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Sustainable Valorization of Olive Oil By-Products: Green Extraction of Phytochemicals, Encapsulation Strategies, and Food Applications

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ABSTRACT

Olive oil (OO) production generates significant amounts of by-products, including olive leaves and pruning residues, olive pomace, OO wastewater, and olive stones. These by-products are rich in bioactive compounds, particularly polyphenols and secoiridoids, which possess antioxidant, anti-inflammatory, antimicrobial, and cardioprotective properties. However, their stability and bioavailability remain challenges, necessitating innovative recovery and stabilization techniques, highlighting their potential in high-value industries such as food, cosmetics, nutraceuticals, and pharmaceuticals. This review explores the sustainable valorization of olive by-products through green extraction methods such as ultrasound-assisted extraction, microwave-assisted extraction, supercritical fluid extraction, and so on, and alternative innovative solvents like deep eutectic solvents (DES). These eco-friendly approaches enhance the recovery of bioactive compounds while minimizing the environmental impact of OO production and the reuse of its by-products. Additionally, this work explores encapsulation techniques for their effectiveness in protecting and stabilizing phenolic compounds, enhancing their solubility, bioavailability, and controlled release across various applications, including food, cosmetics, pharmaceuticals, and nutraceuticals. Recent studies highlight the effectiveness of chitosan, maltodextrin, cyclodextrin, and alginate as encapsulating agents for OO bioactive compounds, enhancing their stability. Likewise, the review emphasizes the environmental challenges arising from OO residues and discusses the potential role of olive by-products in circular economy strategies, underlining their potential in sustainable alternatives as biodegradable packaging materials to conventional paper derived from forest-based feedstocks, synthetic additives, animal feed, functional foods, dietary

Laura Aracely Contreras-Angulo and Hassan Laaroussi have contributed equally to this work.

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supplements, agricultural eco-solutions, and other applications. Moreover, it critically discusses future directions and possible challenges. The findings support the pivotal role of integrated biorefinery approaches in transforming OO by-products from agro-industrial waste into high-value resources, enhancing their efficient industrial applications, promoting sustainability and driving a force in future bioeconomies.

1 | Introduction

Olive is a popular fruit of all civilizations worldwide with multifaceted use purposes. It is widely appreciated and integrated as a main ingredient in the daily diet of several countries (Rivas-Garcia et al. 2023). *Olea europaea* L. belongs to the Oleaceae family and originated from ancient Persia and Mesopotamia around 5000 years ago. Then, it is introduced to the other parts of the Mediterranean basin (Kapellakis et al. 2008). Actually, olives are cultivated in all Mediterranean countries, and Spain, Portugal, Italy, Greece, Türkiye, and Morocco are the main producers worldwide.

The olive, a perishable fruit, is composed of three distinct structural parts: the epicarp (skin), the mesocarp (pulp), and the woody endocarp (stone), which encases the seed. These fruits are typically composed of 35%–53% water and 18%–27% oil, which, due to their dense chemical composition and wide range of properties, is used as a raw material to produce various products.

The extraction process of olive oil (OO) has been assessed using stone mortars since 5000 BC. For OO recovery, three different techniques to extract them from olives are used including traditional pressing mills, and two or three-phase centrifugation systems (Ammari et al. 2025). The growing demand for OO imposes to amplify and develop extraction techniques in order to meet this demand (Mili and Bouhaddane 2021). Simultaneously, the new agricultural policies adopted in several countries have led to amplified new plantations to cover the rising demand for OO (Neves and Pires 2018).

On the other hand, enormous amounts of residues are generated during olive processing (Ammari et al. 2025), with an important economic impact on OO producers. The annual OO residues' worldwide production is estimated at 30 million m³/year (Asfi et al. 2012; Kavvadias et al. 2010). It presents a high environmental burden because of its high organic load proportion and phytotoxic components like phenolic compounds (Abboud et al. 2025). Furthermore, from an environmental perspective, the reuse of OO waste through its conversion into sustainable bioenergy support the green economy by reducing dependence on fossil fuel (Alharbi and Ghonimy 2025). On the other side, the nutritional and bio-functional value of OO by-products remains largely unexplored. Therefore, exploring sustainable technological strategies for the valorization of liquid and solid OO by-products is crucial and necessary to maximizing their potential. In this way, the environmental impact can be mitigated, while fostering high-value sustainable innovation and enhancing the efficient use of these bioresources.

Within this framework, this review emphasizes the environmental challenges arising from OO residues and underscore the

immense potential of olive industry by-products by showcasing cutting-edge ecological processing methods for recovering valuable compounds, innovative encapsulation techniques for phenolic compounds, and their recent advanced application as functional ingredients in the nutraceutical sector. Together, these approaches position OO by-products as powerful, untapped sources of phytoactive compounds with high economic value.

2 | OO Production Process and Main Generated By-Products

Nowadays, the OO production sector has had a growing socio-economic impact, mostly due to its health-beneficial effects, partially attributed to extra virgin OO (EVOO) (Contreras et al. 2020). OO is known as a fundamental functional food in the Mediterranean diet. Owing to its rich and varied composition of nutri-functional ingredients and bioactive components, OO has been linked with multiple health benefits, which makes it a food product of increasing demand. For instance, according to the International Olive Council (IOC), the annual world OO production reached 3010,000 t (year 2022 production data), and therefore generates millions of tons of liquid and solid by-products (Otero et al. 2021).

Regarding OO production (Figure 1), in the first step (washing and cleaning), the olives are washed with water and subjected to mechanical and pneumatic means, such as a vibrating sieve, to separate them from the leaves and pruning of the olive tree, as well as other impurities (first by-products).

In the second step (milling and malaxation), the washed olives are ground by breaking up the stones, skin cells, and pulp to obtain a homogeneous paste. The paste is formed by a semi-liquid mixture of two types of solids (fragments of the stones and parts of the pulp and peels) and immiscible liquids (water and oil). After milling, the malaxation step is necessary to generate oil coalescence, and production of some physical and chemical changes in the olive paste, important in the differentiation and quality of OO. A variety of enzymatic processes, including oxidation and hydrolysis, take place during malaxation and are necessary to promote the solubility of olive components. This is accomplished by lowering the oxygen concentration, forming monoglycerides and diglycerides, and converting polyunsaturated fatty acids (PUFAs) into derivatives of carbonyl and short-chain aldehydes.

In the third step, after malaxation, the olive paste is processed for oil extraction. The separation can be performed by pressing methods (traditional and high-pressure equipments), or by two- or three-phase centrifugal separations, resulting in a liquid phase (mixture of oil and water) and a semi-solid phase (olive pomace [OP]).

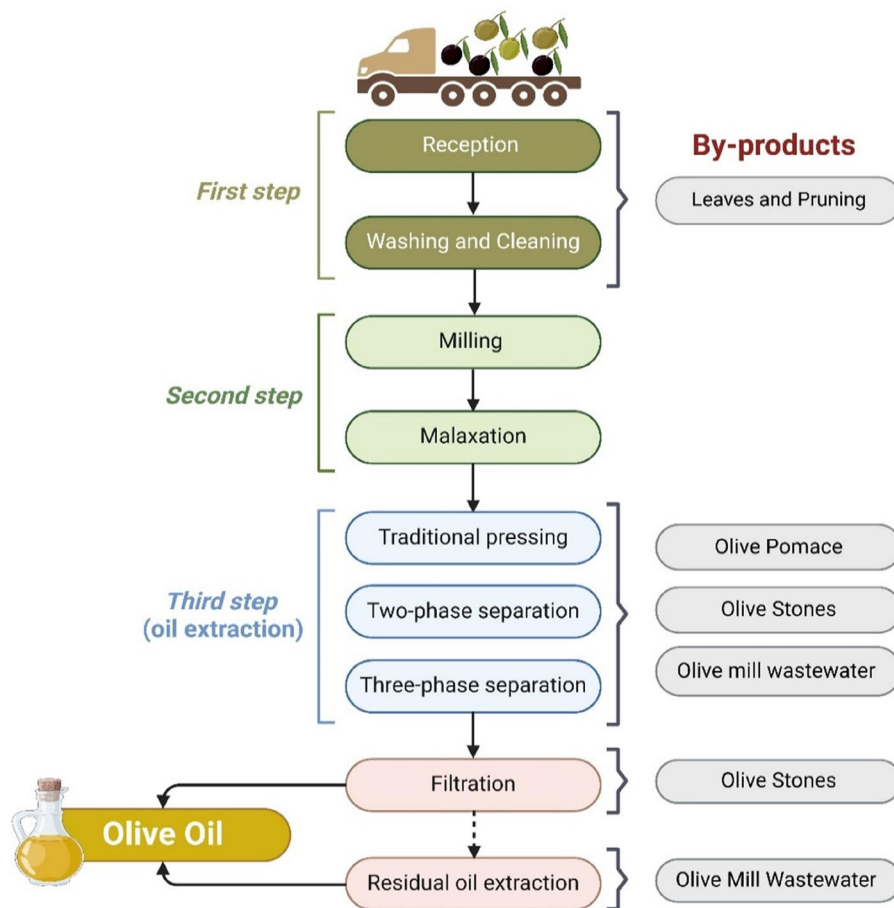


FIGURE 1 | Process of olive oil production and its by-products.

During the three- or two-phase separation systems, the separation of the oil occurs due to differences in density between the other components (water, olive stones [OS], and other residual solids from biomass).

In the three-phase system, water is typically added to separate and purify the oil, resulting in the separation of the remaining water and clarified oil. A paste centrifugation results in the formation of three phases: a solid phase (composed of OP) and two liquid phases (one oil and one water). The oil phase obtained in this process has about 2%–5% water droplets and some solids, so it is necessary to perform a new separation by centrifugation. At this stage of the process, a significant amount of environmentally harmful wastewater (olive mill wastewaters [OMWW]) and OP are generated, and these are the main by-products that need to be valorized.

In the two-phase system, the decantation/centrifugation generates two phases: an oil phase and a semi-liquid pomace phase, composed of pulp with residual oil and water. The semi-liquid can be centrifuged again to recover more oil. In this system, a lower quantity of OMWW and a higher quantity of OP are generated, compared to the three-phase system.

In the end, filtration is necessary as a final step, so that the resulting OO is available to be packaged and stored before being delivered for marketing.

As already mentioned, there are many by-products obtained during the OO production process, which can be divided into (i) leaf and pruning biomass (L&P), (ii) OMWW, (iii) OP, and (iv) OS (Nunes et al. 2016; Otero et al. 2021). These generated by-products are usually unprocessed (they are not fully exploited) and discarded directly into the environment, which consists of a real biological and ecological concern for OO -producing countries and surrounding areas. To minimize its negative effects on the environment and to limit its heavy economic impact, research on bio-waste management technologies still requires additional progress in the OO industry (Pérez et al. 2021). In this context, considering the complex composition of OO by-products (i.e., volatiles, lipids, sugars, pectins, nitrogenous chemicals, polyalcohols, and polyphenols), it remains necessary to choose and adopt the appropriate extraction method/technology to recover specific value-added bioactive and functional molecules from by-products generated in OO production.

2.1 | General Composition of Olive Oil By-Products

The individual composition of OO by-products depends on several factors, such as the region where the olives are grown (cultivation conditions like meteorology, soil composition, etc.), the olive species variability, the state of ripeness, the processing methods used to extract the OO, and the methods to determine

the specific content of different components, not all of them are appropriate for the olive. It is important to note that not all of them are suitable for olives due to the high amount of fat and polyphenols present in this biomass (Rodrigues et al. 2015).

2.1.1 | Olive Leaves and Pruning

L&P by-product is the combination of branches and leaves accumulated during pruning and harvesting, as well as collected during the cleaning process at olive processing factories. L&P presents a vast composition, including nutrients, fiber, and bioactive compounds, making them valuable for multiple applications (Servian-Rivas et al. 2022).

In terms of macronutrients, L&P presents a high polysaccharide content, about 40% cellulose, 16%–25% hemicelluloses, and 15%–25% lignin; around 20% non-structural compounds, including extractives (mainly phenolic compounds, detailed in the next sections), proteins (5%–10%), and minerals. The lipid content is generally low (around 1%–3%) but includes small amounts of beneficial fatty acids, such as oleic acid (García Martín et al. 2020; Servian-Rivas et al. 2022).

2.1.2 | Olive Stones

The stone accounts for 10%–30% of the total weight of the olive, that is, an annual production of around 4 million tons in the Mediterranean region (Kellil et al. 2024; Rodríguez et al. 2008). Cellulose (20%–34% of glucose), hemicellulose (21%–27% of xylose), and lignin (21%–40%) are the main components of this lignocellulosic by-products, although fat (5%) and protein (3%–17%) are present in considerable quantities (Padilla-Rascón et al. 2020; Rodríguez et al. 2008). Ash and related mineral content are one of the lowest fractions of this by-product, representing less than 0.5% of the total biomass.

OS is widely used as a raw material for the production of heat and electricity, but recently the OS has also been considered a raw material for the recovery and production of value-added products. Phenolics (around 2.8 mg/g OS) are the main components of great interest in this by-product (detailed in the following sections), providing economic value in its use as a product for food, cosmetic, and therapeutic purposes (Kellil et al. 2024). Moreover, the oil extracted from the OS is characterized by a high content (16%–25%) of PUFAs (Abdel Rahman et al. 2024; Maestri et al. 2019).

On another front, by proposing a high-performance and sustainable biorefinery process, it is possible to produce xylitol, furfural, ethanol, and poly-3-hydroxybutyrate (PHB) from OS (Hernández et al. 2014).

2.1.3 | Olive Pomace

OP is the primary solid by-product of the extraction of OO and accounts for approximately 35%–40% of the total weight of the olives processed in the mill, reaching 2,881,500 t/year

worldwide (Loschi et al. 2024; Selim et al. 2022). Depending on the extraction method used for the oil recovery, this by-product is a heterogeneous biomaterial composed of fragments of olive skin (epicarp), pulp (mesocarp), and crushed stone (endocarp). Fresh OP contains a considerable content of water (around 50%–70%), though this can vary on the basis of the extraction method (e.g., traditional pressing, two-phase or three-phase extraction systems), and residual oil (approximately 5%–10%) (Nunes et al. 2016). These properties make fresh OP difficult to handle properly due to its considerable moisture content, which can accelerate microbial growth and spoilage, making drying or further processing necessary.

In fact, OP compounds and residual oils can leach into waterways, leading to eutrophication and degradation of aquatic ecosystems (Dich et al. 2025). Moreover, the decomposition of OP releases greenhouse gases like methane, which contribute significantly to climate changes (García-Rández et al. 2025).

OP major chemical compounds are carbohydrates (about 30%), crude fiber (20%–67%) composed of cellulose, hemicellulose (xylose, manose, galactose, and arabinose) and lignin (30%–41.6%), protein (1%–9%), 3%–20% fat (oleic acid and other C2–C7 fatty acids), about 1%–17% ash, polyalcohols, and polyphenols such as phenolic acids and alcohols, secoiridoids, lignans, and flavones (Nunes et al. 2021; Quero et al. 2022; Ribeiro et al. 2020). Taking into account the abovementioned chemical composition, the OP is increasingly recognized for its potential applications across various industries. As is well known, the beneficial human health effect of bio-valuable compounds from olive by-products have been addressed in several publications and patents; however, their potential integration as feed ingredients has received less attention.

2.1.4 | Olive Mill Wastewater

OMWW is a brown-colored dark liquid (pH 3–6) by-product composed of water naturally present in olives and water used during several phases of oil extraction process (83%–94%), a small amount of olive fruit soft tissues (skin or pulp), and residual oil (1%–14%) (Agabo-García et al. 2023). OMWW can vary somewhat in content in addition to water. Still, it is usually made up of many organic substances (3.5%–15%) such as, 13%–53% of carbohydrates (raffinose, lactose, glucose, and fructose), 8%–16% of nitrogen forms mainly amino acids (glycine, proline, histidine, arginine, and tyrosine), 3%–10% of organic acids (oleic acid (70%), lactic acid, citric acid, acetic acid, and palmitic acid), 3%–10% of polyalcohols, 2%–15% of phenolic compounds, and at lower amounts it contains tannins, pectins, carotenoids, and aldehydes (Agabo-García et al. 2023; Zahra El Hassani et al. 2023). It is noteworthy that this by-product has a significant concentration of water soluble phenolics (up to 53% of the phenolics found in the olive fruit), including caffeic acid, ferulic acid, tyrosol, hydroxytyrosol, luteolin, syringic acid, *p*-coumaric acid, and protocatecholic acid, tannins, anthocyanines, stcoiridoids, and catechols (Shabir et al. 2023). The inorganic fraction (0.4%–2.5%) contains potassium (47%), carbonates (21%), phosphates (14%), sodium (7%), magnesium, iron, copper, and other trace elements (lead [Pb], cadmium [Cd], etc.) (Shabir et al. 2023).

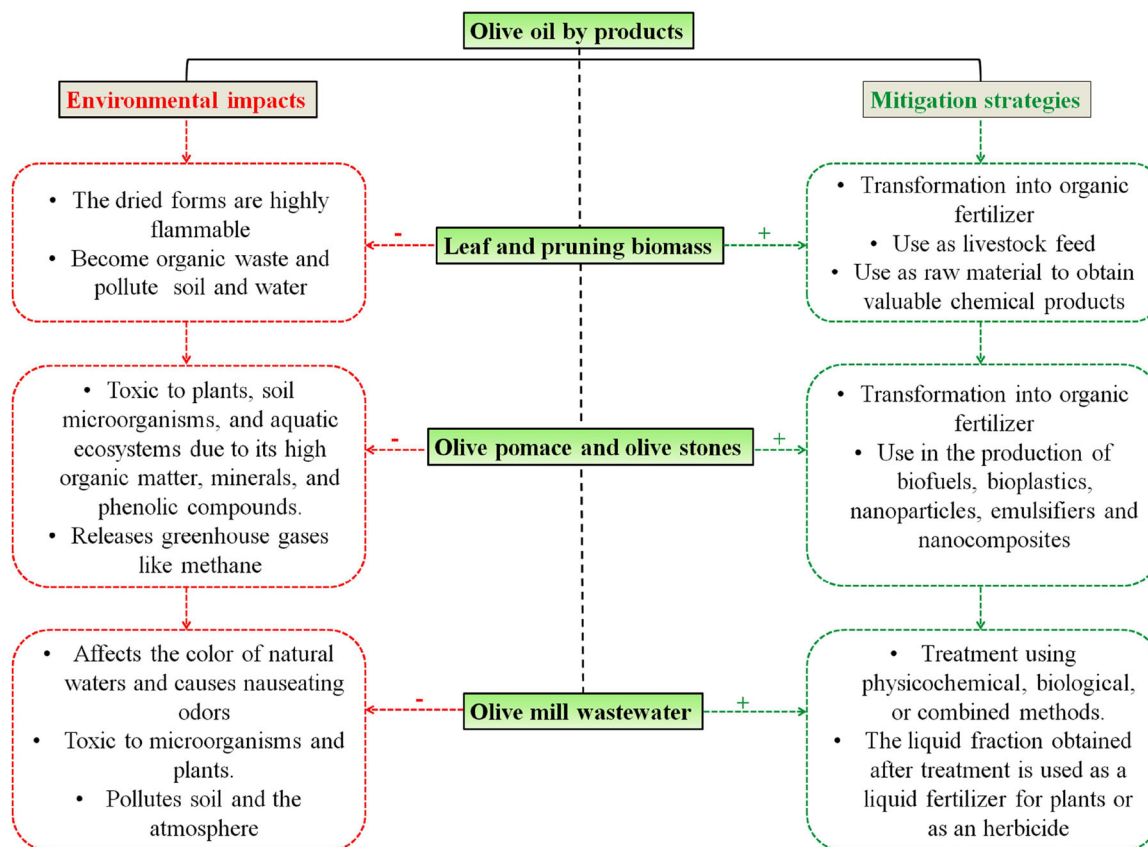


FIGURE 2 | Environmental impacts and mitigation strategies for olive oil by-products.

3 | Strategies to Mitigate the Environmental Impact of OO By-Products

The OO industry generates enormous amounts of undervalued and low-cost by-products that impact the environment, due to their low pH, and high content of organic loads. OO by-products, L&P, OMWW, OP, and OS, if not managed properly, can have negative effects on soil, water, and air quality. It is important to analyze the environmental impact of each by-product and discuss possible valuable solutions to mitigate these negative effects on the environment and potential health problems associated with a strong economic impact (Paulo and Santos 2021). Conversely, transforming agricultural by-products into value-added products aligns with the 2030 Agenda for Sustainable Development, contributing to the achievement of the Sustainable Development Goals (SDGs) adopted by all United Nations Member States. This approach also fosters circular economy practices and significantly reduces the environmental footprint of agricultural activities.

The environmental impacts and potential mitigation strategies related to OO by-products are summarized in Figure 2.

Olive L&P, pruned from trees or collected during harvest, are less harmful by-products, but they still need adequate disposal, and more importantly, developing industrial strategies for their valorization. These by-products in dry form are highly flammable, increasing wildfire risk in olive-growing regions. Moreover, leaves and branches, if not processed, contribute to organic agricultural waste accumulation, causing contamination of soil and water and

the release of greenhouse gases. L&P residues are usually burned in the field, which is associated with the production of organic aerosol, mainly composed of alkane groups (Contreras et al. 2020; Servian-Rivas et al. 2022). The actual strategy for reducing the negative environmental effects of L&P olive by-products is the transformation in composting, which can be turned into organic fertilizer, adding nutrients to soils. In some cases, dried olive L&P are used as livestock feed, providing economic benefits. L&P has the potential to be a feedstock to obtain different valuable chemicals after biomass treatment and transformation, like bioethanol (Fanourakis et al. 2024), xylitol (Mateo et al. 2015), lignin, and cellulose nanomaterials (Ben Mabrouk et al. 2023; Toledano et al. 2013), and interesting antioxidants such as oleuropein, tyrosol, and hydroxytyrosol that are valued in the pharmaceutical and cosmetic industries (Fanourakis et al. 2024; Oliveira et al. 2021; Sánchez-Monedero et al. 2024).

The OP by-product obtained after the extraction of OO, containing olive pulp, skins, stones, and some water, and OO remains (Loschi et al. 2024). This biomass is rich in organic matter and minerals, but also in phenolic compounds, which are toxic to plants and soil microorganisms in large quantities. OP compounds and residual oils can leach into waterways, causing eutrophication and harming of aquatic ecosystem. Moreover, the decomposition of OP releases greenhouse gases like methane, a climate change potentiator.

Strategies for mitigating the negative effects of OP and OS include their application as compost for soil amendment, due to the

high organic content and minerals. It has been found that the application of OP as a biofertilizer has a positive impact on the soil quality and on the phytochemical composition of some plants such as *Rosmarinus officinalis* (Alaoui et al. 2023).

OP and OS can be used as a biofuel, directly burned to generate energy, or processed into pellets for heating, and used to obtain biodiesel and emulsifiers (glycerol) (Heinzl et al. 2022). This method can be considered an agri-food waste reduction strategy and can help to reduce dependence on fossil fuels. But in this way, the recovery of valuable components from this by-product is not highlighted. Currently, these by-products are used to extract useful compounds such as phenolic compounds for later use in foods, pharmaceuticals, and cosmetics (Quero et al. 2022). OP and OS are also rich in lignin and polysaccharides that make this by-product suitable for biofuels, bioplastics, nanoparticles, and nanocomposites production with interest in the food industry, agriculture, and so on (Contreras et al. 2020; Tolisano et al. 2023). However, its use at the industrial level must be increased using alternative and environmentally friendly technologies.

The management of the high fluxes of hazardous OMWW obtained in the OO production process represents one of the biggest environmental challenges in all OO-producing countries. The phenomenon of contamination affects first the color of natural waters and the release of nauseating odors (e.g., methane products), causing long-distance pollution of the three ecosystem matrices by contaminating surface and ground waters, as well as diffuse pollution of soil and atmosphere. The global OMWW generation is estimated to vary between 10 and 30 million m³, corresponding approximately to 0.55 and 2 L of OOWW for every kilogram of pressed olives (El-Abbassi et al. 2012). Even though this produced residue is far less than residues generated from other agro-food products, the environmental impact is thought to be substantial. According to El-Abbassi et al. (2012), 1 m³ of OMWW is equivalent to 200 m³ of domestic sewage in terms of environmental contamination and produces a pollution load equivalent to 1500 people in a single day. These data reaffirm its significant impact on the ecosystems. In fact, uncontrolled OMWW discharge increases soil hydrophobicity and affects its general composition/characteristics, mainly nitrogen immobilization, salinity, acidity, and nutrient leakage, promoting significant toxic effects (Khdair and Abu-Rumman 2020). The phytotoxic effect of OMWW, mainly linked to the complex composition higher in fat, minerals, and phenolic compounds, has been investigated, demonstrating their negative effect on agriculture and food system preservation (Enaime et al. 2020). Moreover, previous studies documented the toxic effect of OMWW on microorganisms and plants (El-Abbassi et al. 2012; Zahi et al. 2022). Accordingly, this wastewater product exerts its bio-toxic effect due to its rich content on organic load, fatty acids, tannins, inorganic substances, and phenolic compounds; and high level of chemical oxygen demand (COD) and biochemical oxygen demand (BOD) from 200 and 100 kg/m³, respectively, significantly associated with pollution problems (Sciubba et al. 2020; Shabir et al. 2023).

On the other hand, in order to increase the quality of OMWW and eradicate or at least reduce its related environmental pollution, researchers have been trying to develop treatment methods (physico-chemical, biological, or combined) for OO manufactur-

ers (Issa et al. 2023; Zahi et al. 2022). According to the literature, the biological treatments of OMWW consist of aerobic and anaerobic digestions, co-composting, and biopesticides and generally are used to remove phytotoxic compounds. OMWW has been treated with a variety of chemical techniques to remove or reduce their organic content (COD, phenolic content, etc.), such as membrane reactors, electrocoagulation, hydrothermal carbonization, combined Fenton and ozone/Fenton processes, electrohydrolysis, and photocatalytic degradation using a nano-ZnO-magnetite composite. Moreover, physical treatment of the OMWW was investigated, like liquid-liquid extraction (ethyl acetate), filtration, and nanofiltration (silicon carbide membrane), adsorption (charcoal, bentonite, etc.), flocculation, coagulation, and their combinations in order to remove phenolic compounds, heavy metals, COD, and other hazardous components of OMWW (Al-Essa 2018; Zahi et al. 2022).

The resultant liquid fraction after different treatments was rich in polyphenols and nutrients, and this liquid could be used as a liquid fertilizer source of plant nutrients and thereby rendering this effluent potentially suitable for recycling as a soil amendment (Volpe et al. 2018; Zahra El Hassani et al. 2023). Furthermore, OMWW nutritional value, possible herbicidal activity, and capacity to suppress soil-borne plant diseases make it valuable in organic and sustainable farming (Mechri et al. 2011).

4 | Green Process Technologies to Recover Valuable Compounds From Olive By-Products

The OO industry represents an important productive sector in some Mediterranean countries, generating different sustainable and low-cost by-products with valuable properties that make them suitable for obtaining important biomolecules with high commercial value, mainly polyphenols.

The recovery of added-value biomolecules from OO by-products (and other biological matrices) is a crucial step and a leading strategy to promote their subsequent incorporation as functional ingredients in food, feed, and nutraceutical sectors and enhance their applications in cosmetic and pharmaceutical products.

As solvents with different polarities are required for the extraction process and selective isolation of target phyto-compounds with different chemical structures, the choice of solvents should be based on the polarity and chemical nature of the biomolecules to be extracted. This guarantees greater recovery and increased selectivity for a chemical group of molecules or even a specific molecule. For instance, antioxidant molecules, like phenolic acids (e.g., caffeic acid), flavonoids (apigenin, rutin, etc.), and secoiridoids (e.g., oleuropein), are normally extracted using water, ethanol, and methanol as polar solvents and/or propanol and acetone alone, or organic solvents mixed with water (Ferreira-Santos, Zanuso et al. 2020). However, these conventional solvents have been found to be ineffective as they take a long time to extract the desired molecules and even more time to purify/isolate the target molecule. In addition, this experimental procedure involves a higher volume of organic/petroleum-based solvents, which might generate a large amount of hazardous waste (Ferreira-Santos, Zanuso et al. 2020).

It is therefore still necessary to look for new, safer, and more effective extraction processes, such as the combination of green process technologies and ecological solvents (non-toxic, non-volatile, recyclable, and biodegradable solvents) (Roselló-Soto et al. 2015). These strategies aim to reduce the environmental impact and avoid the harmful effects of organic solvent residues in OO extracts or extracted molecules. This is extremely important as they are normally intended for human consumption, as pharmaceuticals and nutraceuticals, incorporated into functional or fortified foods, used in cosmetic formulations, and utilized in the agricultural sectors.

In response to high consumer expectations and their increasing demand for healthier lifestyles and taking into consideration the worldwide legislative changes toward more environmentally agricultural systems and sustainable methods of extracting, preserving, and improving food quality; the food processing and industrial sectors are currently undergoing a real green revolution (Sagar et al. 2018). Reducing and minimizing the use of hazardous solvents in the extraction processes of bio-valuable compounds is currently a priority of the first line in European Union (EU) policy. According to this perspective, the EU strategy 2010–2050 aims to reduce the use of hazardous solvents during the extraction process of bio-compounds intended for human consumption (Cvijetko Bubalo et al. 2018). Accordingly, the selection of appropriate green solvents is mostly based on their characteristics (flammability, explosiveness, volatility, mass transfer, and other aspects), safety (eyes, lungs, and skin irritation, mutagenicity, carcinogenicity, and other toxic effects), environmental footprint (soil and water contamination, persistence, ozone layer depletion) and process sustainability (solvent recycling ability). More importantly, it should also be efficient to recover high-quality extracts and conserve the bio-properties of the extracted molecules to meet both technological and economic demands (Murador et al. 2019).

Finding suitable extraction methodologies is important in valorizing by-products derived from OO production. Ideally, an appropriate extraction technique for the recovery of bio-valuable compounds should be efficient, sustainable, environmentally friendly, and viable to be used on an industrial scale (Clodoveo et al. 2021).

Figure 3 illustrates the advantages of eco-extraction processes for recovering valuable biocompounds, highlighting several key benefits, such as the prevention of bioactive compound degradation during extraction, the simplification of the necessary steps, the acceleration of the process compared to traditional methods, and the efficient use of energy to reduce consumption. Furthermore, these processes promote the use of environmentally friendly, non-toxic, and biodegradable solvents, minimize waste by converting by-products into valuable resources, maximize extraction yields, and allow for greater selectivity, facilitating the recovery of specific molecules of interest (Ferreira-Sousa et al. 2024). Together, these features promote sustainability and ensure the efficient recovery of high-value biomolecules. However, their economic viability depends on various factors, including equipment costs, energy consumption, and maintenance requirements. While promising at the laboratory scale, challenges remain regarding scalability and industrial implementation, particularly in achieving consistent performance, regulatory compliance,

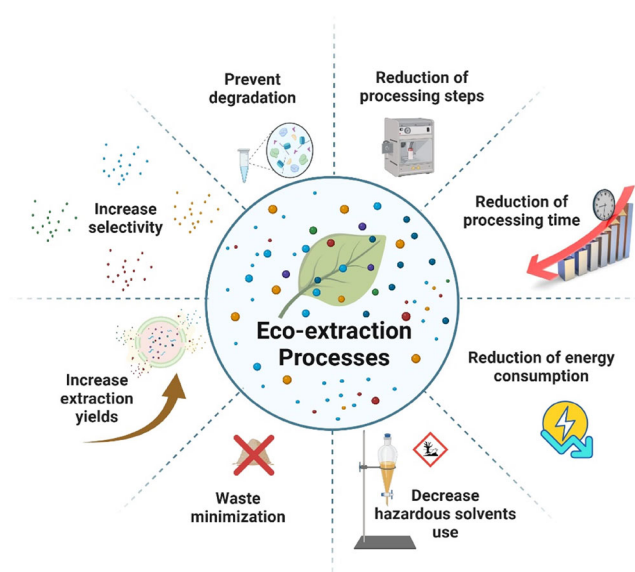


FIGURE 3 | Advantages of efficient extraction techniques for recovering bioactive compounds from olive oil by-products.

and integration with existing processing lines. Despite these limitations, continued advancements in process optimization and equipment design are making these technologies increasingly feasible for industrial-scale applications, especially in the context of circular economy models and high-value compound recovery from agro-industrial by-products (Ferreira-Sousa et al. 2024).

For this reason, green solvents—such as water (the greenest solvent), deep eutectic solvents (DES), CO_2 , among others are recommended as efficient and safe options for modern extractions based on eco-friendly process technologies (López-Salas, Expósito-Almellón et al. 2024). These green solvents can recover a large number of target biomolecules from various chemical classes from several feedstocks, including OO and OO by-products.

Looking at the bibliography and using the combined words of “Olive by-products; Green solvents” (ScienceDirect database), we can see that in the last 10 years, there has been an exponential increase in the number of papers (174 in 2014 to 1134 in 2024) dealing with the use of green alternative solvents in the recovery of bioactive and functional compounds from olive by-products. In addition, the number of articles related to the extraction of biofunctional compounds with DES from olive by-products has grown significantly over time, rising from 10 in 2014 to 39 in 2019 and reaching 214 in 2024. This search shows a growing concern for the use of more sustainable processes in the valorization of OO by-products.

Some examples of using DES to extract valuable compounds from OO by-products are listed below:

- de Almeida Pontes et al. (2021) tested different DES prepared with choline chloride (ChCl) and carboxylic acids in the extraction of phenolic compounds from olive leaves. Their results demonstrate that ChCl:acetic acid (1:2 molar ratio) with 50% of water extracted the highest amount of phenolic

compounds, totaling 470.03 mg/kg olive leaves (15% more than ethanol).

- Mir-Cerdà et al. (2024) used natural DES (NaDES) has a green extraction solvents, and their results showed that ChCl:glycerol (1:5 ratio) with 30% water, was more efficient than conventional solvents to extract phenolic compounds from olive leaves, namely, oleuropein and luteolin and their derivatives, 3-hydroxytyrosol, and verbascoside.
- Chanioti and Tzia (2018) evaluated different ChCl-based NaDES with a combination of citric acid or lactic acid or maltose or glycerol and an addition of 20% water, which were successfully applied to the recovery of phenolic compounds and secoiridoids from OP. These NaDES, mainly ChCl: citric or lactic acids, were more effective than conventional solvents, that is, water and 70% ethanol, to obtain oleuropein, hydroxytyrosol, caffeic acid, vanillin, rutin, and luteolin.
- Ünlü (2021) optimized the extraction of phenolics and secoiridoids using NaDES and methanol as a conventional solvent. The results provided revealed that glucose:fructose:water (1:1:11) NaDES was found to extract the highest amount of oleuropein and caffeic acid from olive leaves, showing better recovery than methanol.

These results, together with many other works, show a possible encouraging change from organic solvents with NaDES to an environmentally friendly process. Typically, NaDES are well known as emerging ecological solvents derived from safer, abundant, cheaper, and biodegradable organic compounds present in our daily diet, such as amines, sugars, choline polyalcohol, and carboxylic acid (Lobato-Rodríguez et al. 2023). NaDES display good physicochemical characteristics on the basis of their liquid state at different temperature degrees, high solubilization degree, adaptable viscosity, and low volatility among other characteristics, which meet the exigencies of green chemistry (Lobato-Rodríguez et al. 2023). Even though they can be modified to have increased affinity for the target compounds, the Federal Drug Administration (FDA) does not yet regulate NaDES as there are limited shared data regarding the biological activity and toxicity of the extracted materials, which restrict their industrial use, especially in the nutraceutical and pharmaceutical sectors (Cvjetko Bubalo et al. 2018). Furthermore, the high boiling point characteristic of these green solvents (affecting their separation from the final mixture) might limit their industrial applications.

Additionally, alternative-assisted extraction technologies, including microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), subcritical water extraction (SWE), supercritical fluid extraction (SFE), pressurized liquid-assisted extraction (PLAE), ohmic heating-assisted extraction (OHAE), high-voltage electrical discharges (HVED), high hydrostatic pressure-assisted extraction (HHPAE), and others, are recognized as effective and viable strategies to recover valuable compounds from natural feedstocks like OO by-products (Table 1). The combination of the appropriate solvent and extraction technology is critical for enhancing the efficiency of the process, guaranteeing maximum recovery of target compounds while minimizing resource use and environmental impact (Ferreira-Sousa et al. 2024).

Due to the above-mentioned advantages, eco-friendly and sustainable processes are increasingly used for the extraction of bio-functional compounds. The combination of these innovative and emergent technologies and selective green solvents under controlled conditions have been mostly applied for the extraction of antioxidant compounds, especially phenolic molecules, from a wide variety of plant-based foods, and by-products.

Polyphenols are a class of a variety of chemical molecules (phenolic acids, coumarins, flavonoids, tannins, lignans, and stilbenes) present in different terrestrial and aquatic resources such as cereals, fruits, plants, algae, and other natural matrices (more than 8000 compounds identified). These secondary metabolites are vital components for the human development (not synthesized by the organism) because they have an enormous biological properties, such as being antioxidant, anti-inflammatory, anti-obesity, anti-allergenic, anti-viral, anticancer, anti-thrombotic, antimicrobial, anti-mutagenic, vasodilator and cardioprotective effects, among others (Di Donato et al. 2018; Ferreira-Santos et al. 2022; Ferreira-Santos, Genisheva et al. 2020; Quero et al. 2022; Sánchez et al. 2023).

From a chemical structure point of view, the presence of hydroxyl groups and benzene ring(s) are the common and shared characteristics of all phenolic molecules. In addition to the carbon side chain, the positioning of hydroxyl groups on the benzene ring(s) gives rise to a variable number of phenolic molecule (Ferreira-Santos, Zanuso et al. 2020). According to their chemical structure, flavonoids and non-flavonoids molecules are regrouped into two main groups, namely, lipophilic and hydrophilic antioxidants. For this reason, the recovery of these compounds from natural sources required the choice of suitable solvents and appropriate processes, green technologies, for example, to better recover and preserve the biological properties of the extracted components.

In recent years, scientists are interested to extract polyphenols and other high-added value molecules agri-food by-products, including OO by-products using different emergent technologies (Table 1).

Secoiridoids, like polyphenols, are secondary metabolites found mainly in plants from the *Oleaceae* (e.g., olives), *Gentianaceae* and other related families. They are notorious for their presence in olives and OO (oleuropein, oleacein, and ligstroside, etc.), where they contribute to several beneficial health properties due to their potent antioxidant, neuroprotective, antimicrobial, anticancer, and anti-inflammatory activities (Filardo et al. 2024). For instance, OL are notably rich in oleuropein (up to 14% dry weight [dw]), along with other secoiridoids (ligstroside, oleuroside, secologanoside, etc.), and phenolics such as verbascoside, luteolin, and apigenin derivatives (Khanlar et al. 2025). OP, a semi-solid OO residue, is a rich source of hydroxytyrosol, tyrosol, and various other secoiridoids, whereas OMW contain mainly hydrophilic phenolics, especially hydroxytyrosol, and its derivatives (López-Salas, Díaz-Moreno et al. 2024; Loschi et al. 2024).

In recent years, owing to their well-known health benefits, researchers have been interested in extracting polyphenols, secoiridoids, and other bioactive molecules from OO by-products for imperative industrial applications. For that, the sustainable

TABLE 1 | Innovative approaches for the recovery of high-added value compounds from olive by-products.

Extraction methods	Solvents/Conditions	TPC	Target compounds	References
Olive leaves				
UAE	DES—Glucose:fructose:water (1:1:1) (50% water)/37 kHz/140 W/75°C/60 min	116 mg GAE/g	Oleuropein (1630.80 mg/kg), caffeic acid (112.77 mg/kg), luteolin (1.34 mg/kg)	Ünlü (2021)
	DES—ChCl:fructose:water (5:2:5) (50% water)/37 kHz/140 W/75°C/60 min	195 mg GAE/g	Oleuropein (853.46 mg/kg), luteolin (0.49 mg/kg)	
	DES—ChCl:lactic acid (1:2) (50% water)/37 kHz/140 W/75°C/60 min	118 mg GAE/g	Oleuropein (290.07 mg/kg), caffeic acid (0.09 mg/kg), luteolin (0.401 mg/kg)	
	DES—ChCl:ethylene glycol (1:2) (50% water)/37 kHz/140 W/75°C/60 min	98 mg GAE/g	Oleuropein (1031.57 mg/kg), caffeic acid (0.08 mg/kg), luteolin (0.25 mg/kg)	
	Water/20 kHz/450 W, 55%/27°C/29 min	81 mg GAE/g	Oleuropein (6.914 mg/g), hydroxytyrosol (0.547 mg/g)	Rosa et al. (2021)
OHAE	DES-polypropylene glycol:lactic acid:water (28.6/33.6/7.8)/360 W/25°C/20 min	21 mg GAE/mL	Oleuropein (6.47 mg/mL), verbascoside (0.76 mg/mL)	Marijan et al. (2022)
	Water:glycerol:cyclodextrin (33%-60%-7%)/60°C/3 h	58.1 mg GAE/g	Luteolin diglucoside, luteolin glucoside, rutin quercetin 3-orutinoside, oleuropein, oleuropein isomer, apigenin rutinoside, apigenin rhamnoside (not quantified)	Mourtzinis et al. (2016)
	Ethanol 60%–80%/25 kHz/1–10 V/cm/55–75°C/15 min	n.d.	Oleuropein (26.18 mg/g extract), verbascoside (1.04 mg/g), tirosol (0.34 mg/g), hydroxytyrosol (1.38 mg/g) luteolin 7-O-glucoside (4.12 mg/g), apigenin 7-O-glucoside (3.47 mg/g), rutin (3.78 mg/g), and rutin (3.78 mg/g)	Markhali and Teixeira (2024)
MAE	Water/2.45 GHz/1000 W/86°C/3 min	104 mg GAE/g	Oleuropein (14.468 mg/g), hydroxytyrosol (0.590 mg/g)	Rosa et al. (2021)
	2 M citric acid- 59.8% ethanol/2.45 GHz/1000 W/97.4°C/3 min	52 mg GAE/g	Isorhamnetin (11.65 mg/g), luteolin (2.13 mg/g), and rutin (0.89 mg/g)	Darvishzadeh and Orsat (2022)
	Ethanol 70%/500 W/40°C/30 min	1445 mg GAE/L	Oleuropein (514 mg/L)	Boli et al. (2022)
	Ethanol 70%/600 W/20°C/20 min	n.d.	Oleuropein (72.08 mg/g), hydroxytyrosol (0.43 mg/g)	Di Meo et al. (2022)
	Water/600 W/20°C/20 min	n.d.	Oleuropein (58.89 mg/g), hydroxytyrosol (0.34 mg/g)	
	Citric buffer (pH = 4.5)/novozyme, 400 W, 60°C, 5 min	35 mg GAE/g	Oleuropein (14,354.3 mg/kg), hydroxytyrosol (680.0 mg/kg), caffeic acid (51.4 mg/kg), vanillin (762.3 mg/kg), rutin (2672.7 mg/kg), and luteolin (164.2 mg/kg)	Chanioti et al. (2016)

(Continues)

TABLE 1 | (Continued)

Olive pomace				
PEF	Metanol 60%/1:10 s/L/5000 pulses/25°C/60 min stirring	15 g GAE/kg	Hydroxytyrosol (2 g/kg), luteolin (0.2 g/kg)	Tsevdou et al. (2024)
UAE	DES- ChCl:lactic acid (1:1)/20% water/60 kHz/280 W/60°C/30 min	2 mg GAE/g	Oleuropein (0.78 mg/g), hydroxytyrosol (1.07 mg/g), caffeic acid (0.005 mg/g), vanillin (0.05 mg/g), rutin (0.21 mg/g), and luteolin (0.08 mg/g)	Chanioti and Tzia (2018)
	Methanol/20 kHz/200 W/56°C/3 min	4 mg GAE/g	Gallic acid (6.9 g/100 g OP extract), protocatechuic acid (19.5 g/100 g), hydroxybenzoic acid (3.9 g/100 g), vanillic acid (9.7 g/100 g), caffeic acid (2.8 g/100 g), cinnamic acid (5.1 g/100 g), syringic acid (16.3 g/100 g), sinapic acid (6.5 g/100 g), ferulic acid (11.1 g/100 g), <i>p</i> -coumaric acid (2.9 g/100 g), rutin (7.6 g/100 g), hesperidin (6.1 g/100 g); and quercetin (1.6 g/100 g)	Mojerlou and Elhamirad (2018)
	Water/40 kHz/100 W/26–46°C/10–60 min	45 mg GAE/g	Hydroxytyrosol and derivatives, oleacein and derivatives, verbascoside, isoverbascoside, oleuropein and derivatives, ligustroside, elenolic acid, hydroxybenzoic acid, quercetin, luteolin, luteolin 7- <i>O</i> -glucoside, deoxyhexosyl-hexoside (not quantified)	Gómez-Cruz et al. (2021)
	Ethanol 90%/20 kHz/135.6 W/cm ² /50°C/3 min	n.d.	Hydroxytyrosol (55.1 mg/g), maslinic acid (381.2 mg/g), and oleanolic acid (29.8 mg/g)	Xie et al. (2019)
	Water/1:10 s/L/4 V/cm/25 kHz/83°C/30 min	12 mg GAE/g	Hydroxytyrosol (28.7 mg/100 g), tyrosol (10.63 mg/100 g), oleuropein (n.d), cinnamic acid (18.45 mg/100 g), <i>p</i> -coumaric acid (44.99 mg/100 g), <i>o</i> -coumaric acid (23.26 mg/100 g), ferulic acid (22.31 mg/100 g), vanillic acid (39.51 mg/100 g), 3,4-dihydroxybenzoic acid (14.20 mg/100 g), syringic acid (n.d), ellagic acid (142.93 mg/100 g), homovanillic acid (103.45 mg/100 g), rosmarinic acid (22.05 mg/100 g), rutin (21.33 mg/100 g), taxifolin (83.10 mg/100 g), naringenin (125.11 mg/100 g), hesperidin (137.30 mg/100 g), quercetin (168.62 mg/100 g), catechin (63.15 mg/100 g), and resveratrol (6.68 mg/100 g)	Quero et al. (2022)

(Continues)

TABLE 1 | (Continued)

Olive pomace			
	Ethanol 50%/1:10 s/L/4 V/cm/25 kHz/83°C/30 min	18 mg GAE/g	Hydroxytyrosol (33.36 mg/100 g), tyrosol (21.09 mg/100 g), oleuropein (254.38 mg/100 g), caffeic acid (2.59 mg/100 g), cinnamic acid (9.99 mg/100 g), <i>p</i> -coumaric acid (48.41 mg/100 g), o-coumaric acid (69.81 mg/100 g), ferulic acid (13.83 mg/100 g), vanillic acid (72.77 mg/100 g), 3,4-dihydroxybenzoic acid (17.61 mg/100 g), syringic acid (42.98 mg/100 g), ellagic acid (147.82 mg/100 g), homovanillic acid (75.54 mg/100 g), rosmarinic acid (62.54 mg/100 g), apigenin (43.13 mg/100 g), rutin (31.46 mg/100 g), taxifolin (94.44 mg/100 g), naringenin (247.42 mg/100 g), hesperidin (93.15 mg/100 g), quercetin (134.94 mg/100 g), catechin (77.68 mg/100 g), and resveratrol (10.34 mg/100 g)
HVED	Ethanol 50%/20 kV/pulse 400 µs/9 min	45 mg GAE/g	Apigenin (58.6 ng/mL extract), diosmetin (47.0 ng/mL), hydroxytyrosol (3016 ng/mL), luteolin (353 ng/mL), oleanolic acid (3386 ng/mL), oleuropein (17,646 ng/mL), quercetin (9.07 ng/mL)
PLAE	Ethanol 50%/1500 PSI/120°C/20 min	n.d.	Quinic acid, hydroxytyrosol, oleanolic acid, and oleuropein (not quantified)
HHPAE	Metanol 40%/1:10 s/L/650 MPa/25°C/1 min	9.3 g GAE/kg	Hydroxytyrsol (10.1 g/kg), luteolin (>0.1 g/kg)
MAE	DES-ChCl:lactic acid (1:1)/20% water/600 MPa/10 min	5 mg GAE/g	Oleuropein (1.94 mg/g), hydroxytyrsol (2.57 mg/g), caffeic acid (0.01 mg/g), vanillin (0.10 mg/g), rutin (0.66 mg/g), luteolin (0.12 mg/g)
	Metanol 60%/1:10 s/L/300 W/50°C/5 min		Hydroxytyrsol (11.4 g/kg), luteolin (0.4 g/kg)
	DES-ChCl:lactic acid (1:1)/20% water//200 W/60°C/30 min	10 mg GAE/g	Oleuropein (7.56 mg/g), hydroxytyrsol (0.89 mg/g), caffeic acid (0.01 mg/g), vanillin (0.12 mg/g), rutin (0.74 mg/g), luteolin (0.17 mg/g)
	Ethanol 12%/30 bar/850 W/100°C/16 min	35 mg GAE/g	Oleanolic acid (3.60 mg/g) and hydroxytyrsol (5.87 mg/g)
(Continues)			

TABLE 1 | (Continued)

Olive mill wastewater				
UAE	Ethanol 50%/37 kHz/220 W/40°C/120 min	9 mg TYeq/g	Secoiridoids (2.61–82.57 mg/kg), organic acids (307.05–690.42 mg/kg), flavonoids (5.70–832.31 mg/kg), phenolic acids and aldehyde (6.93–193.70 mg/kg), phenols (5.76–511.37 mg/kg), fatty acids derivatives (1.99–27.60 mg/kg), triterpenic acids (1.85–46.78 mg/kg)	Sánchez-Arévalo et al. (2022)
Olive stones				
PLAE	Water/50 bar/50°C/90 min	281 mg GAE/kg	Hydroxytyrosol (2.74 mg/100 g), catechin (7.77 mg/100 g), vanillic acid (0.40 mg/100 g), syringic acid (0.06 mg/100 g), oleuropein (3.12 mg/100 g), <i>p</i> -coumaric acid (0.04 mg/100 g), and ferulic acid (0.03 mg/100 g)	Nakilcioğlu-Taş and Ötleş (2020)
MAE	Ethanol 22%/500 W/40°C/40 min	3 mg GAE/g	Phenols (7.23 mg GAE/g) and flavonoids (0.36 mg QE/g)	Djema-Landri et al. (2021)
	DES-ChCl: citric acid (1:2)/200 W/60°C/12,000 rpm/30 min	7 mg GAE/g	Hydroxytyrosol (3.37 mg/g), oleuropein (16.86 mg/g), rutin (1.71 mg/g), caffeic acid (0.01 mg/g), luteolin (0.12 mg/g), vanillin (0.24 mg/g)	Chanioti and Tzia (2018)
SFE	Water/300 bar/190°C/60 min	9 mg GAE/g	Hydroxytyrosol (1.25 mg/g)	Caballero et al. (2020)

Note: All the results presented for the dry weight of OO by-products.

Abbreviations: GAE, gallic acid equivalent; HHPAE, high hydrostatic pressure-assisted extraction; HVED, high-voltage electrical discharges; MAE, microwave-assisted extraction; n.d., not determined; OHAE, ohmic heating-assisted extraction; PLAE, pressurized liquid assisted extraction; SFE, supercritical fluid extraction; SWE, subcritical water extraction; TYeq, tyrosol equivalents; UAE, ultrasound-assisted extraction.

valorization of generated bio-residues should be targeted within an integrated value chain. This can be accomplished using innovative processes that combine green solvents with emerging technologies such as UAE, MAE, OHAE, PLAE, and so on (Table 1).

Considering the vast literature on the extraction of phenolic and secoiridoid compounds from OO by-products, it is notable that the majority of studies focus only on the quantification of total phenolic content (TPC) and do not specify the individual compounds extracted. In many cases, the biocompounds recovered are not quantified using advanced analytical techniques such as HPLC (coupled with DAD, MS, etc.). For this reason, in addition to TPC values, only studies that specifically identify and quantify individual phenolic and/or secoiridoid compounds obtained by novel extraction techniques using green solvents are included in Table 1.

Ultrasound (US) is typically used to assist the extraction process for the recovery of these valuable biomolecules, which allows an increase in the extraction yield and reduces the energy consumption, and most importantly, preserves and prevents the environmental impacts generated during the extraction process in order to contemplate different pillars of sustainability in the OO production chain (Ferreira-Sousa et al. 2024). In contrast to traditional techniques, UAE use sound waves with a frequency varied from 20 kHz to 100 MHz. These high intensity sounds generate collapsing cavitation bubbles and accelerate inter-particle collision, as results facilitate the formation of microchannels and pores within the cellular structure, thereby increasing solvent penetration and accelerating the release of intracellular bioactive compounds into the extraction medium (Pereira et al. 2025). Moreover, the process's simplicity, low cost, and lower environmental impacts encourage the industrial use of this emerging technology as an efficient eco-friendly process. Despite the advantages and characteristics of this technology, it is associated with some defects and drawbacks, including the degradation of extracted bio-compounds, particularly, when applying higher US frequency waves for a long period. Indeed, US waves could alter chemical reactions, leading to possible production of free radicals, oxidation, and hydrolysis of extracted thermolabile molecules (Pereira et al. 2025).

UAE has been successfully used to obtain antioxidant molecules from different OO by-products like olive leaves, OP, OMWW, and OS (see Table 1).

In a study by Ünlü (2021), new generation green solvents, NADES were used in combination with UAE by the application of US waves (37 kHz). As a results, the author reveled, at the optimized conditions, the highest total polyphenol and flavonoid yields were achieved with ChCl:fructose:water (5:2:5 molecular ratio) representing 195 mg GAE/g plant and lead to the recovery of important quantities of oleuropein (290 mg/kg), caffeic acid (0.09 mg/kg), and luteolin (0.401 mg/kg). However, the same authors documented that the DES composed of glucose:fructose:water (1:1:11) at the same experimental conditions (37 kHz/75°C/60 min) and significantly increased the recovery of oleuropein (1631 mg/kg), caffeic acid (113 mg/kg), and luteolin (1.34 mg/kg), highlighting the impact of solvents in the extraction process of specific bio-compounds. Mourtzinou et al. (2016) optimized a green extraction

method for the recovery of polyphenols from the olive leaves using cyclodextrins and glycerin eco-friendly cosolvents. These studies found that optimal conditions (7% [w/v] cyclodextrins, 60% [w/v] glycerin, and a temperature of 60°C) facilitated the recovery of TPC (57.5 mg GAE/g dw) and specific bio-compounds such as oleuropein, rutin, luteolin, apigenin, and their derivatives.

Moreover, a comparative study conducted by Rosa and colleagues evaluated polyphenol-rich olive leaf extracts obtained using MAE and UAE as green processing technologies (da Rosa et al. 2021). The results showed that MAE (using water as a solvent, at 2.45 GHz, 1000 W, 86°C for 3 min) led to a higher recovery of TPC (104 mg GAE/g), oleuropein (14.468 mg/g), and hydroxytyrosol (0.590 mg/g). In contrast, UAE (20 kHz, 450 W, water as eco-solvent, 27°C for 29 min) yielded lower concentrations: TPC (81 mg GAE/g), oleuropein (6.914 mg/g), and hydroxytyrosol (0.547 mg/g), which highlight the importance of selecting the appropriate extraction method as well as the associated conditions for a better recovery of bioactive compounds. This higher efficiency can be attributed to enhanced mass transfer induced by microwave energy, especially when using water as a highly responsive polar solvent.

In the same context, OP by-product, OMWW, and OS (or olive cake) were also subjected to UAE. In a recent study, Gómez-Cruz et al. investigated the effect of UAE method and ultra-pure water on total flavonoid compounds (TFC) content, TPC content, and the recovery of several bioactive molecules from OP extracts. In this regard, the effects of different process variables such as sonication time (10–60 min), temperature degree (26–46°C) at an ultrasonic waves power (40 kHz/100 W) on TPC, TFC, and individual phenolic compounds were explored by response surface methodology (RSM) (Gómez-Cruz et al. 2021). Accordingly, the TPC values ranged between 11.49 and 18.05 mg GAE/g dw, and the authors identified the presence of hydroxytyrosol, hydroxytyrosol hexoside, tyrosol hexoside, hydroxytyrosol acetate, oleacein derivative, verbascoside, isoverbascoside, oleuropein hexoside, hydroxy oleacein, oleuropein, oleuropein hexoside, oleacein, ligustroside, elenolic acid, hydroxybenzoic acid, quercetin, luteolin, luteolin 7-O-glucoside, and deoxyhexosyl-hexoside.

Furthermore, a previous investigation carried out by Quero et al. (2022) assessed the phenolic composition of OP using USAE with ethanol-water (50%) mixture and/or water (100%) alone as green solvents. As compared to water extract, results demonstrated that the ethanol/water mixture (50%, V/V) significantly enhanced the extraction efficiency, yielding a higher concentration of total phenolics (18 mg GAE/g vs. 12 mg GAE/g) and specific individual compounds such as hydroxytyrosol (33.36 mg/100 g vs. 28.7 mg/100 g), tyrosol (21.09 mg/100 g vs. 10.63 mg/100 g), oleuropein (254.38 mg/100 g vs. n.d.), and Rutin (31.46 mg/100 g vs. 21.33 mg/100 g).

Owing to its viability, affordability, safety, and environment-friendly characteristics, water is widely used as the cleanest solvent for the extraction of various functional compounds from different biological matrixes. Despite these advantageous characteristics, it is not a suitable/appropriate solvent for the recovery of non-polar and less polar substances, which supports the obtained results.

In addition to UAE, other extraction technologies, such as MAE, have also been used to extract polyphenols as value-added molecules from OO by-products. Aligned with circular economy, sustainability, and zero waste concepts, this emerging technique has recently garnered increasing interest from researchers worldwide and is increasingly recognized as a safe and effective method for recovering biofunctional molecules and valuable ingredients from various natural sources, particularly in the context of valorizing co-products generated by agro-industrial processes. In contrast to several conventional extraction methods, MAE increases the extraction yield from the matrix while reducing solvent use and extraction time. Most importantly, it enhances selectivity and heating efficiency by utilizing a non-contact heating source (Elmas et al. 2025).

For example, Chanioti et al. (2016) investigated the effect of temperature and extraction duration (using citric buffer pH 4.5) on the recovery of antioxidant phenolic compounds from OS and L&P using enzymes (pectinase and polygalacturonase) with or without MAE (400 W). The best results of TPC are reported at 60°C for 30 min (10.61 mg GAE/g dw for OS and 29.52 mg GAE/g for L&P) with remarkable antioxidant activity (DPPH method) of 10.40 mg trolox/g dw OS and 23.40 mg trolox/g of L&P, respectively. The authors demonstrated that higher temperature (60°C) may promote an increase in the diffusion rate of intracellular phenolics into the solvent promoting their solubility. Moreover, authors documented that microwave-assisted enzymatic extraction (MAEE) at 60°C for 30 min resulted in a better recovery of all quantified biomolecules compared to MAE at the same extraction conditions. The reported values for individual phenolic compounds (MAE vs. MAEE) are oleuropein (180.6 vs. 193 µg/g dw), hydroxytyrosol (202.9 vs. 374.8 µg/g dw), caffeic acid (1.6 vs. 10.8 µg/g dw), vanillin (12.1 vs. 16.3 µg/g dw), rutin (85.8 vs. 200.9 µg/g dw), luteolin (731.7 vs. 1754.9 µg/g dw) (Chanioti et al. 2016). These results highlight the significance of combining enzymatic treatment with other novel and sustainable extraction technologies to improve the efficiency of phenolic compound recovery.

In another work, Chanioti and Tzia (2018) evaluated OS by-product using NaDES and MAE and identified/quantified six phenolic compounds, belonging to different chemical classes. Authors reported that MAE (500 W) improves the recovery of antioxidant-rich extracts with substantial polyphenol content as it can attain high temperatures, which is a critical factor during the bio-compounds extraction process, as most of these processes are temperature dependent. Accordingly, the antioxidant extract obtained at 60°C during an extraction period of 30 min is rich in flavonoids and non-flavonoid molecules (phenolic acids), namely, hydroxytyrosol, oleuropein, rutin, caffeic acid, luteolin, and vanillin (0.09–0.13 mg/g).

In addition to the UAE and MAE, other novel and emergent technologies, such as SFE, PLAE, and OHE, have been tested and recommended for the recovery of antioxidant compounds from OO by-products.

Over the past decade, SFE has been increasingly utilized for the recovery of large game of bio-compounds from functional foods, agro-industrial products, and their associated by-products, including olive-derived residues by transforming the gas to the

supercritical fluid through a specific control in both temperature and pressure parameters (Hedayati et al. 2025). Despite some critical limits and disadvantages (expensive method, energy consumption, and equipment complexity), SEF is an alternative leading technology with multiple advantages such as time reducing, no residual solvents, and selective extraction. In this context, a recent study conducted by Chabni et al. (2025) reported that combining cold pressing with supercritical CO₂ (SFE-CO₂) extraction significantly improved the chemical quality (fatty acids, ultraviolet absorption coefficients, acid, and peroxide values) of recovered OO meeting the EVOO standard. Moreover, authors documented that SFE process leads to a high recovery of specific individual phenolic compounds such as oleuropein (0.4 mg/kg), hydroxytyrosol (13 mg/kg), tyrosol (29 mg/kg), pinoresinol (1.8 mg/kg), and syringic acid (9.6 mg/kg), representing 3.7–16 times higher than those typically found in conventional OO.

Moreover, OHAE, a non-pulsed electro-based technology, induces a cellular membranes disintegrate due to the application of high intensity pulsed electric fields, typically exceeding 1 kV/cm, associated with a voltage varied from 400 and 4000 V across all biological matrices. In fact, based in the Joule effect, once applied, the electric energy is converted into thermal energy (ohmic heating) leading to cellular pores enhancing the extraction of intracellular compounds. Thus, it reduces the need of using non-conventional and hazardous organic solvents or traditional thermal treatment, which might compromise the organoleptic quality and bioactive properties of recovered bio-compounds. Additionally, it is recognized as a sustainable and potential promising technique due to (i) its fast and homogeneous heating; (ii) its high ability in converting electric energy; (iii) selectivity of recovered compounds; and (iv) generation of direct heat associated with time reduction, low energy consumption (Rodrigues et al. 2022).

Recently, Markhali and Teixeira (2024) examined the influence of OHAE as a green approach on the extraction of polar phenols from olive leaves. Their results demonstrated that the OHAE of oleuropein (26.18 mg/g extract), verbascoside (1.04 mg/g), tyrosol (0.34 mg/g), hydroxytyrosol (1.38 mg/g) luteolin 7-O-glucoside (4.12 mg/g), apigenin 7-O-glucoside (3.47 mg/g), and rutin (3.78 mg/g) at 75°C with 80% ethanol were significantly higher than other tested approaches (conventional heating, 40%, 60% water-ethanol solvent and extraction temperature of 45°C, 60°C. Moreover, OHAE boosts the recovery of high-added-value molecules from natural origins by destabilizing the cell membranes and enhancing the formation of pores (electro-permeabilization), thus facilitating and increasing the solvent(s)-biomolecules surface interaction (Rocha et al. 2018). In general, this emergent extraction process—OHAE reduces the environmental footprint generated following the extraction procedure of conventional techniques, by decreasing water consumption and waste generation (Chemat et al. 2017).

In summary, although OO by-products represent a promising source of valuable phytochemicals, their economic feasibility must be carefully considered. Although the recovery of bioactive compounds from waste streams contributes to sustainability goals and aligns with circular economy principles (mentioned previously), the costs associated with extraction technologies,

purification, and quality control can be significant. Moreover, phytochemicals are widely distributed in the plant kingdom, and in many cases, alternative sources, such as herbs, spices, and agricultural crops, offer more accessible and lower-cost options for industrial use. Therefore, to justify large-scale implementation, the extraction of phytochemicals from olive by-products must demonstrate a favorable cost-benefit ratio, particularly when integrated into existing olive processing infrastructure. Future developments should focus on process optimization, energy efficiency, and solvent recycling to enhance economic viability and competitiveness.

4.1 | Encapsulation of Bioactive Compounds From Olive Oil By-Products

The protection and stabilization of bioactive compounds derived from OO by-products are important to enhancing their bioavailability, solubility, and potential applications in different industries such as pharmaceuticals, cosmetics, and foods. This necessity resulted in the adoption of advanced technologies, such as encapsulation to preserve bioactive compounds functional properties, and extend their usability.

The process of encapsulation is widely studied and accepted, as it is a process of coating a substance with a biocompatible support material (a polymeric matrix or shell) (Ray et al. 2016; Zuidam and Shimoni 2010). The encapsulation allows for the preservation of functional properties, easier handling, provides stability, and avoids undesirable interactions during processing and storage so that they arrive intact until their release at the site of interest. There are different considerations for the use of this technology, such as the type of core or internal phase (e.g., antioxidants, peptides, volatile oils, pigments, dyes, proteins, minerals, and cells), the carrier material (wall material), which must be GRAS (generally recognized as safe), biodegradable, and able to protect internal phase (Nedovic et al. 2011).

According to the sizes of the particles, the encapsulates (particles larger than 1 mm) can be classified as microencapsules (1 and 1000 μm) or nanoencapsules (10–1000 nm) (Oliveira et al. 2023). The main steps in the microencapsulation process are the formation of the core and encapsulants, incorporation, and solidification. The products obtained from this process are called microparticles, microcapsules, and microspheres (Mehta et al. 2022). Encapsulating materials (wall carrier, or coat) can be ethylcellulose, hydroxylpropyl methylcellulose, sodium carboxy methylcellulose, sodium alginate, gelatin, polyesters, chitosan, maltodextrin (MD), cyclodextrin, modified starch, waxes, paraffin, gum acacia, gum arabic (GA) natural gums carrageenan, gluten, and casein, among others (Zabot et al. 2022). Nowadays, different microencapsulation techniques (Figure 4) have been reported efficient in reducing the degradation of core materials such as spray drying and cooling, coacervation, phase separation, fluidized bed or air suspension, freeze drying, molecular inclusion, co-crystallization, interfacial polymerization, and liposome entrapment, and the type of technology used depends on the nature of the core (Choudhury et al. 2021; Jyothi et al. 2010).

Likewise, nanoscale encapsulation is a technology of great interest for different industries, especially in nanomedicine, due

to the multiple applications on specific targets. Nanoencapsulation systems increase the surface-to-volume ratio, which improves the bioavailability of the core. A nanoparticle is a system formed by material surrounding the core (drug or bioactive compounds) (Madani et al. 2022). The different materials used to form the nanoparticle are phospholipids, lipids, caseins, cyclodextrins, amylose, alginate, synthetic polymers [poly(ethylene glycol)], and so on, and the technical preparation include, emulsification, high-pressure, homogenization, ultrasonication, double emulsion, freeze dryer, supercritical fluids, microfluidization, and evaporation like nano-spray dryer and electrospray/electrospinning (Saini et al. 2021).

As previously mentioned, different OO by-products are rich in bioactive compounds, primarily phenolic compounds and secoiridoids. Consequently, numerous studies have focused on the valorization of these by-products, particularly in harnessing their bioactive compounds for potential applications in different industries. In this sense, diverse studies on the encapsulation of OO phenolic compounds have been conducted using diverse methodologies (Table 2).

The work carried out by (Aliakbarian et al. 2017) studied microencapsulation with the wall materials MD and GA alone or in combination as a method to protect phenolic compounds obtained from an extract of OP by a pressure-high temperature agitated reactor, and ethanol-water as solvent. For the microparticle formation, the spray drying technique was used with a temperature input of 160°C, feed flow of 5 mL/min, aspiration rate of 30 m³/h, and the extract-encapsulate solution was 10% w/v (100 g/L). The results showed that the combination of the MD:GA encapsulants in a ratio of 60:40, respectively, allows for increasing the yield to 87.3% compared to the rest of the combinations or the use of a single encapsulating agent. On the other hand, both MD and GA alone, or combined, allow the maintenance of the content of phenolic compounds and antioxidant capacity. Although there were no significant differences, the MD:GA ratio of 60:40 shows a slight increase in the content of phenolic compounds (36.9 mg CAE/g) and scavenging DPPH capacity (12.5 mg TE/g).

Another study conducted by Vitali Čepo et al. (2018) in OP showed that the use of cyclodextrins (β -cyclodextrin, hydroxypropyl- β -cyclodextrin, γ -cyclodextrin, and randomly methylated- β -cyclodextrin) as encapsulating materials, and the encapsulating technique with mini spray dryer, allows to a significant increase in the antioxidant capacity of the encapsulates according to the methods of total reducing capacity, inhibition of the DPPH radical, trolox equivalent antioxidant activity (TEAC), and ORAC (oxygen radical activity assay). Likewise, the OP extract encapsulated with hydroxypropyl- β -cyclodextrin and randomly methylated- β -cyclodextrin, applied in food and biological models, presented higher antioxidant capacity and ability to inhibit lipid peroxidation compared with chemical compounds.

Another carrier material used to encapsulate OP is ethylcellulose, by double emulsion development by (Paulo et al. 2022). In these works, two concentrations of OP extract (F1: 5% and F2: 10%) were used, finding that increasing the concentration of load in

TABLE 2 | Encapsulation techniques for the protection and stabilization of bioactive compounds from olive oil (OO) by-products.

Olive oil by-product	Bioactive compounds	Encapsulation type	Carrier material	Encapsulation techniques	Main finding	References
Olive pomace (OP)	Phenolic compound	Microcapsule	Arabic gum Maltodextrin	Spray dryer	Encapsulation yield of 87.3%, the coating agents protect the phenolic compound	Aliakbarian et al. (2015)
	Phenolic compounds	Microcapsule	Hydroxypropyl- β -cyclodextrin β -cyclodextrin γ -cyclodextrin Randomly methylated- β -cyclodextrin	Spray dryer	Hydroxypropyl- β -cyclodextrin and randomly methylated- β -cyclodextrin provide antioxidant protection of phenolic compounds (0.1%–3%) in food and biological models	Vitali Čepo et al. (2018)
	Phenolic compounds, tyrosol, hydroxytyrosol	Microcapsule	Ethylcellulose	Double emulsion Solvent evaporation	Encapsulation efficiencies above 85%, high load increase particle size, and are thermogravimetrically stable	Paulo et al. (2022)
	Phenolic compound	Nanocapsule	Maltodextrin	Supercritical-assisted atomization	Encapsulation efficiency of 69.9%, and particle size of 712 nm at 10% maltodextrin. Delay the degradation of phenolic compounds until 24 h	Aliakbarian et al. (2017)
	Phenolic compound	Nanocapsule	Rocket seed gum Chia seed gum	Ultrasonication	Prevent degradation of phenolic compounds High encapsulation efficiency (67.01% and 82.86%)	Akcecek et al. (2021)
	Phenolic compounds	Microcapsule	Chitosan–tripolyphosphate	Ionotropic gelation lyophilization	Encapsulation efficiency of 64%–65%. Nanoparticles exhibited antioxidant capacity in cell-free assays and a THP-1 cell model of oxidative stress	Fierri et al. (2024)

(Continues)

TABLE 2 | (Continued)

Olive oil by-product	Bioactive compounds	Encapsulation type	Carrier material	Encapsulation techniques	Main finding	References
Olive leaves (L&P)	Phenolic compounds (Oleuropein)	Microcapsule	Inulin	Spray dryer	Encapsulation efficiency over 87%. Protection of polyphenols in processed food	Urzúa et al. (2017)
	Secoiridoids, simple phenols Elenoic acids, oleosides, flavonoids	Microcapsule	Sodium alginate	Spray dryer	Encapsulation protects the bioactive compounds from degradation during gastric digestion	González et al. (2019)
	Phenolic compounds	Nanocapsule	Whey protein Pectin	Multiple emulsion	Encapsulate efficiency over 70%, delaying the release of phenolic compounds	Mohammadi et al. (2016)
	Phenolic compounds	Nanocapsule	Poly (lactic acid)	Nanoprecipitation	Provide stability to the polyphenolic extract in cosmetic formulation	Kesente et al. (2017)
Olive mill wastewater (OMWW)	Secoiridoid: hydroxytyrosol, tyrosol, and verbascoside	Microcapsule	Maltodextrin and acacia fiber	Spray dryer	Inhibition of the Maillard reaction in milk and cookies	Troise et al. (2020, 2014)
	Biophenols	Microcapsule	Modified starch	Freeze drying	Protection in the preparation of yogurt against microorganisms by pH changes	Petrotos et al. (2012)
	Phenolics compounds	Microcapsule	Maltodextrin and acacia fiber	Spray dryer	Increased antioxidant and antiglycative actions	Navarro et al. (2015)
	Phenolics compounds	Nanocapsule	Miglyol 812, Span 80, Milli-Q water, and Tween 80	Double emulsion	Phenolic compound retention of 68.6% and antioxidant capacity of 89.5%, after 35 days of storage	Niknam et al. (2020)
Olive stones (OS)	Phenolic compounds	Microcapsule	Sunflower wax	CO ₂ saturated solutions (PGSS)	Encapsulation efficiency of 87.3%. Coating agents protected phenolic compounds effectively	Kellil et al. (2024)
	Phenolic compounds	Microcapsule	Chitosan	Spray dryer	Encapsulation yield and efficiency of 79.81% and 76.89%, respectively. Protection of polyphenols during storage. Increase antioxidant activity	Nakilcioglu-Taş and Ötleş (2020)

Abbreviations: L&P, leaf and pruning; PGSS, particles from gas saturated solutions.

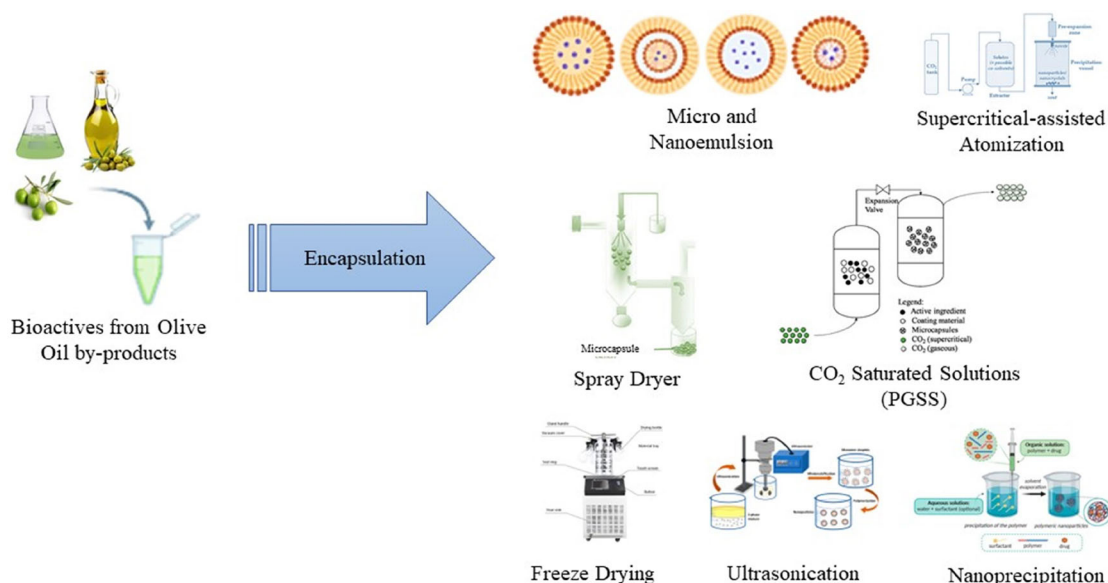


FIGURE 4 | Encapsulation techniques for bioactive compounds recovered from olive oil by-products.

the microparticle, reduced the efficiency of the encapsulation, evaluated through antioxidant capacity (F1: 96% and F2: 83%) and the content of phenolic compounds (F1: 96% and F2: 94%); likewise, the size of the microparticle is increased (F1: 5.8 μm and F2: 19.3 μm). Similarly, thermogravimetric analysis showed that this encapsulation system can be used in foods made by thermal processes.

Similarly, nanotechnology has been used in OP bioactives encapsulation. For example, Aliakbarian et al. (2017), nanoencapsulated polyphenols from the OP by-product (extracted previously by ethanol: water, 50%:50%) with MD at different concentrations 10%, 30%, and 50% w/w. The encapsulation technique used was supercritical assisted atomization (SSA) with a drying chamber temperature (TC) of 75°C, 85°C, and 95°C. According to the results, an MD concentration of 10% w/w and TC of 95°C were the optimal operating conditions, showing the best results in terms of humidity, solubility, particle size (712 nm), and shape (spherical), DPPH—antioxidant capacity (98.8 mg TE/mL of extract) and encapsulation efficiency of phenolic compounds (105 mg caffeic acid/g). The particle loaded with phenolic compounds obtained by SSA has the potential to be used as a nutraceutical ingredient in food formulation.

For its part, Akcicek et al. (2021), optimized the formulation of nanoparticles for the stabilization of hydromethanolic extracted phenolic compounds from OP (mainly composed by hydroxytyrosol (2857 $\mu\text{g/g}$ extract), luteolin (746 $\mu\text{g/g}$), tyrosol (359 $\mu\text{g/g}$), myricetin (348 $\mu\text{g/g}$), gallic acid (314 $\mu\text{g/g}$), quercetin (217 $\mu\text{g/g}$), and other minor compounds like ellagic acid, catechin, coumaric acid, kaempferol, and so on. To form the nanoparticle, the authors used 0.1% of OP extract, which was added dropwise to the gum solutions (0.1% of rocket seed gum or chia seed gum—wall materials), using Tween 20 (0.5%) as a surfactant. The mixture was shaken, ultrasonicated (100 W for 1 min), centrifuged, and lyophilized. According to the results, the encapsulation efficiency was higher in the nanoparticle formed rocket seed gum, with 82.26%, and a particle size of 318 nm, in comparison

with chia seed gum nanoparticles (67.01% of encapsulation efficiency and a particle size of 490 nm). A high % efficiency indicates a higher stability of the particle due to the formation of hydrogen bonding. The OP phenolic compounds-nanoparticles allow the release of phenolic compounds to be delayed at 24 h under physiological pH conditions, and their antioxidant capacity increases by about 50% compared to nanoencapsulated phenolic extract, revealing an increase in the stability of OP phenolics.

Olive leaves are by-products and an excellent source of polyphenolic compounds (Table 1). For this reason, there are some studies on this subject, such as the one developed by Urzúa et al. (2017), which microencapsulates olive leaves phenolic extracts with inulin using spray drying methodology. The results showed an encapsulation efficiency of over 87% under optimal conditions (inlet air temperature 136°C, relation olive leaves extract:insulin 1:1.8), and a yield of 64.3%. In doughs processed (fries' technologies), prepared with wheat gluten and starch and with incorporation of formulated OP extract-microparticles, the phenolic compounds content and antioxidant capacity were maintained. Thus, microencapsulation technology not only protects the compounds during some technological processing of foods. On the other hand, González et al. (2019) stated that sodium alginate microencapsulated olive leaf extracts by spray dryer, which presents a encapsulation efficiency of 60.8%, with a yield of 51.5%, under optimal encapsulation conditions (olive leaf extract:sodium alginate ratio 1:1.6, and inlet temperature of 135°C). The content of phenolic compounds in the microparticle showed a slight decrease. However, the chromatographic profile (secoiridoids, simple phenols, elenolic acids, oleosides, flavonoids, and other phenolic compounds) revealed an increase in hydroxytyrosol glucoside content. Likewise, in this work, the authors demonstrated that the microencapsulation of olive leaf extracts protects phenolics from degradation during gastrointestinal digestion, specifically oleuropein (secoiridoid), allowing for high bioaccessibility and potential bioavailability (González et al. 2019).

Other studies on olive leaves have been developed using nanotechnological systems. Mohammadi et al. (2016) carried out an experiment to form a single or two-layer nanoparticle from methanolic-MAE olive leaf extract (7%) using pectin and whey protein biopolymers. For micro-emulsion (W/O), the olive extract was mixed dropwise with soybean and span 80 (sorbitan monooleate), whereas for multiple emulsions (W/O/W), were prepared two solutions: (1) The micro-emulsion was mixed with whey protein concentrate (WPC), and (2) the nano-emulsion was mixed with whey protein and pectin (WPC-P). The results showed an increased encapsulation efficiency of phenolic compounds in WPC-P (96.64%) compared to 93.34% in WPC. At 22 days of storage, the pectin stabilizes the double emulsion, and this also allows delaying the release of phenolic compounds; therefore, these characteristics provide it with high antioxidant potential. These results encourage the application of W/O/W olive leaves stabilized extracts in food fortification.

In this sense, another research group encapsulates olive leaf extract (20%) with biodegradable poly(lactic acid) to form a nanoparticle by the nano-precipitation method (Kesente et al. 2017). The olive leaf extract-loaded nanoparticle was added to a cosmetic formulation. The particle size obtained was 246.3 nm, and the encapsulation efficiency was 49.2%. Despite being low, this value allowed the formulated base cream to slightly increase its stability and keep up to 3 months of storage at 40°C. The nanoparticle protected the phenolic content of the extract, which allowed the charged nanoparticle to provide stability to the cosmetic formulation.

OMWW by-product of the OO process with a high phenolic content, and in this sense, for its possible use, encapsulation technology has been used, according to various investigations (Table 2). In this sense, Troise et al. (2014) designed a microparticle of MD and acacia fiber (1:median ratio) loaded with OMWW extract, using spray-drying technology, which was added at concentrations of 0.05% and 0.1% w/v to raw cow's milk, and heat treatment (ultrahigh-temperature, UHT) was carried out, finding that the addition of the microencapsulation reduced the content of reactive carbonyl species (hydroxycarbonyls and dicarbonyls), thus inhibiting the Maillard reaction that causes undesirable flavors, indicating that the addition of the OMWW microparticle, which presented the phenolic acids hydroxytyrosol, tyrosol, and verbascoside, allowed to improve the quality of the milk in addition to provide nutritional functionality. The same authors reported a similar effect of the microparticles of MD and acacia fiber loaded with OMWW in cookies. They found that the microparticle loaded with OMWW and incorporated in cookie formulation inhibited the Maillard reaction. This is mainly related to the content of hydroxytyrosol, tyrosol, and verbascoside present in OMWW (Troise et al. 2020).

Another study by Petrotos et al. (2012) demonstrated that the addition of an OMWW encapsulation (microparticle formed with a matrix of modified starch, and lyophilized), in the formulation of a yogurt, managed to improve the microbiological quality of the yogurt, by modifying the pH, and slowing down the growth of molds. Likewise, nano-encapsulation of OMWW with MD and acacia fiber by spray drying technology showed antiglycative characteristics due to its capacity to trap reactive carbonyl species.

Therefore, this nano-encapsulated product could be considered an ingredient in the food and pharmaceutical industries (Navarro et al. 2015). Niknam et al. (2020) reported a nanoemulsion loaded with polyphenols-rich extract from OMWW using a rotor-stator mixer, ultrasonic homogenizer, and microfluidizer systems. The preparation method used was double emulsion, with Miglyol 812, Span 80, Milli-Q water, and Tween 80. The optimal nanoparticle obtained by a microfluidizer has a size of 105.3 nm, and the stability was evaluated in terms of the retention of the phenolic compounds and the antioxidant capacity after 35 days of storage at room temperature, with values of 68.6% and 89.5%, respectively. This result allows this nanoemulsion to have potential for its use in different industries such as food and feed formulations and cosmetics.

Relative to the OS, Kellil et al. (2024) explore the encapsulation using the particles from gas saturated solutions (PGSS) technique to improve the stability of phenolic-rich oils extracted from OS (sunflower wax wall material). The PGSS technique was optimized under varying conditions, including pressures (10 and 20 MPa), oil-to-wall material ratios (1:10 and 3:10), and nozzle sizes (600 and 1000 µm). The optimal encapsulation conditions were identified as 10 MPa pressure, a 1:10 oil-to-wall material ratio, and a 600 µm nozzle size. These conditions resulted in microparticles (particle size of 525 µm) with an encapsulation efficiency of 70% and a yield of 75.5%, which effectively improve the oxidative stability of the OS oil for up to 60 days at 40°C. The results indicate that the PGSS encapsulation method enhances phenolic oil stability, enabling the development of powdered ingredients from OS by-products suitable for food and cosmetic applications. As reported in Table 2, Nakilcioğlu-Taş and Ötleş (2020) optimized the OS phenolic extraction using a pilot-scale pressurized water extractor and obtained the best extraction conditions, 50°C, 50 bar, and 90 min (TPC = 281 mg GAE/kg OS). In their work, the authors stabilize OS phenolic-rich extracts by microencapsulation performed using spray drying with 1% chitosan as the encapsulating agent (reported in Table 2). Spray drying at an air inlet temperature of 200°C achieved a phenolic encapsulation efficiency of 76.9%. To assess stability, microcapsules were stored for 180 days at -20°C, 4°C, and 25°C. The highest degradation occurred at -20°C, whereas 4°C best preserved phenolic (24.17% TPC) and antioxidant capacity (15.63% DPPH, 20.39% FRAP). These findings suggest that 4°C is the optimal storage condition, making these microcapsules suitable as food, cosmetic, and pharmaceutical ingredients.

5 | Advanced Applications of OO By-Products in the Food Industry

As mentioned, OO is one of the most consumed and valorized natural product in the world. Due to the high demand for this functional food, an extensive charge of waste is continuously generated, especially in Italia, Morocco, Spain, Portugal, Greece, and Türkiye as native producers.

Nowadays, the increasing awareness for environmental protection from one side and the rising demand for the sustainable valorization of OO co-products have led the largest scientists and industries to take benefit from this natural treasure and

explore new alternatives. Currently, the incorporation of bio-functional components, especially phenolic compounds, from the OO production process as nutraceutical and/or food additives is a leading tendency in the pharmaceutical industry and food sector. Throughout history, bio-functional products (which include any organic food, natural products/or their extracts with high health benefits and endowed with strong biological activities) have been developed and applied to enhance various food characteristics and to boost their functional properties. Besides their other health profits and therapeutic properties basically due to their richness of micro/macro-antioxidant nutrients and secondary metabolites, OO and its generated by-products have been commonly used in cosmetic preparations and food processing for their aromatic, antioxidant, and preservative properties. Due to the rising environmental regulations and the increasing demand for food safety and a healthier lifestyle, OO and olive residues derived from the OO industry have marked special attention as powerful shelf-life enhancers and as food additives, and preserving agents, which mainly due to their antioxidant and antimicrobial properties.

Given the current market transition oriented by the growing demand for organic products, hydroxytyrosol, a bio-functional compound present mainly in OO, OMWW, and olive leaves has been proposed, among other bio-molecules, as an excellent alternative food additive to synthetic ones accompanied the most often with serious health side effects (Silva et al. 2022). Currently, several companies in the United States are commercializing this molecule as a bio-preservative agent according to its well-known properties for increasing the end products' shelf life (Galanakis et al. 2015). It has been documented that the addition of hydroxytyrosol-rich-polyphenol extract to refined oil, prevented the biodegradation of the α -tocopherol and increased its antioxidant capacity (Esposto et al. 2015). Similarly, other scientific reports showed that phenolic acids and flavonoids recovered from OO by-products improve the antioxidant properties of different food matrices. Authors have related this capacity mainly to oleuropein and hydroxytyrosol among other phenolic molecules (Araújo et al. 2015). Moreover, several experiments have been made on different vegetable oils using antioxidant compounds from OO and OL as natural conserving components and thus, remarking OO by-products as innovative functional agro-waste food with health-promising properties (Gullón et al. 2020; Otero et al. 2021). Hydroxytyrosol has also been incorporated as an active ingredient in the spread, dressing, and derived tomato products as a natural fungicide against *Botrytis cinerea* and thus a powerful preservative agent (Yangui et al. 2010). In addition, olive by-products have been also employed in the meat, wine, and milk industries providing efficient advanced applications.

In milk and other dairy products, the potential preventive effect of phenolic fraction recovered from olive co-products against the Maillard reaction was examined. For this purpose, Troise et al. (2014) demonstrated that the incorporation of antioxidant-rich OMWW powder into milk before ultra-pasteurization has led to a significant inhibition of off-flavor compounds formation during the heat treatment and improves both the sensorial and nutritional characteristics of ultra-pasteurized milk. Accordingly, the authors stated that the incorporated OMWW extract did not affect either sensory properties (astringency, bitterness, and flavor) or physical properties (color and viscosity).

Regarding meat products, Fasolato et al. (2016) examined the potential effect of polyphenols-rich extracts recovered by an eco-friendly strategy as food-conservative agents. Indeed, the addition of purified phenolic extract from olive vegetation water to fresh Italian sausages exhibited a significant inhibition of food-borne pathogens growth, like *Staphylococcus aureus* and *Listeria monocytogenes*. Obtained results highlighted the importance of phenolic compounds from OO vegetation water as a promising source of bio-functional ingredients to improve the quality of fresh sausages and thus, their food safety. Within this framework, in 2022, Topuz and Bayram (2022) reported that olive leaves crude extracts, and oleuropein purified from these extracts could extend the shelf life of food products and improve their functional efficacies due to their high antioxidant and potent antimicrobial properties.

Moreover, several researchers have reported application in feed formulation targeting the high-quality characteristics and healthy nutritional value of the derived OO bioproducts (Paié-Ribeiro et al. 2025). For example, Nasopoulou et al. (2011) conducted comprehensive study on OP as feed for livestock and aquaculture. Accordingly, moderate consumption of OP increased unsaturated free fatty acids and decreased saturated free fatty acid levels both in milk and meat (Rodríguez et al. 2008). Furthermore, the integration of OP as functional ingredient and techno-functional agent has gained widespread use as preservatives to improve the quality and functionality of end-food products/foodstuffs. Recently, OP derived bio-compounds are extremely used in the food industry as diet supplements and active ingredients for improving the shelf life and sensory quality of end-food products, enhancing health, and preventing disease. In general, these are incorporated as powerful bio-antioxidant ingredients in foodstuffs, especially in fish and meat products; fermented milk, bread, pasta, and other dairy products (Difonzo et al. 2021).

Actually, L&P are used to produce pulp and paper sheets, nanocellulose, cellulose nanofibers, and lignin micro/nanoparticles making it a novel candidate for reinforcing the pulp and paper industry, for the production of functionalized films interesting for food packaging, and for cosmetics applications, offering an eco-friendly alternative to conventional paper derived from forest-based feedstocks. (Fillat et al. 2018; Selim et al. 2022). In fact, cellulose, extracted from olive by-products, is used as biodegradable packaging materials as well as developed to produce lightweight yet strong paper sheets in the paper manufacturing, thereby reducing dependence on traditional wood-based resources meeting the zero waste value chain and circular economy concept (Ben Mabrouk et al. 2023). However, several challenges may arise that limits its large-scale industrial applications, particularly those related to the complex steps required for its recovery and their associated costs. Moreover, the quality and the consistency of the extracted cellulose from OO residues vary depending on the raw material and processing methods, which is recognized as potential issue that affect the performance of the final products. Globally, even these added value compounds contribute to preserving and reducing dependence on traditional wood-based resources, scaling up their industrial production still requires further technological optimization and economic feasibility studies.

Other applications of these by-products are the leaf extract bioactives as a natural and sustainable alternative to synthetic preservatives in food and cosmetic formulations, promoting safety and product shelf life extension (Mitrea et al. 2024).

In this regard, several patents (EP-A 1 582 512, WO/2004/005228, WO/2005/075614, WO/2013/007850, WO/2002/0218310, US 2002/0058078, US/2002/0198415, US 6414808, 2355778, 6746706, etc.) and commercial reformulations based on polyphenol compounds especially, oleuropein, and hydroxytyrosol present in L&P, OMWW, OP, and OS have been developed (Galanakis et al. 2015; García-Pastor et al. 2023; OMPI n.d.).

In summary, various OO derived phenolic compounds (oleuropein, hydroxytyrosol, luteolin, etc.) have significant biological properties (particularly antioxidant, anticancer, anti-inflammatory, antimicrobial, and cardio-protective activities) and have been scientifically shown efficient to be incorporated as food additives and preservative ingredients in a variety of food products, including meat, oil, milk, and their derivate products (García-Pastor et al. 2023).

6 | Conclusion and Future Perspectives

The OO industry represents an essential productive sector in many Mediterranean countries such as Italia, Morocco, Spain, Portugal, Greece, and Türkiye; generating high amounts of different bio-residues known as OO by-products, such as L&P, OP, OMWW, and OS. Despite the economic value of the biomolecules present in these by-products, there is a substantial environmental issue associated with their accumulation and elimination. Thus, converting these agri-food bio-wastes into functional products with high added value is a leading strategy of numerous actual research lines. Nowadays, trying to meet the high expectation levels and the growing demands of consumers toward a healthier lifestyle, intending to consume foods with less synthetic preserves, the current trend involves the incorporation of OO by-products, as natural preservative agents and techno-functional ingredients in food manufacturing using integrated strategy aligned with a responsible ecological and social footprint. In this context, based on their abundant and cheaper characteristics, OO by-products constitute a suitable organic source for recovering target bio-compounds (like phenolic and secoiridoid compounds) with high potential for innovative functional food applications. However, despite the high technological progress, several technical and financial hurdles must still be overcome. In particular, DES have recently emerged as promising green alternatives to conventional organic solvents, and their industrial-scale application remains limited due to key commercialization barriers, including high production costs of certain DES. Likewise, encapsulation technologies are still constrained by high production costs, technical complexity, and limited compatibility with food processing systems, which continue to hinder their commercial-scale use. Therefore, more in-depth research associating the extraction/purification/stabilization processes of the target molecules with their economic up-scale is needed to fit into the paradigms of bio-economics and circular economy. To keep up with the evolution of food technology and considering the consumers' awareness, competitiveness and evolving international economic landscape, future development should focus on

integrated and scalable biorefinery platforms/approaches for OO by-products for the simultaneous recovery of multiple high-value compounds, the implementation of green and cost-effective technologies and the reinforcement of interdisciplinary collaborations to facilitate industrial application, regulatory acceptance, and sustainability, especially in Mediterranean producing regions.

Author Contributions

Laura Aracely Contreras-Angulo: conceptualization, methodology, writing – original draft. **Hassan Laaroussi:** conceptualization, methodology, writing – original draft, writing – review and editing. **Driss Ousaid:** conceptualization, writing – original draft, writing – review and editing, methodology. **Meryem Bakour:** writing – review and editing. **Badiaa Lyoussi:** writing – review and editing, supervision. **Pedro Ferreira-Santos:** writing – review and editing, supervision, conceptualization, methodology, writing – original draft, project administration, funding acquisition.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data used to support the findings of this study are included within the article.

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