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An Overview of Wastewater Treatment Alternatives for Olive Mill Industries: A Systematic Review

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ABSTRACT

Background: The olive production industry is experiencing rapid growth owing to its health advantages. Nevertheless, a major challenge it encounters is the highly variable wastewater generated from olive oil mills (OMW). To tackle this issue, a range of treatment methods has been adopted, which include physical, thermal, biological, physicochemical, and biophysical treatments, as well as sedimentation, advanced oxidation processes, and combined approaches. This review emphasizes recent studies concerning techniques aimed at eliminating contaminants from OMW.
Methods: This review paper provides an overview of the approaches and technologies used to treat and recover OMW, based on an analysis of 50 peer-reviewed articles published between 2000 and 2025.
Results: OMW is characterized by high concentrations of salts (10 dSm^{-1}), organic matter (130,000-200,000 mgL^{-1}), suspended solids (2170-3480 mgL^{-1}), and particularly phenols (360 mgL^{-1}). It also exhibits high biological oxygen demand (18,000-77,000 mgL^{-1}) and chemical oxygen demand (160,000-180,000 mgL^{-1}). Typically, OMW is dark brown with a foul odor and contains significant amounts of organic and inorganic compounds, such as potassium (2700-7200 mgL^{-1}), phosphorus (300-1100 mgL^{-1}), and lipids (3.0-23 mgL^{-1}).
Conclusion: The complexity of OMW shows that the scientific community has yet to determine a definitive treatment method. Combining technologies such as precipitation, adsorption, advanced oxidation, and membrane filtration has been shown to enhance the treatment of OMW.

1. Introduction

With over 900 olive cultivars and genotypes thriving in Mediterranean regions and areas with mild winters and hot summers, olive oil production has become a cornerstone activity in countries bordering the Mediterranean Sea. This includes Italy, Portugal, Spain, Greece, and North African nations, including Algeria, Morocco, Tunisia, Libya, and Egypt. Additionally, significant quantities of olive oil are produced in countries such as France, Serbia, Montenegro, North Macedonia, Cyprus, Syria, Turkey, and Jordan (Rostami et al., 2024). In 2023, Iranian olive oil production decreased to approximately 4,000 tons due to various factors, including alternate bearing, amid increased olive oil production in European countries and a twofold rise in global olive oil prices, marking a recent low. However, in 2024, a significant increase in both olive fruit and oil production in Iran is anticipated, with estimated figures of 150,000 tons and 11,000 tons, respectively. Overall, Iran is emerging as a developing country in the global landscape of olive cultivation and oil production (Shabir et al., 2023).

Olive oil production is rapidly emerging as a significant sector within the agricultural-food industry in China and other countries, including the United States-particularly California, which boasts a Mediterranean-like climate-along with Australia, Japan, Argentina, Chile, New Zealand, and the Middle East, especially Saudi Arabia. Notably, China has favorable conditions for olive tree cultivation and is expected to become a major global olive oil producer in the near future. Over the past few decades, the olive oil industry has

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experienced remarkable growth, driven by the modernization of olive oil mills in response to the increasing global demand for olive oil (Ochando-Pulido et al., 2016; Press, 2002).

Figure 1 illustrates olive oil production by country in 2024. Spain, with over 1,700 mills, is the largest producer among European Union (EU) member states. In Spain, 70% of olive oil is produced in the Andalusia region, where approximately 850 mills process around 5,000,000 tons of olives annually, yielding about 1,022,000 tons of olive oil (Ochando-Pulido et al., 2016; Press, 2002). Olive oil production has also seen significant growth in Southern European countries, the Middle East, and North Africa-regions known for their Mediterranean-based diets (Press, 2002).

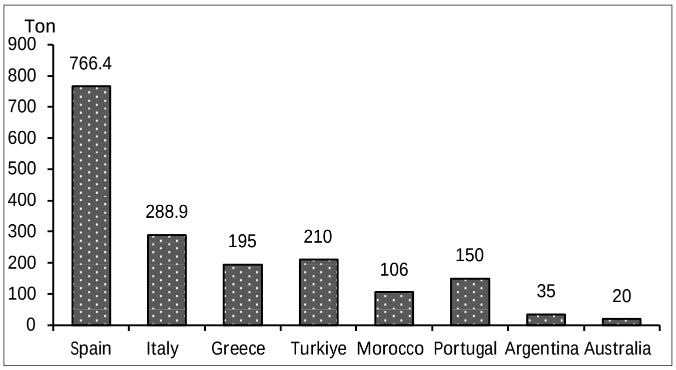

Figure 1. Olive oil production in various countries in 2024 (International Olive Council, 2013-2014)

The effluent generated from the milling procedure ranges between 0.5 and 1.5 m^3 for every 1000 kg of olives, contingent on the specific methodology employed. Olive mill wastewater (OMW) produced is one of the dangerous industrial effluents for the environment (Paraskeva & Diamadopoulos, 2006). A serious challenge to the environment will be posed by the increasing olive industry in the world. The goals of this article are 1) reviewing the characteristics of OMW, 2) comparing the treatment methods of OMW, and 3) introducing the highly efficient methods for pollutant removal.

2. Materials and Methods

This review provides a thorough examination of current methods and technologies used for the treatment and resource recovery of Olive Mill Wastewater (OMW). A systematic literature search was conducted using major scientific databases, including Scopus, Web of Science (WoS), PubMed, SpringerLink, ScienceDirect, MDPI, and IOP Publishing, supported by Google Scholar to identify additional relevant gray literature. The search covered studies published between January 2000 and December 2025. To ensure comprehensive coverage, the search strategy incorporated controlled keywords combined with Boolean operators, including terms such as: "olive mill wastewater" and "treatment"; "olive oil industry" and "wastewater" and "technology"; "OMW" and ("biological treatment" or "advanced oxidation processes" or "physicochemical treatment" or "resource recovery"); and "olive waste" not "olive pomace combustion." Article selection followed clearly defined operational criteria. Inclusion criteria consisted of peer-reviewed scientific papers published between 2000-2025, written in English, available in full text, and focusing on OMW treatment, management methods, or resource recovery, including experimental, review, or technology-focused research. Exclusion criteria eliminated articles without accessible full text, studies not directly related to OMW (e.g., those exclusively examining olive pomace combustion), research lacking methodological detail or significant scientific data, and duplicate records. In total, 100 publications were initially identified; after removing duplicates, title and abstract screening eliminated non-relevant studies, and full-text evaluation resulted in 51 peer-reviewed articles selected for detailed analysis. The review categorizes OMW treatment methods into physical, thermal, biological, physicochemical, biophysical, chemical, and advanced oxidation processes (AOPs), as well as combined and hybrid systems. The comparative analysis highlights the effectiveness, advantages, limitations, and sustainability potential of each method. Additionally, emphasis is placed on emerging technologies that not only reduce pollution but also enable the recovery of valuable resources, contributing to circular economy goals within the olive oil industry. By bringing together multidisciplinary innovations, this study provides valuable insights for researchers, practitioners, and policymakers seeking to improve OMW management and promote environmental sustainability.

3. Results and Discussion

3.1 Nutritional Value and Health Benefits of Olive Oil

Numerous studies have demonstrated the health benefits associated with olive oil consumption. Evidence suggests that a diet rich in olive oil can significantly reduce blood pressure in both adult men and women. Comparative studies have shown that olive oil, especially when compared to high oleic sunflower oil, effectively lowers both systolic and diastolic blood pressure. Research conducted in Spain has indicated that men adhering to a Mediterranean diet, rich in olive oil, tend to have lower blood pressure. When comparing refined and extra-virgin olive oils (the latter being considered the highest quality), studies have shown that extra-virgin olive oil can reduce systolic blood pressure in hypertensive patients. Additionally, extra-virgin olive oil has lower free acidity and peroxide values than virgin olive oil (Yousefi et al., 2018). However, regarding other cardiovascular risk factors such as diastolic blood pressure, blood glucose, overall lipids, and LDL cholesterol, no significant differences in the positive effects of various olive oil types have been observed. Adherence to a Mediterranean diet, centered around olive oil, has been linked to a reduced risk of metabolic syndrome, characterized by a cluster of conditions including hypertension, abdominal obesity, elevated triglycerides, insulin resistance, and high levels of uric acid. Furthermore, the combination of olive oil with omega-3 fatty acids, and the consumption of olive oil in inflammatory conditions has shown significant health benefits (Press, 2002). Table 1 presents a breakdown of the composition of olive oil in its various forms.

Shifting from a low-fat to a higher-fat diet, particularly one rich in olive oil and oleic acid, has been associated with a reduced risk of certain cancers, especially breast cancer. As illustrated in Table 1, a diet that includes olive oil has been shown to decrease tissue sensitivity to damage caused by free radicals, thereby lowering the risk of breast cancer. Olive oil has also demonstrated benefits in preventing prostate cancer, as evidenced by the lower rates of this disease in Southern European populations, including those in Greece, Italy, Spain, and Portugal, where olive oil consumption is high. Additionally, olive oil has been linked to a reduced risk of various oral and pharyngeal cancers. Cardiovascular diseases and cancer are among the conditions that can be prevented through a diet rich in olive oil (Press, 2002).

Table 1. Composition of Olives (Awad et al., 2004)

Parameter (%)	Pulp	Stone	Seed
Water	50-60	9.3	30
Oil	15-30	0.7	27.3
Sugar	3-7.5	41	26.6
Polyphenol	2-2.25	0.1	0.5-1

3.2 The Impact of Olive Oil Extraction Processes on Wastewater

In recent years, water scarcity and pollution have become major problems and challenges for human societies. Various pollutants, including heavy metals, radioactive materials, total dissolved solids, and both organic and inorganic compounds, are significant water contaminants (Asadifard et al., 2021). These variations are influenced by several factors, including olive cultivar, soil conditions, pesticide and fertilizer use, harvest time, climatic conditions, and the specific oil extraction method. In modern olive oil mills, the most common methods for extracting oil from olive paste include pressing (traditional or batch), centrifugation (continuous), three-phase centrifugation, and the relatively new two-phase centrifugation. In the traditional pressing process, the amount of water added during oil extraction is low (3-5 L per 100 kg of processed olives). Consequently, the volume of liquid waste generated is minimal, but the waste is much more concentrated compared to other methods. Additionally, this method yields wastewater with higher levels of chemical oxygen demand (COD), polyphenols, and total solids. Despite producing a wastewater stream with a higher pollutant load, the low extraction temperature results in high-quality olive oil. Three-phase centrifugation processes generate two types of waste: solid waste with a moisture content of approximately 40-50% and liquid waste. Centrifugation processes, which gained popularity in Greece in the early 1970s, have largely replaced traditional pressing methods. Centrifugation requires the addition of hot water (1.25-1.75 times more than the pressing process), leading to a higher volume of OMW and the loss of valuable compounds in the wastewater. The total solids content of this wastewater is approximately double that of traditional pressing. Due to the residual oil content (4-9.5%) in the three-phase centrifugation process wastewater, in some countries such as Spain and Greece, it is sent to oilseed extraction plants, where it is further processed with heat and hexane for additional oil extraction (Markou et al., 2010).

In the mid-1990s, the two-phase process was introduced to olive oil mills to reduce the volume of OMW generated by three-phase processes by up to approximately 75%. The sole byproduct of this process is a two-phase OMW residue, commonly known as wet olive cake, with a moisture content ranging from 55% to 75%. This high moisture content makes transportation, storage, and management challenging. Due to its unique physicochemical properties, two-phase OMW cannot be directly composted or incinerated and requires pre-treatment, which increases costs. Consequently, operators of three-phase mills have been reluctant to switch to the two-phase process, although in some cases, it may be the only viable option (Markou et al., 2010). The two-phase process operates on a similar principle to three-phase centrifugation but without the use of water, producing only two streams: olive oil and a residue composed of olive pomace and OMW, creating a very wet olive cake known as *alpeorujo*. The olive tree (*Olea europaea L.*) belongs to the *Oleaceae* family and the Olea genus. Its fruit contains 50% moisture (Fard et al., 2020). Table 2 presents a comparison of the wastewater generated in the two-phase and three-phase pressing processes. This extraction method is less complex, consumes less energy, and produces a higher quality olive oil compared to three-phase pressing. However, despite being considered an environmentally friendly process (due to an 80% reduction in wastewater production), the problem remains unresolved as new waste is generated that presents new challenges for treatment and disposal (Tsagaraki et al., 2007). Due to its inherent challenges, the two-phase process should be minimized and used only in specific cases. Consequently, it cannot completely replace three-phase processes. In many instances, attempts to substitute it have led to more problems. It is now evident that the number of two-phase plants in a region should be balanced with the number of three-phase plants; three-phase plants must have sufficient land for treating their OMW. If the accumulation of two-phase and three-phase OMW residues becomes excessive, large masses of wet solid waste will form near the plant, exposed to rain and causing odor and leachate problems (Markou et al., 2010). Table 3 presents the impact of production processes on olive oil characteristics.

Table 2. Characteristics and properties of wastewater produced during the various stages of the three-phase and two-phase olive oil extraction processes (Borja et al., 2006)

	Three-phase process			Two-phase process		
Effluent	Solids (%)	Oil (%)	COD (g/kg)	Solids (%)	Oil (%)	COD (g/kg)
Washing of olive	0.51	0.14	7.87	0.54	0.10	0.87
Horizontal centrifuge	6.24	0.96	73.82	0	0	0
Vertical centrifuge	0	0	0	1.43	0.57	1.17
Final Effluent	4.86	0.31	68.61	2.82	0.29	2.25

3.3 Environmental Challenges of Olive Oil Mill Wastewater

With the growing demand for olive and olive oil production, and the consequent expansion of this industry, particularly in European regions and those with Mediterranean climates, numerous adverse environmental impacts have emerged. The significant increase in wastewater volume, especially due to the transition from traditional batch pressing methods to more modern centrifuge-based processes, has exacerbated the issue. While these advanced processes enhance yield and efficiency by up to 21%, they also generate substantial wastewater streams. An olive oil mill employing modern processes can produce several cubic meters of OMW and olive washing wastewater (OWW) daily (Ochando-Pulido et al., 2016). The uncontrolled discharge of OMW has severe environmental consequences, leading to foul odors, soil contamination, hindered plant growth, groundwater leaching, disruption of self-purification processes, harm to aquatic organisms, and overall ecological degradation. Furthermore, the presence of phytotoxic pollutants such as phenolic compounds, long-chain fatty acids, tannins, and halogenated organic compounds makes OMW resistant to biological degradation. The concentrations of these contaminants can vary significantly depending on the extraction process, cultivation practices, and the quality and maturity of the olives (Karaouzas et al., 2011), as detailed in Table 4. OWW typically contains high concentrations of suspended solids (predominantly skin, pulp, and remnants of branches and leaves), making its reuse extremely challenging (Aboutaleb et al., 2018). As shown in Table 4, these samples are characterized by a low acidic pH of 4.5. This low value makes the biological treatment of olive mill wastewater difficult, as bacteria thrive optimally in the pH range of 6.5-7.5. If the pH of the OMW is not adjusted before discharge, it may also impact the pH of natural waters.

Table 3. Influence of the production process on OMWW characteristics

Parameter	Press process	Two-Phase	Three-Phase	References
pH	4.5-5 4.5±0.3	- -	4.7-5.2 4.8±0.3	(Azbar et al., 2004) (Aktas et al., 2001)
COD (g/L)	120-130 65.7±27.1 90-100	- 5-25 -	40 13.4±19.5 33	(Azbar et al., 2004) (Caputo et al., 2003) (Azbar et al., 2004)
BOD (g/L)	90 -	- 23-100	40 -	(Aktas et al., 2001) (Awad et al., 2004)
TSS (%)	0.1	-	0.9	(Azbar et al., 2004)
TSS (g/L)	0.1	-	0.9	(Caputo et al., 2003)
Total N (%)	5-2	-	0.28	(Azbar et al., 2004)
Total N (mg/L)	1.8	-	0.3	(Caputo et al., 2003)
Polyphenols (%)	1-2.4 1.7	- -	0.5 0.63	(Azbar et al., 2004) (Caputo et al., 2003)
Polyphenols (mg/L)	-	181	-	(Ochando-Pulido et al., 2016)
Grease (%)	0.03	-	0.5-2.3	(Azbar et al., 2004)

Table 4. Characteristics of olive mill wastewater

Parameter	References			
	(Azbar et al., 2004)	(Parvin & Tareq, 2021)	(Sierra et al., 2001)	(Eroğlu et al., 2004)
pH	3-5.9	4.7-5.7	4.5-6	4.86
BOD (g/L)	23-100	13.5-46	35-100	17.88
COD (g/L)	40-220	16.5-190	40-195	72.20
Carbohydrates (%)	2-8	2-8	-	-
Polyphenols (g/L)	0.002-80	5-256.8	3-24	0.13
Total solid (g/L)	1-102.5	-	-	42.24
N (g/L)	0.3-1.2	-	5-15	-
K (g/L)	-	0.73-8.6	2.7-7.2	7.81
P (g/L)	-	-	0.3-1.1	-
Ca (g/L)	-	0.03-1.1	0.12-0.75	0.55
Na (g/L)	-	0.05-0.8	0.04-0.90	0.41
Mg (g/L)	-	0.03-1.19	0.10-0.40	0.28
Lipid (g/L)	1-23	0.58-7	0.3-24	-

3.3.1 Effects of OMW on Soil

The negative impacts of OMW on soil include its potential effects on seed germination and plant growth, particularly when applied directly as an organic fertilizer (Sdiri Ghidaoui et al., 2019). Due to their high pH, organic content, biological oxygen demand (BOD), COD, short and long-chain fatty acids, and high and low-molecular-weight polyphenols, these mill wastes are highly polluting and toxic (Foti et al., 2021). In some cases, due to their high toxicity, these materials have been used as herbicides (Fernández-Hernández et al., 2014). On the other hand, the application of pre-treated OMW to agricultural land can increase soil nutrient capacity, enhance plant growth, promote fruit formation, photosynthesis, and potassium and organic matter concentrations (Kavdir & Killi, 2008). The disposal of pre-treated OMW, being rich in nutrients, especially potassium, stimulates plant growth and can be used as a biomass fuel, compost, or raw material for obtaining valuable products such as antioxidants and enzymes. Additionally, olive mill solid residues can be used for heavy metal removal or as bio-sorption matrices (Al Bawab et al., 2018). The type of olive, the quantity, the oil extraction methods, and most importantly, the pre-treatment method are the most critical factors in determining the positive or negative effects of these wastes on soil (Peraldo-Neia et al., 2011).

3.3.2 Effects of OMW on Water

Significant environmental concerns arise when olive mill wastewater from the extraction process is discharged into water bodies without treatment (Alaoui & Penta, 2016). Olive mill wastewater contains toxic chemicals and pollutants that impact water quality and pH levels. The disposal of OMW in water bodies has negative consequences, including increased levels of polyphenols, toxic organic compounds, BOD, COD, and foul odors. Untreated OMW discharged into rivers, wetlands, and lakes reduces dissolved oxygen, leading to the death of fish and other aquatic organisms, as well as other unpleasant effects such as putrid fumes resulting from the

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decomposition of organic matter. Untreated OMW also contains various pathogens and toxic microbes, particularly phenolic compounds, which are harmful to humans (Shabir et al., 2023). Pretreatment of OMW can improve wastewater quality and remove some of its toxicity. In the following sections, olive mill wastewater pretreatment methods will be discussed, including the use of filters, adsorbents, oxidation, and lime application. The application of these processes before the main treatment of this wastewater will improve the efficiency of treatment (Barbera et al., 2013).

3.4 The Improvement of the Physicochemical Properties of OMW

Pre-treatment and treatment methods for improving the physicochemical properties of OMW wastewater are illustrated in Figure 2. These methods are applied to the wastewater discharged from olive oil mills.

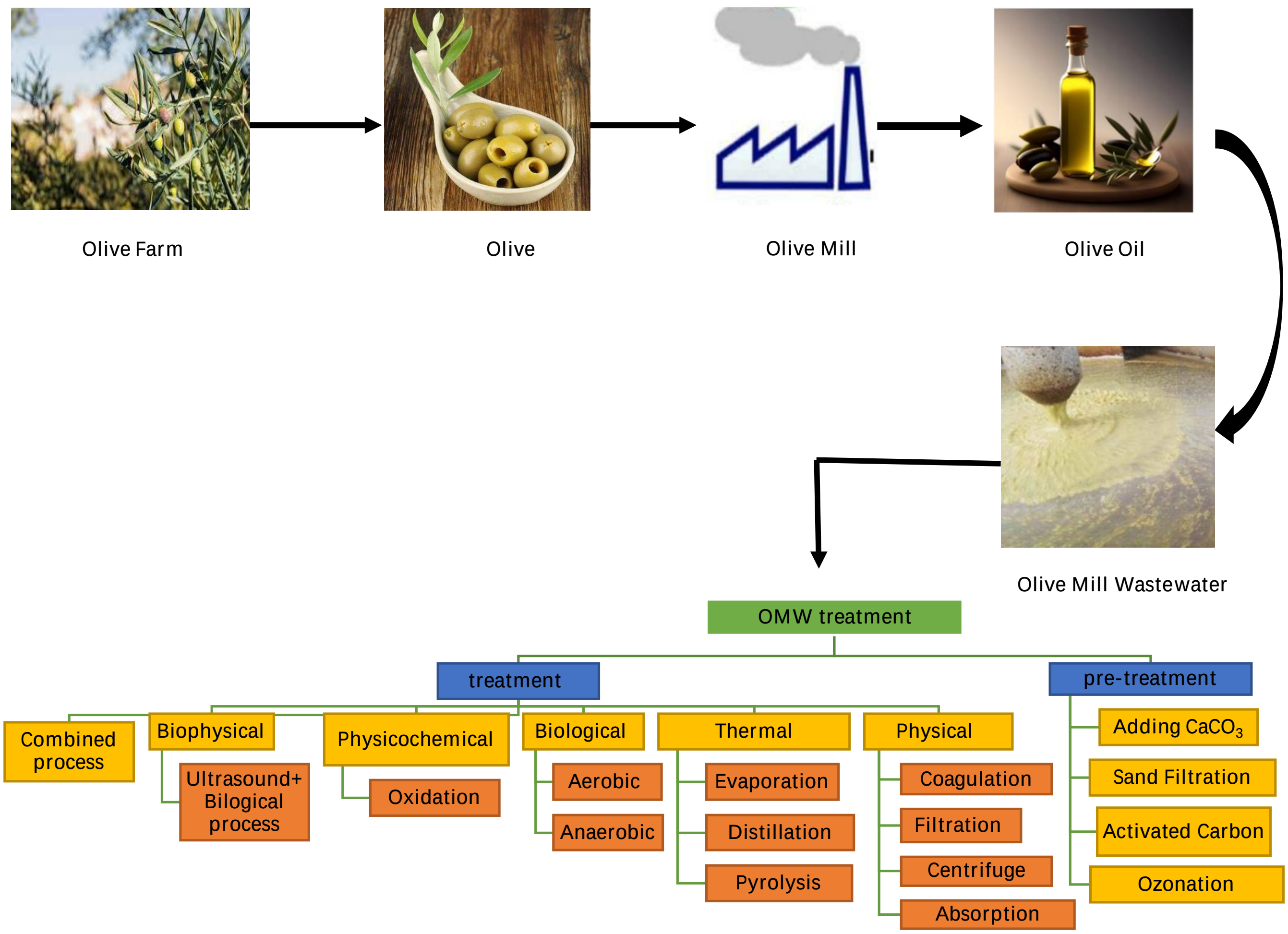

Figure 2. Olive oil manufacturing and purification

3.4.1 Pre-treatment Methods

The presence of organic compounds such as alcohols, polyphenols, organic acids, and lipids in OMW renders it toxic to plants, adversely affecting soil quality. If not properly managed, OMW can harm vegetation and pose significant environmental concerns. However, OMW is also rich in organic matter and minerals, particularly potassium, which can enhance the physicochemical and biological properties of soil, leading to improved crop productivity and soil fertility.

3.4.1.1 Addition of $CaCO_3$

Organic content in OMW can be degraded through pre-treatment processes involving the addition of lime or lime bentonite. Subsequent processes such as sedimentation, centrifugation, and filtration can significantly reduce fat and polyphenol content by up to 99.5% and 43%, respectively. The formation of insoluble salts and calcium carbonate salts contributes to a substantial reduction in the impact of fats, improving the biodegradability of the wastewater (Shabir et al., 2023).

3.4.1.2 Oxidation with Ozonation

As a potent oxidizing agent, ozone can react with double bonds. According to equation (1), ozonation can reduce phenolic color by up to 90% through the generation of hydroxyl radicals in OMW evaporation ponds, depending on the contact time. While larger organic molecules can be broken down into smaller organic compounds, resulting in a slight reduction of around 18-20%, the phenolic content of wastewater decreases significantly after ozonation (Radmehr et al., 2022). Under specific conditions, the ozonation process generates OH from O_3 to initiate non-selective oxidation (indirect mechanisms). Various mechanisms explain the complex generation of OH due to the oxidizing power of ozone, with the primary process depicted in equation (1). A secondary mechanism involves the presence of other oxidants or radiation, significantly increasing OH production. For instance, in the Peroxone process (O_2/H_2O_2), OH is produced from the decomposition of Hydroperoxide, which is generated from H_2O_2 decomposition, as shown in equations (2 and 3). In the third method, ozone/UV irradiation, additional H_2O_2 is produced as an oxidant through ozone photolysis, as shown in equations (4 and 5) (Deng & Zhao, 2015).

Equ (1): $O_3 + 3H_2O_2 \rightarrow 2OH + O_2 + 2H_2O$
Equ (2): $H_2O_2 \rightarrow HO_2^- + H^+$
Equ (3): $HO_2^- + O_3 \rightarrow OH + O_2^- + O_2$
Equ (4): $O_3 + H_2O + hv \rightarrow H_2O_2 + O_2$
Equ (5): $H_2O_2 + hv \rightarrow 2OH$

Consequently, OH radicals can be generated via at least three pathways**:** (1) direct ozonation (Equation 1), (2) the combination of ozone and hydrogen peroxide (Equations 2 and 3), and (3) the combination of ozone and UV radiation (Equations 4 and 5) (Deng & Zhao, 2015). Ozonation conducted before anaerobic treatment has been identified as an effective pre-treatment step (Khattabi Rifi et al., 2021).

3.4.1.3 Filtration

Filtration of OMW using sand filters can reduce COD by up to 40%. When combined with powdered activated carbon (PAC), this reduction can be as high as 67% (Shabir et al., 2023). One treatment method for OMW involves a pilot treatment system consisting of two columns, each 10 cm deep with sand at the top and bottom, and 60 cm deep with gravel. One column is fed with raw OMW, while the other is fed with OMW diluted to 50% with municipal wastewater. The water, at a rate of 2 cm per day (1.5 liters per day), is collected by a drain at the process outlet after passing through the filter. Diluting the OMW with municipal wastewater ensures a significant reduction in the organic load and enrichment with microorganisms, facilitating the mineralization of organic matter, but it must comply with environmental discharge regulations. For diluted OMW, the reduction rates of raw COD (75%), soluble COD (91%), and polyphenols (90%) are higher compared to raw OMW, which showed reductions of raw COD (36%), soluble COD (33%), and polyphenols (53%) (Benaddi et al., 2023). The use of additional treatment methods, such as physical, thermal, biological, combined, or physicochemical methods, which will be discussed later, is essential after pre-treatment processes. This is because pre-treatment alone is insufficient to remove or reduce pollutants in OMW, including COD, BOD, total suspended solids (TSS), color, phenols, and other contaminants.

3.5 Treatment Methods for OMW

Various methods exist to mitigate the environmental impact of OMW, encompassing physical, thermal, biological, physicochemical, biophysical, and combined approaches. While each of these processes can contribute to reducing pollution, none can eliminate contaminants on their own. Therefore, pre-treatment processes are essential before applying these methods (Shabir et al., 2023).

3.5.1 Physical Treatment

Physical treatment is one of the primary treatment methods employed in wastewater processing. It involves processes such as filtration, adsorption, and coagulation. Due to the need for storage, this method requires a significant amount of space. Additionally, if the basins are not adequately waterproofed, there is a risk of soil and groundwater contamination (Shabir et al., 2023).

3.5.1.1 Adsorption

A continuous layer of zeolite can serve as an effective medium for treating OMW. Experiments using columns with various feed flow rates and zeolite particle sizes have demonstrated significant reductions in phenolic compounds and COD, particularly when using smaller zeolite particles (Al Bawab et al., 2018). Various sedimentation, filtration, and flotation tests have been conducted on OMW using blue bentonite (AB), red volcanic tuff (RVT), lime (CaO), aluminum sulfate (alum), ferric chloride, and sodium carbonate. Results for COD removal and turbidity reduction showed that alum, lime, and AB were highly effective in reducing turbidity and COD, while RVT, ferric chloride, and sodium carbonate had a less significant impact. Turbidity removal with alum, lime, and AB was 95%, 99%, and 96%, respectively, while COD removal was 65%, 69%, and 37.5%, respectively. However, due to the high cost of alum, its use is not recommended, whereas lime and AB are both inexpensive and readily available (Al Bawab et al., 2018).

Adsorption of phenols and organic compounds from OMW is achieved through various pre-treatment processes such as sedimentation and filtration. These processes, coupled with batch adsorption using activated carbon as an adsorbent, have resulted in a maximum reduction of the organic load of approximately 71% and phenol removal of about 81% (Al-Malah et al., 2000).

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3.5.1.2 Activated carbon

Activated carbon, a black powder primarily composed of microporous carbon-based materials, can serve as both a pretreatment and post-treatment step. Recognized as an effective adsorbent, it can be produced from various carbon-rich materials such as wood, coal, coconut shells, and petroleum residues. The production of activated carbon involves carbonization processes followed by carefully controlled activation stages. Due to its high porosity, suitable pore size distribution, and robust mechanical properties, activated carbon finds extensive applications (Benaddi et al., 2023). The dynamic response of phenol concentration, pH, and COD at different activated carbon dosages (3-24 g/L) indicates an optimum point where maximum adsorption capacity is achieved. The use of activated carbon as an adsorbent resulted in a maximum adsorption capacity for the tested activated carbon dosages of less than 4 h for phenols up to about 94% and for total organic matter to about 83% (Azzam et al., 2004). Finally, the adsorption isotherm obtained for the activated carbon is of type II (Hasani et al., 2024). For instance, a purification protocol employing a three-stage countercurrent adsorption process using activated carbon at a dosage of approximately 24 g/L for OMW was able to reduce COD from 160,000 mg/L to 22,300 mg/L, while phenols decreased from 1450 mg/L to 15 mg/L, and pretreatments also showed effective reductions in COD, phenols, and total solids (Azzam et al., 2004).

3.5.1.3 Coagulation

Coagulation employs agents such as aluminum or iron salts to destabilize colloidal particles in wastewater. Additionally, Conventional chemical coagulation is considered an old method for dye and COD removal in textile effluent (Assadi et al., 2016). Subsequently, flocculation is used to create flocs that can be removed through sedimentation and filtration. The application of lime and aluminum sulfate for the treatment of OMW resulted in reductions of parameters such as COD, polyphenols, suspended solids, and color. Among these, the sole use of lime led to significant reductions. However, challenges such as the generation of large sludge volumes and high costs for coagulant recovery exist (Hasani et al., 2024).

3.5.1.4 Heat Treatment

Distillation, evaporation, and pyrolysis are the most common methods for water removal. Although they have significant operational costs, evaporation can concentrate OMW by 70-75%. Pyrolysis offers the advantages of reducing waste volume and the possibility of energy recovery, but it also requires expensive factors and may release harmful compounds into the atmosphere (Caputo et al., 2003).

3.5.1.4.1 Evaporation

Olive mill wastewater is placed in evaporation ponds with a depth of 0.7 to 1.5 meters and is insulated with a 1.5 mm thick geomembrane layer. The depth of the ponds is chosen to ensure complete evaporation before the next olive growing season. After drying, olive mill wastewater is either burned or used as organic fertilizer or as an additive in compost due to its high potassium and phosphorus content. Self-purification during evaporation is also carried out by microorganisms present in olive mill wastewater. Over time, the chemical composition of olive mill wastewater changes due to aerobic or anaerobic fermentations in the evaporation ponds, with bacteria and yeasts present in OMW being the responsible agents for this degradation (Jarboui et al., 2008).

3.5.1.4.2 Distillation

In the distillation method, wastewater discharged from olive oil mills can be concentrated using a distillation apparatus. This process reduces the wastewater volume by up to 70%, and the residue can be used as fuel to heat the distillation apparatus or as fertilizer in agriculture. The distilled water can be used in the milling process, and the distilled content, after being mixed with lime, can also be used for irrigation. The major drawback of this method is its high energy cost (Benaddi et al., 2023).

3.5.1.4.3 Pyrolysis

Thermal decomposition offers an effective way to utilize biomass, which is particularly relevant in agricultural areas where biomass by-products are abundant. Pyrolysis is a chemical process that employs heat to convert biomass into liquid (bio-oil), charcoal, and non-condensable gases such as acetic acid, acetone, and methanol. Pyrolysis produces a solid product (charcoal) with a porous structure and suitable surface area for use as activated carbon. The liquids obtained from pyrolysis contain a variety of chemical compounds that can be used to produce chemicals, adhesives, and other products (Shabir et al., 2023).

3.5.2 Biological Treatment

Biological wastewater treatment processes are widely used worldwide. They are biologically safe, reliable, and in most cases, cost-effective. Organic residues and mineral nutrients can be removed through biological treatment. Since phenolic compounds inhibit microorganisms, care must be taken in selecting the microorganisms used and their suitability for treating olive mill wastewater. Biological processes are reliable, environmentally friendly, and cost-effective for treating OMW (Souilem et al., 2017).

3.5.2.1 Aerobic Processes

Naturally occurring microorganisms play a crucial role in wastewater treatment. Bacteria, fungi, protozoa, and other microbes are examples of these microorganisms. Ultimately, they feed on a wide range of complex chemicals present in wastewater. Bioreactors are used in aerobic treatment processes to provide optimal growth conditions for microorganisms by adding dissolved oxygen, organic matter, and nitrogen. During this process, microbes act as decomposers, oxidizing complex organic molecules and returning them to simple carbon forms that can be released back into the environment (Shabir et al., 2023).

Aerobic biological treatment involving microbes such *as Geotrichum candidum, Candida tropicallis, Pleurotus ostreatus, Bacillus pumilus, Aspergillus niger, A. terreus, Azotobacter vivelandii*, and others has long been used for OMW treatment, resulting in a 32% increase in germination index compared to untreated OMW. These microorganisms significantly reduce the concentration of phenolic compounds and enzyme secretion (Esteves et al., 2021). Table 5 shows the effectiveness of each type of microorganism in the aerobic treatment process and its impact on reducing COD, color, and phenol.

Table 5. Aerobic microorganisms' impact on OMW degradation

Microorganism	Results	Reference
Geotrichum candidum	65% COD and 75% color removal	(Assas et al., 2002)
Pleurotus ostreatus	Up to 78% phenol removal	(Fountoulakis et al., 2002)
Aspergillus niger	35–65% COD reduction	(Cereti et al., 2004)
Candida tropicallis	62.8% COD and 51.7% phenols removal	(Fadil et al., 2003)
Azotobacter vivelandii	90–96% COD reduction	(Piperidou et al., 2000)

3.5.2.2 Anaerobic

During anaerobic processes, biomass waste is converted into biogas (by bacteria in the absence of oxygen) and compost (Arvanitoyannis et al., 2007). The produced biogas (mainly methane) has high economic value as it can be used for heat and electricity generation (Rajeshwari et al., 2000). Anaerobic processes carried out by bacteria involve three main stages: In the first stage, anaerobic bacteria hydrolyze complex organic compounds such as polysaccharides and polyphenols into monomers (Tsagaraki et al., 2007). In the second stage, *acetogenic* bacteria convert these monomers into organic acids (acetic, lactic, formic) and alcohol. Finally, methanogenic bacteria convert these acids into biogas (60-80% methane). These processes are influenced by temperature, pH, time, chemical composition, and toxic substances. These processes are typically operated under mesophilic (30-40°C) or thermophilic (50-60°C) conditions, with hydraulic retention times (HRT) ranging from 10 to 35 days, depending on the reactor type and organic load. To enhance performance, various technologies such as Up-flow Anaerobic Sludge Blanket (UASB) reactors, contact reactors, and anaerobic filters have demonstrated COD removal efficiencies of up to 80%. However, challenges remain, particularly in maintaining pH stability (optimal range: 6.8-7.2) and ensuring a balanced carbon-to-nitrogen (C/N) ratio, as excess nitrogen, for instance, from urea, can inhibit *methanogenesis*. Furthermore, recalcitrant compounds such as polyphenols and condensed tannins are only partially degraded under anaerobic conditions. The slow growth rate and sensitivity of methanogenic archaea further limit the robustness and scalability of these processes for high-strength OMW. Pretreatment or post-treatment methods, such as dilution, filtration, centrifugation, and chemical treatments, are essential to increase the efficiency of this method. Mixing OMW with other organic wastewater can reduce costs and improve nutrient balance. Combined treatments have shown that up to 80% of COD can be removed, but the problem of decolorization of wastewater remains (Tsagaraki et al., 2007).

The UASB reactor is considered the most popular bioreactor for treating agricultural and industrial wastewater with high organic loads (Esteves et al., 2021). Since COD is a major pollutant in OMW, it was reduced under specified parameters. After eight months, UASB showed 46-84% COD removal, and the organic load decreased from 27,000 mg/L to less than 5,000 mg/L, allowing direct discharge of urban OMW wastewater (Benaddi et al., 2023).

3.5.3 Physicochemical Treatment

3.5.3.1 Oxidation Processes

A promising approach for treating olive oil mill wastewater (OMW) involves advanced oxidation processes (AOPs). AOPs operate by generating hydroxyl radicals (OH), which are highly reactive species with a strong oxidation potential. These radicals can interact with a broad spectrum of organic and inorganic compounds. Owing to their instability, OH radicals must be continuously produced in situ through chemical reactions involving ozone, hydrogen peroxide, UV radiation, titanium dioxide, or combinations thereof.

As detailed in the pretreatment section, ozone can be employed to generate free radicals. This method has demonstrated a significant reduction in TSS by 82.5%, COD by 47.5%, and phenolic compounds by 94.3%. However, since ozonation is an oxidative process, methane generation does not occur during this step.

Another AOP involves the use of ultraviolet radiation (UV). In this process, hydroxyl radicals can be formed in the presence of photons and catalysts, or oxidants. Titanium dioxide is the most commonly used catalyst, with the corresponding reaction depicted in Equation (6). Additional OH radicals can be produced under UV irradiation in the presence of oxidants such as H_2O_2 or O_3. For instance, a single H_2O_2 molecule can be dissociated by UV radiation to yield two OH radicals, as illustrated in Equation (7).

Equ (6): $TiO_2 + hv \rightarrow e^-_{cb} + hv^+_{vb}$
Equ (7): $H_2O_2 + hv \rightarrow 2OH$

Additionally, at wavelengths shorter than 242 nanometers, OH radicals can also be produced through the photolysis of water, as shown in Equation (8).

Equ (8): $H_2O + hv \rightarrow OH + H$

Among the metals that activate H_2O_2 to produce hydroxyl radicals, iron is the most common, leading to a 62% reduction

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in phenolic compounds. In the Fenton process, H_2O_2 reacts with Fe^{2+} to produce reactive species such as hydroxyl radicals. The key reactions involved are:

Equ (9): $Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^{\cdot} + OH^{-}$

Equ (10): $Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + HO_2^{\cdot} + H^{+}$

While OH radicals are produced (Equation 9), they can be consumed by other reactions (Equation 10). The optimal ratio of hydrogen peroxide and iron (II) minimizes the undesired consumption of OH. Fe^{3+} forms ferric hydroxide sludge, which must be removed and properly managed, contributing to operational costs. The Fenton process works best under acidic conditions, limiting its application in wastewater treatment. Modified Fenton processes, such as photo-Fenton (enhancing Fe^{3+} reduction with UV) and electro-Fenton (electrochemical generation of reactants), have been developed (Deng & Zhao, 2015).

The pH, organic matter concentration, and hydrogen peroxide dosage significantly affect the treatment efficiency of OMW. Iron and hydrogen peroxide generate hydroxyl radicals most effectively at neutral pH, reducing phenolic compounds by 50% within 3 hours of reaction. Additionally, an acidic environment and a peroxide concentration of 9.5 molar are suitable for enhanced treatment efficiency. Phenolic compounds are reduced by 62% and COD by 84% using this method (Benaddi et al., 2023).

3.5.3.2 Biophysical Treatment

A combined method of ultrasonic irradiation and aerobic biological degradation for reducing toxic phenolic compounds is considered one of the biophysical treatments. This method has a significant impact on the toxic components of wastewater. Various factors influence the degradation of phenols, COD, and BOD, including the duration of ultrasonic treatment, the intensity of ultrasonic waves, and the frequency of ultrasonic waves. Results show that exposure to ultrasonic waves for 90 minutes leads to an 81% reduction in phenols. In the aerobic degradation stage, the maximum COD removal is approximately 80% (Shabir et al., 2023).

3.5.3.3 Advanced Oxidation Coagulation

Due to the high pollution load of OMW and the impacts of its direct discharge into the environment, various treatment methods exist. One such method is coagulation and flocculation, where treated wastewater is used as a growth substrate for *Xanthomonas* microorganisms and the production of xanthan biopolymer. Various coagulants like iron, lime, and aluminum can be used, but lime is more efficient due to its low cost. The combined use of coagulants at different doses and lime significantly increases the efficiency of pollutant removal. The principle of coagulation is based on destabilizing suspended colloidal particles in wastewater by adding a coagulant, thereby facilitating their aggregation. The primary coagulants used are based on aluminum and iron salts. This process is always followed by flocculation, which enhances contact between destabilized particles that come together to form a floc that can be easily removed by sedimentation and filtration. Coagulation-flocculation with lime and aluminum sulfate reduces the organic load of COD and polyphenols. The best results were obtained with lime treatment, combining 15 g/L aluminum sulfate and 120 g/L lime. Lime treatment alone resulted in a 75%, 50%, 43%, and 50% reduction in polyphenols, suspended solids, COD, and color, respectively, with the production of 135 g/L sludge (Hasani et al., 2024).

3.5.4 Combined Treatments

The combined use of two treatment processes is one of the methods for removing organic pollutants from OMW. These processes involve a coagulation stage, in which Al^{3+} and Fe^{3+} ions are used as coagulants, followed by an advanced oxidation process (AOP). Advanced oxidation processes, including UV, O_3, O_3/UV, and H_2O_2/UV, are used depending on the treatment process time. For AOPs, the COD removal achieved using Al^{3+} is 54%, while for Fe^{3+} ions at pH 9, it reaches 58% (Al-Qodah et al., 2014). However, when advanced oxidation processes are used alone, the COD removal percentage is between 10 and 39%. The COD removal percentage for oxidation processes is 90% for O_3, 95% for O_3/UV, and 94% for H_2O_2/UV (Akdemir & Ozer, 2009).

A combined treatment involving sedimentation, filtration, centrifugation, and activated carbon adsorption resulted in up to 94% phenol and 83% organic matter removal. Biological treatments for OMW include oxidation, evaporation, and composting, typically initiated with adsorption onto solid beds to return nutrients to agriculture and prevent soil problems. Composting, the microbial degradation of organic waste under aerobic or anaerobic conditions, is a common method for converting OMW into fertilizer, improving soil quality, and reducing its negative impacts. Composting with the addition of bulking agents produces mature compost in about 2 months. Benefits of compost include increased water-holding capacity, microbial activity, and nutrient content. Biochars, produced from the pyrolysis of biomass, act as effective sorbents (when produced under optimized conditions) or fertilizers, enhancing soil nutrients and microbial activity (Shabir et al., 2023). OMW can be effectively treated using a combination of electrocoagulation and ozonation. Electrocoagulation can remove 82.5% of TSS and 47.5% of COD within 70 minutes at a current density of 45 mA/cm², using iron-aluminum electrodes. Subsequently, ozonation further improves the removal of organic compounds (Salameh, 2015).

4. Conclusion

Treating OMW presents several major challenges. This wastewater is characterized by high levels of pollution, containing large amounts of COD, BOD, phenolic compounds, fats, suspended solids, and high electrical conductivity (EC). The latter indicates increased salinity levels that hinder both biological treatment and reuse in agriculture. Phenolic substances, in particular, are toxic and resistant to biodegradation, making conventional biological processes less effective. Furthermore, the composition of OMW can vary significantly depending on factors such as the type of olives used, processing techniques, and seasonal changes, which complicates the design and consistency of treatment systems. Many treatment methods also require extensive land area, which may not be available, and advanced solutions like membrane technologies or advanced oxidation processes are often too expensive for small-scale or traditional producers. In addition, if OMW is not properly treated, it can severely damage soil and water ecosystems, and in many regions, weak regulatory oversight contributes to inadequate wastewater management. Numerous treatment options for OMW exist, encompassing biological, physical, thermal, physicochemical, biophysical, and advanced processes, either individually or in combination. These methods vary in complexity, ease of implementation, and cost. The highest removal percentages achieved through different methods in scientific studies are as follows: Anaerobic: 80% COD removal, Aerobic: 63% phenol removal, Adsorption: 98% for both COD and phenol removal, Ozonation and electrocoagulation: 47.5% COD removal, Combination of ultrasound and aerobic: 80% for both COD and phenol removal.

OMW poses a significant environmental concern and is often considered waste. However, with appropriate treatment, it can be transformed into a recoverable resource. This paper provides a detailed overview of existing OMW treatment processes, laying the groundwork for exploring the potential of combining different methods. Due to the complex nature of OMW treatment, the development of new methods and technologies, primarily at the laboratory scale, has become a challenge for researchers. Currently, no universal strategy exists. The most promising approach is to consider OMW treatment and valorization as a regional problem and define decentralized treatments that can be implemented for a group of olive oil mills in a specific geographical area. This would result in economies of scale and facilitate the adoption of costlier technologies that individual mills cannot afford, ensure compliance with environmental regulations, and enhance resource recovery from OMW. The risks associated with environmental pollution could be mitigated through commercial insurance by utilizing international law within domestic, regional, or global insurance frameworks that adhere to the principles governing such policies (Seyrafian et al., 2025). Furthermore, the European Commission is advocating for a transition towards a circular economy, which aims to extend the product lifecycle through increased recycling and reuse, thereby benefiting both the environment and the economy. A gradual approach seems to be emerging as a new research trend, which initially focuses on recovering all valuable compounds from OMW, followed by the treatment of the semi-depleted effluent.

Authors' Contributions

Mohammad Reza Shojaei: Methodology; Formal analysis; Investigation; Resources; Writing (Original Draft). **Armin Fashi, Mehdi Shojaei:** Resources; Writing (Review and Editing). **Abbasali Zamani:** Methodology; Conceptualization; Supervision; Resources; Writing (Review and Editing).

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Conflicts of 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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Ethical considerations

This article does not contain any studies with human participants or animals performed by any authors.

Using Artificial Intelligence

All authors have stated that their research didn't use any artificial intelligence (AI) techniques.

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