

Review

Unveiling the potential of olive oil production residues as adsorbent materials for water treatment: A literature review [☆]

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ABSTRACT

Olive oil is a nutritionally and economically valuable product whose global production has steadily increased, alongside the generation of large volumes of solid and liquid waste. Olive oil mill wastewater and solid residues such as olive pomace and olive stones have become major environmental concerns due to their high pollutant load. At the same time, these byproducts offer an opportunity: their valorization as low-cost, sustainable adsorbents for water treatment. Addressing this dual environmental challenge, this review provides a comprehensive and systematized synthesis of the current state of research on the use of olive oil production residues for water decontamination via adsorption. Specifically, the study maps the types of byproducts used, their target pollutants, removal efficiencies, and adsorption capacities. Unlike previous reviews, this work emphasizes studies that apply raw or minimally processed residues, as well as experiments conducted with real wastewater or under environmentally relevant conditions. The data are presented in a structured and comparative format, highlighting promising results and underexplored combinations. By identifying trends, gaps, and practical applications, this review contributes to advancing the development of circular economy-based, eco-friendly solutions for water pollution control and provides a valuable resource for future research and implementation.

1. Introduction

Olive oil is a highly valued food product in a healthy diet and eating paradigm (Riolo et al., 2022; Antonopoulou and Demopoulos, 2023; González-Rámila et al., 2023). As a product always present in the Mediterranean diet (Riolo et al., 2022), it generates a high demand which, in turn, is satisfied with higher levels of production, predicted to reach 3.2 million tons in 2024 (Olive Oil Times, 2024). Mediterranean countries like Spain are also leaders in olive oil production, with an estimated output for ~6 million tons in 2024, followed by Italy and Turkey (World Population Review, 2024).

Despite its extremely positive characteristics as a food product, olive oil production generates negative externalities, particularly those associated with the waste generated. The production of waste biomass produced by this agri-food industry is estimated to be superior to 40 Mt/year, and the olive oil mill wastewater (OMWW) produced is estimated to be 10–30 million m³/year (Enaime et al., 2024). Both OMWW and olive mill solid waste, resulting from the olive oil production process, are major environmental concerns. The OMWW presents a dark color, unpleasant odor, and low pH when discarded without prior treatment (Zahi et al., 2022). Due to its

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high content of organic compounds (mostly phenols), it is considered extremely toxic to ecosystems, limiting its application as a raw material (Shabir et al., 2023). The phenolic compounds in this waste have strong antioxidant, anti-inflammatory, and antibacterial activities (Solomakou and Goula, 2021) and when present in the human body, they can cause serious problems in the skin, digestive system, and cardiovascular diseases (Abu-Nada et al., 2021). In terms of environmental impact, this waste disposal can lead to soil infertility and the development of numerous mosquito species (Solomakou and Goula, 2021).

New solutions for the valorization of these residues generated by olive oil production (Dahdouh et al., 2023), such as energetic, agricultural, or water treatment solutions, are emerging (Bouhia et al., 2023; Dahdouh et al., 2023; Mohamed Abdoul-Latif et al., 2023). Other applications for olive oil production residues include the valorization of their bioactive compounds in pharmaceutical and cosmetic products, food supplementation, and food packaging (Madureira et al., 2022; Selim et al., 2022). Moreover, their application in construction materials, agricultural compost, or as biogas is also being investigated by different studies (Aranda et al., 2015; Díaz-García et al., 2017; Cinardi et al., 2024).

A different use of olive oil production residues is their application as adsorbent materials for the removal of a diversity of pollutants (Anastopoulos et al., 2015), including in water treatment (Jodeh et al., 2018; Hamed et al., 2019; Khiari et al., 2019; Aziz et al., 2024). This is an extremely valuable application as it addresses the global issue of water pollution.

Although water is an essential resource for all living beings, its contamination has been increasing and becoming one of the major environmental and human health concerns (Rathi et al., 2021). Effluents from wastewater treatment plants are among the principal causes of water pollution (Morin-Crini et al., 2022), an even more serious problem, especially since this water is subsequently applied to irrigation and diverse domestic activities. The main pollutants detected in aquatic systems include dyes, pharmaceuticals, heavy metals, and pesticides (Rathi et al., 2021) and the presence and permanence of these contaminants in waters have proven to be serious environmental and health concerns (Rathi et al., 2021).

Dyes are hazardous compounds with an affordable price and high binding strength, also known to be discharged, largely untreated, through effluents from various industries (Anastopoulos et al., 2018; Al-Ghouthi and Dib, 2020; Ferkous et al., 2022). The complexity of their chemical structure hinders their degradation (Sridhar et al., 2022), and, as a consequence, aquatic life is affected due to the inhibition of light penetration in water, preventing photosynthesis, causing a reduction of the available oxygen and so affecting all forms of life together with a change in the color of water (Anastopoulos et al., 2018; Al-Ghouthi and Dib, 2020; Ferkous et al., 2022). In addition, human health is also affected due to its toxic and carcinogenic effects (Anastopoulos et al., 2018; Al-Ghouthi and Dib, 2020; Ferkous et al., 2022). Methylene blue is one of the most extensively used dyes in the textile industry, recognized for its toxicity, harmful effects on human health, and environmental persistence (Oladoye et al., 2022).

Similarly, pharmaceuticals include a broad range of stable and persistent compounds, which are difficult to degrade. The main sources of pollution include inappropriate discharge by pharmaceutical industries and the consequence of human consumption, through excretion. Pharmaceutical compounds are frequently found in wastewater, even after treatment (Rizzi et al., 2019; Flores-Céspedes et al., 2020; Raupp et al., 2021; Sundararaman et al., 2022). The accumulation of these compounds leads to the development of antimicrobial resistance (Delgado-Moreno et al., 2021; Mechnou et al., 2022) and the possibility of further chronic or lethal effects (Boudrahem et al., 2019). Even if aquatic organisms are first affected, they are followed by accumulation in the food chain, causing serious threats to the whole ecosystem, including humans. Additional ecotoxicological concerns are the unpredictability of their behavior when in contact with other chemicals present in the environment (Samal et al., 2022).

Heavy metals, like pharmaceuticals, are emerging contaminants (Wang et al., 2024) considered priority pollutants by the United States Environmental Protection Agency (USEPA) (Sodhi et al., 2022). They are described as toxic and persistent, resisting degradation, which leads to their accumulation in the environment for a long time being dangerous for human health and other forms of life (Sodhi et al., 2022; Wang et al., 2023). While some heavy metals, such as Cd and As, are toxic at low concentrations, others, such as Zn, Fe, and Cu, are necessary for life at low concentrations but become toxic at higher concentrations. These metals accumulate in the body replacing minerals and impairing the function of several organs. For example, lead is the most toxic non-essential metal, which has carcinogenic effects when accumulated (Vagnoni et al., 2024). On the other hand, copper is an essential nutrient for the functioning of the blood and immune systems, but longer exposures can cause nausea, headaches, or even illness (Sodhi et al., 2022).

For the above reasons, greater emphasis has been placed on water decontamination, and more efficient and innovative treatment methods are being required. Different approaches can be used to reduce water pollution, such as physical, chemical, or biological techniques. The adsorption strategy is considered more efficient than the usual techniques (Saravanan et al., 2021) and considered very attractive due to the possibility of reusing the material through regeneration and its low cost. Furthermore, the development of green fabrication for sustainable adsorbent materials through the production of eco-friendly materials is nowadays a mode of action (Wang and Wang, 2022) and some examples include the use of cinnamon bark for methylene blue adsorption (Yardımcı and Kanmaz, 2023), the use of coffee waste for the removal of ibuprofen (Xing et al., 2023), and agro-waste-based adsorbents for the removal of bisphenol A (Tokula et al., 2023), methylene blue (Jawad et al., 2021) or drugs (Ali Ahmad, 2023; Ndoun et al., 2023).

Given the growing interest in adsorption as a cost-effective and efficient water treatment method, an increasing trend in research has explored the potential of agro-industrial wastes as alternative adsorbents. Among these, residues from olive oil production, such as olive pomace, olive oil mill wastewater, and olive stones, have emerged to be particularly promising, not only due to their abundance but also for their capacity to help mitigate a major environmental issue: water pollution. Fig. 1 illustrates an upward trend in the number of annual publications on the topic over the past 10 years. In addition to the growing interest demonstrated by the scientific community, the identification of patents related to an invention involving adsorbents derived from olive residues highlights the potential for technology transfer and the industrial application of these materials.

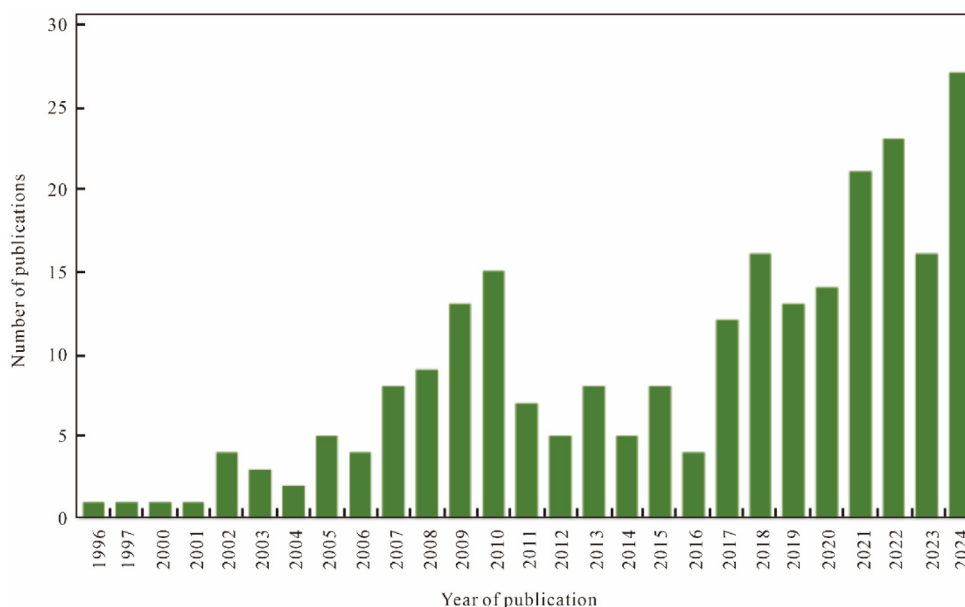


Fig. 1. Yearly publications dedicated to olive oil production residues as adsorbent materials for water treatment (1996–2024) (Search performed on PubMed database using the following research terms: “olive” and “pomace or residues or waste” and “adsorption or water treatment or decontamination or removal,” and selecting the query box “title/abstract”).

In this sense, the main aim of the current work is to unveil the potential and value of olive oil residues as adsorbents for water treatment. Although some studies have explored this potential, [Bhatnagar et al. \(2014\)](#) and [Anastopoulos et al. \(2015\)](#) have focused on limited categories of byproducts or have not systematically evaluated their performance under real-world conditions. In response to these limitations, this review provides a comprehensive and updated synthesis of the literature, with an emphasis on four secondary objectives: (i) the use of raw or minimally processed olive oil residues; (ii) experimental data involving real wastewater or environmental matrices; (iii) a systematic cross-analysis linking specific olive byproducts to the pollutants they effectively remove; and (iv) discussion of the impact in the context of the circular economy and its contribution for more sustainable development. To our knowledge, no previous review has combined these dimensions in a unified and structured manner. Furthermore, the data is presented in a systematized and schematic format, facilitating comparison and practical interpretation. This approach not only adds value to existing studies but also provides a useful and accessible resource for researchers and practitioners working on sustainable water treatment solutions.

2. Data and methods

The present research used the public and free database, PubMed, given its extensive indexing of peer-reviewed journals and comprehensive coverage across a wide range of scientific disciplines, and its recognition for offering the optimal update frequency ([Falagas et al., 2008](#); [Vardakas et al., 2015](#)). The literature search in the PubMed database was conducted using predefined keywords associated with olive oil production waste and adsorption and combined with the Boolean operators (“and” and “or”). The specific search string was the following: “olive” and “pomace or residues or waste” and “adsorption or water treatment or decontamination or removal”. The search process focused on the query filter “title/abstract” and aimed to cover the articles published in the complete time frame provided by the database, so the period was from 1996 to 2024. The absence of additional restrictions in the search process contributed to a more comprehensive set of results while maintaining alignment with the study’s scope and objectives, namely, the identification of existing literature on the development of adsorbent materials derived from olive oil production waste.

A total of 210 results were found and submitted to manual screening, allowing the exclusion of non-relevant studies. The exclusion criteria included publications addressing topics different from the scope of this review (e.g., composting, biogas production, and enzyme production), reporting on applications different from water treatment or adsorbents not derived from olive oil production waste, and literature reviews. Additionally, adsorption studies performed at a temperature different from room temperature were also excluded.

As a result, a total of 66 studies containing information on adsorbent materials derived from olive oil production waste applied to the removal of pollutants from water were included in this study and discussed in the next sections. Notably, the quality of the included studies is high, as nearly 90% (57 out of 66) were published in Q1 journals according to the SCImago Journal Rank (SJR), as detailed in Table S1. [Fig. 2](#) represents a visual preferred reporting items for systematic reviews and meta-analyses (PRISMA) scheme that describes the selection process for the publications used in this review.

3. Olive oil production residues tested as adsorbents and targeted water pollutants

The studies selected, based on the methodology described (Fig. 2) report, on one side the different olive oil production residues tested as adsorbent materials, and on the other, the diversity of target water pollutants for which the developed adsorbent materials were tested. The next sections detail the results obtained, unveiling the main conclusions related to the effectiveness and efficiency of different olive oil production residues as adsorbents for different water pollutants.

3.1. Olive oil production residues tested as adsorbents

To understand how different works explored the residues from the olive oil production process as adsorbent materials, we started by depicting the different residues involved in this industrial process. The information related to the production workflow and associated residues of the olive oil production process was collected from studies reported by Hung et al. (2005) and Anastopoulos et al. (2015). Fig. 3 schematically represents the olive oil production process and the respective production residues explored as adsorbents in the 66 selected scientific publications. Some of the works included studied more than one residue as adsorbent material, thus counted as many times as the residue tested. Moreover, the designations found in each article for each residue varied, and after careful analysis, the residues used as described in Table S1 were standardized.

Fig. 3 highlights the fact that olive pomace (OP) and cake are the most investigated residues as adsorbents, followed by studies investigating stone, olive tree pruning waste (OTPW), and olive oil mill wastewater (OMWW). This is not a surprise since OP is the most abundant residue of the olive oil production process (Malkoc et al., 2006), reported to be produced in large quantities in Mediterranean countries (Stasinakis et al., 2008; Hawari et al., 2009). Besides the unpleasant odor, significant amounts of this waste are discarded into the environment with negative impacts including toxicity (Erses Yay et al., 2012). Nevertheless, the cellulosic structure of this residue makes it to possess many active binding sites that could act as an adsorbing agent (Hawari et al., 2009). Moreover, the origin of olive cake is OP passing through the drying and extraction process (Anastopoulos et al., 2015). Olive stones (OS) can be part of OP or they can be separated from it.

The OMWW also consists of the toxic liquid waste usually discharged into waters without undergoing any treatment (Zahi et al., 2022; Shabir et al., 2023). However, due to its organic matter and recoverable carbon contents, it allows the development of more stable and efficient composites that can be further used as adsorbent materials (Mechnou et al., 2022).

Different from the above residues, OTPW is produced on a large scale, resulting from the olive pruning process, and is usually set on fire after harvest, contributing to the greenhouse effect (Blázquez et al., 2015; Anastopoulos et al., 2018).

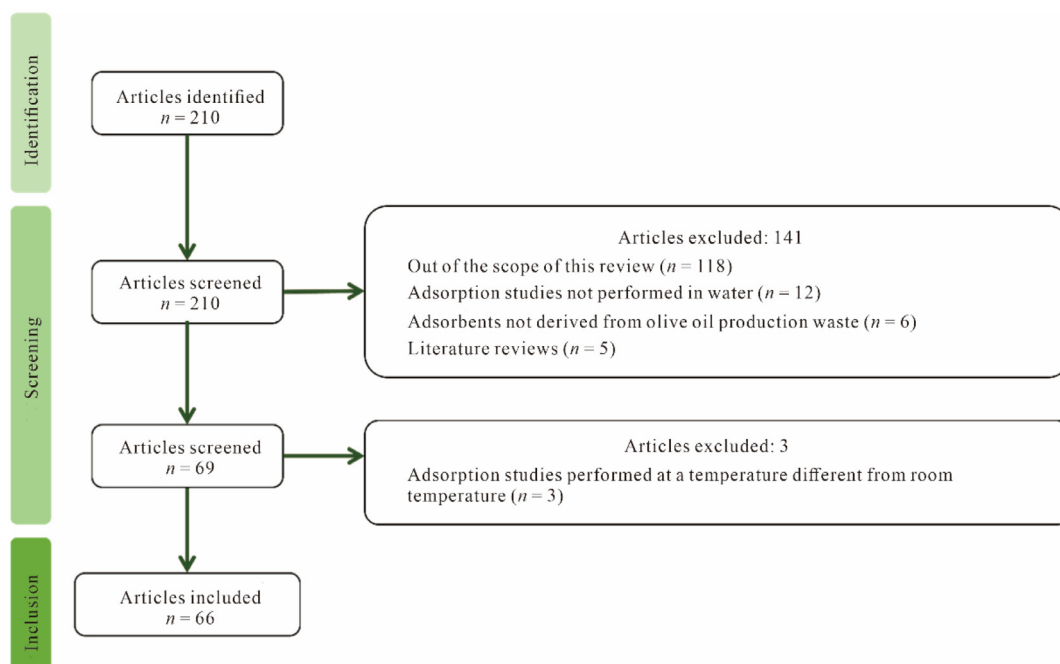


Fig. 2. The preferred reporting items for systematic reviews and meta-analyses (PRISMA) scheme for the literature search process on the use of waste-based adsorbents derived from olive oil production for adsorption of water pollutants (A manual screening was performed, and articles were excluded according to the criteria described.) *n*, number of articles.

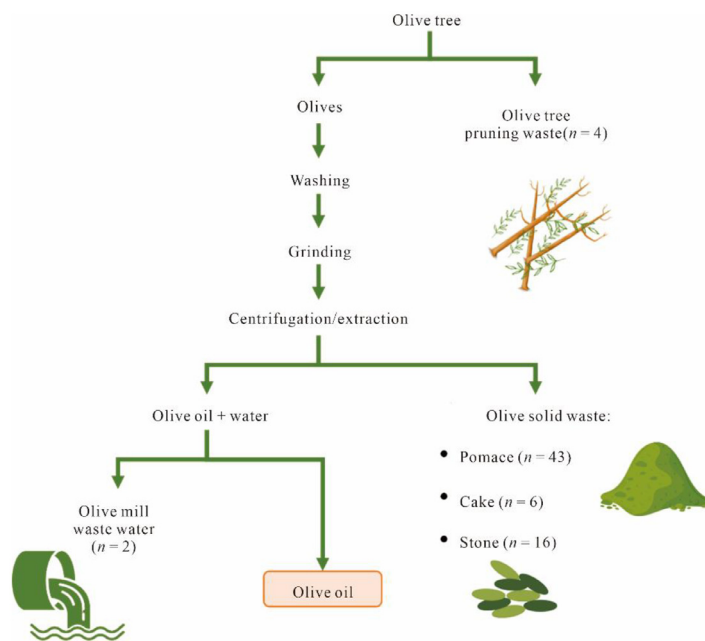


Fig. 3. Olive oil production process showing the residues tested as adsorbent materials (highlighted in bold) (The number of articles (*n*) that test each residue type as adsorbent (in aqueous solutions) is also represented.).

	Heavy metal	Phenolic compound	Dye	Drug	Agriculture chemical	Bisphenol A	Nitrite ion	Radionuclide
OP/OC	25	7	7	7	4	1	0	1
OS	6	2	2	4	3	1	1	0
OTP	1	1	1	1	0	0	0	0
OMWW	0	0	2	1	0	0	0	0
Total	32	10	12	13	7	2	1	1

OP, olive pomace; OC, olive cake; OS, olive stone; OTP, olive tree pruning; OMWW, olive oil mill wastewater.

Fig. 4. Adsorbent derivatives from olive oil production waste and target water pollutant categories (The data represent the number of publications exploring this combination. The images of heavy metals, drugs, dyes, and agriculture chemicals were freely downloaded from Pixabay). OP, olive pomace; OC, olive cake; OS, olive stone; OTP, olive tree pruning; OMWW, olive oil mill wastewater.

3.2. Targeted pollutants and residues tested as adsorbents

Based on the studies included in our sample, the pollutants were grouped for which the olive oil production residues were tested as adsorbents into 8 categories: heavy metals, phenolic compounds, dyes, drugs, agriculture chemicals, bisphenol A, nitrite ions, and radionuclides. In this categorization, the phenolic compounds category also includes the OMWW phenols, and the agriculture chemicals include herbicides, algicides, acaricides, fungicides, and antibacterial agents.

Fig. 4 illustrates the type of residue being tested as adsorbent material as well as the pollutant category being investigated for their removal from water, and the number of publications exploring those combinations. Table S1 exhibits more detailed information.

Olive pomace or cake were the most tested adsorbents targeting several pollutant categories, with the studies confirming its ability to remove heavy metals, phenolic compounds, dyes, drugs, agriculture chemicals, bisphenol A, and radionuclides from water. Moreover, olive pomace or cake were the only adsorbents tested for real samples contaminated with copper, lead, heavy metal mixtures and effluents containing phenolic compounds (Fernández-González et al., 2018; Hamed et al., 2019; Sayin et al., 2021; Akar et al., 2022; Haydari et al., 2022). Stones were also investigated for the same pollutant categories, differing in only one category, instead of radionuclides, they were tested to adsorb nitrite ions (Fig. 4).

The remaining residues, OTPW and OMWW, were only investigated in 6 out of 66 identified studies and only for heavy metals, phenolic compounds, dyes, and drugs (Fig. 4). This may be due to the fact that these residues only recently started to be investigated as adsorbents (after 2015), while the oldest study investigating olive solid waste is from 2002 (Pagnanelli et al., 2002).

Heavy metals are undoubtedly the most tested category, followed by drugs, dyes, phenolic compounds, and agricultural chemicals. Bisphenol A, nitrite ions, and radionuclides were also investigated, albeit by a more limited number of studies.

In the next sections, the conclusions reached by the studies analyzed concerning the effectiveness and efficiency of the diverse olive oil production residues as adsorbent materials for the different pollutants analyzed are summarized.

3.3. Effectiveness and efficiency of olive oil production residues in water pollutants removal

Data collected from the effectiveness and efficiency of water pollutants removal by the different adsorbent materials described in the studies analyzed included the percentage of pollutant removal and the adsorption capacity corresponding to the maximum adsorption capacity through the Langmuir isotherms. In the next sections these parameters were compared and represented in the respective tables.

3.3.1. Removal of heavy metals

(1) *Copper*. The lowest value for copper removal from aqueous solution in batch mode was close to 60%, using olive mill residues (OMR) at 10 g/L (Vegliò et al., 2003). Instead, Khiari et al. (2019) and Sepúlveda et al. (2023) using OP achieved higher removal rates (> 86.5%) via half the concentration of adsorbent and 20 times lower amount of copper. This could be expected considering the different ratios of adsorbent to pollutant. Also, a hybrid biocomposite resulted in copper removal close to that of the previous studies (Akar et al., 2022), using an identical ratio of adsorbent to pollutant according to the study by Khiari et al. (2019). In the real wastewater tests, the removal rate obtained was close to 90% either in batch or in column systems (Akar et al., 2022). In this application, besides higher removal rates, it contains the biopolymer chitosan that may facilitate adaptation to real effluents by acting as a support material (Akar et al., 2022) and its biodegradability is a plus from a sustainability perspective. Similarly, a recent work studying the sodium alginate used in the OP composite shows water copper removal rates superior to 90% (Elboughdiri et al., 2024). In this case, alginate can also contribute to copper's adsorption due to its already described biosorption capacities regarding copper (Lagoa and Rodrigues, 2009). Nevertheless, it must be stressed that in both cases, with chitosan or alginate addition, associated production costs will increase.

Activated carbon from olive stone (e.g., potassium olive stone activated carbon (KOSAC)) is the reported residue with the lowest removal percentage for copper, although it is the best in terms of the adsorption capacity, with a value of 230.2 mg/g (Ozcan et al., 2024). In Table 1 it is possible to compare this value to the value reported for olive stone alone. The adsorption capacity for the transformed residue is one order of magnitude higher (Hansen et al., 2010; Ozcan et al., 2024). In terms of transformed residues, the biochar obtained from OMWW and the KMnO_4 -modified OP also presents high adsorption capacity values in column or batch assays (Baccar et al., 2009; Arán et al., 2016). As for raw OP, the highest value adsorption capacities of 23.6 mg/g were reported by Khiari et al. (2019).

(2) *Lead*. Only two studies investigated the removal of lead from aqueous solutions using adsorbents based on residues from olive oil production, Blázquez et al. (2015) untreated and chemically treated olive stones (OS) and olive tree pruning waste (OTPW) and Sayin et al. (2021) tested an OP-derived magnetic-chitosan biocomposite. The OP biocomposite removed almost 100% of the lead present in the real wastewater, either in batch or column assays (Sayin et al., 2021). Regarding OS and OTPW, the study was performed with batch assays observing that untreated residues present lower adsorption capacity than treated residues (Blázquez et al., 2015). Moreover, the OTPW presented a higher adsorption capacity than olive stones (Blázquez et al., 2015). Table 2, organized by residue type and publication year, shows the removal percentages and the adsorption capacities for lead achieved by these materials.

(3) *Other heavy metals*. Fewer studies addressed the application of olive oil production residues in single heavy metal removal. For example, three recent studies focus on arsenic removal by an OP biochar. Similar adsorption capacities of 1–5 mg/g were achieved at 25 °C (Capobianco et al., 2020; Di Caprio et al., 2022, 2024). In the case of chromium, the residue tests included raw OP and activated carbon from OS containing chitosan (Malkoc et al., 2006; Ba et al., 2018). At 25 °C, the highest adsorption capacity achieved by OP for chromium VI was 10.8 mg/g (Malkoc et al., 2006). Regarding the OS-transformed residues, the developed activated carbon achieved an adsorption capacity of 38.3 mg/g, and 105.4 mg/g when combined with chitosan, which showed that the addition of chitosan can improve the adsorbent capacities of the developed materials (Ba et al., 2018).

Concerning cadmium, cerium, mercury, nickel, and zinc, only one study was found for each of these heavy metals. The removal of cadmium was tested using a succinylated-olive stone biosorbent that achieved 99% removal and an adsorption capacity of 200 mg/g (Aziz et al., 2009). In the case of cerium, a magnetic nanocomposite from OP was tested, achieving an adsorption capacity of 90.9 mg/g (Akbas et al., 2021). The removal of mercury was investigated using biochar from solid waste of the olive oil production process with a

Table 1

Comparative summary of the performances of adsorbents based on olive oil production residues for the removal of copper from aqueous solutions.

Adsorbent material	Adsorption data		Reference
	Removal (%)	Adsorption capacity (Q; mg/g)	
OP (OMR)	60	–	Vegliò et al. (2003)
OP	–	0.4	Francesca et al. (2008)
OP	92	23.6	Khari et al. (2019)
OP	86.5–92.5	12.9	Sepúlveda et al. (2023)
OP	79.5	–	Elboughdiri et al. (2024)
OP biosorbents	–	2.2–4.3	Francesca et al. (2008)
OP AC unmodified and KMnO ₄ -modified	–	12.0–35.3	Baccar et al. (2009)
OP biochars	–	0.66–7.07	Pellera et al. (2012)
OP hybrid biocomposite (TE-OP@C)	88–98	–	Akar et al. (2022)
OP composite with SA	94.5	–	Elboughdiri et al. (2024)
OS	–	18.4	Hansen et al. (2010)
KOSAC	27–52	230.2	Ozcan et al. (2024)
OMWW biochar	–	24.1	Arán et al. (2016)

Notes: AC, activated carbon; KOSAC, potassium olive stone activated carbon; OMR, olive mill residues; OMWW, olive oil mill wastewater; OP, olive pomace; OS, olive stone; SA, sodium alginate; TE-OP@C, thamnidium elegans cells, olive pomace, and chitosan.

The table is organized by residue type and publication year.

Table 2

Comparative summary of the performances of adsorbents based on olive oil production residues for the removal of lead from aqueous solutions (The table is organized by residue type and publication year).

Adsorbent material	Adsorption data		Reference
	Removal (%)	Adsorption capacity (Q; mg/g)	
OP biocomposite (MagOPIC)	98.9–99.0	–	Sayin et al. (2021)
OS	–	6.3	Blázquez et al. (2015)
OS chemically treated	–	49.1	Blázquez et al. (2015)
OTPW	–	26.7	Blázquez et al. (2015)
OTPW (chemically treated)	–	123.8	Blázquez et al. (2015)

Notes: MagOPIC, magnetic op chitosan biocomposite; OTPW, olive tree pruning waste.

maximum adsorption capacity of 104.6 mg/g (Hanandeh et al., 2016). Nickel was removed with an adsorption capacity of 10.6 mg/g in batch assays using dried OP (Nuhoglu and Malkoc, 2009). Finally, for zinc, untreated olive oil mill solid residues presented an adsorption capacity of 5.6 mg/g at 25 °C (Hawari et al., 2009).

(4) Mixtures of heavy metals. Several other studies tested the adsorbent materials derived from olive oil production waste in heavy metals removal from solutions containing mixtures of these pollutants. Table 3 summarizes the results, highlighting the type of adsorbent material, the removal percentages, and the adsorption capacities.

In a study using OP, the lowest removal rates were obtained for all the heavy metals tested (Pagnanelli et al., 2002). Two other batch studies using biochar from olive mix waste and solid remnants after saccharification of olive mill solid waste (OMSW) revealed high removal rates ($\geq 70\%$) for cadmium, copper, lead, nickel, and zinc. However, for selenium, the removal rates were much lower ($\leq 35\%$) (Abdelhadi et al., 2017; Abu Tayeh et al., 2020).

Comparing the studies carried out by Pagnanelli et al. (2005) and Martín-Lara et al. (2008), the best adsorption capacities for copper and cadmium were obtained in the latter study where OP was treated with phosphoric acid. However, for the untreated OP residues, Table 3 shows that both studies present similar adsorption capacities for copper and cadmium. The hydrolyzed olive cake revealed similar adsorption capacities for copper (Fernández-González et al., 2018) when compared to the OP treated with phosphoric acid (Martín-Lara et al., 2008). Moreover, the hydrolyzed olive cake was also tested for the removal of six heavy metals in mining wastewater revealing removal rates higher than 90% for all the compounds, except for manganese and lead, achieving 59.6% and 77.3% of removal, respectively (Fernández-González et al., 2018).

A recent study using olive stone char also investigated the removal of several heavy metals, however, the adsorption capacities do not stand out when compared to the other described materials (Table 3) (Pereira et al., 2024).

Finally, the developed material with the highest removal rates for mixtures was the cellulose extracted from olive industry solid waste that was tested for copper and lead, showing adsorption capacities of 54.1 and 146.3 mg/g, respectively (Hamed et al., 2019), that delivered removal rates near 90% for both pollutants when applied to sewage.

Table 3

Comparative summary of the performances of adsorbents based on olive oil production residues for the removal of heavy metals present in mixtures from aqueous solutions, sewage, and mining water (The table is organized by residue type and publication year).

Adsorbent material	Heavy metals in the mixture	Adsorption data		Reference
		Removal (%)	Adsorption capacity (Q; mg/g)	
OP (OMSW)	Cadmium	20	> 0.17	Pagnanelli et al. (2002)
	Copper	45	> 0.38	
	Lead	75	> 0.62	
	Mercury	63	> 1	
	Zinc	9	> 0.13	
OP	Cadmium	–	5.5	Pagnanelli et al. (2005)
	Copper	–	10.2	
OP	Cadmium	–	3.4	Martín-Lara et al. (2008)
	Copper	–	11.4	
OP treated with phosphoric acid	Cadmium	–	11.2	Martín-Lara et al. (2008)
	Copper	–	30.5	
OP (OMxW) biochar	Cadmium	88	–	Abdelhadi et al. (2017)
	Copper	99	–	
	Nickel	70	–	
	Lead	99	–	
	Selenium	20	–	
	Zinc	90	–	
Solid remnants after saccharification of OP (OMSW)	Cadmium	78	–	Abu Tayeh et al. (2020)
	Copper	83	–	
	Nickel	81	–	
	Lead	85	–	
	Selenium	35	–	
Cellulose extracted from OP (olive oil solid waste)	Copper	94	54.1	Hamed et al. (2019)
	Lead	In sewage: 99	89	
		In sewage: 86	89	
Hydrolyzed olive cake	Copper	Mining wastewater	Batch	Fernández-González et al. (2018)
		99	30	
		93	22.2	
		98	41.5	
		60	3.6	
		77	5.9	
		93	12.7	
OS chars	Cadmium	–	1.0	Pereira et al. (2024)
	Copper	–	10.1	
	Lead	–	18.9	
	Nickel	–	12.5	
	Zinc	–	5.0	

Notes: OMSW, olive mill solid waste; OMxW, olive mix waste.

3.3.2. Removal of phenolic compounds

Regarding phenolic compounds (PC), OP proved to be the best adsorbent in olive mill wastewater (Stasinakis et al., 2008). A removal higher than 90% was obtained with OP at 50 g/L for a PC concentration of 56 mg/L, at a pH range of 4.6–5.2 (Stasinakis et al., 2008). Whereas 4 g/L of activated carbon derived from olive stones resulted in only 73% adsorption of the contaminant present at 205 mg/L (Galiatsatou et al., 2002). The 12.5 times lower and about 3.7 times higher concentrations of adsorbent and PC were used, respectively, which are considerable differences, so it is natural that the removal capacity obtained is lower, even when using treated residues as adsorbents. The pH range may also influence the results since it was higher (5.2–5.9) than in the study of Stasinakis et al. (2008). Regarding the adsorption capacity, the OP bio-sorbent developed by Haydari et al. (2022) is the most powerful adsorbent for PC from OMWW. In this set of results, it is also interesting to observe that adsorbents in the format of columns achieved higher adsorption (Lissaneddine et al., 2021; Haydari et al., 2022; Aziz et al., 2024). The study of Aziz et al. (2024) stands out with the highest adsorption capacity. Nevertheless, it should be considered that a temperature of 39 °C was applied in this work. Table 4 summarizes the removal percentages and the adsorption capacities for these materials regarding phenolic compounds.

3.3.3. Removal of dyes

Several studies investigated the olive oil production residues' capacity for the removal of different dyes, such as methylene blue, crystal violet, malachite green, acid yellow 61, and RR198 (Akar et al., 2009; Ahmed Alshareef et al., 2022; Mechnou et al., 2023). Olive pomace was investigated for the removal of RR198, showing an adsorption capacity of approximately 105 mg/g (Akar et al., 2009). A similar value of 111.7 mg/g is obtained for the adsorption capacity of olive cake hydrochar regarding crystal violet (Ahmed Alshareef et al., 2022). Mechnou et al. (2023) reported that a composite of olive mill wastewater had the best adsorp-

Table 4

Comparative summary of the performances of adsorbents based on olive oil production residues for the removal of phenolic compounds from aqueous solutions (The table is organized by residue type and publication year).

Adsorbent material	Pollutant	Adsorption data		Reference
		Removal (%)	Adsorption capacity (Q; mg/g)	
OP	Total phenols from OMWW	Batch: > 90 Column: 90	11.4	Stasinakis et al. (2008)
OP	PC from OMWW	–	Batch: 68 Column: 159	Lissaneddine et al. (2021)
OP AC (OH AC)	P, PMP, and PNP	–	24.9–61.7	Hamadneh et al. (2020)
OP AC (OH AC) using MgCl ₂	P, PMP, and PNP	–	43.9–122.0	Hamadneh et al. (2020)
OP biosorbent	PC from OMWW	–	Batch (phenol solution): 789.3 Columns (real effluent of OMWW): 643.9	Haydari et al. (2022)
OP AC	PC in table olive processing wastewater	–	Column: 1 952.3	Aziz et al. (2024)
Olive cake AC	Total phenol in OMWW	85	9.9	Abu-Dalo et al. (2021)
OS AC	Total phenol in OMWW	–	91.7	Galiatsatou et al. (2002)
OS carbon	Total phenol in OMWW	–	75.2	Galiatsatou et al. (2002)
OS carbon modified with urea	Total phenol in OMWW	–	39.2	Galiatsatou et al. (2002)
OS AC	PSS	–	296–359	Esteves et al. (2022)
OS AC using KOH	PSS	–	337.6–358.5	Esteves et al. (2022)
OTPW AC	PSS	–	188.6–244	Esteves et al. (2022)

Notes: OH, olive husk; OMWW, olive oil mill wastewater; P, phenol; PC, phenolic compounds; PMP, p-methoxyphenol; PNP, p-nitrophenol; PSS, polyphenolic synthetic solution.

tion capacities achieved of 1 063.3 and 39.8 mg/g for the removal of malachite green and acid yellow 61, respectively. Methylene blue (MB) was the most investigated dye, with more than 10 studies found.

The removal efficiency of MB from aqueous systems was shown to be higher when using biochar derived from OP at 30 g/L for a contaminant concentration of 50 mg/L, achieving 99% removal. Using the same biochar with a pre-treatment, the removal capacity dropped only 0.9% at half the previous concentration (Tayibi et al., 2020). The study using activated carbon of OP attained a removal percentage of 95% (Hamieh et al., 2024), and in another study, 80% adsorption of MB at 10 mg/L was obtained by OP at 45 g/L (Banat et al., 2007). In this study, even with concentrations of pollutant 5 times lower and adsorbent concentrations 1.5 or 3 times higher, the removal obtained was lower when compared to the reports of Tayibi et al. (2020). This may be related to the absence of treatment of biomass waste and possibly the pH at which the study was conducted, but this information is omitted in the article. It is worth noting that nanocrystalline cellulose derived from olive waste showed even lower removal percentages of MB between 70% and 80% (Jodeh et al., 2018). Finally, and very interesting is the study using olive stones, without any residue treatment, obtained a removal rate close to 94% (Alardhi et al., 2023).

Regarding the best adsorption capacity (Q) of MB, the nano olive stones were revealed to be the most potent residue with an adsorption capacity of 476 and 625 mg/g for black and green stones (Al-Ghouti and Dib, 2020). This result is impressive since the only treatment was to pass the olive stones through the drying and smashing processes. Moreover, it should be compared with the results obtained with olive stones not smashed into the nanoscale, for which the adsorption capacity is one order of magnitude lower, as shown in Table 5 (Alardhi et al., 2023). Moreover, the adsorption capacities obtained by Al-Ghouti and Dib (2020) using the natural residue were very close to the results obtained when the residue was transformed into activated carbon, as recently reported by Ozcan et al. (2024), where the removal percentage was lower than those described in the work of Al-Ghouti and Dib (2020).

All the remaining studies found and represented in Table 5, except the study of Banat et al. (2007), use residues that have been modified by some treatment, representing an additional environmental issue. Moreover, the difference obtained for the adsorption capacity of OP in the format of the batch assay (42.3 mg/g) and column (7.12 mg/g) is evidenced by Banat et al. (2007). Additional works investigated a carbon/oxocalcium composite from OMWW and hydrochar from olive oil cake in the simultaneous removal of MB and paracetamol or MB and crystal violet, respectively (Ahmed Alshareef et al., 2022; Mechnou et al., 2022). The simultaneous removal of MB and paracetamol by the carbon/oxocalcium composite from OMWW achieved an adsorption capacity of 1 141.7 and 469.1 mg/g, respectively (Mechnou et al., 2022). In the other study, the removal of MB and crystal violet by hydrochar from olive oil cake achieved an adsorption capacity of 228.2 and 111.7 mg/g, respectively (Ahmed Alshareef et al., 2022). Table 5 shows the removal percentages and the adsorption capacities for these materials regarding MB.

Table 5
Comparative summary of the performances of adsorbents based on olive oil production residues for the removal of methylene blue from aqueous solutions.

Adsorbent material	Adsorption data		Reference
	Removal (%)	Adsorption capacity (Q; mg/g)	
OP	Column: 52.3–70.1	Batch: 42.3 Column: 7.1–16.2	Banat et al. (2007)
OP treated with KOH	–	122.2	Ferkous et al. (2022)
OP treated with KOH/PEG-SG	–	114.3	Ferkous et al. (2022)
OP NCs	73	–	Jodeh et al. (2018)
OP MNCs	79	–	Jodeh et al. (2018)
OP activated biochars	98–99	2.6–31.8	Tayibi et al. (2020)
OP AC (OMSW AC)	95	500	Hamieh et al. (2024)
Black nano OS	–	476	Al-Ghouti and Dib (2020)
Green nano OS	–	625	Al-Ghouti and Dib (2020)
OS	93.7	44.5	Alardhi et al. (2023)
OS AC impregnated with zinc	39–65	727.1	Ozcan et al. (2024)
OTPW	–	129.9	Anastopoulos et al. (2018)
OTPW composted	–	250.0	Anastopoulos et al. (2018)

Notes: MNCs, magnetic nanocrystalline cellulose; NCs, nanocrystalline cellulose; PEG-SG, polyethylene glycol-silica gel composite.

The table is organized by residue type and publication year.

3.3.4. Removal of other pollutants

Although less extensively studied, the removal of drugs, agriculture chemicals, bisphenol A, nitrite ions, and radionuclides from aqueous solutions using olive oil production residues was also investigated. Those studies and main results were illustrated.

Tetracycline removal was tested with OP, OP chitosan film, and OS-activated carbon, with the latter showing a higher adsorption capacity (Boudrahem et al., 2019; Rizzi et al., 2019). Regarding diclofenac, three studies tested OS-activated carbon (Delgado-Moreno et al., 2021; Al-sareji et al., 2024; Pereira et al., 2024), and the others tested OS char (Delgado-Moreno et al., 2021; Al-sareji et al., 2024; Pereira et al., 2024). The work of Pereira et al. (2024) resulted in the highest adsorption capacity (Table S2). Finally, a produced char from pitted and wet olive mill waste was shown to perform better than OS and OTPW chars for diclofenac, ibuprofen, and triclosan removal (Delgado-Moreno et al., 2021).

Studies concerning agriculture chemicals' adsorption by olive oil production residues were shown in Table S3. The compounds diuron, 2,4-dichlorophenoxyacetic acid, and 3,4-dichloroaniline were investigated in several studies (Baçaoui et al., 2002; Quirantes et al., 2017; El Ouahedy et al., 2020; Flores-Céspedes et al., 2020; Ozcan et al., 2024). Fly ashes from OP and OS-activated carbon showed the highest adsorption capacity for diuron, 3,4-dichloroaniline, and 2,4-dichlorophenoxyacetic acid (Quirantes et al., 2017; Ozcan et al., 2024).

For bisphenol A (BPA), porous carbon materials from olive stone were tested and an adsorption capacity of 476 mg/g was obtained (El Ouahedy et al., 2020). An additional study showed the simultaneous removal of drugs, agricultural chemicals, and BPA in a mixture (Weidemann et al., 2018).

The removal of nitrite ions was studied for OS activated carbon tested in batch and column obtaining an adsorption capacity of 7 and 3.65 mg/g, respectively (Zyoud et al., 2015). Finally, with OP the Ga-67 radionuclides were 97% removed (Eroglu et al., 2009).

3.3.5. Comparative summary of the maximum adsorption capacities reported for olive oil production residues derived adsorbents

A global overview of the maximum adsorption capacities reported for the adsorbents derived from olive oil production residues according to the target pollutant was represented in Fig. 5. For heavy metals, it is possible to observe that the adsorption of copper was headed by OS chemically treated (Fig. 5a), while activated carbon from OTPW led to the removal of lead (Fig. 5b).

The chemical transformation of olive pomace residues is present in most of the studies analyzed showing considerable improvements in the adsorption capacities. When transformed into biochar or activated carbon, OP revealed a large capacity to remove the drug cefazolin and phenolic compounds from real OMWW (Escudero-Curiel et al., 2023; Aziz et al., 2024), values were represented by the maximum ones in Figs. 5c and 5e.

Regarding dyes, an OMWW composite was found to be highly efficient for malachite green (Mechnou et al., 2023). The OS untreated residues, in turn, stand out for methylene blue removal (Fig. 5d), thus providing an ideal solution in the context of the circular economy by eliminating additional resource usage (Al-Ghouti and Dib, 2020). In agricultural chemicals, few data were found but OS seem to provide higher adsorption capacities than OP (Fig. 5f) with high efficiency in the removal of the agriculture chemical 2,4-dichlorophenoxyacetic acid (Blázquez et al., 2015; Ozcan et al., 2024).

In general, the data shows the potential of olive oil residues as adsorbent materials for water treatment. The next sections discuss the impact of these solutions on the circular economy and the challenges that must be addressed before they can be applied in real-world settings.

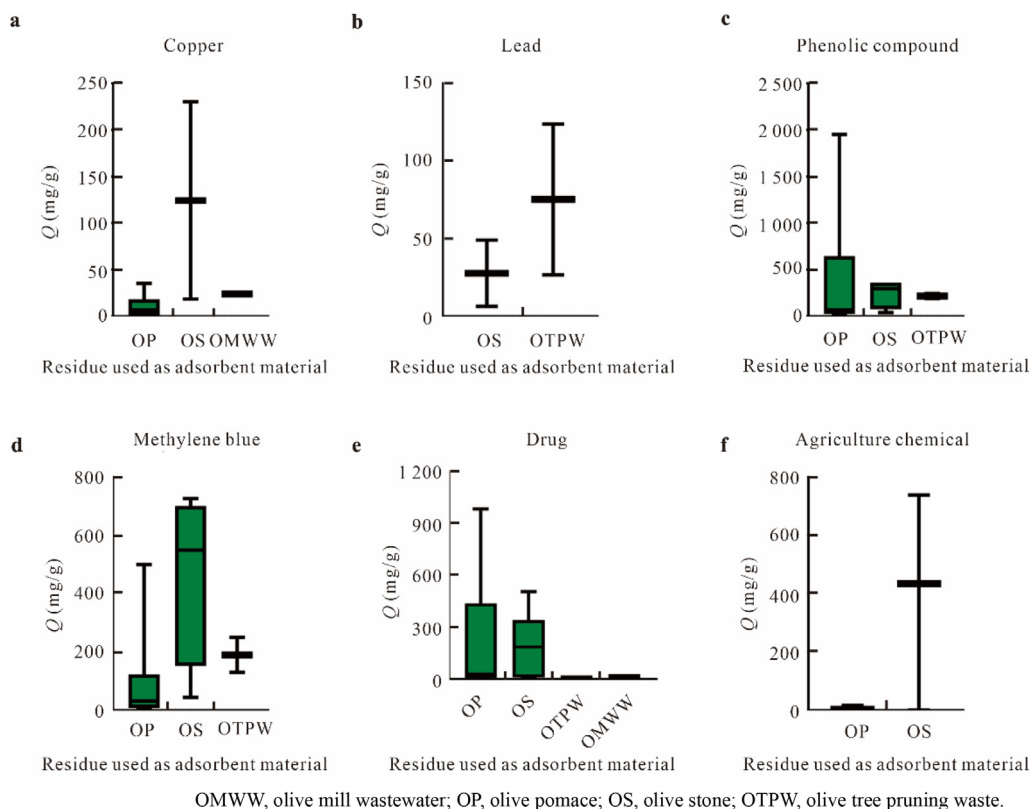



Fig. 5. Distribution of maximum adsorption capacities (Q) for: (a) copper, (b) lead, (c) phenolic compounds, (d) methylene blue, (e) drugs, and (f) agriculture chemicals. OMWW, live oil mill wastewater; OP, olive pomace; OS, olive stone; OTPW, olive tree pruning waste.

4. Contribution to a circular and more sustainable economy

The current literature review systematized the studies addressing the upcycling opportunities provided by olive oil production residues to face a global environmental problem, i.e., water contamination. From the exposure above, these residues' potential as adsorbent materials with application in water treatment processes becomes evident, thus, simultaneously solving two negative environmental externalities of anthropogenic origin. The results presented are of utmost importance in the context of the United Nations 2030 Sustainable Development Agenda, particularly, for “Goal 12: Responsible Consumption and Production” and its targets 12.4 (i.e., “Responsible Management of Chemicals and Waste”) and 12.5 (i.e., “Sustainably Reduce Waste Generation”), and “Goal 15: Life and Land” and its target 15.1 (i.e., “Conserve and restore terrestrial and freshwater ecosystems”). In fact, besides solving the problem of the toxic olive oil production residues and their harmful effects on ecosystems, like land infertility or plagues and diseases in human beings, their use as adsorbent materials may contribute to the above mentioned target 15.1.

All the applications tested and reported above obviate the environmental problem caused by olive oil production, i.e., the waste generated. Therefore, preserving and improving land productivity and freshwater resources contribute to the transition from a linear to a circular economy, essential for a regenerative food system (Ellen MacArthur Foundation, 2015a, 2015b), a critical goal in the political agenda, and for “Goal 2: Zero hunger”. The studies analyzed underline the different circularity potentials of the various residues and target pollutants tested, considering the need for prior treatment, or not for use as adsorbent material. For example, the study of Khiari et al. (2019) highlighted the high adsorption capacity of OP residues as unmodified adsorbent materials, while Alardhi et al. (2023) report the use of olive stones, without any residue treatment and a removal rate close to 94%. Both report the potential of untreated olive oil residues for water pollution treatment, which is an added value from a circular economy perspective because neither energy nor additional resources need to be used for further transformations. Along the same line, the great adsorption capacity of nano olive stones for MB was demonstrated by Al-Ghouthi and Dib (2020) via passing the olive stones through the drying and smashing processes, and added arguments to the circularity potential for using olive oil production residues. Fig. 6 resumes the adsorption capacities achieved by raw materials to the different pollutant categories, highlighting the potential of using olive oil production residues directly in wastewater treatment.

As such, the current paper identifies, the advances in research into the use of olive oil production waste that can contribute to a cleaner and more competitive Europe in a systematic way, as set out in the Action Plan for the New Circular Economy (European Commission, 2020) and the European Green Deal strategy (European Commission, 2019). Particularly, this work unveils several solutions



	Olive pomace	Olive stones	Olive tree pruning waste
Copper	23.6 (Khiari et al., 2019) 12.9 (Sepúlveda et al., 2023)	18.4 (Hansen et al., 2010)	—
Lead	—	6.3 (Blázquez et al., 2015)	26.7 (Blázquez et al., 2015)
Heavy metal mixture	5.5 Cd ²⁺ ; 10.2 Cu ²⁺ (Pagnanelli et al., 2005) 3.4 Cd ²⁺ ; 11.4 Cu ²⁺ (Martin-Lara et al., 2008)	—	—
Phenolic compound	—	1.4 (Stasinakis et al., 2008) 68 – 159 (Lissaneddine et al., 2021)	—
Dye (methylene blue)	7.1 – 42.3 (Banat et al., 2007)	476 – 625 (Al-ghouti and Dib 2020) 44.5 (Alardhi et al., 2023)	129.9 (Anastopoulos et al., 2018)
Drug	16 tetracycline (Rizzi et al., 2019) 11 diclofenac; 10 ibuprofen; 13.8 triclosan (Delgado-Moreno et al., 2021)	—	—

Fig. 6. Comparative summary of the adsorption capacities (Q) (mg/g) of the olive oil production process raw residues in the removal of the different pollutants in water.

to move from a linear to a circular paradigm in the olive oil production process, which can also contribute to a better ecological and chemical status in surface waters and good chemical and quantitative status in groundwater, a medium-term objective of the EU Soil Strategy for 2030 (European Commission, 2021). Nevertheless, to implement the sustainable environmental solutions identified, collaboration between different stakeholders, such as academic researchers, olive oil production industries, and water treatment entities, is crucial.

5. Summary, future perspectives, and concluding remarks

In this review, through a systematic literature review, data regarding removal rates and adsorption capacities for the different olive oil residues used as adsorbent materials targeting different water pollutants were collected, and the results published were compared when possible.

In summary, OP is the most investigated residue tested as an adsorbent material with a larger number of publications investigating this application and investigating its adsorption capacity for a higher variety of pollutants. Moreover, the data collected in this study also indicates that OP is the only residue tested as adsorbent material outside laboratory conditions, which proved effective as adsorbent material in real environments for the removal of heavy metals and phenolic compounds from olive mill wastewaters (Fernández-González et al., 2018; Hamed et al., 2019; Sayin et al., 2021; Akar et al., 2022; Haydari et al., 2022). Nevertheless, for other pollutant classes, some studies indicate that other residues may perform better with higher adsorption capacities as is the environmentally friendly case of OS untreated residues (Al-Ghouti and Dib, 2020).

Overall, the findings presented in this review support the growing interest in the upcycling of olive oil production residues for the development of adsorbent materials, highlighting the potential of this emerging field to contribute to sustainable water treatment solutions in tertiary treatments. Nonetheless, several challenges must be addressed to enable the practical application of these materials. Future research should, for instance, explore the performance of residues other than olive pomace (OP), particularly olive stones (OS), which have shown high adsorption efficiency for the different classes of pollutants in laboratory conditions. It is essential to assess their behavior in real contaminated water samples, since factors, such as pH, organic matter content, and the complexity of the matrix, may significantly influence adsorbent performance. In addition, it is important to investigate support systems that enable the practical application of these materials, such as adsorption columns that can incorporate untreated olive residues. While some studies have shown promising results for OP residues in such systems (Baccar et al., 2009; Arán et al., 2016; Sayin et al., 2021; Akar et al., 2022), broader validation is needed. Furthermore, the safety of the developed adsorbent materials must be ensured through toxicity assessments and analysis of microbial growth potential, allowing for the prediction of their environmental impact in target ecosystems. Prototypes should also be tested under real-world conditions to evaluate key operational parameters, such as stability, reusability, lifespan, and cost-efficiency. Finally, implementation studies are crucial, as the transition from research to application involves navigating various technology readiness levels and meeting regulatory requirements. These include, for example, potential certification processes for uncertified raw materials and compliance with Regulation (EC) No. 1907/2006, i.e., Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) in Europe, both of which may present financial and administrative barriers to deployment.

However, it should be noted that the results presented in the current work have some limitations associated with the data collection from the studies reviewed, namely the fact that data were collected only on the results of tests performed at temperatures close to room temperature (20–25 °C, rarely 30 °C). Moreover, the comparison of adsorbents' performance was based on the adsorption capacity when this data was reported, since the percentage of pollutants' removal always depends on the concentration of the adsorbate and

adsorbent used, and some studies lack this information. Additionally, this study relied on a single database, PubMed, which, may represent a methodological limitation despite its broad coverage and public accessibility. Despite the limitations acknowledged, they do not undermine the validity or relevance of the study.

In conclusion, the potential contributions of the proposed solutions for using olive oil production residues, particularly olive pomace, as adsorbent materials were highlighted, supporting a more circular and sustainable economy by mitigating the environmental impacts of agro-industrial waste and offering a sustainable pathway to upcycle these by-products. The extensive update of the 66 works published in the literature highlighted the potential of olive oil production residues used as adsorbent materials. Moreover, the current study emphasized the different byproducts investigated for a diversity of pollutants, in the real-world environment, and applied in the water treatment process as raw materials, avoiding additional resources and costs. The latter is particularly relevant in the context of a circular economy paradigm and guidelines for future developments in the area, such as new technologies for wastewater treatment based on natural byproducts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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