues, which are frequently underutilized despite their high biochemical potential. By-products resulting from tomato processing, wastewater from olives and sea buckthorn residues represent heterogeneous waste streams originating from different technological processes, yet sharing a common characteristic: a substantial content of biologically active compounds. These residues contain phenolic compounds, carotenoids, organic acids and dietary fibers, exhibiting antioxidant, antimicrobial and functional properties. This review provides a comparative analysis of agro-industrial wastes derived from tomato, olive and sea buckthorn processing, with emphasis on their chemical composition, environmental impact and biotechnological valorization potential. Current extraction and recovery methods, both conventional and emerging, are discussed in terms of efficiency, sustainability and industrial-scale applicability. In addition, potential applications of recovered bioactive compounds in the field of food biotechnologies are highlighted, in accordance with sustainable production systems and circular economy principles.

Key words: *bioactive compounds, olive, sea buckthorn, tomato, waste.*

INTRODUCTION

Food production and processing in developing countries generates high levels of waste and by-products, causing negative environmental impacts and significant costs. However, the resulting by-products have a high potential to provide bioactive compounds used in the production of food additives, contributing to the correction of nutritional deficiencies and improving diet quality (Torres-León et al., 2018).

Currently, new strategies for waste reduction, use and recovery, as well as enrichment of the economic value of by-products, represent an important challenge that needs to be implemented (Silva et al., 2021).

Extracts from plant material present numerous benefits for human health, chemical compounds that have beneficial effects on human health are integral parts of plants, often included in their defense system, defined as biologically active components (Žlabur et al., 2018). Various industries have shown significant interest in the application of bioactive plant compounds, such as the pharmaceutical industry for the production of drugs and the food industry for the production of food supplements classified as "superfoods" (Žlabur et al., 2018).

Bioactive compounds include both essential nutrients, such as vitamins and minerals, and non-nutritional compounds. While some of these contribute to nutritional intake, their predominant function is related to biological activity and physiological effects exerted on the body, beyond simple nutritional value. (Riccardi, 2022) such as phytochemicals, polyphenols, carotenoids, flavonoids, probiotics, enzymes, and other naturally occurring compounds that exert beneficial physiological effects on the human body beyond basic nutritional value. Minerals are represented by macroelements (calcium, phosphorus, magnesium, chlorine, sulfur, sodium, potassium) and microelements (iron, cobalt, manganese, molybdenum, copper, zinc, vanadium, iodine, selenium, fluorine, chromium, bromine). According to the scientific

literature, the category of biologically active substances, other than minerals and vitamins, can include: flavonoids, carotenoids, allyl and diallyl sulfides, indoles, monoterpenes, phenolic acids, sterols, pectins, resveratrol from red grapes, prebiotics, etc. (Banu, 2007).

Food waste and food by-products can be nutritionally rich food ingredients with functional properties. Food waste is made up of materials intended for human consumption that are subsequently disposed of, lost, degraded or contaminated (Girotto et al., 2015). Ecologically sustainable food must reconsider by-products resulting from the food industry as a source of valuable compounds (antioxidants, fibers, etc.) that could be used as new products or raw materials in the food industry (Rodriguez-Lopez et al., 2020).

Industrial by-products from fruits and vegetables consist mainly of peel, pomace and seed fractions, which could be a good source of compounds with high nutritional value such as proteins, polysaccharides, dietary fibers, flavor compounds and phytochemicals (Galanakis, 2012).

Several examples of fruit and vegetable industry by-products and wastes that can serve as sources of bioactive ingredients for use in the food industry will be presented and discussed in this paper.

VALORIZATION POTENTIAL OF WASTEWATER FROM OLIVE PROCESSING

Wastewater produced during olive processing - such as washing water and effluents from the oil extraction stage - shows a complex and highly variable chemical composition that depends on the processing technology used (traditional, press-based, two-phase, or three-phase centrifugation), as well as the olive variety and specific operating conditions. (Paraskeva & Diamadopoulos, 2006).

One of the main characteristics of wastewater from the olive industry is the extremely high organic load. Chemical oxygen demand (COD) values reported in the literature range from 50 to 220 g/L, while biochemical oxygen demand (BOD_5) is usually between 30 and 100 g/L, indicating a high BOD_5/COD ratio, typical of effluents rich in biodegradable compounds (Roig et al., 2006; El-Abbassi et al., 2012). The BOD_5/COD ratio is frequently between 0.4 and 0.6, suggesting a moderate biodegradability potential, limited however by the presence of phenolic compounds with an inhibitory effect on microorganisms (Paraskeva & Diamadopoulos, 2006). Wastewaters from olive processing have a slightly acidic pH, with values reported between 4.0 and 6.0, due to the presence of organic acids and phenolic compounds (Niaounakis & Halvadakis, 2006). The electrical conductivity varies between 1 and 12 mS/cm, reflecting the high concentration of dissolved mineral salts (El-Abbassi et al., 2012).

Phenolic compounds represent the most problematic fraction, but also the most valuable in terms of recovery potential. The total concentration of polyphenols is reported in the range of 0.5–10 g/L, depending on the extraction method and the maturity of the olives (Cassano et al., 2018). The organic matter is composed of: carbohydrates (10-50 g/L), lipids (0.5-5 g/L), proteins and amino acids (1-10 g/L) (El Abbassi et al., 2012).

The particular chemical composition of wastewater from olive processing explains both the difficulty of treating them by conventional methods and the increased interest in biotechnological recovery methods. The high content of phenolic compounds and organic matter makes these waters suitable for antioxidant recovery processes and controlled fermentation, provided that pretreatment steps are applied (Cassano et al., 2018; Koutrotsios et al., 2023).

Polyphenols recovered from olive wash waters, especially hydroxytyrosol, tyrosol and their derivatives, show a high **antioxidant capacity**, comparable or superior to currently used synthetic antioxidants butylated hydroxytoluene (BHT) and butylated hydroxyanisole (BHA) (Gullón et al., 2023). According to studies conducted by Cassano (2018), phenolic extracts obtained from wash waters delay lipid oxidation in vegetable oils and meat products; extend the shelf life of foods rich in fat; reduce the formation of secondary oxidation compounds. (Cassano et al., 2018). These compounds can be used in products such as: margarines, sauces, bakery products.

According to EFSA (European Food Safety Authority), hydroxytyrosol has a role in protecting blood lipids against oxidative stress

when consumed in adequate amounts. Thus, olive polyphenols are associated with beneficial effects on cardiovascular and metabolic health.
Extracts obtained from washing waters can be used as bioactive ingredients for functional beverages and fermented dairy products (El-Abbassi et al., 2012)

Natural antimicrobial agents and biopreservatives

Phenolic compounds in olive washing waters exhibit antimicrobial activity against pathogenic and spoilage microorganisms, including *Listeria monocytogenes, Escherichia coli* and *Staphylococcus aureus* (Roig et al., 2006).
Yılmaz (2024) evaluated the antimicrobial effects of olive wastewater extract on microorganisms related to food spoilage and foodborne diseases. The results demonstrated that the extract exhibited significant activity against spoilage bacteria or food pathogens, suggesting its potential as a natural biopreservative in foods (Yılmaz et al., 2024).

Integration in bakery products and plant foods

Phenolic extracts can also be used in bakery products or processed plant foods, where they contribute to increasing the total antioxidant capacity without significantly affecting the sensory properties, when used in controlled concentrations (Gullón et al., 2023). Recently, the integration of olive mill wastewater (OMWW) in bakery products has become a topic of interest for the development of functional foods. Restivo et al. (2025) demonstrated that bread can be manufactured using olive mill wastewater as a partial or total replacement of water in the dough, which leads to an increase in the total phenolic content and antioxidant capacity of the final product. Research has shown that bread obtained with olive mill wastewater exhibits up to a fourfold increase in antioxidant activity (measured in Trolox equivalents) compared to the control bread.
Also, studies conducted by Galanakis et al. (2018) showed that phenols in olive mill wastewater can act as natural biopreservatives, inhibiting microbial growth and extending the shelf life of bakery products. These polyphenols can be incorporated either directly, by replacing water in the dough, or in the form of concentrated extracts, while maintaining their functional effect.
Another study conducted in Egypt (2025) used dried olive mill wastewater in bread and biscuits, demonstrating improved dough rheological properties and increased bread volume, as well as increased oxidative stability and total phenolic content (Jeba et al., 2025). In addition, Karadağ et al. (2024) integrated olive mill wastewater polyphenols into cake formulations, demonstrating that these bioactive ingredients do not negatively affect the texture of the products and improve antioxidant properties.

VALORIZATION OF WASTE AND BY-PRODUCTS FROM TOMATO PROCESSING

Tomato processing waste (tomato pomace) includes peels, seeds and residual pulp after juicing and represents approximately 10-40% of the total mass of processed tomatoes, depending on the type of product and the technology used (Knoblich et al., 2005).
Tomato processing waste is rich in dietary fiber, protein, lipids, and represents an important source of carotenoids (especially lycopene), polyphenols, and vitamins. Lycopene content in dried tomato waste can reach high levels depending on processing conditions, and significant antioxidant activity has been demonstrated using DPPH and ABTS assays (Kuvendziev et al., 2018, Szabo et al., 2021). These bioactive compounds are associated with anti-inflammatory, anticancer, and cardiovascular protective effects (Story et al., 2010)
Extracts from tomato waste, rich in carotenoids (especially lycopene) and phenolic compounds, can be used as natural antioxidants in oxidation-sensitive food systems. The study conducted by Popescu C et al. (2022) demonstrated that extracts from tomato processing waste can be applied to vegetable oils (e.g. soybean oil) in order to reduce oxidative damage during heating, suggesting a natural alternative to synthetic antioxidant additives in industrial food products (Popescu et al., 2022).
Several studies demonstrate that tomato waste (tomato pomace), rich in lycopene, β-carotene and phenolic compounds, can be utilized as a natural antioxidant in food products, contributing to the reduction of lipid oxidation

and the improvement of oxidative stability. Tomato pomace extracts have been shown to effectively reduce lipid oxidation in meat products, while extracts obtained from tomato skins and seeds exhibit high antioxidant activity, supporting their application as functional food ingredients (Ćetković et al., 2015).

Tomato pomace, as a source of fiber, carotenoids and antioxidants, is increasingly used to improve the nutritional and functional quality of food products. In a recent review, Silva et al. (2023) report that pomace can be incorporated into bakery products, sausages, dairy products or snacks as a natural functional ingredient that improves oxidative stability, increases fiber content and can extend shelf life. (Silva et al. 2023)

Studies conducted by Domínguez et al. (2020) demonstrate that partial replacement of wheat flour with 10-20% tomato pomace flour in bread allows obtaining a functional product, rich in fiber, carotenoids and antioxidant compounds, while maintaining sensory and rheological properties comparable to conventional bread, which indicates a significant potential for the valorization of tomato waste in the bakery industry (Domínguez et al., 2020).

Chabi et al. (2024) demonstrated that bioactives from tomato waste can be used to produce microcapsules of oleoresins (concentrated carotenoid extracts), which, added to juices (e.g. orange juice), confer antioxidant activity without significantly affecting the sensory quality of the product. These microcapsules can function as a natural ingredient for food fortification with antioxidants (Chabi et al., 2024).

Studies conducted by Calvo et al. (2020) showed that pomace extracts combined with vegetable oils (e.g. sunflower or rapeseed oil) improve the oxidative stability and nutritional properties of the oils, due to the high content of carotenoids and antioxidant compounds. Thus, pomace becomes a natural functional additive for edible oils that can partially replace synthetic antioxidants (Calvo et al., 2020).

Bioactive compounds, especially lycopene, β-carotene and phenols extracted from tomato pomace, exhibit antioxidant, anti-inflammatory, antimicrobial and anticancer potential. Recent scientific reviews indicate that these compounds can be used in nutraceutical formulations and dietary supplements to support cardiovascular health, the immune system, and reduce the risk of chronic diseases (Shah et al., 2020). Bioactive compounds in tomato waste reduce cell proliferation and oxidative stress, and are linked to a reduced risk of prostate and lung cancer (Tang et al., 2011; Giovannucci, 2002)

VALORIZATION OF WASTE AND BY-PRODUCTS FROM SEA BUCKTHORN PROCESSING

The waste resulting from the processing of sea buckthorn (*Hippophae rhamnoides*), also known as sea buckthorn pomace, is a rich source of bioactives: dietary fiber, polyphenols, flavonoids, minerals, fatty acids and carotenoids, which remain in the solid residues after the extraction of juice or oil. Instead of being considered a valueless residue, this pomace can be effectively utilized to obtain functional ingredients, bioactive extracts and to improve the nutritional profile of food products, in line with the principles of circular economy and sustainable production.

Sea buckthorn pomace is rich in polyphenols, flavonoids and carotenoids, compounds that confer significant antioxidant properties and can be recovered for food or nutraceutical uses. Successive extraction with food solvents or by green methods (ultrasound, supercritical CO_2) showed that this waste material can provide bioactive fractions with high antioxidant activity and free radical inhibition capacity.

Sea buckthorn by-products, including pomace, skins, and berries, are rich in bioactive compounds such as polyphenols, flavonols, carotenoids, vitamins (water- and fat-soluble), and minerals. These compounds confer multiple functional properties, making sea buckthorn waste a promising ingredient for functional foods, beverages, and nutraceutical products.

Bioactive compounds from sea buckthorn by-products, especially polyphenols, flavonols (quercetin, kaempferol, isorhamnetin), catechins, and carotenoids, exhibit strong antioxidant activity. This has been confirmed using DPPH, ABTS, and ORAC assays (Dienaitė et al., 2020; Mihalcea et al., 2021). Their antioxidant potential contributes to:

Improving oxidative stability in bakery products, beverages, and fortified foods

Preserving sensitive nutrients and bioactives

Supporting general health through free radical scavenging, Addition of 6-10% dried pomace to wheat bread increased fiber, protein, and antioxidant compounds while conferring strong antioxidant activity (Stanciu et al., 2023).

Sea buckthorn pomace incorporated into rye bread at 15-20% enhanced antioxidant content (Călin et al., 2024).

Extracts rich in polyphenols and carotenoids were used in functional beverages and fortified foods, improving oxidative stability and delivering health-promoting antioxidants (Mihalcea et al., 2021; Dienaitė et al., 2020).

Certain compounds in sea buckthorn by-products possess antimicrobial activity, which can extend the shelf life of products. Bread with 6-10% pomace showed antimicrobial effects, alongside antioxidant benefits, improving functional properties and reducing caloric energy (Stanciu et al., 2023). Sea buckthorn berry flour at 1-5% improved shelf life in wheat bread without negatively affecting sensory properties (Ghendov-Mosanu et al., 2020).

Sea buckthorn by-products are a rich source of dietary fiber, vitamins, minerals, and proteins, enhancing the nutritional value of foods and supplements.

Dried pomace at 6-10% in wheat bread increased fiber, protein, and polyphenol content; optimal sensory results were observed at ~8% addition (Stanciu et al., 2023).

Rye bread with 15–20% pomace showed increased bioactive content and antioxidant compounds, although higher additions influenced texture and moisture (Călin et al., 2024).

Cereal biscuits enriched with 5-20% sea buckthorn biomass improved oxidative stability and sensory appeal (Janotkova et al., 2021).

Extracts from sea buckthorn by-products can be incorporated into beverages and fortified foods as functional ingredients due to their high content of polyphenols, flavonols, and carotenoids. Advanced extraction techniques - supercritical CO_2, pressurized solvent extraction, ultrasound-assisted extraction - allow recovery of bioactive-rich fractions (Cosma et al., 2021).

Fortified beverages and functional foods enriched with antioxidant extracts (Dienaitė et al., 2020; Mihalcea et al., 2021)

Synbiotic beverages containing sea buckthorn bioactives with probiotics and prebiotic fibers to support digestive and immune health (Maftei et al., 2023)

Sea buckthorn processing waste (pomace-SBP) provides bioactive compounds suitable for functional supplements and nutraceuticals.

Flavonols (isorhamnetin, quercetin, kaempferol), catechins, and carotenoids with antioxidant and antiproliferative potential (Dienaitė et al., 2020)

Polyphenols that inhibit enzymes associated with oxidative stress and protect LDL-cholesterol and DNA, supporting metabolic and cardiovascular health (Renan and Fereidoon, 2024)

Carotenoids (zeaxanthin, β-carotene) with improved stability via microencapsulation technologies (Gherasim et al., 2024)

Vitamins (water and lipid-soluble, e.g., vitamin C, carotenoids) contributing to broad-spectrum antioxidant action and general health support (Dianu et al., 2024)

Potential physiological benefits in regulating glucose metabolism, lipid profiles, and inflammatory markers, relevant for metabolic syndrome and cardiovascular risk management (Shing et al., 2025)

Sea buckthorn bioactives affect color, taste, texture, and shelf life of foods. Optimal inclusion levels balance enhanced nutritional and functional properties with consumer acceptability.

Wheat bread with 8% pomace showed favorable sensory properties while improving nutritional and functional characteristics (Stanciu et al., 2023)

Sea buckthorn powders at 3-10% in bakery products modified texture, moisture, and color but maintained bioactive content (Nilova and Malyutenkova, 2018; Popovici, 2022).

The sustainable valorization strategies for tomato, sea buckthorn, and olive mill wastewater are summarized in Figure 1.

Figure 1 highlights the multiple pathways through which these by-products can be transformed into value-added products, energy sources, and other applications such as soil additives or sorbents. It illustrates how bioactive compounds, dietary fibers, proteins, and oils can be recovered and utilized, while also showing the potential for energy recovery through pyrolysis or combustion.

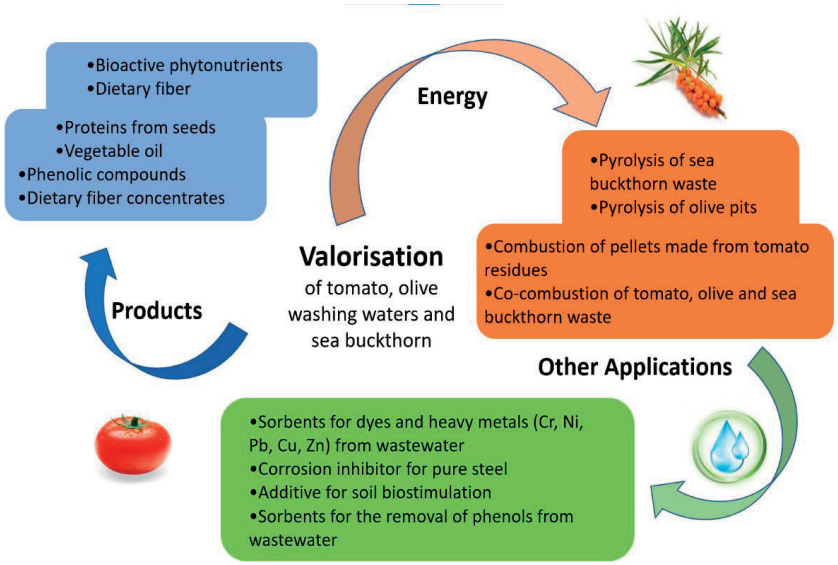

Figure 1. Integrated Valorization of Tomato, Sea Buckthorn, and Olive Mill Wastewater By-Products for High-Value Compounds Recovery

The overview emphasizes the versatility of these agri-food wastes, demonstrating that despite differences in composition and functional properties, all three streams can contribute to the development of sustainable, functional, and nutritionally enriched products. Figure 1 thus reinforces the main conclusion of this review: effective valorization of these by-products supports environmental sustainability, circular economy principles, and the creation of functional foods and nutraceuticals.

CONCLUSIONS

This paper highlights that olive mill wastewater, tomato waste, and sea buckthorn waste are valuable sources of bioactive compounds and nutrients, offering substantial potential for valorization in the food and nutraceutical industries. Olive mill wastewater is particularly rich in soluble polyphenols, including oleuropein and hydroxytyrosol, as well as flavonoids, which exhibit strong antioxidant activity. These compounds can be recovered and utilized as natural antioxidants in foods, functional ingredients, and nutraceutical products, while also helping to mitigate the environmental impact of wastewater.

Tomato pomace contains significant amounts of carotenoids, such as lycopene and β-carotene, polyphenols, dietary fiber, and minerals, maintaining considerable antioxidant activity. It can be incorporated into bakery products, snacks, beverages, and supplements to enhance nutritional value and provide natural antioxidants.

Sea buckthorn pomace is rich in polyphenols, flavonoids, carotenoids, fiber, and micronutrients, making it suitable for applications in bakery, functional beverages, fortified foods, and nutraceutical formulations. The use of these by-products results in products with enhanced antioxidant activity, improved nutritional profiles, and added functional benefits, while also supporting circular economy principles.

In conclusion, all three agri-food waste streams possess high bioactive potential, and the recovery of their antioxidant compounds for integration into functional foods represents an effective strategy to reduce environmental risks and increase the added value of secondary resources. Such practices contribute to the development of a sustainable food industry and innovative nutraceuticals, providing both health and economic benefits.

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