

Advanced oxidation technologies for the treatment and detoxification of olive mill wastewater: a general review

Reda Elkacmi and Mounir Bennajah

ABSTRACT

Olive oil production has an economic importance for Mediterranean countries, ensuring employment opportunities and export earnings. The crushing units produce two types of residues, one solid (pomace) and the other liquid, called olive mill wastewater (OMW). This by-product has adverse effects on the olive oil sector and particularly on the quality of waters into which they are discharged. Hence, there is a critical need to orient the scientific research toward the treatment of this hazardous waste. Several techniques have been proposed and developed for OMW management. However, the advanced oxidation processes (AOP) remain the most advantageous with high treatment efficiencies. This trend allowed achieving a significant detoxification of OMW. A considerable amount of effort has been expanded to provide detailed and critical reviews on the use of this alternative technology in the treatment of water and wastewaters. Regrettably most, if not all, of these review papers were not focused mainly on OMW application. This paper aims to highlight the ancient and recent progress of various types of oxidation techniques for OMW treatment. Moreover, principles, advantages, limitations, and efficiencies of each method are presented, to gain a more scientific understanding of the most feasible approach regarding the treatment of this harmful residue.

Key words | advanced oxidation processes, chemical, electrochemical, olive mill wastewater, photochemical, sonochemical

Reda Elkacmi (corresponding author)
Environmental and Agro-Industrial Process Team,
Department of Chemistry and Environment,
Faculty of Sciences and Technology,
University Sultan Moulay Slimane,
BP 523, Beni-Mellal,
Morocco
E-mail: redakcm@gmail.com

Mounir Bennajah
Department of Process Engineering,
National School of Mineral Industries of Rabat,
BP 753 Agdal, Rabat,
Morocco

INTRODUCTION

Currently, there is a lack of common international laws regulating the discharge of olive mill wastewater (OMW), resulting in an increasing environmental hazard. The hazard of OMW is mostly due to its high acidity (pH between 3 and 6), its high organic load (COD over 80–200 g/L), (BOD₅ over 12–60 g/L) and its high content of microbial growth-inhibiting compounds, such as phenolic compounds and tannins (Cebeci *et al.* 2016; Azzam 2018; Bampalioutas *et al.* 2019).

The estimated annual volume of OMW generated by the Mediterranean region is approximately 30 million m³

and this huge amount is creating a serious ecological and environmental issue resulting in severe consequences for the soil and water quality (Gudiña *et al.* 2016).

The extraction of olive oil is achieved through traditional methods of discontinuous pressing in the traditional mills or 'mâasra', as named locally in Morocco, and produced 0.5 m³ of OMW from 1,000 kg of processed olive, while the continuous method (two-phase and three-phase systems) releases about 1.5 m³ per 1,000 kg of olive (Elkacmi *et al.* 2016a). A disadvantage of this last method is that it uses more water to extract the oil compared with the other techniques and consequently generates larger quantities of OMW. Water is used in some of these stages to extract most of the olive oil. Once the olives are crushed mechanically, the resulting paste is mixed and kneaded to increase the yield of recovery and help small

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oil droplets to coalesce and agglomerate, thus facilitating the separation of the oil and water phases. Less water is required for the discontinuous process (about 40%) compared to the continuous system, which varies from 70 to 110% (Bouknana *et al.* 2014), therefore traditional techniques contribute to preserving water resources.

For the above-mentioned traditional press system, the extraction is carried out without significant addition of water, which affects the organic loading rate and suspended solids. Indeed, the OMW of traditional units are more loaded and more concentrated than those of modern units. Some authors have reported that the COD of OMW from the continuous olive oil extraction process varies over the range of approximately 20–200 g/L, compared to 100–390 g/L for the press processes (Sassi *et al.* 2006).

OMWs have a cloudy appearance, reddish-brown to black in color and this color is a function of the state of degradation of the phenolic compounds and the olives from which they derive, it has a smell reminiscent of olive oil, but when fermented it assumes a fetid smell.

As is widely known, the composition of this type of aqueous waste depends on several factors, such as climatic and soil conditions, harvesting and carriage systems, olive cultivars, degree of fruit maturation, storage time, irrigation management and processing technology (Kıpçak & Akgün 2018). Table 1 summarizes the overall composition of OMW given by several authors from the top 10 olive oil producing countries according to the International Olive Council (IOC) in 2016 (IOC 2016).

In Morocco, as in other olive oil producing countries, in most cases OMW is still discharged into water or land without any treatment, either directly or through the public sewer system. These effluents are responsible for serious problems of pollution, creating a major nuisance and disturbance to the receiving environment. Several studies have proven the negative effects of these wastes on soil properties and plants (Buchmann *et al.* 2015), on aquatic ecosystems (Leris *et al.* 2019) as well as in air medium (Casanovas *et al.* 2015). For all these reasons, much attention has been paid to the fight against pollution posed by this harmful waste. In the last decade, various management methods have been applied for the prevention of pollution caused by OMW, which can be categorized into physical, biological, chemical and electrochemical.

OMW evaporation ponds (lagooning) remains one of the most popular physical techniques, especially in developing countries like Morocco due to its ease and lower cost (González-González & Cuadros 2015), but due to the need for large surfaces, the release of bad odors, and the very low degradation, it was replaced by more efficient and costly evaporation panels to maximize the elimination of the liquid fraction of the effluent (De Ursinos & Padilla 1992).

Membrane filtration is another common investigated OMW treatment method and this novel process can remove 88% of the dark color, 95% of COD and 70% of phenolic compounds (El-Abbassi *et al.* 2011). However, it must always be preceded by a pre-treatment, with a

Table 1 | Main characteristics of raw OMW from the top 10 olive oil producing countries

Countries	Production (ton)	pH	EC mS/cm	COD g/L	BOD ₅ g/L	TSS g/L	Total phenols g/L	References
Spain	1,401,600	4.7	–	82	–	15	1.2	Garcia <i>et al.</i> (2000)
Italy	474,600	5.0	–	28.4	–	29	1.409	Cassano <i>et al.</i> (2013)
Greece	320,000	4,6	17	47	–	50.3	8.1	Chatzisymeon <i>et al.</i> (2009b)
Turkey	143,000	4.28–4.85	10.04–12.01	55.73–91.55	29.93–38.60	14.08–33.50	2.439–4.509	Değermenci <i>et al.</i> (2016)
Tunisia	140,000	4.8	8.8	58.5	17	41.7	9.1	Mekki <i>et al.</i> (2008)
Morocco	130,000	4.32	11.25	24.49	11.64	3.59	3.15	Elkacmi <i>et al.</i> (2017b)
Portugal	109,100	5.1–5.8	–	7.45–68.48	0.5–9.50	3.13–30.22	0.027–1.051	Amaral <i>et al.</i> (2008)
Algeria	83,500	4.7	–	74.5	–	–	16.5	Iboukhoulef <i>et al.</i> (2013)
Jordan	29,500	4.91	7.64	58.614	36.329	–	2.269	Ayoub <i>et al.</i> (2014)
Egypt	25,000	3.8–5.2	–	45.334–134.40	12–78	17,71–66,286	19.78–22.029	El-Gohary <i>et al.</i> (2009)

high-energy demand and permanent renewal of the membranes, hence the high cost of the process.

Biological treatment of OMW has been the subject of several studies, which have shown the possibility of treating OMW microbiologically. Aerobic and anaerobic biological degradation were effective in removing organic matter from OMW. The major disadvantage of aerobic biological degradation is the consumption of oxygen, while anaerobic biological degradation requires an aerobic pre-treatment to reduce the rate of aromatic compounds (González-González & Cuadros 2015; Bampalioutas *et al.* 2019).

Other investigators employed physicochemical methods, such as adsorption, to promote the biodegradability of organic compounds by using several adsorbents: activated carbon (Azzam *et al.* 2010), zeolite (Aly *et al.* 2018), sawdust (Jeguirim *et al.* 2012), bentonite (Al-Essa 2018), natural clays (Azzam *et al.* 2015) and different adsorbent matrices such as Azolla, granular active carbon, resin, and zeolite (Padovani *et al.* 2013; Ververi & Goula 2019). Due to the high organic load of OMW, these chemical processes generally require the addition of large amounts of reagents, which raises the problem of the production of putrescible sludge and the high cost of used products.

Another alternative for OMW treatment is the coagulation-flocculation process based on the addition of chemical substances (aluminium sulphate ($\text{Al}_2(\text{SO}_4)_3$) and ferric sulphate ($\text{Fe}_2(\text{SO}_4)_3$) causing coagulation, precipitation, or destruction of organic load (Esteves *et al.* 2019). This type of treatment remains the most global and the least expensive compared to the mass of materials eliminated, but the presence of residual aluminum and iron can cause significant problems for ecosystems and human health, such as Alzheimer's and other diseases (Xu *et al.* 2018a).

Other techniques were also investigated for the conversion of OMW to high value added products. For example, the possibility of utilizing these effluents as fertilizer or compost and examining the effect of these techniques on soil properties and plant growth (Paredes *et al.* 2002; Belaqziz *et al.* 2016; Galliou *et al.* 2018), use as animal feed, biogas production (Salgado *et al.* 2015; Maragkaki *et al.* 2018), polyphenols recovery (Cassano *et al.* 2016; Víctor-Ortega *et al.* 2016) and other natural products such as volatile fatty acids (VFAs) (Scoma *et al.* 2016), dietary fiber suspensions

(Galanakis *et al.* 2010), oleic, linoleic acid and glycerol (Elkacmi *et al.* 2016b, 2017a).

In recent years, research studies in the field of water and wastewater treatment have proved that electrochemical techniques can effectively remove or reduce a wide range of soluble or colloidal pollutants such as wastewater containing heavy metals, suspensions, oil and oil-in-water emulsion.

The first document reporting the use of electricity in water treatment was published in the UK nearly 40 years ago (Strokach 1975), this innovative method has been shown to be effective in water purification using anodic dissolution of iron metal. Similarly, Pan *et al.* (2016) and Hashim *et al.* (2017) confirmed that the electrocoagulation process was capable of reducing contaminants from drinking water. In addition, the use of various combinations of oxidants, radiation and catalyst has been studied for the degradation of organic pollutants from drinking water (Krystynik *et al.* 2015; Wang *et al.* 2016; Sillanpää *et al.* 2018).

Due to the lack of water resources in many countries, it is a truism nowadays to guide research towards novel and efficient technologies in order to reduce the organic loads from various types of industrial effluents. Advanced oxidation processes (AOP) have proved very successful in treating wastewaters including tannery wastewaters (Vilardi *et al.* 2018), textile wastewaters (Pourgholi *et al.* 2018), municipal wastewaters (Serna-Galvis *et al.* 2019), oil refinery wastewaters (Bustillo-Lecompte *et al.* 2018), pulp and paper wastewaters (Klidi *et al.* 2018), dairy wastewaters (Markou *et al.* 2017), pharmaceutical wastewaters (Yang *et al.* 2018), surfactant wastewater (Arslan *et al.* 2018) and mine wastewaters (Meng *et al.* 2019). It has also been used to remove heavy metals (Li *et al.* 2019), landfill leachate (Joshi & Gogate 2019), phenol (Niu *et al.* 2018) and many other components (Huang *et al.* 2018; Sable *et al.* 2018; Tawabini & Makkawi 2018; Rubio-Clemente *et al.* 2019).

The application of AOP to OMW has attracted considerable attention due to its high efficiency, ease of operation, short reaction time, low sludge production, safety and environmental compatibility. Numerous studies have been carried out for reducing the pollutant load including COD, polyphenols, suspended solids, turbidity and coloration by different advanced oxidation techniques.

Based on the Scopus database and from the first review study conducted by Rege *et al.* (1991), more than 3,500

review papers dealing with the applications of AOP for water and wastewater treatment have been published. Figure 1 presents a summary of review articles undertaken on water and wastewater treatment by AOP over the past 30 years.

With the notable exception of *Ochando-Pulido et al. (2017)*, conversely, until now, a review study summarizing all research results of these attractive techniques in OMW treatment has, to our knowledge, not been reported elsewhere. Their review article presented the application of these AOP processes for the removal of different toxic pollutants from OMW, including total organic carbon (TOC), COD, BOD₅, color, and phenolic compounds with emphasis on the parameters assessed, removal effectiveness, and the degradation mechanisms of pollutants. However, the authors only elaborated on a few physicochemical techniques while disregarding many of the key related articles that are available in open literature. The main missing item is the combination section, being the most efficient and widely studied technique in the last decades for OMW treatment. Moreover, many AOPs are either not mentioned or not classified in most articles. Classification in that sense would be performed based on the nature and the mode of production of hydroxyl radicals (chemical, photochemical, sonochemical and electrochemical).

For all these reasons, the objective of this paper is to overview and discuss the applications of AOP proposed to date for the detoxification of OMW, to give greater insight and details on the AOP technologies comprising chemical, photochemical, sonochemical, and electrochemical applications, as well as their combination with biological

techniques and other technologies. The influence of operating parameters that affect these processes and the comparison of results with those obtained from other investigations are discussed. Over 351 publications are presented with 314 cited and analysed that can serve as a basis to help inform researchers and professionals concerning the application of AOP for OMW purification and decontamination.

ADVANCED OXIDATION PROCESSES (AOP)

Principle of (AOP)

AOP was described in the USA in 1987 by *Glaze et al. (1987)* as ‘water treatment processes at ambient temperature and pressure’. These methods were based on the intermediacy of hydroxyl and other radicals and remain among the most efficient and environmentally friendly technologies that contribute to a high degree of recalcitrant organic compounds oxidation (*Yang et al. 2016*).

With the advent of AOP, it has been known that the common principle is the ‘in situ’ generation of highly potent and reactive oxidizing species called free radicals such as hydroxyl radical (OH[•]), superoxide ion (O₂⁻), ozonide anion (O₃⁻), hydrogen peroxide (H₂O₂), HO₂[•] and HO₂⁻ radicals, and their oxidation potentials (vs. SHE) are given in the following order: OH[•] (E⁰ = 2.80 V) > O₃ (E⁰ = 2.07 V) > H₂O₂ (E⁰ = 1.77 V) > HO₂[•] (E⁰ = 1.70 V) > O₂ (E⁰ = 1.23 V). Once the hydroxyl radicals are formed, the organic pollutants are oxidized producing biodegradable intermediates, and are then mineralized to water, carbon dioxide and inorganic salts.

Many advantages of AOP have been reported: (i) Significant reduction of inorganic and organic compounds (*Miklos et al. 2018*); (ii) complete mineralization of organic contaminants to carbon dioxide, water and mineral salts (*Leal et al. 2018*); (iii) generating non-toxic by-products without release of secondary pollutants (*Bustillo-Lecompte et al. 2018*); (iv) high reactivity and non-selectivity of hydroxyl radicals towards pollutants (*Yang et al. 2019*); (v) uses as treatment or pretreatment of wastewater (*Ramteke & Gogate 2015*).

It should be noted that the AOP can be classified according to the nature of the phases (homogeneous or heterogeneous) or depending on the mode of production

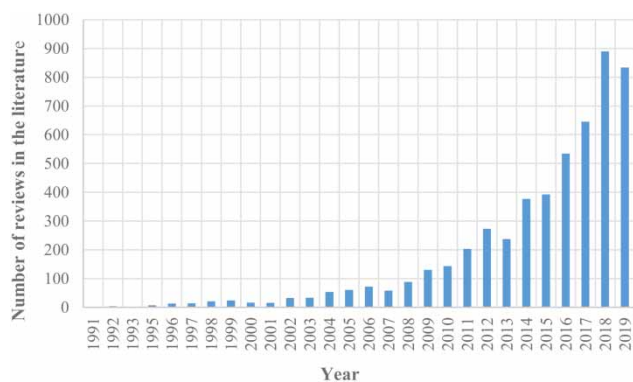


Figure 1 | Summary of review studies about the water and wastewater treatment by AOP in the period 1991–2019.

of hydroxyl radicals: Chemical, photochemical, sonochemical, and electrochemical. Moreover, they can also be coupled with other techniques, such as AOP, physicochemical or biological processes. Tables 2–6 provide a summary of all AOPs applied to several kinds of wastewater.

The efficiency of all these processes depends on several parameters such as pH, temperature, type of pollutant,

oxidant concentration, UV light intensity and parasite reactions consuming hydroxyl radicals.

OMW is one of the most polluting among all industrial wastes. The number of studies proving its risk to humans, natural resources and the environment is very important, therefore, the search for solutions of this problem has become a public concern and an absolute necessity.

Table 2 | Summary of main chemical advanced oxidation processes for water and wastewaters treatment

Advanced oxidation process	Description	Wastewater/organic matter	Reference	
Chemical	Fenton's reagent ($\text{Fe}^{2+}/\text{H}_2\text{O}_2$)	Tannery wastewater	Vilardi <i>et al.</i> (2018)	
		Mine wastewater	Meng <i>et al.</i> (2019)	
		Heavy metals	Li <i>et al.</i> (2019)	
		Textile wastewater	Babaei <i>et al.</i> (2017)	
		Paper wastewater	Xu <i>et al.</i> (2019)	
		Petroleum refinery effluent	Diya'uddeen <i>et al.</i> (2015)	
		Phenols	Gümüř & Akbal (2016)	
		P-hydroxyl benzoic acid	Rivas <i>et al.</i> (2001a)	
		Landfill leachate wastewater	Iskander <i>et al.</i> (2019)	
		Winery wastewater	Ferreira <i>et al.</i> (2018)	
	Fenton-like reaction ($\text{Fe}^{3+}/\text{H}_2\text{O}_2$)	Olive mill wastewater	Esteves <i>et al.</i> (2017)	
		Petroleum refinery effluent	Aziz & Daud (2012)	
		Textile wastewater	Khataee <i>et al.</i> (2016)	
		Formaline wastewater	Kajitvichyanukul <i>et al.</i> (2006)	
		Pesticides	Cheng <i>et al.</i> (2016)	
		Antibiotics	Mackulak <i>et al.</i> (2015)	
		Olive mill wastewater	Kallel <i>et al.</i> (2009a)	
	Fenton-like reaction (Fe^{3+} -zeolite Y)	2,4-xylydine	Rios-Enriquez <i>et al.</i> (2004)	
		Fenton-like reaction (Fe-NaY, Fe-USY, and Fe-ZSM-5)	Phenols	Ovejero <i>et al.</i> (2001)
			1,1-dimethylhydrazine	Makhotkina <i>et al.</i> (2006)
	Fenton-like reaction ($\text{Cu}^{2+}/\text{H}_2\text{O}_2$)	Olive mill wastewater	Iboukhoulef <i>et al.</i> (2016)	
		Ozonation (O_3)	Drinking water	Yu <i>et al.</i> (2016)
			Landfill leachate wastewater	Amr <i>et al.</i> (2016)
			Pharmaceutical wastewater	Ebrahim <i>et al.</i> (2018)
			Paper wastewater	Wu <i>et al.</i> (2018)
			Textile wastewater	Malik <i>et al.</i> (2017)
			Tannery wastewater	Schrank <i>et al.</i> (2017)
Olive mill wastewater			Benitez <i>et al.</i> (1999a)	
Drinking water			Čehovin <i>et al.</i> (2017)	
Pharmaceutical wastewater			Yang <i>et al.</i> (2018)	
Textile wastewater	Bilińska <i>et al.</i> (2017)			
Peroxonation ($\text{O}_3/\text{H}_2\text{O}_2$)	Landfill leachate wastewater	Chen <i>et al.</i> (2019)		
	Olive mill wastewater	Beltrán <i>et al.</i> (1999)		
	Textile wastewater	Minière <i>et al.</i> (2018)		
	Paper wastewater	Kumar & Sharma (2017)		
	Nitrogen-containing compounds	Oliviero <i>et al.</i> (2003)		
Wet air oxidation (WAO)	Olive mill wastewater	García García <i>et al.</i> (1990)		
	Phenols, carboxylic acids, and nitrogen-containing	Kumari & Saroha (2018)		
Catalytic wet air oxidation (CWAO)	Olive mill wastewater	Rivas <i>et al.</i> (2001e)		

Table 3 | Summary of main photochemical advanced oxidation processes for water and wastewaters treatment

Advanced oxidation processes	Description	Wastewater/organic matter	Reference
Photochemical	Photolysis of H ₂ O ₂ (H ₂ O ₂ /UV)	Drinking water	Miralles-Cuevas <i>et al.</i> (2017)
		Textile wastewater	Yen (2016)
		Pesticides	Cerreta <i>et al.</i> (2019)
		Pharmaceutical wastewater	Lutterbeck <i>et al.</i> (2015)
		Petroleum refinery effluent	Bustillo-Lecompte <i>et al.</i> (2018)
		Olive mill wastewater	Hodaifa <i>et al.</i> (2015)
	Photolysis of O ₃ (O ₃ /UV)	Drinking water	Mestankova <i>et al.</i> (2016)
		Textile wastewater	Bonfante de Carvalho <i>et al.</i> (2018)
		Pharmaceutical wastewater	Paucar <i>et al.</i> (2019)
		Winery wastewater	Lucas <i>et al.</i> (2010)
		Paper wastewater	Munir <i>et al.</i> (2019)
		Phenols	Suzuki <i>et al.</i> (2015)
		Petroleum refinery effluent	Souza <i>et al.</i> (2016)
		Olive mill wastewater	Benitez <i>et al.</i> (1997b)
	Photo-Fenton (H ₂ O ₂ /Fe ²⁺ (Fe ³⁺)/UV)	Textile wastewater	Leszczyński (2018)
		Phenols	Kavitha & Palanivelu (2016)
		Pesticides	Singh <i>et al.</i> (2019a)
		Antibiotics	Lima <i>et al.</i> (2017)
		Landfill leachate wastewater	Silva <i>et al.</i> (2016)
		Olive mill wastewater	García & Hodaifa (2017)
	Photo-Peroxanation (H ₂ O ₂ /O ₃ /UV)	Drinking water	Turnip & Hutagalung (2015)
		Textile wastewater	Pourgholi <i>et al.</i> (2018)
		Pharmaceutical wastewater	Lester <i>et al.</i> (2011)
		Phenols	Kusic <i>et al.</i> (2006)
		Olive mill wastewater	Beltrán <i>et al.</i> (1999)
	Homogeneous photocatalysis (Fe ³⁺ /UV)	Textile wastewater	Xu (2001)
		Pesticides	Catastini <i>et al.</i> (2002)
Phenols		Mazellier & Bolte (1997)	
Heterogeneous photocatalysis (TiO ₂ /UV)	Drinking water	Liu <i>et al.</i> (2010)	
	Textile wastewater	Rasheed <i>et al.</i> (2018)	
	Tannery wastewater	Zhao <i>et al.</i> (2017)	
	Landfill leachate wastewater	Hassan <i>et al.</i> (2016)	
	Paper wastewater	Priya <i>et al.</i> (2015)	
	Phenols	Singh <i>et al.</i> (2019b)	
	Petroleum refinery effluent	Palaniandy <i>et al.</i> (2016)	
	Olive mill wastewater	El Hajjouji <i>et al.</i> (2008)	

Table 4 | Summary of main sonochemical advanced oxidation processes for water and wastewaters treatment

Advanced oxidation processes	Description	Wastewater/organic matter	Reference
Sonochemical	Ultrasonic irradiation	Drinking water	Zhou <i>et al.</i> (2018)
		Textile wastewater	Jaafarzadeh <i>et al.</i> (2018)
		Pharmaceutical wastewater	Xiao <i>et al.</i> (2014)
		Phenols	Yehia <i>et al.</i> (2015)
		Petroleum refinery effluent	Almasi <i>et al.</i> (2016)
		Olive mill wastewater	Atanassova <i>et al.</i> (2005)

Coloring matter, COD, polyphenols and organic compounds are the major contaminant in the OMW and have to be removed before discharging the effluent into the aquatic ecosystem.

Considering the above points, AOP has consistently proved to be the most concrete solution to remove excessive pollutants from OMW. As presented in the tables, the generation of hydroxyl radicals achieved

Table 5 | Summary of main electrochemical advanced oxidation processes for water and wastewaters treatment

Advanced oxidation processes	Description	Wastewater/organic matter	Reference
Electrochemical	Anodic oxidation (AO)	Drinking water Textile wastewater Paper wastewater Landfill leachate wastewater Tannery wastewater Petroleum refinery effluent Pharmaceuticals wastewater Pesticides Phenols	Trellu <i>et al.</i> (2016) Bassyouni <i>et al.</i> (2017) Klidi <i>et al.</i> (2018) Ukundimana <i>et al.</i> (2018) Körbahti & Turan (2016) Mohanakrishna <i>et al.</i> (2018) Garcia-Segura <i>et al.</i> (2015) Millán <i>et al.</i> (2019) Pillai & Gupta (2016)
	Electro-Fenton (EF)	Olive mill wastewater Drinking water Textile wastewater Landfill leachate wastewater Tannery wastewater Petroleum refinery effluent Pharmaceuticals wastewater Pesticides Phenols Olive mill wastewater	Jum'h <i>et al.</i> (2017) Trellu <i>et al.</i> (2016) Gökkuş <i>et al.</i> (2018) Hassan <i>et al.</i> (2017) Cruz-Rizo <i>et al.</i> (2017) Davarnjad <i>et al.</i> (2015) Olvera-Vargas <i>et al.</i> (2015) Zhao <i>et al.</i> (2012) Gümüş & Akbal (2016) Bellakhal <i>et al.</i> (2006)

Table 6 | Summary of main combinations of advanced oxidation processes for water and wastewaters treatment

Advanced oxidation processes	Description	Wastewater/organic matter	References
Combined with other treatments	Coupling with (AOP)	Drinking water Textile wastewater Paper wastewater Landfill leachate wastewater Tannery wastewater Petroleum refinery effluent Pharmaceuticals wastewater Pesticides Phenols Olive mill wastewater	Trellu <i>et al.</i> (2016) Soares <i>et al.</i> (2017) Ginni <i>et al.</i> (2017) Li <i>et al.</i> (2016) Selvabharathi <i>et al.</i> (2016) Sivagami <i>et al.</i> (2019) Madhavan <i>et al.</i> (2010) Landeros <i>et al.</i> (2017) Chu <i>et al.</i> (2012) Canizares <i>et al.</i> (2007b)
	Coupling with biological treatments	Drinking water Textile wastewater Paper wastewater Landfill leachate wastewater Tannery wastewater Petroleum refinery effluent Pharmaceuticals wastewater Phenols Olive mill wastewater	Szczuka <i>et al.</i> (2019) Roshini <i>et al.</i> (2017) Abedinzadeh <i>et al.</i> (2018) Baiju <i>et al.</i> (2018) Srinivasan <i>et al.</i> (2012) Souza <i>et al.</i> (2011) Marcelino <i>et al.</i> (2017) Mendez <i>et al.</i> (2015) Amor <i>et al.</i> (2015)
Combined with other treatments	Coupling with physicochemical treatments	Drinking water Textile wastewater Paper wastewater Landfill leachate wastewater Tannery wastewater Petroleum refinery effluent Pharmaceuticals wastewater Pesticides Phenols Olive mill wastewater	Lu <i>et al.</i> (2016) Vasconcelos <i>et al.</i> (2016) Arslan-Alaton & Seremet (2004) Oumar <i>et al.</i> (2016) Naumczyk & Kucharska (2017) Saber <i>et al.</i> (2017) Ashraf <i>et al.</i> (2016) Pliego <i>et al.</i> (2014) Canizares <i>et al.</i> (2004b) Madani <i>et al.</i> (2015)

through different AOP allow maximum removal efficiency of the organic load.

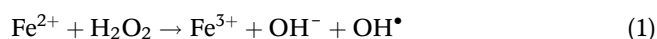
In this review paper, the five categories of AOP for treatment of OMW are summarized below.

Chemical advanced oxidation processes

Fenton and Fenton-like reagent ($\text{Fe}^{2+}/\text{Fe}^{3+}/\text{H}_2\text{O}_2$)

Fenton processes have been classified as a simple way of producing (OH^\bullet) radicals, not only for their simplicity and short reaction time, but also because of their flexibility allowing easy manipulation (run and control), as well as requiring less equipment and the inexpensive chemicals required (Nidheesh *et al.* 2013; Babuponnusami & Muthukumar 2014; Xu *et al.* 2018a, 2018b). There are a number of important factors that affect the treatment efficiency outstandingly including pH, temperature, reagents (Fe^{2+} and H_2O_2) concentrations, and the initial concentration of pollutants.

The oxidation reaction with H_2O_2 is not powerful enough to completely degrade organic contaminants. However, when mixed with a catalyst iron (II) (Fe^{2+}) to form the Fenton reagent, the oxidation potential of (H_2O_2) increases. A mixture of (Fe^{2+}) salts and (H_2O_2) is added directly to the wastewater, according to the following reaction:



The hydroxyl radicals (OH^\bullet) produced during the decomposition of hydrogen peroxide in the presence of ferrous iron are highly reactive and a non-specific oxidant, able to reduce a wide range of organic pollutants in water and wastewater. Four main stages of Fenton process have been identified: pH adjustment to a range of 2.5–3.5 to avoid precipitation and formation of iron hydroxides, thus inducing low catalytic activity, followed by oxidation reaction, neutralization/coagulation and precipitation in a solid–liquid separation tank (Gopu *et al.* 2018).

For OMW, as for many other industrial wastewaters, this chemical process showed highly significant efficiency. For example, Rivas *et al.* (2001d) studied the reduction of

the COD of a 500 mL OMW sample diluted with synthetic urban wastewater (initial COD concentration = 14.65 g/L), by using initial reagents concentrations varying between 0.2 and 1.0 M for H_2O_2 and 0.01–0.1 M for Fe^{2+} , acidic pH (2.5–3) and temperature (0–50 °C). This work reported that 80–90% of COD was removed after 8 h with 0.01 M of Fe^{2+} and 1 M of H_2O_2 at a temperature of 54 °C. Furthermore, a kinetic study of the process was carried out to describe the H_2O_2 decomposition and the reaction between Fe^{2+} and H_2O_2 .

Vlyssides *et al.* (2004) were able to ensure complete elimination of phenolic compounds, 60% of DCO and 40% of DBO₅ within 2 h, by the addition of 2–3 g/l of ($\text{FeSO}_4, 7\text{H}_2\text{O}$) and 3 mL of H_2O_2 ratio of 60%. Similar findings were reported by Nasr *et al.* (2004) who used 5 mol of H_2O_2 and 0.4 mol of Fe^{2+} in a 250 mL capacity reactor containing 100 mL of OMW sample to achieve removal of 86% of COD per liter of crude OMW.

Lucas & Peres (2009a) concluded that using (H_2O_2 : Fe^{2+}) with a 15 molar ratio, treatment of 500 mL of Portuguese OMW by Fenton's reagent removed 70% COD under 30 °C of temperature and initial pH of 3.5. A modified pseudo-first-order equation was developed to simulate the kinetics of the COD removal to describe the process for future industrialization.

Esteves *et al.* (2017) recently studied the treatment of synthetic OMW by Fenton's process in a batch and continuous stirred-tank reactor (CSTR). The effect of the different influential parameters mentioned above was determined and the OMW sample was prepared by mixing the six most abundant phenolic acids. The treatment achieved up to 63% total organic carbon (TOC) reduction and maximum degradation of total phenol (TPh) up to 99% in a batch reactor (250 mL of OMW). Under the same operating conditions ($\text{Fe}^{2+} = 100$ ppm, $\text{H}_2\text{O}_2 = 2.0$ g/L, $T = 30$ °C) and in a continuous stirred-tank reactor (2 and 26 mL/min⁻¹ flow rates), they obtained 47.5% of TOC and 96.9% of TPh removal efficiencies as well as 75% of COD and 70% of BOD₅ abatements have been registered in both reactors.

Despite all these positive results, the Fenton reaction has a number of disadvantages: the slow regeneration rate of Fe^{2+} , the need to operate in an acid medium, the use of high doses of reagents, the need for separation of the

dissolved iron and the high accumulation of iron sludge which requires additional treatment to treat this secondary pollution. The replacement of iron by other catalyst metals, the photo Fenton process and the combination with other techniques were suggested as an alternative to overcome these limitations (Oturán & Aaron 2014).

Kallel *et al.* (2009a) demonstrated that Fenton process zero-valent iron (Fe^0) and H_2O_2 permit high degradation efficiency of organic pollutants. The effect of H_2O_2 and Fe^0 concentration, pH and initial COD concentration were elucidated. The results obtained after the reaction time of 3 h showed complete decolorization of OMW samples and 50% of COD removal under optimal conditions (2.0–4.0 of pH, 9.5 M of H_2O_2 and 20 g/L of Fe^0). The same author confirmed that at acidic pH, COD removal increased with H_2O_2 initial concentration and reached the maximum value of COD removal of around 92% by using 1 M as the optimal dose of H_2O_2 . In addition, phenolic compounds were identified using gas chromatography coupled to mass spectrometry (GC–MS), it can be concluded that zero-valent $\text{Fe}/\text{H}_2\text{O}_2$ has the potential to completely degrade these organic compounds present in OMW (Kallel *et al.* 2009b).

Nieto *et al.* (2009, 2010, 2011) first proposed the oxidation of OMW using FeCl_3 as catalyst, with this homogeneous Fenton-like system ($\text{Fe}^{3+}/\text{H}_2\text{O}_2$), and they reported the possibility of treating these effluents from laboratory scale to industrial applications. Over 92.6% of COD and 99.8% of TPh were removed at pH 3.0, $\text{H}_2\text{O}_2 = 100$ g/L, $\text{FeCl}_3/\text{H}_2\text{O}_2$ ratio = 0.04, and temperature of 8–12 °C. The kinetic study was carried out using a two-step first order model. The kinetic parameters at room temperature and pH of 3 were determined. In the temperature range 5–40 °C, the results showed that maximum efficiency was achieved at 30 °C (Nieto *et al.* 2011). The optimization of the operating parameters using a continuous stirred tank reactor (CSTR) at pilot scale was investigated by Hodaifa *et al.* (2013). Experimental results showed that the optimum $\text{FeCl}_3/\text{H}_2\text{O}_2$ ratio was in the range of 0.026–0.058, $\text{Fe}^{3+} = 0.34$ –0.40 g/L to give a removal efficiency of 97% of COD and 99% of phenolic compounds with reaction times not longer than 3 h.

A $\text{Cu}^{2+}/\text{H}_2\text{O}_2$ Fenton-like process was reported to significantly enhance the removal of phenolic compounds from OMW (Iboukhoulef *et al.* 2016). Results indicated that the use of copper Cu (II) as a catalyst is capable of

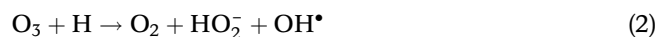
achieving an average purity level ranging from 43 to 62% degradation at 30 and 50 °C, respectively in 65 min of treatment.

Peroxonation ($\text{O}_3/\text{H}_2\text{O}_2$)

As an alternative approach, ozonation has been widely used in water and wastewater management, and ozone (O_3) is typically utilized as a powerful oxidizing agent ($E^0 = 2.07$ V) for removing organic and inorganic pollutants from aqueous solutions.

The detoxification of OMW by this application has been extensively investigated, especially in combination with other techniques. Oxidation by H_2O_2 and O_3 separately is not effective for high concentrations of pollutants, as stated by Benitez and his research group (Benitez *et al.* 1997a). From a diluted OMW sample (10–50%), over 6 and 22% COD, 40 and 70% aromatic compounds and 90% TPh removal were achieved, at a temperature of 20 °C and 10 mbar of ozone pressure. Benitez *et al.* (1999a) concluded that by using O_3 alone, 17–28% of COD, 100% of polyphenols and 76% of aromatic compounds were removed after 2 h at a temperature of 40 °C and pressure of 17.7 mbar. Canizares *et al.* (2009) were capable of removing 77.2% of COD and 67.8% of TOC. Chedeville *et al.* (2009) chose to use a suitable gas/liquid contactor allowing the application of ozonation for OMW treatment. At pH = 5, temperature of 20 °C, liquid flow rate of 0.9 L/h, gas flow rate of 0.3 Nm^3/h and ozone concentration of 23 g/ Nm^3 , the degradation of phenolic compounds was up to 80 and 48% of COD removal with 95% of ozone mass transfer.

The combination between O_3 and H_2O_2 , called peroxonation process, was reported as more efficient than ozonation alone because hydrogen peroxide is intended to accelerate the decomposition of ozone in water and thus produce more hydroxyl radicals according to the reaction below:



Previous results have shown the efficacy of the oxidation system by $\text{O}_3/\text{H}_2\text{O}_2$ for drinking water and wastewater treatment (Shokri *et al.* 2016; Bourgin *et al.* 2017;

Malvestiti *et al.* 2018; Wang *et al.* 2018). Unfortunately, few studies have been found in the literature regarding the detoxification of OMW by this combination. Beltrán *et al.* (1999) found that using 10^{-3} M of H_2O_2 combined with 3–4 g of ozone, allowed a total disappearance of aromatic content and coloration, 90% COD and 60% total carbon (TC) removal, and a remarkable increase in the biodegradability (BOD/COD) from 0.16 to 0.8. It has been found that this system suffers from the low solubility of O_3 in aqueous solutions on the one hand and high cost of reagent on the other.

Wet air oxidation and catalytic wet air oxidation

Numerous studies have been reported in the literature regarding the treatment of water and wastewater by using wet air oxidation (WAO) and catalytic wet air oxidation (CWAO). The aim of these processes is to oxidize organic and inorganic pollutants in aqueous media at high pressure up to 200 bar and temperature ranging from 125 to 320 °C (Liu *et al.* 2017b; Barge & Vaidya 2018). The principle of the techniques is based on promoting contact between oxygen and the aqueous solution to ensure the conversion of organic compounds to carbon dioxide, water and harmless products (Yousefifar *et al.* 2017). García García *et al.* (1990) presented the use of pure oxygen under 250 °C and 35 bars partial pressure for removing 99% of phenolic compounds. Rivas *et al.* (2001e) investigated the efficiency of supercritical wet air oxidation by using hydrogen peroxide as the oxygen source. They were able to reduce COD by 79% and phenol by 98% at 250 bar of total pressure and 500 °C of temperature from OMW samples diluted 50 times.

Catalytic Wet Air Oxidation (CWAO) can be considered as a more efficient alternative for OMW treatment. Many heterogeneous catalysts were used such as metal oxides, noble metals, etc. Rivas *et al.* (2001b) described the use of CuO/C and Pt/Al₂O₃ for the oxidation of OMW diluted 10 times with synthetic urban wastewater, 50 and 80% of COD and phenolic compounds have been removed, respectively, under relatively mild conditions of temperature and pressure (180 °C and 70 bar total pressure). Pham Minh *et al.* (2006, 2007a, 2007b, 2008) investigated the application of platinum and ruthenium catalysts supported on titanium (TiO₂) and zirconium (ZrO₂) oxides for the degradation of

two phenolic compounds (p-hydroxybenzoic and p-hydroxyphenylacetic acids) present in OMW at 140 °C and 50 bar total pressure. Their results suggested that approximately 97% of TOC and a total reduction of phenolic compounds were achieved in a stirred batch autoclave and in a fixed bed reactor. Gomes *et al.* (2007) published data on organic matter and color reduction using Pt/C and Ir/C as catalysts. The results revealed that the maximum COD and color removal efficiency was recorded at 200 °C and 6.9 bar of oxygen partial pressure after 8 h of reaction time.

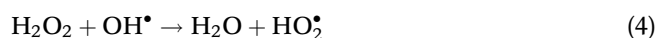
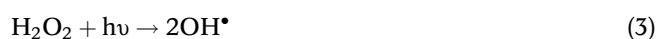
Wet hydrogen peroxide catalytic oxidation (WHPCO) is another form of advanced oxidation technology based on hydroxyl (OH[•]) and perhydroxyl (HO₂[•]) radicals generation using solid catalysts. Najjar *et al.* (2009) proposed the use of Fe-BEA zeolite as catalysts at moderate temperature (T = 28 °C) and atmospheric pressure. It was concluded that the WHPCO could be successfully used in the elimination of 59% of color, 40% of TPh, 30% of COD and 28% of TOC after 12 h of treatment. Giordano *et al.* (2007) studied the degradation of phenolic compounds using copper supported on zeolite and pillared clay, a removal efficiency of more than 90% was registered in 3 h at 80 °C.

It is important to indicate that WHPCO is still more advantageous than CWAO because the first technique operates under mild conditions, whereas the second one requires specific conditions and materials which make it more expensive and less widely employed.

Photochemical advanced oxidation processes

Photolysis of H₂O₂ (H₂O₂/UV)

The use of UV radiation has received considerable attention for the abatement of organic pollutants from water and wastewater. The combination of H₂O₂ and UV radiation allows increasing OH[•] formation, which will react with H₂O₂ by secondary reactions:



Given its ability to produce more radicals, OH[•] and HO₂[•] were the first to be more reactive as a highly highly active

oxidizing agent, and only a few studies in the literature have focused on the use of photolysis of H_2O_2 for the treatment of OMW. Uğurlu & Kula (2007) suggested using this photochemical advanced oxidation process. The first results of this study showed that 90% of color, 90% of phenol and 30% of lignin were removed after 7 days. The second part of the study also showed that the removal rate was increased to 99, 100 and 40% of color, phenol and lignin, respectively, after the treatment of OMW with lime.

As a single $\text{H}_2\text{O}_2/\text{UV}$ application does not appear to be efficient for OMW treatment, it is discussed to combine it with other techniques, which will be exemplified later in this paper.

Hodaifa *et al.* (2015) were capable of obtaining removal percentages of 40–48% for COD, 39.4–51.9% for TC, 33–48% for TOC, and 66.8–93.4% for turbidity under operation conditions: pH = 3, temperature of 293.15 °K and agitation rate of 150 rpm.

Photolysis of O_3 (O_3/UV)

The photolysis of O_3 (O_3/UV) involves the irradiation of ozone molecules by UV radiation, promoting the formation of OH^\bullet radicals according to the main reactions (5) and (6):



It is well known that many papers demonstrated that the O_3/UV system could be an effective tool for the treatment of wastewaters resulting from textile, pharmaceutical, winery, paper and petroleum industries (Benitez *et al.* 1997b; Lucas *et al.* 2010; Souza *et al.* 2016; Bonfante de Carvalho *et al.* 2018; García-Ballesteros *et al.* 2019; Paucar *et al.* 2019). In the case of OMW, it should be noted that the only study focused on its management by this combination is the research described by Benitez *et al.* (1997b). In this paper, the effect of the UV radiation alone on the degradation of COD, TPh and aromatic compounds of the OMW was reported. In addition, a comparative study with ozone plus UV radiation was established. They reported an increase on the removal efficiencies of the pollutants by the combined system (O_3/UV) instead of using UV alone,

the abatement rates of COD, TPh and aromatic compounds removals ranged between 5.2–10.3, 0–58.1 and 73.1–97.5%, respectively.

As explained before, the use of ozone alone or combined with hydrogen peroxide or UV radiation is often insufficient to meet wastewater treatment objectives due to the selectivity of molecular ozone, while their combination with other techniques becomes a major necessity.

Photo-Fenton ($\text{H}_2\text{O}_2/\text{Fe}^{2+}$ (Fe^{3+})/UV)

Aiming to produce a relative high concentration of Fenton catalyst, the use of a photo-Fenton system as a method for the treatment of various types of wastewater has been technically developed. The method is based on the Fenton reaction between H_2O_2 and Fe^{2+} or Fe^{3+} coupled with UV radiations.

In the case of OMW, under optimum conditions, Badawy *et al.* (2009) investigated the effectiveness of this photochemical oxidation in removing 84, 87, 97.44 and 98.31% of TOC, COD, TPh and total suspended solids (TSS), respectively. In another research paper, Justino *et al.* (2010) were able to achieve complete elimination of phenolic compounds from supplemented diluted OMW or buffer with phenols. They concluded that the photo-Fenton technique is more efficient than biological or enzymatic treatments. This finding is similar to the results of Gernjak *et al.* (2003), who reported a total degradation of six abundant phenolic compounds from agro-industrial wastewaters.

Gernjak *et al.* (2004) studied the treatment of OMW by solar photo-Fenton in a falling film photoreactor. Results showed that 85% of COD and total dephenolization were achieved for 19 L of pre-treated OMW by using $\text{Fe}^{2+} = 5 \text{ mM}$ and $\text{H}_2\text{O}_2 = 5 \text{ g/L}$.

In another recent study conducted by García & Hodaifa (2017), the treatment of local OMW by photo-Fenton using artificial UV light lamps was investigated in a batch reactor. Over 90% of COD, TC, TOC, TPh and turbidity were removed efficiently at a pH of 3, $\text{FeCl}_3 = 3.0 \text{ g/L}$, $\text{H}_2\text{O}_2 > 8 \text{ g/L}$ within 30 min of reaction time.

Photo-peroxanation ($\text{H}_2\text{O}_2/\text{O}_3/\text{UV}$)

Ozone combined with hydrogen peroxide and UV radiation was considered an effective method for the treatment of

hazardous organic compounds in drinking water and wastewaters. H_2O_2 and UV light are used to activate ozone in neutral aqueous solutions. In this combined system, O_3 absorbs UV radiation and produces hydrogen peroxide, which forms hydroxyl radicals by photolysis of H_2O_2 .

In another part of their article, Beltrán *et al.* (1999) found that the same elimination rates quoted in the paragraph above relate to the peroxonation ($\text{O}_3/\text{H}_2\text{O}_2$) by using ozone combined with hydrogen peroxide and/or 254 nm UV radiation.

Given that the phenolic compounds are responsible for the toxicity of OMW, Kusic *et al.* (2006) also used photo-peroxonation process for the degradation of these natural constituents. A complete phenol removal and a reduction in the TOC by 58% of the aqueous solution was achieved. Nevertheless, this technique has limitations, such as the low solubility of O_3 .

Homogeneous photocatalysis (Fe^{3+}/UV)

This AOP process involves the excitation of Fe^{3+} with UV radiation, without addition of other chemical components such as H_2O_2 . This homogeneous photocatalysis system consists of the photo-reduction reaction of iron (III) in aqueous solution to produce iron (II) and OH radicals.

On the other hand, as has also been stated in the paragraph above, the polyphenols are one of the most abundant elements in the OMW. Mazellier & Bolte (1997) studied the effectiveness of the Fe^{3+}/UV system in the treatment of phenolic compounds. They concluded that 80–85% of 2,6 dimethylphenol (DMP) was removed.

Heterogeneous photocatalysis

Proven by the large number of publications devoted to this technique since its discovery and development (Fujishima & Honda 1972; Frank & Bard 1977), the use of heterogeneous photocatalytic processes was found to be one of the most efficient ways of generating hydroxyl radicals. The addition of semiconductor materials stimulate the reduction of a wide variety of organic and inorganic compounds in drinking water and wastewater (Liu *et al.* 2010; Hassan *et al.* 2016; Palaniandy *et al.* 2016; Zhao *et al.* 2017; Rasheed *et al.* 2018; Singh *et al.* 2019a, 2019b).

Several photocatalysts, such as ZrO_2 , MoO_3 , Fe_2O_3 , ZnO , CeO_2 , Al_2O_3 , Bi_2O_3 , CdO , CdS , HgO , PbO , Sb_2O_3 and TiO_2 , have been tested (Karunakaran & Anilkumar 2007). Experiments showed impressive results of treatments using titanium dioxide (TiO_2). When the latter was subjected to ultraviolet spectrum, hydroxyl radicals were generated on the surface of the semiconductor and oxidize organic pollutants. TiO_2 proved to be effective in reducing the organic load of OMW relative to other photocatalytics due to its many potential advantages including: (i) high stability, good performance and low cost, (ii) operation under ambient conditions with the possibility of using solar irradiation, (iii) the absence of significant mass transfer limitations when fine particles are used as photocatalysts.

El Hajjouji *et al.* (2008) reported heterogeneous photocatalysis for treatment and detoxification of diluted OMW (1/100). After 24 h of experiment, removal efficiencies for COD, coloration and TPh were 22.2, 57 and 94.3%, respectively. In this study, the authors confirmed that the difference between the three abatement results were caused by the presence of three phases, which correspond to the presence of three categories of organic molecules and the presence of pectin compounds, differing in their sensitivity to oxidation by the UV/ TiO_2 system.

Chatzisyneon *et al.* (2009c) achieved complete decoloration (>90%) and 50% of mineralization. They also concluded that treatment efficiency was increased with decreasing initial COD and increasing contact time and catalyst concentration. Badawy *et al.* (2009) investigated the effect of catalyst type, pH, catalyst dose and irradiation time for the treatment of three-phase OMW. They were able to remove 68.8, 67.3, 40.19 and 48.9% of COD, TOC, TPh and TSS, respectively, after 60 min irradiation time.

Baransi *et al.* (2012) proposed the addition of powdered activated carbon (PAC) to TiO_2 for the photocatalytic degradation of caffeic acid and p-coumaric acid, which are considered among the most abundant phenolic compounds. The authors found out that the combined TiO_2 -PAC sorbent yielded a significant removal rate in comparison to removal by TiO_2 and PAC alone, 87% of the total polyphenols were degraded and only 57.9% of COD was reduced within 24 h of 365 nm UV irradiation.

Ruzmanova *et al.* (2013) examined the performance of prepared catalyst Magnetic Core Titanium Dioxide

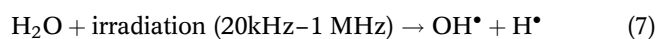
Nanoparticles ($\text{Fe}_3\text{O}_4/\text{SiO}_2/\text{TiO}_2$) for the treatment of OMW. After 2 h of experiment, 50% of the COD was removed by using 1.5 g/L of $\text{Fe}_3\text{O}_4/\text{SiO}_2/\text{TiO}_2$ nanoparticles.

A major drawback of using (TiO_2/UV) system for the treatment of OMW, making it difficult for use on an industrial scale, is the colloidal nature of the fine particles of the semiconductor. Therefore, the recovery of the catalyst becomes more difficult due to the slow sedimentation rate of the fine particles. Additionally, the UV irradiation efficiency and life of UV lamps were reduced by the formation of dark catalytic sludge (Oturán & Aaron 2014).

Sonochemical advanced oxidation processes

A new technology developed by several researchers has been shown to be an attractive alternative in destroying a wide range of organic contaminants. The sonochemical process is a boon to water and wastewater treatment because it has the capability of reducing the polluting load by ultrasonic radiation.

This technique is based on the use of ultrasonic irradiation to activate the chemical reactions, the hydroxyl radicals are produced in water by applying sound wave frequencies of 20 kHz and 1 MHz:



High-power ultrasound produces strong microbubble cavitation in aqueous solution which generates shock waves and reactive free radicals as very powerful oxidants that can degrade a wide range of organic compounds. Due to its simplicity and no production of toxic by-products, this technique has great applying perspectives in drinking water and wastewater treatment (Atanassova *et al.* 2005; Xiao *et al.* 2014; Yehia *et al.* 2015; Almasi *et al.* 2016; Zhou *et al.* 2018).

It is of great interest to highlight that a considerable amount of effort has been expended in the use of ultrasonic irradiation for OMW treatment as well as the reduction of phenolic compounds. It has been shown that the sonochemical degradation of OMW depends on several operating parameters. Figure 2 generalizes the parameters related to the technique, the parameters related to the reaction medium, and the parameters related to pollutants.

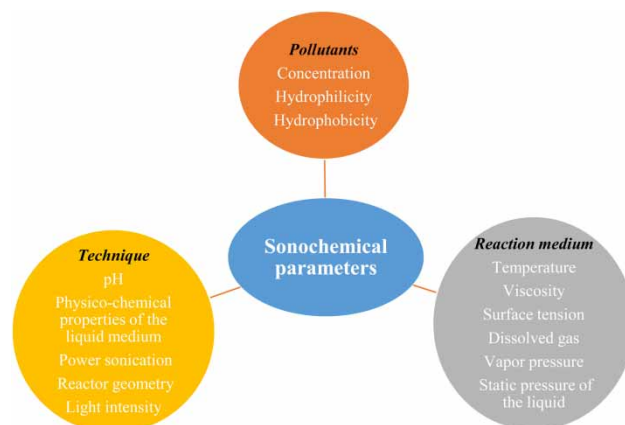


Figure 2 | An illustration of the main parameters influencing the sonochemical degradation of OMW.

Significant numbers of studies have focused on the applicability of this method for the degradation of phenolic compounds. Some extensive and detailed articles, which focus mainly on the degradation of these constituents in aqueous medium, are summarized in Table 7.

To the best of our knowledge, there have been a few publications that focused on the application of the sonochemical advanced oxidation processes alone for the treatment of OMW, this is due to the fact that the amount of generated OH^\bullet radicals remains low and insufficient, as well as the high cost of the process. For this reason, several researchers have studied the combination of sound irradiation with other oxidants such as H_2O_2 and O_3 or combined with other technologies, in order to increase the efficiency of the decomposition of pollutants and to reduce the treatment time.

Atanassova *et al.* (2005) documented a reduction of the antioxidant activity and total phenolic content of diluted OMW samples collected from olive extraction units that use a continuous process (two- and three-phase systems). The authors reported that under optimal values of process parameters (80 kHz ultrasonic frequency, 150 W applied power, 240 min irradiation time and 25 °C), the removal performance of TPh were reduced by about 14 and 24% for the sonicated two-phase and three-phase samples, respectively. They also reported that in the presence of 5 and 10% NaCl, the removal rate of TPh was 19 and 15%, respectively for the two-phase samples with 31 and 28%, respectively, for the three-phase samples.

Table 7 | Overview of main research works on sonochemical oxidation of phenolic compounds in recent years

Phenols	Experimental conditions	Main results	References
p-nitrophenol	Power = 84 W frequency = 20 kHz T = 30 °C, pH = 5	The p-nitrophenol reduction fit the first order kinetics model with current-dependent parameters The reaction products are: NO ₂ -,NO ₃ -, benzoquinone hydroquinone, 4nitrocatecho1, formate, and oxalate	Kotronarou <i>et al.</i> (1991)
Phenol	Power = 30 W frequency = 20, 487 kHz T = 25 °C	After 300 min sonication, the degradation rate of phenolic pollutants is higher at 487 kHz than at 20 kHz	Petrier <i>et al.</i> (1994)
p-nitrophenol	Frequency = 321 kHz T = 25 °C, pH 4–10 Water-absorbed power = 170 W/kg	A detailed study on the sonolysis of 4-nitrophenol in argon-saturated solution The reaction products are: NO ₂ -,NO ₃ -, 4-Nitrocatechol, hydroquinone, benzoquinone, 4-aminophenol	Tauber <i>et al.</i> (2000)
2-, 3- and 4-chlorophenol and pentachlorophenol	Power = 200 W Frequency = 200 kHz Under air and argon atmosphere	A total degradation rate under argon and 80–90% after one-hour of sonolysis	Nagata <i>et al.</i> (2000)
p-chlorophenol	Three different ultrasonic devices used: Probe and cup-horn system: Power = 475 W, frequency = 20 kHz Beaker system: Power = 850 W, frequency = 850 kHz T = 35–39 °C, atmospheric pressure	After 20 min sonication, over 2, 25 and 50% degradation was achieved in cup-horn, beaker and probe respectively. The degradation of intermediate products follow a first-order kinetic rate The reaction products are: hydroquinone, 1, 4-benzoquinone, 4-chlorocatechol, 4-chlororesorcinol	Teo <i>et al.</i> (2001)
p-coumaric and p-hydroxybenzaldehyde	Power = 150 W Frequency = 80 kHz T = 25–70 °C	After 150 min sonication, 56 and 60% of COD and polyphenols have been removed	Vassilakis <i>et al.</i> (2004)
Phenol, 4-chlorophenol (4-CP), 2,6-dichlorophenol (2,6-DCP), 2,4,6-trichlorophenol (2,4,6-TCP) 2,3,4,6-tetrachlorophenol (2,3,4,6-TeCP), and pentachlorophenol (PCP)	Power = 200 W Frequency = 580 kHz T = 20 °C	After 40 min sonication, the degradation rate of chlorinated phenolic pollutants followed the order: 580 kHz (91–93%) > 1,000 kHz (84–86%) > 28 kHz (17–34%) The degradation rate followed the order: PCP > 2,3,4,6-TeCP > 2,4,6-TCP > 2,6- DCP > 4-CP > phenol at various frequencies	Park <i>et al.</i> (2011)

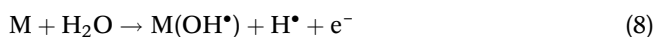
Electrochemical advanced oxidation processes

It is worth mentioning that one of the most studied treatments is the use of an electrochemical advanced oxidation process for toxic pollutant degradation. The main objective of this technique is to minimize the amount of chemical reagents by producing the oxidants directly in the medium by electrochemistry (Burgos-Castillo *et al.* 2018). It has been proven that the electrochemical process offers simplicity, efficiency, environmental compatibility, safety and selectivity, with a low cost particularly when compared to biological treatment (Li *et al.* 2018). Among the existing electrochemical treatments, there are two major forms of free radical production: Direct (anodic oxidation process) and indirect (electro-Fenton process).

Anodic oxidation (AO)

The main interest of the direct action lies in its effectiveness in eliminating a specific compound in solution. This technique allows an electron transfer of the pollutant to the surface of a working electrode (Hamad *et al.* 2018).

The mechanism can be represented as shown below:



where M represents the material of the anode and M(OH[•]) the hydroxyl radical adsorbed on the surface of the anode. The latter is a very powerful oxidant capable of completely oxidizing organic substances.

Several insoluble electrodes with high oxygen overvoltage (BDD, Pt, Ti/IrO₂, Ti/RuO₂, Ti/SnO₂, PbO₂, Gr, etc.) are commonly used. The choice of electrode material as well as the electrolysis conditions have great importance in the liquid effluent treatment (Penteado *et al.* 2017; Tran *et al.* 2017).

Concerning OMW, a considerable number of reported studies have demonstrated that the removal of organic compounds from these hazardous wastes by AO is very simple and highly efficient. Israilides *et al.* (1997) described an electrolysis cell containing a Ti/Pt as anode and stainless steel 304 as cathode in the presence of sodium chloride (NaCl) 4% as electrolyte, after 10 h of treatment, 80% TOC, 93% COD, 99.5% TPh and 99% TSS removal

have been registered with an energy consumption of 2.3 kW h/kg COD removed. Longhi *et al.* (2001) applied AO with PbO₂ at current densities ranging from 500 to 2,000 A/m². They concluded that the removal efficiency of TPh was increased at a level that allows complementary biological treatments without significantly decreasing the total organic content of the effluent.

Another group of researchers have also been working on the electrochemical oxidation of OMW by the use of a Ti/Ta/Pt/Ir as anode. After 120 min of treatment, the main results of this study are a complete degradation of phenols and decolorization with 35% COD reduction (Gotsi *et al.* 2005). Similarly, Giannis *et al.* (2007) obtained 70.8% COD reduction, complete odor, color and TSS removal after 8 h of electrolysis by using the same electrode materials and NaCl 3% as electrolyte.

Belaid *et al.* (2006) adopted a modified Grignard reactor divided into two cylindrical compartments separated by a cation-exchange membrane using platinized expanded titanium electrodes. As a result, 90% color efficiency, 85% removal of phenols, 40% COD and 45% TOC reduction were achieved from undiluted OMW after 5 h of treatment at 9.8 A current intensity. Panizza & Cerisola (2006) have also shown that the AO over Ti/TiRuO₂ was able to completely remove the COD, the aromatics and coloring matters, after 30 h at 5 A and in the presence of 5 g/L NaCl. Un *et al.* (2008) determined that 99.6% DCO, 99.85% turbidity, 99.54% oil-grease and 100% TPh could be removed by the use of Ti/RuO₂ anode with a specific energy consumption (SEC) and energy cost of around 5.35–27.02 kWh/kg COD and 0.88 €/kg COD, respectively. Optimum conditions included 7 h treatment time, 135 mA/cm² current density, 2 M NaCl concentration, 7.9 cm³/s recirculation rate of OMW and 40 °C temperature.

Kotta *et al.* (2007) investigated the electrochemical oxidation of OMW with Ti/Pt anodes. They determined that the presence of unfiltered solids had virtually no impact on TPh removal (95% after 180 min of treatment at 20 A). In addition, it was observed that the dissolved solids content in OMW samples affects the electrochemical treatment efficiency, since it increases the color and the COD value of samples. In a similar way, Kul *et al.* (2015) also used Ti/Pt as anode and Ti mesh plates as cathode. The effects of the different operational parameters were investigated.

The results showed that AO could remove 100% of COD, 78% of TOC and 100% of TPh after 5 h of treatment without any pH adjustment using NaCl concentration of 0.25 M at current density of 7.69 mA/cm² and temperature of 10 °C. The SEC was 451.25 kWh/m³ and the running cost was determined as 6.02 €/kg COD.

It is worth highlighting that several articles authored by Canizares *et al.* (2002, 2003a, 2003b, 2004a, 2004b, 2004c, 2004d, 2004e, 2005, 2007b, 2009) were interested in the use of a new electrochemical technique based on the introduction of a new type of electrode material, namely boron-doped diamond (BDD), for the degradation of organic pollutants present in wastewaters including OMW. The results revealed that AO with conductive diamond electrochemical oxidation (CDEO) was considered as one of the most effective methods for the total mineralization of aromatic compounds in the OMW with very high efficiency. Up to 98.4% of COD abatement and 99% of TOC removal could be ensured with a SEC of 110 kWh/m³ and operation cost ranged between 2.4 and 4 €/kg equivalent O₂ (Canizares *et al.* 2009).

The BDD has also been proposed to be a good candidate for the oxidation of table olive processing wastewater (TOPW) (Deligiorgis *et al.* 2008). In the best conditions (30 A for 14 h), it was possible to achieve 73% COD removal with 16.3 g COD/(m³Ah) energy efficiency. Similarly, Chatzisyneon *et al.* (2009b), Bouhssine *et al.* (2013) and Jum'h *et al.* (2017) confirmed that this type of electrode material promotes a remarkable depuration of OMW. Based on the first, the effect of initial COD load, treatment time, current intensity, initial pH and H₂O₂ dose were investigated. Under 20 A current intensity and 15 h electrolysis time, the results were a 19% reduction in COD and a 36% decrease in phenols with a SEC of 96 kWh/kg COD removed. Moreover, the kinetic study determined that the COD removal obeyed the zero-order model (Chatzisyneon *et al.* 2009b). Bouhssine *et al.* (2013) also tested the BDD anode system performance in OMW treatment. The best results were obtained using a current density of 1.29 A/cm² after 30 min of electrolysis, achieving 43, 60 and 63% for dark color, COD and TPh removal, respectively. Jum'h *et al.* (2017) were capable of removing 85% COD with no supporting electrolytes and over 90% COD removal efficiency can be achieved by adding Na₂SO₄ and NaCl after 7 h of treatment for COD loads of 72.9 and

33.8 g/L, and after 2 h for a COD load of 0.18 g/l. In addition, the results showed minimal values of turbidity ranging between 0.98 and 8 NTU and a complete discoloration for the three different raw OMW samples (Jum'h *et al.* 2017).

Chatzisyneon *et al.* (2009a) also evaluated the efficiency of Ti/IrO₂ anode in the electrochemical treatment of model solutions containing various aromatic compounds and an OMW sample. The results revealed that it was possible to achieve 100% color, 100% TPh and 30% COD removal at 43 Ah/L charge passed, 80 °C temperature, 50 A/cm² current density and 5 mM NaCl concentration.

Using a Ti/RuO₂ anode, Papastefanakis *et al.* (2010) compared their results with those of Ti/IrO₂ (Chatzisyneon *et al.* 2009a). The OMW oxidation over Ti/RuO₂ was more effective in the degradation of 52% COD than the Ti/IrO₂ anode (30%) with color reduction of 86%, 38% of TOC and 84% of TPh at 50 mA/cm² and 28 Ah/L charge passed. In addition, they concluded that decolorization of OMW using a Ti/RuO₂ anode was also less sensitive to changes in salt concentrations.

More recently, Fajardo *et al.* (2017) obtained good results in the treatment of OMW by the same anode materials. In the first part, they reported that 100% of COD and TPh were removed from synthetic mixture of six phenolic compounds at pH of 3.4, 10 g/L of NaCl and 119 mA/cm² of current density. While the second part discusses the detoxification of an undiluted OMW, after 180 min of treatment with the same optimised parameters, 17.2 and 100% of COD and TPh removal, respectively, were achieved with SEC of 162 kWh/m³.

Unfortunately, the main drawback of this process lies in its high operating cost due to the high energy consumption (Liu *et al.* 2017a, 2017b). In addition, the conductivity of the effluent must be sufficient to allow the passage of the current without excessive electricity consumption. When the conductivity of the OMW is too low, an addition of sodium chloride is generally necessary. In addition, the presence of a solid deposit on the cathode surface increases the electrolytic cell's resistance (Khaled *et al.* 2015; Markou *et al.* 2017).

Electro-Fenton (EF)

Several studies emphasize that the electro-Fenton process (EF) is a powerful technique for the treatment of water

and various industrial effluents (Khoufi *et al.* 2004; Zhao *et al.* 2012; Davarnejad *et al.* 2015; Olvera-Vargas *et al.* 2015; Gümüş & Akbal 2016; Trellu *et al.* 2016; Cruz-Rizo *et al.* 2017; Hassan *et al.* 2017; Gökkuş *et al.* 2018).

This indirect electrochemical method has emerged as a novel treatment technology for the reduction of a wide range of toxic organic compounds. As is the case in the AO, the EF process involves the *in situ* generation of the reagents necessary for the production of hydroxyl radicals by applying electrical energy. According to Fenton's mechanism cited above under 'Fenton and Fenton-like reagent ($\text{Fe}^{2+} + \text{H}_2\text{O}_2$)', this method represents a Fenton's reaction assisted by electrochemistry, it is based on the fact that Fe^{2+} ions react with H_2O_2 to electrochemically release (OH^\bullet) radicals. As reviewed by Babuponnusami & Muthukumar (2014), the EF process can take multiple configurations depending on the addition or the formation of Fenton's reagent and hydrogen peroxide during electrolysis. Also, it should be noted that the efficiency of this system is influenced by various parameters such as pH of the medium, temperature, current intensity, type of electrode and catalyst concentration.

It is worth noting that, in early reports, the EF process was widely applied to remove recalcitrant phenolic compounds from synthetic mixtures (Gümüş & Akbal 2016; Khatri *et al.* 2018), which gives a clear idea about the feasibility of this technique towards OMW composed predominantly of these organic matters.

However, a limited number of studies have focused on the field of OMW treatment by EF alone which leads to modest treatment efficiencies. Khoufi *et al.* (2004) indicated that EF oxidation could be an important stage for a complete detoxification of OMW, which yielded a dephenolization of around 78%. Afterwards, Bellakhal *et al.* (2006) confirmed that EF with a Pt/carbon-felt cell proved to be effective with a dose of 0.5 mM of Fe^{2+} , low-intensity electrical current of 200 mA at pH = 3 leading to a complete mineralization in 9 h and a total decolorization after 7 h.

The EF process comes with the added benefit and advantage of overcoming some drawbacks of the Fenton reagent, but at the same time it still suffers from major limitations such as the need for acidic medium activity, separation of the dissolved iron, the management of the resulting iron sludge and the excessive concentration of

iron cations at the end of the treatment (Roth *et al.* 2016). Last but not least, note that, in conjunction with other conventional technologies, this kind of AOP becomes more efficient and more useful, especially with the biological methods, which will be discussed at the end of this review article.

Electrocoagulation (EC)

With regard to the technique of electrocoagulation (EC), also listed under electrochemical oxidation, over the years, several studies have been developed on EC treatment processes for difficult and recalcitrant wastewaters like OMW, mainly owing to its simplicity, low energy consumption, effectiveness, low sludge formation and low dissolved solids (Elkacmi *et al.* 2017c).

The main basic steps of electrocoagulation process are presented in Figure 3. Both iron and aluminum can create active coagulant species to remove the organic load and phenolic compounds. Significant effort has been made to adopt this technique for the treatment of OMW.

Inan *et al.* (2004) investigated the treatment of OMW by electrocoagulation. Over 52% of COD for the aluminum anode against 42% COD for the iron anode were removed efficiently at a pH of 6.2, current density of 20 mA/cm² and a residence time of 30 min.

Adhoum & Monser (2004) proposed the use of aluminum electrodes to remove 76% of COD, 91% of polyphenols and 95% of dark color after 25 min of electrolysis with low electrode consumption (2.11 kg/m³ of treated OMW). Ün *et al.* (2006) studied the treatment of fresh OMW using either iron or aluminum as sacrificial electrodes in the presence of H_2O_2 and polialuminum chloride (PAC). Under optimal conditions (2.3% H_2O_2 + 0.5 g/L PAC), the removal efficiency of COD was in the range of 62–86% whereas oil-grease and turbidity removal was 100%. Moreover, they found that the energy cost was in the range of 0.18–6.75 €/kg COD removed. Khoufi *et al.* (2007) obtained higher COD and TPh removal efficiencies (over 43% removal for COD and 90% for TPh) when utilizing both electrocoagulation and sedimentation combinations. Hanafi *et al.* (2010) were able to remove more than 70% of COD, PP and coloration from an OMW sample diluted five times after 15 min with initial pH of 4.2, 2 g/L of NaCl, and current density of 250 A/m².

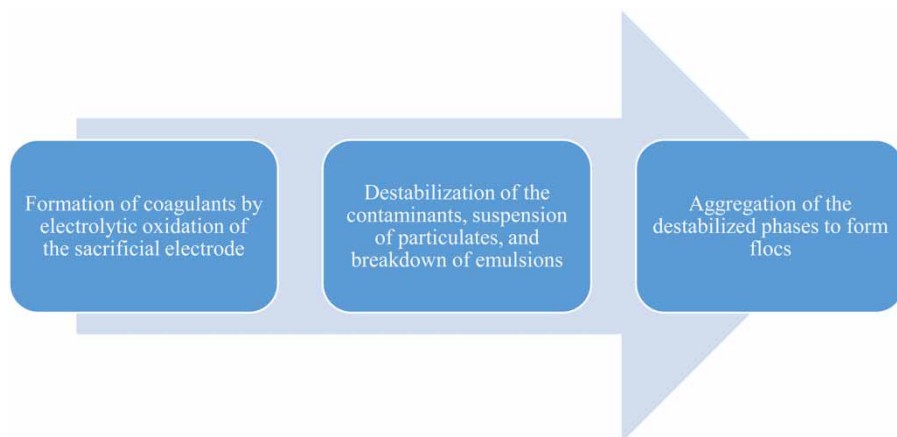


Figure 3 | Main basic steps of electrocoagulation process (Elkacmi & Bennajah 2019).

Esfandyari *et al.* (2015) reported that 96% COD, 93.6% BOD₅, 94.4% TPh, 91.4% color, 88.7% turbidity, 97% TSS and 97.1% oil and grease were removed from the OMW diluted four times by using bipolar aluminum electrodes under optimized conditions ($[H_2O_2] = 1,000$ mg/L, NaCl = 1 g/L, pH = 4, current density = 40 mA/cm², and reaction time = 30 min).

Table 8 summarizes the advantages and disadvantages of each technique. Some processes such as O₃/H₂O₂, O₃/UV and TiO₂/UV are limited by the mass transfer phenomena, while the low cost, efficiency and environmental benefits are an added advantage of some other techniques such as Fenton and sonochemical oxidation processes.

Fenton's reagent remains the most reliable and widely used method for detoxification of OMW. Iron and H₂O₂ are cheap and non-toxic elements, there are no mass transfer limitations due to the homogenous catalytic nature, no energy involved as catalyst, as well as a considerable flexibility and ease of construction of industrial installations, but in view of the limitation of sludge reduction, the electrochemical processes have been shown to be effective in treating OMW. Encouraging results were yielded either by direct anodic oxidation or by indirect electro-Fenton methods. A comparative of the removal efficiencies and operating costs of the main AOP applied for OMW treatment is reported in Table 9. Despite its high energy consumption compared to other techniques, the electrooxidation can be considered as a suitable alternative to achieve an effective and total detoxification of OMW.

Combination of AOP with other treatment processes

A considerable number of studies have also been undertaken on the combination of different AOP for a complete treatment and fractionation of OMW. As presented in Table 6, among combined treatments applied to OMW we can find three forms: coupling with (AOP), coupling with biological treatments, as well as coupling with physico-chemical processes.

Combination with AOP

In some cases, AOP are used as a pre-treatment whenever the aim is to improve the degradation of organic compounds and reduce the toxicity of OMW, sometimes being followed by another AOP making the combined overall process more efficient. Garcia & Beltran-Heredia (2008) published the results of a combined Fenton's reagent and ozonation process. The first process leads to about 33 and 90% COD and TPh removal, respectively. While the latter process leads to 26% of COD and 62% of TPh removal efficiencies. Also, they have concluded that 73–84% COD abatement can be reached with the combination of the two AOPs. Martins *et al.* (2010) ran a Fenton process pretreatment before ozonation under different operational conditions in order to reduce the COD level. They observed a COD removal rate of around 73–84%.

Canizares *et al.* (2007a) studied the treatment of OMW with three AOPs: conductive diamond electrooxidation

Table 8 | Advantages and disadvantages of different AOP

Techniques	Advantages	Disadvantages
Fe ²⁺ /Fe ³⁺ /H ₂ O ₂	Simple, low cost materials, production of strong oxidant, high efficiency, easy implementation in the industrial scale	Low regeneration rate of Fe ²⁺ , low pH requirement, high doses of reagents, sludge generation, parasitic reactions, difficulty in storage and transport of H ₂ O ₂
O ₃ /H ₂ O ₂	Simple free radical production, high bactericide activity, less time consuming, high removal efficiencies	Low solubility of O ₃ in aqueous solutions, limited mass transfer, high cost of reagent, ineffectiveness at high pollutants concentrations, high energy consumption, short lifetime of UV lamps
WAO and CWAO	Mild operating conditions, small plant for operations, higher mineralization of pollutants, adapted with flow rates and effluent compositions, no production of secondary pollution	High capital cost, high energy consumption
H ₂ O ₂ /UV	Simple, cheap and sure source of radicals, high decomposition yield of H ₂ O ₂ , oxidation of a wide range of organic compounds, no sludge production	Difficulty in storage and transport of H ₂ O ₂ , short lifetime of UV lamps, low absorption coefficient of H ₂ O ₂ , lack of reactor design for UV illumination, generation of by-products
O ₃ /UV	Easy handling, relatively short reaction times, production of strong oxidant	Selectivity of molecular ozone, high operating cost, limited mass transfer, incomplete treatment of effluents, short lifetime of UV lamps, generation of by-products
H ₂ O ₂ /Fe ²⁺ (Fe ³⁺)/UV	High efficiency, equipment simplicity, no sludge production, an additional generation of radicals, possibility of coupling with solar energy	High operating cost, high energy consumption, short lifetime of UV lamps
H ₂ O ₂ /O ₃ /UV	High hydroxyl radicals production, combines O ₃ /H ₂ O ₂ and UV/O ₃ systems, high removal efficiencies	High cost of reagent, high energy consumption, short lifetime of UV lamps
Fe ³⁺ /UV	High efficiency, no need for hydrogen peroxide addition, less expensive method in comparison with H ₂ O ₂ /Fe ²⁺ (Fe ³⁺)/UV and H ₂ O ₂ /UV processes, no mass transfer limitation	Low pH requirement, high energy consumption, short lifetime and limited efficiency of UV lamps
TiO ₂ /UV	Simple, available and low cost materials, operation at ambient conditions, wide pH range, oxidation of a wide range of organic compounds, possibility of coupling with solar energy	Formation of dark catalytic sludge, limited mass transfer, short lifetime and limited efficiency of UV lamps, difficulty in the recovery of the catalyst after treatment, difficulty of use on industrial scale
Sonochemical	Simple, environment friendly, ambient operating conditions, no production of toxic by-products	High capital cost, low OH ⁻ radical production, incomplete treatment of effluents
Electrochemical	Rapid, strong oxidation ability, lower temperature and pressure requirements, treatment of large volumes, no need for chemical reagents or large amounts of catalyst, low sludge production	High energy consumption, high operating cost, need for maintenance, need for high conductivity effluent

(CDEO), ozonation and Fenton oxidation. The study found that both ozonation at alkaline pH and Fenton oxidation are not able to achieve a complete mineralization compared to CDEO, due to the presence of carboxylic acids as intermediate products which can no longer be oxidized by hydroxyl radicals. They also concluded that combined Fenton oxidation and CDEO increased the COD removal performance.

Kaplan *et al.* (2011) described the removal efficiency of three toxic phenolic compounds in OMW (vanillic acid, o-coumaric acid and protocatechuic acid) under UV light irradiation during the electro-Fenton process. The experimental results reveal that 90% mineralization was achieved after consumption of 0.27 mAh over 3 h of treatment using carbon felt working electrodes. Recently, a similar approach was adopted by Flores *et al.* (2017). There

Table 9 | Selected examples of comparative AOP in the treatment of olive mill wastewater

References	Technique	OMW source	Initial pollutant concentration	Removal efficiency	Operation conditions	Mode	Specific energy consumed	Operating cost
Canizares <i>et al.</i> (2009)	Fe ²⁺ /Fe ³⁺ /H ₂ O ₂	Not identified	Not identified	%COD = 73.98% %TOC = 70.72%	pH = 3 ± 0.1 V = 100 mL [Fe ²⁺] = 700 mg/L [H ₂ O ₂] = 18,000 mg/L	Batch	–	0.7–3.0 €/kg equivalent O ₂
Mert <i>et al.</i> (2010)	Fe ²⁺ /H ₂ O ₂ Fe ³⁺ /H ₂ O ₂	Not identified	COD = 115,000 mg/L TPh = 5,580 mg/L	Fe ²⁺ /H ₂ O ₂ %COD = 90% %TPh = 91% Fe ³⁺ /H ₂ O ₂ %COD = 93% %TPh = 95%	pH = 3 [Fe ²⁺] = 3,000 mg/L [H ₂ O ₂] = 3,500 mg/L [Fe ³⁺] = 2,500 mg/L [H ₂ O ₂] = 3,000 mg/L	Batch	–	4.81 €/kg equivalent O ₂ 4.29€/kg equivalent O ₂
Canizares <i>et al.</i> (2009)	O ₃ /H ₂ O ₂	Not identified	Not identified	%COD = 77.2% %TOC = 67.8%	V = 2 L Flow-rate: 0.5 L/min	Batch	1,814 kWh/m ³	8.5–10.0 €/kg equivalent O ₂
Michael <i>et al.</i> (2014)	H ₂ O ₂ /Fe ²⁺ (Fe ³⁺)/UV	Three-phase	COD = 13,000 mg/L	%COD = 87%	[Fe ²⁺] = 80 mg/L [H ₂ O ₂] = 1000 mg/L Irradiation time = 4 h	Batch	–	0.16 € /kg COD removed
Ahmed <i>et al.</i> (2011)	H ₂ O ₂ /Fe ²⁺ (Fe ³⁺)/UV	Three-phase	COD = 2000–7000 mg/L TOC = 180–300 mg/L	%COD = 95%	pH = 3 [Fe ²⁺] = 30 mg/L [H ₂ O ₂] = 3000 mg/L Temperature = 26 °C Irradiation time = 3 h	Batch	–	3.15 € /m ³
Yalılıkılıç <i>et al.</i> (2013)	Acide cracking + coagulation + ultrafiltration + O ₃ /H ₂ O ₂ /UV	Not identified	COD = 128,000 mg/L TPh = 3440 mg/L TOC = 26,400 mg/L	%COD = 99.44% %TPh = 99.93% %TOC = 99.40%	pH = 3 Temperature = 20 °C CH ₂ O ₂ = 500 mg/L [H ₂ O ₂] = 700 mg/L	Batch	–	7.15 € /m ³
Chatzisyneon <i>et al.</i> (2009c)	TiO ₂ /UV	Three-phase	COD = 5100 mg/L	%COD = 20%	pH = 4.8 Temperature = 28 ± 2 °C V = 350 mL Treatment times = 4 h	Batch	5,000 kWh/kg COD removed	–
Canizares <i>et al.</i> (2009)	CDEO	Not identified	Not identified	%COD = 98.37% %TOC = 99%	V = 0.6 L	Batch	110 kWh/m ³	2.4–4.0 €/kg equivalent O ₂
Chatzisyneon <i>et al.</i> (2009b)	BDD anodic	Three-phase	COD = 40,000 mg/L TPh = 3500 mg/L	%COD = 19% %PP = 36%	Treatment time = 15 h Current intensity = 20 A [H ₂ O ₂] = 500 mg/L	Batch	96 kWh/kg COD removed	7–10 €/kg COD removed
Hanafi <i>et al.</i> (2010)	Electrocoagulation	Classic process	COD = 20,000 mg/L PP = 260 mg/L	%COD = 70% %PP = 70%	Aluminum electrode Treatment time = 15 min Current density = 250 A/cm ²	Batch	2.63 kWh/kg COD removed	0.27 € /kg COD removed
Israilides <i>et al.</i> (1997)	Electrooxidation	Not identified	COD = 178,220 mg/L TOC = 26,550 mg/L VSS = 46,620 mg/L TPh = 11,410 mg/L	%COD = 93% %TOC = 80.4% %VSS = 98.7% %TPh = 99.4%	Ti/Pt electrode Treatment time = 10 h Current density = 0.26 A/cm ²	Batch	12.3 kWh/kg COD removed	–
Un <i>et al.</i> (2008)	Electrooxidation	Three-phase	COD = 41,000 mg/L PP = 215 mg/L Turbidity = 4,050 NTU Oil-grease = 1970 mg/L	%COD = 99.6% %PP = 100% Turbidity = 99.54% Oil-grease = 99.54%	Ti/RuO ₂ anode Treatment time = 7 h Temperature = 40 °C Current density = 35 mA/cm ² Recirculation rate = 7.9 mL/s	Batch	5.35–27.02 kWh/kg COD	0.88 €/kg COD removed

(continued)

Table 9 | continued

References	Technique	OMW source	Initial pollutant concentration	Removal efficiency	Operation conditions	Mode	Specific energy consumed	Operating cost
Amaral-Silva <i>et al.</i> (2017)	Fenton-coagulation-biological	Not identified	COD = 6450 mg/L TSS = 3190 mg/L TPh = 21 mg/L	% COD = 58% %TSS = 40% % COD = 89% % COD = 43% % COD = 62% % COD = 95%	Lab scale Coagulation: pH = 3.4 [Fe ₂ (SO ₄) ₃] = 3000 mg/L Fenton: [Fe ²⁺] = 1500 mg/L [H ₂ O ₂] = 15,000 mg/L Industrial scale Flow rate: 1.5 m ³ /h V = 450 m ³ T = 22 ± 2 Coagulation: pH = 5.2–5.8 [Fe ₂ (SO ₄) ₃] = 2500–3000 mg/L Fenton: Biological Treatment time: 60 days	Batch Continuous	2.96 kWh/m ³	1.44 €/kg COD removed 2.7 €/m ³

was a comparative study involving three AOPs for 4-hydroxyphenylacetic acid degradation spiked in OMW. The three processes compared are anodic oxidation (AO), electro-Fenton (EF) and photoelectro-Fenton (PEF). The results showed that PEF gives the highest removal efficiencies due to the large photolytic action of UV radiation on photosensitive by-products. A reduction of 80% of TOC and improvement in biodegradability were observed.

Ghanbari *et al.* (2016) proposed a new combination system between electro-Fenton-like and anodic oxidation processes. At pH 3–3.5 and 300 mA electrical current, the research group observed a significant improvement in the COD removal of up to 65% by this system in comparison with the separate application of electro-Fenton-like and electro-generation of H₂O₂ along with anodic oxidation using PbO₂ and copper anodes.

Combination with biological treatments

It has been confirmed in a large number of studies that biological processes are relatively simple techniques that can be successfully employed in the OMW treatment field. However, the presence of high concentrations of aromatic and phenolic compounds inhibits the activity of the microorganisms, which leads to rather poor results of removal efficiencies making this kind of treatment inappropriate for OMW detoxification, thus increasing the interest in combined systems for improved performances.

A compilation of relevant published data with respect to biological process, AOP and the main results under various process conditions is presented in Table 10.

The Fenton process is an effective conventional method for the removal of organic pollutants, which can be used as a pretreatment for OMW purification. Amor *et al.* (2015) studied the pretreatment of OMW by Fenton reagent. The obtained results revealed that 63.6–88% COD removal efficiency could be achieved in the combination of Fenton's reagent with the anaerobic biological treatment. Lucas *et al.* (2013) indicated that aerobic biodegradation alone cannot ensure a complete treatment. In this regard, the use of Fenton's reagent pretreatment becomes a major necessity to improve the removal yields (80.7% COD and 93.7% TPh). Using the same combined system for green TOPW, the removal of organic load in terms of COD and

TPh can reach 79–94.77 and 36.66–73.33% removal efficiencies, respectively (Kotsou *et al.* 2004). Beltran-Heredia *et al.* (2001) used two chemical oxidation processes (Fenton's reagent and ozonation) followed by anaerobic digestion and up to 72.5% of COD and 94.8% of TPh were removed under optimal conditions.

Always in combination with anaerobic treatment, WHPCO allowed achieving around 75, 78 and 61% of COD, BOD₅ and TOC removals, respectively (El-Gohary *et al.* 2009). In addition, Azabou *et al.* (2010) reported 70% reduction of the inhibition of the marine photobacteria *Vibrio fischeri* luminescence with a remarkable reduction of the COD, colour and TPh by using two different catalytic systems: ((Al-Fe) pillared inter layer clay (PILC/H₂O₂/ultra-violet radiations) at 25 °C and ((Al-Fe)PILC/H₂O₂) at 50 °C. Rivas *et al.* (2000) carried out a study concerning the treatment of TOMW by an integrated WAO-aerobic biodegradation process. This study illustrated the ability to remove 77.1, 48.4 and 87% of COD, TC and TOC removal, respectively. Another study by Minh *et al.* (2008) showed that over 97% TOC and 100% TPh removal were obtained after coupling CWAO and an anaerobic digestion treatment.

An electrochemical process coupled with a biological system is also a promising treatment technology that significantly reduces COD, TPh and color. For example, the results attained by Kyriacou *et al.* (2005) and Gonçalves *et al.* (2012) reveal the potential of combined systems (anaerobic/aerobic process/electrochemical process) for OMW depollution. The use of RuO₂ DSAs-type as an anode for anaerobically digested OMW gives a complete removal of 99, 100 and 100% of COD, TPh and color, respectively (Gonçalves *et al.* 2012). Furthermore, Kyriacou *et al.* (2005) applied an electrochemical process to TOPW after aerobic microbial degradation using a selected strain of *Aspergillus niger*, the percentage of COD and TPh removal were around 96%. Khoufi *et al.* (2006) showed that a combined process EF and anaerobic digestion provides a total depuration of OMW compared to EF alone.

Benitez *et al.* (2001a) proposed a treatment process comprising H₂O₂/UV, Fenton's reagent and photo-Fenton, followed by an anaerobic process. The combined system yielded 63–78% of COD abatement, and they found that 277–282 mL CH₄/g COD was removed for the methane yield coefficient.

Costa & Alves (2013) suggested applying heterogeneous photocatalysis (TiO₂/UV) after anaerobic digestion. Under the best conditions, a 90.8 ± 2.7% destruction of TPh was obtained, with a 79.3 ± 1.9 and 50.3 ± 6.3% reduction of color and COD respectively. Oz & Uzun (2015) studied the combination of ultrasound oxidation and anaerobic degradation of fresh and diluted OMW. The main results revealed that methane production increased up to 20% for ultrasound pretreated diluted OMW compared with the untreated one.

Ozonation oxidation coupled with biological treatment has raised much attention in OMW treatment during the past decades. Andreozzi *et al.* (1998) reported that the use of a combined ozone-anaerobic process improved the unsaturated lipids and TPh reduction by 50%, while the COD abatement remained unchanged.

Benitez *et al.* (1999a) tested the combination of two successive steps: an ozonation followed by an aerobic degradation, and an aerobic degradation followed by an ozonation. In the first combined process, 84.6% of COD was removed at pH = 7, T = 20 °C and PO₃ = 1.73 kPa. In the second combined system, the total conversion obtained was 81.8% at PO₃ = 1.69 kPa and the same pH and temperature. Two years later, Benitez confirmed that ozonation followed by aerobic degradation led to 85 and 88% of COD and TPh reduction, respectively (Benitez *et al.* 2001b). In a similar way, the same authors' group found that a single ozonation process led to 82–92% of COD reduction, an O₃/UV system led to 88–96% of COD reduction, and aerobic degradation of the OMW previously oxidized by an ozonation treatment provided 96–97% of COD reduction, which is similar to the combined ozonation plus UV radiation (Benitez *et al.* 2002). Also, in another study on black olive wastewater, Benitez *et al.* (1999b) found a reduction of 85% of COD and 88% of TPh by using a coupled ozonation and aerobic degradation process (Benitez *et al.* 1999b).

Beltran-Heredia *et al.* (2000a, 2000b) demonstrated that the application of ozone to aerobically pretreated OWM has been found to result in significant removal efficiencies (Beltran-Heredia *et al.* 2000a), in comparison to the results of ozonation followed by aerobic degradation (Beltran-Heredia *et al.* 2000b). Over 98.57% of COD, 97.6% of polyphenols and 95.82% of aromatic compounds were removed efficiently.

Table 10 | Main results reported for the treatment of OMW by means of AOP combined with biological treatments

Advanced oxidation processes	Biological processes	Experimental conditions	Main results	References
Fenton's process	Anaerobic process	pH: 3.5 Temperature: 20 °C H ₂ O ₂ /Fe ₂ C ratio: 15:1 H ₂ O ₂ /COD ratio: 0.2	(i) Fenton's reagent leads to a 17.6 and 82.5% of COD and TPh reduction, respectively (ii) Anaerobic process leads to COD conversion between 52.6 and 74.0% (iii) Combined Fenton reagent/anaerobic digestion treatment leads to COD conversion between 63.6 and 88.0% (iv) Methane production ranged between 281 and 322 mL of CH ₄ /g COD removed	Amor et al. (2015)
Fenton's process and ozonation	Aerobic process	pH: 4.84 Temperature: 10, 20, 30 and 40 °C Fe ²⁺ /H ₂ O ₂ ratio: 1:10, 1:15 and 1:20 Ozonation times: 1.8–8.7 h Ozone pressure: 0.35–1.21 kPa	(i) Fenton's reagent leads to 32.7 and 94% of COD and TPh reduction, respectively (ii) Ozonation process leads to 26.6 and 43.7% of COD and TPh reduction, respectively (iii) Combined Fenton reagent/anaerobic digestion treatment leads to a 84.2 and 81.3% of COD and TPh reduction, respectively (iv) Combined ozonation/anaerobic digestion treatment leads to a 72.5 and 94.8% of COD and TPh reduction, respectively	Beltran-Heredia et al. (2001)
Fenton's process	Aerobic process	pH: 3.5 H ₂ O ₂ /COD ratio: 0.20 H ₂ O ₂ /Fe ²⁺ molar ratio: 15	(i) Aerobic biodegradation alone leads to 83 and 61% of COD and TPh removal, respectively (ii) The combined process leads to 80.7 and 93.7% of COD and TPh removal, respectively	Lucas et al. (2013)
Fenton's process	Aerobic process	pH: 4.5–4.8 Temperature: 25 °C [Fe ²⁺]: 0.5 g/L [H ₂ O ₂]: 2, 4, 6, 8 g/L	The combined process leads to 79–94.77% and 36.66–73.33% of COD and TPh reduction, respectively	Kotsou et al. (2004)
Wet hydrogen peroxide catalytic oxidation (WHPCO)	Anaerobic process	pH: 2–5 Fe ²⁺ /H ₂ O ₂ ratio: 1:10, 1:25 and 1:50 H ₂ O ₂ /COD ratio = 0.1:1.1, 0.1:2.2, 0.1:3.3 and 0.1:4.4	COD, BOD ₅ and TOC removal rates of 75, 78 and 61%, respectively	El-Gohary et al. (2009)
Wet hydrogen peroxide catalytic oxidation (WHPCO)	Anaerobic process	pH: 5.2 Temperature: 25–50 °C [H ₂ O ₂] = 2*10 ⁻² M (Al-Fe)PILC = 0.5 g/L	Reduction of the inhibition of the marine photobacteria <i>Vibrio fischeri</i> luminescence by 70%	Azabou et al. (2010)
Wet air oxidation (WAO)	Aerobic process	pH: 7 Temperature: 20 °C Treatment time: 10 h	Aerobic biodegradation of wet air oxidized TOPW leads to 77.1, 48.4 and 87% of COD, TC and TOC removal, respectively	Rivas et al. (2000)

(continued)

Table 10 | continued

Advanced oxidation processes	Biological processes	Experimental conditions	Main results	References
Catalytic wet air oxidation (CWAO)	Anaerobic process	pH: 4.7–5.4 Temperature: 140 and 190 °C. Total air pressure: 70 bar	Removal efficiencies of 97 and 100% were obtained for TOC and TPh, respectively	Minh <i>et al.</i> (2008)
Electrochemical process	Anaerobic process	pH: 4.7–8.9 Temperature: 20 ± 2 °C Electrolysis charge: 10.4*10 ⁴ CL ⁻¹ Supporting electrolyte KNO ₃ concentrations: 0.1 M	(i) By using IrO ₂ anode, 14, 91 and 85% removal rates of COD, TPh and color, respectively (ii) By using RuO ₂ DSAs-type as anode, 99, 100 and 100% removal rates of COD, TPh and color, respectively	Gonçalves <i>et al.</i> (2012)
Electro-Fenton (EF)	Anaerobic process	pH: 4 [H ₂ O ₂]: 0–1.5 g/L Current density: 1.25–10 A/dm ²	(i) EF process leads to 65.8 and 33.1% of TPh and toxicity reduction, respectively (ii) In the combined process, total depuration of OMW has been achieved	Khoufi <i>et al.</i> (2006)
Electrochemical process	Aerobic process	pH: 4.5–5.0 [H ₂ O ₂]: 0, 2.5 and 5.0%	(i) Aerobic biodegradation alone leads to 66–86 and 65% of COD and TPh removal, respectively (ii) The combined process leads to 96% of COD and TPh reduction	Kyriacou <i>et al.</i> (2005)
H ₂ O ₂ /UV Fenton's reagent Photo-Fenton	Anaerobic process	pH: 12.6 Temperature: 20–35 °C. [Fe ²⁺]: 2.4*10 ⁻³ and 4.8*10 ⁻³ M [H ₂ O ₂]: 0.055–0.11 M	(i) The single UV radiation leads to 35 and 20% of COD and aromatic compounds removal, respectively (ii) The H ₂ O ₂ /UV system gives 41–76% of COD and 52% of aromatic compounds removal (iii) The combined process leads to 63–78% of COD reduction, and 277–282 mL CH ₄ /g COD removed for the methane yield coefficient	Benitez <i>et al.</i> (2001a)
Heterogeneous photocatalysis (TiO ₂ /UV)	Anaerobic process	pH: 4.8–7.5 Temperature: 37 °C Treatment time: 8–24 h	Over 90.8 ± 2.7%, 79.3 ± 1.9% and 50.3 ± 6.3% removal efficiencies of TPh, color and COD respectively	Costa & Alves (2013)
Ultrasound	Anaerobic process	pH: 5.14 Temperature: 35 ± 2 °C Power: 50–100 W Frequency: 20 kHz Power densities: 0.2 and 0.4 W/mL	(i) The application of ultrasound alone increased soluble chemical oxygen demand/total chemical oxygen demand SCOD/TCOD ratio from 0.59 to 0.79 (ii) An increase in methane production of 20% for ultrasound pretreated diluted OMW compared with the untreated one	Oz & Uzun (2015)

Ozonation	Anaerobic process	pH: 5.09–8 Treatment time: 1–7 h Temperature: 35 °C	(i) TPh and unsaturated lipids removal percentages up to 50% without variation of COD concentration (ii) Ozonated OMW have stronger inhibitory effect compared to untreated ones on methanogenic bacteria. Nevertheless, this effect is not present on acidogenic bacteria	Andreozzi et al. (1998)
Ozonation	Aerobic process	pH: 7 Temperature: 20 °C Ozone pressure: 1.69 and 1.73 kPa	(i) Ozonation followed by aerobic degradation leads to 84.6% of COD removal (ii) Aerobic degradation followed by ozonation leads to 81.8% of COD removal	Benitez et al. (1999a)
Ozonation	Aerobic process	pH: 13.5 Temperature: 28 ± 0.2 °C Ozone pressure: 0.82 and 1.22 kPa	(i) Single aerobic process leads to 80 and 75% of COD and TPh reduction, respectively (ii) Ozonation followed by aerobic degradation leads to 85 and 88% of COD and TPh reduction, respectively	Benitez et al. (2001b)
Ozonation, O ₃ /UV	Aerobic process	pH: 9.07–13.05 Temperature: 20 °C Ozone pressure: 4.70 kPa Flow-rate: 40 L/h	(i) Single ozonation process leads to 82–92% of COD reduction (ii) O ₃ /UV system leads to 88–96% of COD reduction (iii) Ozonation process followed by aerobic degradation leads to 96–97% of COD reduction	Benitez et al. (2002)
Ozonation	Aerobic process	pH: 13.5 Temperature: 28 ± 0.2 °C Ozone pressure: 0.82 and 1.22 kPa Flow-rate: 60 L/h	(i) Single aerobic process leads to 80 and 50–75% of COD and TPh reduction, respectively (ii) Ozonation followed by aerobic degradation leads to 85 of COD and 88% of TPh reduction	Benitez et al. (1999b)
Ozonation	Aerobic process	pH: 7–13.6 Temperature: 10, 20 and 30 °C Ozone pressure: 5.093 and 5.601 kPa Flow-rate: 125 L/h	(i) Single ozonation process leads to 55, 84 and 76% of COD, TPh and aromatic compounds reduction, respectively (ii) Single aerobic degradation leads to 90, 80 and 35% of COD, TPh and aromatic compounds reduction, respectively (iii) Aerobic degradation followed by ozonation process leads to 98.57, 97.6 and 95.82% of COD, TPh and aromatic compounds reduction, respectively	Beltran-Heredia et al. (2000a)
Ozonation	Aerobic process	pH: 4–9 Temperature: 10–30 °C Treatment time: 4–6 h Ozone pressure: 4.36 and 4.48 kPa	(i) Single ozonation process leads to 24–33 and 30–67% of COD and TPh reduction, respectively (ii) Ozonation followed by aerobic degradation leads to 82 and 76% of COD and TPh reduction, respectively	Beltran-Heredia et al. (2000b)

(continued)

Table 10 | continued

Advanced oxidation processes	Biological processes	Experimental conditions	Main results	References
Ozonation	Aerobic process	pH: 4–10 Flow-rate: 20 L/h Acidic timing (min): 0–20, 155–165 Alkaline timing (min): 20–155, 165–180	(i) For TOPW, 87.4% of COD and 97.3% of TPh were removed (ii) For OMW, 99% of COD and 90% of TPh were removed	Rivas <i>et al.</i> (200c)
Ozonation, O ₃ /UV	Aerobic process	pH: 3 Temperature: 25 °C Treatment time: 4–6 h Flow-rate: 35 L/h	(i) Ozonation followed by aerobic degradation leads to 87% of COD reduction (ii) Aerobic degradation followed by ozonation process leads to 80% of COD reduction (iii) O ₃ /UV followed by aerobic degradation leads to 90.7% of COD reduction (iv) Aerobic degradation followed by O ₃ /UV leads to 81.8% of COD reduction	Lafi <i>et al.</i> (2009)
Ozonation	Anaerobic process	pH: 7.5 Temperature: 35 °C Biological treatment time: 55 days Ozonation time: 30–240 min Ozone pressure: 1–4.9 kPa Flow-rate: 90 L/h	(i) Anaerobic digestion resulted 81, 95, 95% and 295 L CH ₄ /kg COD of COD, BOD ₅ , TPh removal and methane yield coefficient, respectively (ii) Ozonation post treatment leads to 16–52% of COD and 68–89% of TPh reduction	Beltran de Heredia & Garcia (2005)
Ozonation	Encapsulated biomass	pH: 7–8.5 Temperature: 20–25 °C Treatment time: 1 h O ₃ – 48 h biotreatment Flow-rate: 1 L/min	(i) Ozonation alone leads to 20% COD and 61% TPh removal (ii) The combined process leads to 36% COD and 61% TPh removal	Oz <i>et al.</i> (2018)

Rivas *et al.* (2000) studied the treatment of TOPW and OMW by combined ozonation and aerobic biodegradation. For the first effluent, 87.4% of COD and 97.3% of TPh were removed, and for the second one 99 and 90% of COD and TPh removal, respectively, were reached. With a procedure similar to that developed above, Lafi *et al.* (2009) concluded that COD removal was 87% when using ozonation followed by aerobic digestion, and 90.7% of COD after O₃/UV followed by an aerobic process.

Beltran de Heredia & Garcia (2005) ran a continuous anaerobic digestion before the ozonation process in order to follow the evolution of COD, BOD₅, TPh concentration and methane production. The results achieved under the stable conditions during 55 days in the bioreactor proves that anaerobic biodegradation can be successfully used to remove 81% of COD, 95% of BOD₅ and TPh, with a gas production rate of 295 L CH₄/kg COD. When ozonation was implemented after anaerobic process, 16–52% of COD and 68–89% of TPh degradation was achieved after 4 h of treatment.

Recently, Oz *et al.* (2018) proposed a new combined system of ozonation process and encapsulated biomass. Their experimental results showed that up to 36% of COD and 61% of TPh were removed, through ozone pretreatment of OMWW followed by addition of *Delftia EROSY* capsules to OMW for 48 h incubation, which was greater than that obtained by the individual ozonation under the same operating conditions.

Combination with physico-chemical treatments

During the last decade, great concern has been raised over the combination of AOP with physico-chemical treatments, which offers another way to ameliorate the OMW detoxification. As has been confirmed in many publications, simple physical processes such as dilution, lagoons of evaporation, sedimentation, filtration and centrifugation, as well as physico-chemical processes including lime treatment, chemical coagulation-flocculation and adsorption, cannot attain high removal efficiencies. To overcome these limitations and improve process efficiency, a research program was designed with the aim of investigating the introduction of some AOP. Table 11 provides more details on a selected number of applications carried out by means of AOP combined with physico-chemical treatments.

Ginos *et al.* (2006) tested the use of coagulation–flocculation as pre-treatment of OMW followed by the Fenton process. This study yielded 99.7, 78.8 and 35.5% of TSS, TPh and COD reduction, respectively, while 98.7, 84.9 and 61.4% of TSS, TPh and COD were removed, respectively.

Lucas & Peres (2009b) conducted a similar study, but obtained different results. In the Fenton's process, almost 96.8% COD were removed, when the pH was 3.5, mass ratio $R = \text{H}_2\text{O}_2/\text{COD}$ was 3.0 and molar ration $\text{H}_2\text{O}_2/\text{Fe}^{2+}$ was 15. When coagulation/flocculation with lime was used as post-treatment in combination with the Fenton process, more than 99.3% of COD could be degraded effectively, for $R = \text{H}_2\text{O}_2/\text{COD} = 3.0$.

Gomec *et al.* (2007) also used the Fenton reagent in conjugation with acid cracking (AC), lime and anionic/cationic polyelectrolyte (AP, CP). After several combinations were tested, a maximum reduction of COD of 89% was obtained using Fenton's oxidation after AC and CP (10 ppm) treatment. In another research paper, the AC and Fenton process gave satisfactory treatment efficiencies of around 83, 98.6, 77, and 67% for COD, TPh, color and aromaticity, respectively (Madani *et al.* 2015). It was found also that the increase in temperature from 25 to 30 °C did not have a significant influence on the efficiency of the process.

More recently, the Fenton's reagent-ion exchange (IE) system has been studied for detoxification and reduction of pollutants in OMW. Reis *et al.* (2018) chose Lewatit TP 207 as anionic exchange resin. The Fenton's process removed 98.2% of TPh and the COD content by 80.7% in 1 h, while the combined system removed the Fe³⁺ completely compared to 35% of Fe²⁺, which allows the authors to conclude that this type of combination is able to avoid Fenton's main drawback, related to the production of large volumes of sludge.

An innovative application of battery comprising coagulation–flocculation, extraction of phenolic compounds and photo-Fenton post-oxidation of OMW was developed by Papaphilippou *et al.* (2013). The best results were achieved for the photo-Fenton oxidation after coagulation–flocculation and solvent extraction, which degraded 73% of COD and 87% of TPh at pH 3, 0.2 g/L Fe²⁺ and 5 g/L H₂O₂.

Yazdanbakhsh *et al.* (2015) evaluated the efficiency of the Fenton-like process, coagulation and acid cracking

Table 11 | Main results reported for the treatment of OMW by means of AOP combined with physico-chemical treatments

Advanced oxidation processes	Physico-chemical processes	Experimental conditions	Main results	References
Fenton's process	Coagulation–flocculation	pH: 5.1–5.3 [Fe ²⁺]: 2.5, 5 and 10 g/L [H ₂ O ₂]: 0.5, 1, 5 and 10 g/L. Lime concentration: 0–230 mg/L	(i) Coagulation–flocculation alone leads to 99.7, 78.8 and 35.5% of TSS, TPh and COD reduction, respectively (ii) The combined process leads to 98.7, 84.9 and 61.4% of TSS, TPh and COD reduction, respectively	Ginos <i>et al.</i> (2006)
Fenton's process	Coagulation/flocculation	pH: 3.5 Temperature: 30 °C H ₂ O ₂ /Fe ²⁺ : 15 H ₂ O ₂ /COD : 0.25–3	(i) In the Fenton's process, 96.8% of COD has been achieved (ii) A stronger COD reduction (99.3%) with the combined system	Lucas & Peres (2009a, 2009b)
Fenton's process	Acid cracking (AC) + lime + anionic/cationic polyelectrolyte (AP, CP)	pH: 1.7–9.2 [Fe ²⁺]: 2.5, 5 and 10 g/L [H ₂ O ₂]: 750 mg/L	(i) The pre-treatment by AC, AC + AP (5 ppm), AC + AP (10 ppm), lime and lime + AP (9 ppm) leads to a reduction of 72.5, 81.17, 73.85, 56.32 and 41.83% of COD, respectively (ii) Fenton's oxidation after AC and CP (10 ppm) treatment leads to 89% of COD removal	Gomec <i>et al.</i> (2007)
Fenton's process	Acid cracking (AC) + coagulation	pH: 1.5–3.5 treatment time: 4 h Temperature: 25 and 30 °C [H ₂ O ₂] = 0.12–0.5 M [Fe ²⁺] = 0.005–0.03 M	(i) AC removes 47.3, 30.1, 64.3, and 59.1% of COD, TPh, color, and aromaticity, respectively (ii) AC and Fenton process lead to 83, 98.6, 77, and 67% of COD, TPh, color and aromaticity, respectively (iii) The increase in temperature from 25 to 30 °C does not have a significant influence on the efficiency of the process	Madani <i>et al.</i> (2015)
Fenton's process	Ion exchange (IE)	pH: 1.5–4.5 [Fe ²⁺]: 0–5 g/L [H ₂ O ₂]: 0–6 g/L	(iv) In the Fenton's process, 80.7 and 98.2% of COD and TPh have been removed, respectively (v) The tested resin Lewatit TP 207 shows a higher affinity (100% of iron removal efficiency) toward Fe ³⁺ when compared with Fe ²⁺ (35%)	Reis <i>et al.</i> (2018)
Photo-Fenton process	Coagulation-flocculation and solvent extraction	pH: 3 Treatment time: 240 min [FeSO ₄ , 7H ₂ O]: 3.33, 5 and 6.67 g/L FLOCAN 23: 0.287, 0.07 and 0.14 [H ₂ O ₂]: 0, 3, 4, 5 and 6 g/L [Fe ²⁺]: 0, 0.2, 0.4 and 0.6 g/L	(i) The coagulation-flocculation leads to 97 ± 1.3, 72 ± 1.5, and 40 ± 1.3% of TSS, COD and TPh, respectively (ii) 36% of TPh recovery post-coagulation–flocculation was achieved by solvent extraction (iii) 73 ± 2.3 and 87 ± 3.1% removal efficiencies were achieved for COD and TPh, respectively, by combination with photo-Fenton process	Papaphilippou <i>et al.</i> (2013)

Fenton like process	Coagulation and acid cracking (AC)	pH: 1.5–4 Treatment time: 0–400 min Alum concentration: 1000–6000 mg/L Ferric chloride concentration : 1000–6000 mg/L Polyaluminum chloride concentration: 250–1500 mg/L [H ₂ O ₂]: 250–3000 mg/L Zero valent iron concentration: 1–11 g/L	(i) Coagulation process removed 91.2% COD, 91.3% TPh, 98.9% TSS and 99.2% turbidity (ii) The combined process increased the BOD ₅ /COD ratio from 0.14 to 0.83	Yazdanbakhsh <i>et al.</i> (2015)
Photocatalysis, Fenton and photo-Fenton process	Coagulation	pH: 4.3–6 Treatment time: 1–2 h [H ₂ O ₂]/[FeSO ₄] ratio = 6000/600 and 15,000/1,852 (w/w) Coagulant dose: 0–600 mg/L	(i) Coagulation by chitosan was shown to remove 81% of TSS (ii) The combined photo-Fenton/coagulation system was found to be more efficient for COD removal (91%) compared to Fenton one (81%)	Rizzo <i>et al.</i> (2008)
Photo-Fenton Fenton process	Acidification/coagulation/flocculation	pH: 2.6 and 4.6 [H ₂ O ₂]: 0, 15 and 30 g/L [Fe ²⁺]: 0, 2, 6 and 10 Mm Coagulant dose: 0, 0.25 and 1 (w/w)	(i) The acidification followed by Fenton process leads to 15 and 60% of COD and TPh removal, respectively (ii) The acidification/coagulation/flocculation/Photo-Fenton system leads to 75 and 100% of COD and TPh removal, respectively	Gernjak <i>et al.</i> (2007)
Ozonation Photo-Fenton process (Fe(III)/air/solar light)	Centrifugation	pH: 3 Treatment time: 60, 90 and 120 min Flow-rate: 36 L/h	(i) The pre-treatment by centrifugation leads to a reduction of 41.3% of COD (ii) Ozonation alone leads to 31.5 and 63.6% of COD and TPh removal, respectively (iii) Air/light with Fe(III)/Ozonation system leads to 40.3 and 75% of COD and TPh removal, respectively	Andreozzi <i>et al.</i> (2008)
UV/H ₂ O ₂	Lime treatment	pH: 7 Temperature: 25 °C Treatment time: 7 days H ₂ O ₂ (30%) doses: 1–10 mL/100 mL OMW	(i) 90% of color, 90% of phenol and 30% of lignin were removed by single UV/H ₂ O ₂ (ii) The combination with lime yielded 99, 100 and 40% of color, phenol and lignin removals, respectively	Uğurlu & Kula (2007)
UV/H ₂ O ₂	Ultrafiltration (UF)	pH: 4.5 Temperature: 27–37 °C [H ₂ O ₂] = 2*10 ⁻² M	(i) 94 and 100% of COD and TSS removal by using UF alone (ii) In the combined process, 75% of the initial absorbance vanished after 40 min of irradiation	Drouiche <i>et al.</i> (2004)

(continued)

Table 11 | continued

Advanced oxidation processes	Physico-chemical processes	Experimental conditions	Main results	References
H ₂ O ₂ /UV O ₃ /UV	Acid cracking (AC) + ferric coagulation	pH: 2–8 Treatment time: 400–1,440 min [H ₂ O ₂]: 750 mg/L Ozone flow-rate: 0.3 g/h	(i) For acid cracking + ferric coagulation + O ₃ /UV system, 98 and 99% of COD and TPh removal have been reached, respectively (ii) For acid cracking + ferric coagulation H ₂ O ₂ /UV system, 99% of both COD and TPh removal has been reached	Kestioglu <i>et al.</i> (2005)
UV, O ₃ , O ₃ /UV and H ₂ O ₂ /UV	Coagulation/flocculation	pH: 5.6–9 Treatment time: 15, 30, 45, 60 and 90 min [H ₂ O ₂]: 2% Ozone flow-rate: 40 dm ³ /h	(i) Over 10, 19, 37 and 39% of COD were removed by UV, O ₃ , O ₃ /UV and H ₂ O ₂ /UV process (ii) The combined systems coagulation/O ₃ , coagulation/O ₃ -UV and coagulation/H ₂ O ₂ /UV lead to COD reduction rates of 90, 95 and 94%, respectively	Lafi <i>et al.</i> (2010)

(AC) for the treatment of OMW. They found 91.2% COD, 91.3% TPh, 98.9% TSS and 99.2% turbidity removals with a single coagulation stage. After the application of the Fenton-like process with zero valent iron (ZVI) preceded by coagulation and acid cracking pre-treatment, the BOD₅/COD ratio was increased from 0.14 to 0.83.

Rizzo *et al.* (2008) first introduced chitosan as a new coagulant agent to improve removal efficiencies, reaching 81% of TSS removal at natural pH 4.3 and 400 mg chitosan/L. A combined photo-Fenton/coagulation system was then applied to achieve 91% of COD abatement compared to Fenton (81%). Gernjak *et al.* (2007) could not achieve more than 15% of COD and 60% of TPh removal using acidification followed by the Fenton process. Greater COD removal of 75% and total dephenolization were observed by coupling acidification, coagulation/flocculation and photo-Fenton processes. By considering the physical pre-treatment of OMW for COD removal within centrifugation, Andreozzi *et al.* (2008) found that 41.3% COD was obtained, and after 120 min of treatment with ozone, COD was increased to 31.5% with 63.6% of TPh removal. Moreover, they concluded that air/light with a Fe(III)/Ozonation system was able to reduce the COD and TPh; 40.3 and 75%, respectively.

Many authors have reported high removals of organic pollutants of OMW by coupling photolysis of H₂O₂ with other physico-chemical processes. Ugurlu & Kula (2007) showed that approximately 99% removal of color, 100% of phenols and 40% of lignin could be achieved by a combination of UV/H₂O₂ and lime. Drouiche *et al.* (2004) achieved 94 and 100% of COD and TSS removal using an ultrafiltration process (UF) alone. In addition, it has been shown that the use of a UV/H₂O₂ process in combination with UF allows the permeate treatment in batch and continuous modes to be completed after 40 min of irradiation.

Kestioglu *et al.* (2005) examined the utilization of both H₂O₂/UV and O₃/UV oxidation processes combined with acid cracking and ferric coagulation. The results suggested that 99% of both COD and TPh removal efficiencies could be achieved by an acid cracking + ferric coagulation + H₂O₂/UV system at pH 7, T = 20 °C and 440 min treatment time, while for the other system acid cracking + ferric coagulation + O₃/UV, 98% of COD and 99% of TPh removal has been reached. On the other

hand, Lafi *et al.* (2010) tried to integrate a treatment involving a combination of UV, O₃, O₃/UV, H₂O₂/UV and coagulation process to remove the organic loads of OMW. In this work, a degradation degree of 10, 19, 37 and 39% of COD were removed by UV, O₃, O₃/UV and H₂O₂/UV processes, whereas using the combined systems, coagulation/O₃, coagulation/O₃-UV and coagulation/H₂O₂/UV, led to COD reduction rates of 90, 95 and 94%, respectively.

CONCLUSIONS

The growth of the olive sector around the world over the last decade, combined with an increase in the use of vast amounts of water, has contributed to the large amount of OMW being generated. Different methods to reduce the organic load of OMW have been studied. Among these techniques, AOPs have been successfully applied to achieve a complete detoxification of OMW. These include chemical AOP (Fe²⁺/Fe³⁺/H₂O₂, O₃/H₂O₂, wet air oxidation and catalytic wet air oxidation), photochemical AOP (H₂O₂/UV, O₃/UV, H₂O₂/Fe²⁺ (Fe³⁺)/UV, H₂O₂/O₃/UV, Fe³⁺/UV and TiO₂/UV), sonochemical AOP and electrochemical AOP (anodic oxidation and electro-Fenton) as well as combined systems. This review presents recent information on detoxification of OMW by AOP, either alone or in combination with other methods.

In general, among the combined physical, biological and chemical processes used to decontaminate OMW, the choice of the most appropriate treatment is based on several factors: simplicity, safety, energy efficiency, waste sludge production and operating cost. Given the drawbacks of biological methods, such as the need to dilute many times the effluent, thus increasing their effectiveness, aerobic and anaerobic digestion remains the most convenient technique and least expensive wastewater treatment method, which makes their combination with AOP a suitable solution for the removal of toxic organic pollutants from OMW.

In conclusion, further investigation is required on techno-economical evaluation for future industrialization, as well as studies in reactor design and application.

Consequently, great efforts should be made to scale-up AOP experiments from laboratory to industrial size.

REFERENCES

- Abedinzadeh, N., Shariat, M., Monavari, S. M. & Pendashteh, A. 2018 Evaluation of color and COD removal by Fenton from biologically (SBR) pre-treated pulp and paper wastewater. *Process Saf. Environ. Prot.* **116**, 82–91.
- Adhoum, N. & Monser, L. 2004 Decolourization and removal of phenolic compounds from olive mill wastewater by electrocoagulation. *Chem. Eng. Process. Process. Intens.* **43** (10), 1281–1287.
- Ahmed, B., Limem, E., Abdel-Wahab, A. & Nasr, B. 2011 Photo-Fenton treatment of actual agro-industrial wastewaters. *Industrial & Engineering Chemistry Research* **50** (11), 6673–6680.
- Al-Essa, K. 2018 Activation of Jordanian bentonite by hydrochloric acid and its potential for olive mill wastewater enhanced treatment. *J. Chem.* **2018**, 1–10.
- Almasi, A., Mosavi, A., Mohammadi, M., Azemnia, S., Godini, K., Zarei, A., Mohammadi, S. & Saleh, E. 2016 Efficiency of integrated ultrasonic and anaerobic digestion of oil refinery wastewater sludge. *Glob. NEST J.* **18** (4), 771–777.
- Aly, A. A., Alashgar, K. N., Al-Farraj, A. S. & Ibrahim, H. M. 2018 Contaminants and salinity removal of olive mill wastewater using zeolite nanoparticles. *Separ. Sci. Technol.* **53** (11), 1638–1653.
- Amaral, C., Lucas, M. S., Coutinho, J., Crespí, A. L., do Rosário Anjos, M. & Pais, C. 2008 Microbiological and physicochemical characterization of olive mill wastewaters from a continuous olive mill in Northeastern Portugal. *Bioresour. Technol.* **99** (15), 7215–7223.
- Amaral-Silva, N., Martins, R. C., Nunes, P., Castro-Silva, S. & Quinta-Ferreira, R. M. 2017 From a lab test to industrial application: scale-up of Fenton process for real olive mill wastewater treatment. *J. Chem. Technol. Biotechnol.* **92** (6), 1336–1344.
- Amor, C., Lucas, M. S., García, J., Dominguez, J. R., De Heredia, J. B. & Peres, J. A. 2015 Combined treatment of olive mill wastewater by Fenton's reagent and anaerobic biological process. *J. Environ. Sci. Health A* **50** (2), 161–168.
- Amr, S. S. A., Aziz, H. A., Bashir, M. J., Aziz, S. Q. & Alslaibi, T. M. 2016 Comparison and optimization of ozone-based advanced oxidation processes in the treatment of stabilized landfill leachate. *J. Eng. Res. Technol.* **2** (2), 122–130.
- Andreozzi, R., Longo, G., Majone, M. & Modesti, G. 1998 Integrated treatment of olive oil mill effluents (OME): study of ozonation coupled with anaerobic digestion. *Water Res.* **32** (8), 2357–2364.
- Andreozzi, R., Canterino, M., Di Somma, I., Giudice, R. L., Marotta, R., Pinto, G. & Pollio, A. 2008 Effect of combined physico-chemical processes on the phytotoxicity of olive mill wastewaters. *Water Res.* **42** (6–7), 1684–1692.

- Arslan, A., Topkaya, E., Bingöl, D. & Veli, S. 2018 Removal of anionic surfactant sodium dodecyl sulfate from aqueous solutions by O₃/UV/H₂O₂ advanced oxidation process: process optimization with response surface methodology approach. *Sustain. Environ. Res.* **28** (2), 65–71.
- Arslan-Alaton, I. & Seremet, O. 2004 Advanced treatment of biotreated textile industry wastewater with ozone, virgin/ozonated granular activated carbon and their combination. *J. Environ. Sci. Health A* **39** (7), 1681–1694.
- Ashraf, M. I., Ateeb, M., Khan, M. H., Ahmed, N. & Mahmood, Q. 2016 Integrated treatment of pharmaceutical effluents by chemical coagulation and ozonation. *Separ. Purif. Technol.* **158**, 385–386.
- Atanassova, D., Kefalas, P., Petrakis, C., Mantzavinos, D., Kalogerakis, N. & Psillakis, E. 2005 Sonochemical reduction of the antioxidant activity of olive mill wastewater. *Environ. Int.* **31** (2), 281–287.
- Ayoub, S., Al-Absi, K., Al-Shdiefat, S., Al-Majali, D. & Hijazeen, D. 2014 Effect of olive mill wastewater land-spreading on soil properties, olive tree performance and oil quality. *Sci. Horticul.* **175**, 160–166.
- Azabou, S., Najjar, W., Bouaziz, M., Ghorbel, A. & Sayadi, S. 2010 A compact process for the treatment of olive mill wastewater by combining wet hydrogen peroxide catalytic oxidation and biological techniques. *J. Hazard. Mater.* **183** (1–3), 62–69.
- Aziz, A. A. & Daud, W. M. A. W. 2012 Oxidative mineralisation of petroleum refinery effluent using Fenton-like process. *Chem. Eng. Res. Des.* **90** (2), 298–307.
- Azzam, M. O. 2018 Olive mills wastewater treatment using mixed adsorbents of volcanic tuff, natural clay and charcoal. *J. Environ. Chem. Eng.* **6** (2), 2126–2136.
- Azzam, M. O. J., Al-Malah, K., Al-Gazzawi, Z. & Al-Omari, S. A. 2010 Dynamic treatment response of olive mills wastewater using series of adsorption steps. *Clean* **38** (9), 822–830.
- Azzam, M. O., Al-Gharabli, S. I. & Al-Harashsheh, M. S. 2015 Olive mills wastewater treatment using local natural Jordanian clay. *Desal. Water Treat.* **53** (3), 627–636.
- Babaei, A. A., Kakavandi, B., Rafiee, M., Kalantarhormizi, F., Purkaram, I., Ahmadi, E. & Esmaeili, S. 2017 Comparative treatment of textile wastewater by adsorption, Fenton, UV-Fenton and US-Fenton using magnetic nanoparticles-functionalized carbon (MNPs@C). *J. Ind. Eng. Chem.* **56**, 163–174.
- Babuponnusami, A. & Muthukumar, K. 2014 A review on Fenton and improvements to the Fenton process for wastewater treatment. *J. Environ. Chem. Eng.* **2** (1), 557–572.
- Badawy, M. I., Gohary, F. E., Ghaly, M. Y. & Ali, M. E. M. 2009 Enhancement of olive mill wastewater biodegradation by homogeneous and heterogeneous photocatalytic oxidation. *J. Hazard. Mater.* **169** (1–3), 673–679.
- Baiju, A., Gandhimathi, R., Ramesh, S. T. & Nidheesh, P. V. 2018 Combined heterogeneous Electro-Fenton and biological process for the treatment of stabilized landfill leachate. *J. Environ. Manage.* **210**, 328–337.
- Bampalioutas, K., Vlysidis, A., Lyberatos, G. & Vlyssides, A. 2019 Detoxification and methane production kinetics from three-phase olive mill wastewater using Fenton's reagent followed by anaerobic digestion. *J. Chem. Technol. Biotechnol.* **94** (1), 265–275.
- Baransi, K., Dubowski, Y. & Sabbah, I. 2012 Synergetic effect between photocatalytic degradation and adsorption processes on the removal of phenolic compounds from olive mill wastewater. *Water Res.* **46** (3), 789–798.
- Barge, A. S. & Vaidya, P. D. 2018 Wet air oxidation of cresylic spent caustic – A model compound study over graphene oxide (GO) and ruthenium/GO catalysts. *J. Environ. Manage.* **212**, 479–489.
- Bassyouni, D. G., Hamad, H. A., El-Ashtoukhy, E. Z., Amin, N. K. & El-Latif, M. A. 2017 Comparative performance of anodic oxidation and electrocoagulation as clean processes for electrocatalytic degradation of diazo dye Acid Brown 14 in aqueous medium. *J. Hazard. Mater.* **335**, 178–187.
- Belaid, C., Kallel, M., Khadhraou, M., Lalleve, G., Elleuch, B. & Fauvarque, J. F. 2006 Electrochemical treatment of olive mill wastewaters: removal of phenolic compounds and decolourization. *J. Appl. Electrochem.* **36** (10), 1175–1182.
- Belqiz, M., El-Abbassi, A., Lakhali, E. K., Agrafioti, E. & Galanakis, C. M. 2016 Agronomic application of olive mill wastewater: effects on maize production and soil properties. *J. Environ. Manage.* **171**, 158–165.
- Bellakhal, N., Oturan, M. A., Oturan, N. & Dachraoui, M. 2006 Olive oil mill wastewater treatment by the electro-Fenton process. *Environ. Chem.* **3** (5), 345–349.
- Beltrán, F. J., García-Araya, J. F., Frades, J., Alvarez, P. & Gimeno, O. 1999 Effects of single and combined ozonation with hydrogen peroxide or UV radiation on the chemical degradation and biodegradability of debittering table olive industrial wastewaters. *Water Res.* **33** (3), 723–732.
- Beltran de Heredia, J. & Garcia, J. 2005 Process integration: continuous anaerobic digestion– ozonation treatment of olive mill wastewater. *Ind. Eng. Chem. Res.* **44** (23), 8750–8755.
- Beltran-Heredia, J., Torregrosa, J., Dominguez, J. R. & Garcia, J. 2000a Treatment of black-olive wastewaters by ozonation and aerobic biological degradation. *Water Res.* **34** (14), 3515–3522.
- Beltran-Heredia, J., Torregrosa, J., Dominguez, J. R. & Garcia, J. 2000b Aerobic biological treatment of black table olive washing wastewaters: effect of an ozonation stage. *Process Biochem.* **35** (10), 1183–1190.
- Beltran-Heredia, J., Torregrosa, J., Garcia, J., Domínguez, J. R. & Tierno, J. C. 2001 Degradation of olive mill wastewater by the combination of Fenton's reagent and ozonation processes with an aerobic biological treatment. *Water Sci. Technol.* **44** (5), 103–108.
- Benitez, F. J., Beltran-Heredia, J., Torregrosa, J., Acero, J. L. & Cercas, V. 1997a Chemical pretreatment by ozone of wastewaters from olive oil mills. *Toxicol. Environ. Chem.* **60** (1–4), 97–109.

- Benitez, F. J., Beltran-Heredia, J., Torregrosa, J. & Acero, J. L. 1997b Treatments of wastewaters from olive oil mills by UV radiation and by combined ozone-UV radiation. *Toxicol. Environ. Chem.* **61** (1–4), 173–185.
- Benitez, F. J., Beltran-Heredia, J., Torregrosa, J. & Acero, J. L. 1999a Treatment of olive mill wastewaters by ozonation, aerobic degradation and the combination of both treatments. *J. Chem. Technol. Biotechnol.* **74** (7), 639–646.
- Benitez, F. J., Beltran-Heredia, J., Torregrosa, J. & Dominguez, J. R. 1999b Aerobic treatment of black olive wastewater and the effect of an ozonation stage. *Bioprocess Eng.* **20** (4), 355–361.
- Benitez, F. J., Acero, J. L., Gonzalez, T. & Garcia, J. 2001a Organic matter removal from wastewaters of the black olive industry by chemical and biological procedures. *Process Biochem.* **37** (3), 257–265.
- Benitez, F. J., Acero, J. L., Gonzalez, T. & Garcia, J. 2001b Ozonation and biodegradation processes in batch reactors treating black table olives washing wastewaters. *Ind. Eng. Chem. Res.* **40** (14), 3144–3151.
- Benitez, F. J., Acero, J. L., Gonzalez, T. & Garcia, J. 2002 The use of ozone, ozone plus UV radiation, and aerobic microorganisms in the purification of some agro-industrial wastewaters. *J. Environ. Sci. Health A* **37** (7), 1307–1325.
- Bilińska, L., Gmurek, M. & Ledakowicz, S. 2017 Textile wastewater treatment by AOPs for brine reuse. *Process Saf. Environ. Prot.* **109**, 420–428.
- Bonfante de Carvalho, C., Espina de Franco, M., Souza, F. S. & Féris, L. A. 2018 Degradation of acid black 210 by advanced oxidative processes: O₃ and O₃/UV. *Ozone Sci. Eng.* **40** (5), 372–376.
- Bouhssine, I., Tazi, A. & Azzi, M. 2013 Treatment of olive mill wastewater by electrolysis on boron doped diamond (BDD) electrode. *J. Mater. Environ. Sci.* **4**, 354–361.
- Bouknaana, D., Hammouti, B., Salghi, R., Jodeh, S., Zarrouk, A., Warad, I., Aouniti, A. & Sbaa, M. 2014 Physicochemical characterization of olive oil mill wastewaters in the eastern region of Morocco. *J. Mater. Environ. Sci.* **5** (4), 1039–1058.
- Bourgin, M., Borowska, E., Helbing, J., Hollender, J., Kaiser, H. P., Kienle, C., McArdell, C. S., Simon, E. & Von Gunten, U. 2017 Effect of operational and water quality parameters on conventional ozonation and the advanced oxidation process O₃/H₂O₂: kinetics of micropollutant abatement, transformation product and bromate formation in a surface water. *Water Res.* **122**, 234–245.
- Buchmann, C., Felten, A., Peikert, B., Muñoz, K., Bandow, N., Dag, A. & Schaumann, G. E. 2015 Development of phytotoxicity and composition of a soil treated with olive mill wastewater (OMW): an incubation study. *Plant Soil* **386** (1–2), 99–112.
- Burgos-Castillo, R. C., Sirés, I., Sillanpää, M. & Brillas, E. 2018 Application of electrochemical advanced oxidation to bisphenol A degradation in water. Effect of sulfate and chloride ions. *Chemosphere* **194**, 812–820.
- Bustillo-Lecompte, C. F., Kakar, D. & Mehrvar, M. 2018 Photochemical treatment of benzene, toluene, ethylbenzene, and xylenes (BTEX) in aqueous solutions using advanced oxidation processes: towards a cleaner production in the petroleum refining and petrochemical industries. *J. Clean. Prod.* **186**, 609–617.
- Canizares, P., Diaz, M., Dominguez, J. A., Garcia-Gomez, J. & Rodrigo, M. A. 2002 Electrochemical oxidation of aqueous phenol wastes on synthetic diamond thin-film electrodes. *Ind. Eng. Chem. Res.* **41** (17), 4187–4194.
- Canizares, P., Garcia-Gomez, J., Lobato, J. & Rodrigo, M. A. 2003a Electrochemical oxidation of aqueous carboxylic acid wastes using diamond thin-film electrodes. *Ind. Eng. Chem. Res.* **42** (5), 956–962.
- Canizares, P., Garcia-Gomez, J., Saez, C. & Rodrigo, M. A. 2003b Electrochemical oxidation of several chlorophenols on diamond electrodes Part I. Reaction mechanism. *J. Appl. Electrochem.* **33** (10), 917–927.
- Canizares, P., Garcia-Gomez, J., Saez, C. & Rodrigo, M. A. 2004a Electrochemical oxidation of several chlorophenols on diamond electrodes: part II. Influence of waste characteristics and operating conditions. *J. Appl. Electrochem.* **34** (1), 87–94.
- Canizares, P., Lobato, J., Garcia-Gomez, J. & Rodrigo, M. A. 2004b Combined adsorption and electrochemical processes for the treatment of acidic aqueous phenol wastes. *J. Appl. Electrochem.* **34** (1), 111–117.
- Canizares, P., Saez, C., Lobato, J. & Rodrigo, M. A. 2004c Electrochemical treatment of 4-nitrophenol-containing aqueous wastes using boron-doped diamond anodes. *Ind. Eng. Chem. Res.* **43** (9), 1944–1951.
- Canizares, P., Saez, C., Lobato, J. & Rodrigo, M. A. 2004d Electrochemical treatment of 2, 4-dinitrophenol aqueous wastes using boron-doped diamond anodes. *Electrochim. Acta* **49** (26), 4641–4650.
- Canizares, P., Saez, C., Lobato, J. & Rodrigo, M. A. 2004e Electrochemical oxidation of polyhydroxybenzenes on boron-doped diamond anodes. *Ind. Eng. Chem. Res.* **43** (21), 6629–6637.
- Canizares, P., Lobato, J., Paz, R., Rodrigo, M. A. & Sáez, C. 2005 Electrochemical oxidation of phenolic wastes with boron-doped diamond anodes. *Water Res.* **39** (12), 2687–2703.
- Canizares, P., Lobato, J., Paz, R., Rodrigo, M. A. & Sáez, C. 2007a Advanced oxidation processes for the treatment of olive-oil mills wastewater. *Chemosphere* **67** (4), 832–838.
- Canizares, P., Lobato, J., Paz, R., Rodrigo, M. A. & Sáez, C. 2007b Advanced oxidation processes for the treatment of olive-oil mills wastewater. *Chemosphere* **67** (4), 832–838.
- Canizares, P., Paz, R., Sáez, C. & Rodrigo, M. A. 2009 Costs of the electrochemical oxidation of wastewaters: a comparison with ozonation and Fenton oxidation processes. *J. Environ. Manage.* **90** (1), 410–420.
- Casanovas, A., Galvis, A. & Llorca, J. 2015 Catalytic steam reforming of olive mill wastewater for hydrogen production. *Int. J. Hydrogen Energy* **40** (24), 7539–7545.

- Cassano, A., Conidi, C., Giorno, L. & Drioli, E. 2013 Fractionation of olive mill wastewaters by membrane separation techniques. *J. Hazard. Mater.* **248**, 185–193.
- Cassano, A., Conidi, C., Galanakis, C. M. & Castro-Muñoz, R. 2016 Recovery of polyphenols from olive mill wastewaters by membrane operations. In: *Membrane Technologies for Biorefining*. Woodhead Publishing, Sawston, CA, USA, pp. 163–187.
- Catastini, C., Sarakha, M., Mailhot, G. & Bolte, M. 2002 Iron (III) aquacomplexes as effective photocatalysts for the degradation of pesticides in homogeneous aqueous solutions. *Sci. Total Environ.* **298** (1), 219–228.
- Cebeci, M. S., Senturk, I. & Guvenin, U. 2016 Investigation of aerobic degradation of industrial wastewater containing high organic matter: kinetic study. *Eur. Sci. J.* **12** (10), 124–132.
- Čehovin, M., Medic, A., Scheideler, J., Mielcke, J., Ried, A., Kompare, B. & Gotvajn, A. Ž. 2017 Hydrodynamic cavitation in combination with the ozone, hydrogen peroxide and the UV-based advanced oxidation processes for the removal of natural organic matter from drinking water. *Ultrasonics Sonochem.* **37**, 394–404.
- Cerreta, G., Roccamante, M. A., Oller, I., Malato, S. & Rizzo, L. 2019 Contaminants of emerging concern removal from real wastewater by UV/free chlorine process: a comparison with solar/free chlorine and UV/H₂O₂ at pilot scale. *Chemosphere* **236**, 1–10.
- Chatzisympson, E., Dimou, A., Mantzavinos, D. & Katsaounis, A. 2009a Electrochemical oxidation of model compounds and olive mill wastewater over DSA electrodes: 1. The case of Ti/irO₂ anode. *J. Hazard. Mater.* **167** (1–3), 268–274.
- Chatzisympson, E., Xekoukoulotakis, N. P., Diamadopoulos, E., Katsaounis, A. & Mantzavinos, D. 2009b Boron-doped diamond anodic treatment of olive mill wastewaters: statistical analysis, kinetic modeling and biodegradability. *Water Res.* **43** (16), 3999–4009.
- Chatzisympson, E., Xekoukoulotakis, N. P. & Mantzavinos, D. 2009c Determination of key operating conditions for the photocatalytic treatment of olive mill wastewaters. *Catalysis Today* **144** (1–2), 143–148.
- Chedeville, O., Debaq, M. & Porte, C. 2009 Removal of phenolic compounds present in olive mill wastewaters by ozonation. *Desalination* **249** (2), 865–869.
- Chen, W., Luo, Y., Ran, G. & Li, Q. 2019 An investigation of refractory organics in membrane bioreactor effluent following the treatment of landfill leachate by the O₃/H₂O₂ and MW/PS processes. *Waste Manage.* **97**, 1–9.
- Cheng, M., Zeng, G., Huang, D., Lai, C., Xu, P., Zhang, C., Liu, Y., Wan, J., Gong, X. & Zhu, Y. 2016 Degradation of atrazine by a novel Fenton-like process and assessment the influence on the treated soil. *J. Hazard. Mater.* **312**, 184–191.
- Chu, Y. Y., Qian, Y., Wang, W. J. & Deng, X. L. 2012 A dual-cathode electro-Fenton oxidation coupled with anodic oxidation system used for 4-nitrophenol degradation. *J. Hazard. Mater.* **199**, 179–185.
- Costa, J. C. & Alves, M. M. 2013 Posttreatment of olive mill wastewater by immobilized TiO₂ photocatalysis. *Photochem. Photobiol.* **89** (3), 545–551.
- Cruz-Rizo, A., Gutiérrez-Granados, S., Salazar, R. & Peralta-Hernández, J. M. 2017 Application of electro-Fenton/BDD process for treating tannery wastewaters with industrial dyes. *Separ. Purif. Technol.* **172**, 296–302.
- Davarnejad, R., Pirhadi, M., Mohammadi, M. & Arpanahzadeh, S. 2015 Numerical analysis of petroleum refinery wastewater treatment using electro-Fenton process. *Chem. Prod. Process Model.* **10** (1), 11–16.
- Değermenci, N., Cengiz, İ., Yildiz, E. & Nuhoglu, A. 2016 Performance investigation of a jet loop membrane bioreactor for the treatment of an actual olive mill wastewater. *J. Environ. Manage.* **184**, 441–447.
- Deligiorgis, A., Xekoukoulotakis, N. P., Diamadopoulos, E. & Mantzavinos, D. 2008 Electrochemical oxidation of table olive processing wastewater over boron-doped diamond electrodes: treatment optimization by factorial design. *Water Res.* **42** (4–5), 1229–1237.
- De Ursinos, J. F. R. & Padilla, R. B. 1992 Use and treatment of olive mill wastewater: current situation and prospects in Spain. *Grasas Y Aceites* **43** (2), 101–106.
- Diya'uddeen, B. H., Poursan, S. R., Aziz, A. A. & Daud, W. W. 2015 Fenton oxidative treatment of petroleum refinery wastewater: process optimization and sludge characterization. *RSC Adv.* **5** (83), 68159–68168.
- Drouiche, M., Le Mignot, V., Lounici, H., Belhocine, D., Grib, H., Paus, A. & Mameri, N. 2004 A compact process for the treatment of olive mill wastewater by combining OF and UV/H₂O₂ techniques. *Desalination* **169** (1), 81–88.
- Ebrahim, S. E., Van Hulle, S. & Sheikha, I. A. 2018 Removal of pharmaceuticals from synthetic wastewater by ozone. *Assoc. Arab Univ. J. Eng. Sci.* **25** (4), 174–184.
- El-Abbassi, A., Khayet, M. & Hafidi, A. 2011 Micellar enhanced ultrafiltration process for the treatment of olive mill wastewater. *Water Res.* **45** (15), 4522–4530.
- El-Gohary, F. A., Badawy, M. I., El-Khateeb, M. A. & El-Kalliny, A. S. 2009 Integrated treatment of olive mill wastewater (OMW) by the combination of Fenton's reaction and anaerobic treatment. *J. Hazard. Mater.* **162** (2), 1536–1541.
- El Hajjouji, H., Barje, F., Pinelli, E., Bailly, J. R., Richard, C., Winterton, P., Revel, J. C. & Hafidi, M. 2008 Photochemical UV/TiO₂ treatment of olive mill wastewater (OMW). *Bioresour. Technol.* **99** (15), 7264–7269.
- Elkacmi, R., Kamil, N., Bennajah, M. & Kitane, S. 2016a Extraction of oleic acid from Moroccan olive mill wastewater. *BioMed Res. Int.* **2016**, 1–9.
- Elkacmi, R., Kamil, N., Boulmal, N. & Bennajah, M. 2016b Experimental investigations of oleic acid separation from olive oil and olive mill wastewater: a comparative study. *J. Mater. Environ. Sci.* **7**, 1485–1494.
- Elkacmi, R., Boulmal, N., Kamil, N. & Bennajah, M. 2017a Techno-economical evaluation of a new technique for olive mill wastewater treatment. *Sustain. Product. Consumpt.* **10**, 38–49.

- Elkacmi, R., Kamil, N. & Bennajah, M. 2017b Separation and purification of high purity products from three different olive mill wastewater samples. *J. Environ. Chem. Eng.* **5** (1), 829–837.
- Elkacmi, R., Kamil, N. & Bennajah, M. 2017c Upgrading of Moroccan olive mill wastewater using electrocoagulation: kinetic study and process performance evaluation. *J. Urban Environ. Eng. (JUEE)* **11** (1), 30–41.
- Elkacmi, R. & Bennajah, M. 2019 New techniques for treatment and recovery of valuable products from olive mill wastewater. *Handbook of Environmental Materials Management*. (C. M. Hussain, ed.). Springer, pp. 1–20.
- Esfandyari, Y., Mahdavi, Y., Seyedsalehi, M., Hoseini, M., Safari, G. H., Ghozikali, M. G., Kamani, H. & Jaafari, J. 2015 Degradation and biodegradability improvement of the olive mill wastewater by peroxi-electrocoagulation/electrooxidation-electroflotation process with bipolar aluminum electrodes. *Environ. Sci. Pollut. Res.* **22** (8), 6288–6297.
- Esteves, B. M., Rodrigues, C. S. & Madeira, L. M. 2017 Synthetic olive mill wastewater treatment by Fenton's process in batch and continuous reactors operation. *Environ. Sci. Pollut. Res.* **25**, 34,826–34,838.
- Esteves, B. M., Rodrigues, C. S., Maldonado-Hódar, F. J. & Madeira, L. M. 2019 Treatment of high-strength olive mill wastewater by combined Fenton-like oxidation and coagulation/flocculation. *J. Environ. Chem. Eng.* **7** (4), 1–12.
- Fajardo, A. S., Seca, H. F., Martins, R. C., Corceiro, V. N., Freitas, I. F., Quinta-Ferreira, M. E. & Quinta-Ferreira, R. M. 2017 Electrochemical oxidation of phenolic wastewaters using a batch-stirred reactor with NaCl electrolyte and Ti/ruo2 anodes. *J. Electroanal. Chem.* **785**, 180–189.
- Ferreira, R., Gomes, J., Martins, R. C., Costa, R. & Quinta-Ferreira, R. M. 2018 Winery wastewater treatment by integrating Fenton's process with biofiltration by *Corbicula fluminea*. *J. Chem. Technol. Biotechnol.* **93** (2), 333–339.
- Flores, N., Cabot, P. L., Centellas, F., Garrido, J. A., Rodríguez, R. M., Brillas, E. & Sirés, I. 2017 4-Hydroxyphenylacetic acid oxidation in sulfate and real olive oil mill wastewater by electrochemical advanced processes with a boron-doped diamond anode. *J. Hazard. Mater.* **321**, 566–575.
- Frank, S. N. & Bard, A. J. 1977 Heterogeneous photocatalytic oxidation of cyanide and sulfite in aqueous solutions at semiconductor powders. *J. Phys. Chem.* **81** (15), 1484–1488.
- Fujishima, A. & Honda, K. 1972 Electrochemical photolysis of water at a semiconductor electrode. *Nature* **238** (5358), 37–38.
- Galanakis, C. M., Tornberg, E. & Gekas, V. 2010 Dietary fiber suspensions from olive mill wastewater as potential fat replacements in meatballs. *LWT-Food Sci. Technol.* **43** (7), 1018–1025.
- Galliou, F., Markakis, N., Fountoulakis, M. S., Nikolaidis, N. & Manios, T. 2018 Production of organic fertilizer from olive mill wastewater by combining solar greenhouse drying and composting. *Waste Manage.* **75**, 305–311.
- García, J. & Beltran-Heredia, J. 2008 Chemical treatment by Fenton's reagent oxidation and ozonation of wastewaters from olive oil mill. *J. Adv. Oxid. Technol.* **11** (3), 568–572.
- García, C. A. & Hodaifa, G. 2017 Real olive oil mill wastewater treatment by photo-Fenton system using artificial ultraviolet light lamps. *J. Clean. Prod.* **162**, 743–753.
- García, I. G., Pena, P. J., Venceslada, J. B., Martín, A. M., Santos, M. M. & Gomez, E. R. 2000 Removal of phenol compounds from olive mill wastewater using *Phanerochaete chrysosporium*, *Aspergillus niger*, *Aspergillus terreus* and *Geotrichum candidum*. *Process Biochem.* **35** (8), 751–758.
- García-Ballesteros, S., Mora, M., Vicente, R., Vercher, R. F., Sabater, C., Castillo, M. A., Amat, A. M. & Arques, A. 2019 A new methodology to assess the performance of AOPs in complex samples: application to the degradation of phenolic compounds by O₃ and O₃/UV-A-Vis. *Chemosphere* **222**, 114–123.
- García García, P., Garrido Fernández, A., Chakman, A., Lemonier, J. P., Overend, R. P. & Chornet, E. 1990 Application of the jet-reactor technology to the wet oxidation of waste-waters from the olive industries. *Grasas Aceites* **41** (2), 158–162.
- García-Segura, S., Keller, J., Brillas, E. & Radjenovic, J. 2015 Removal of organic contaminants from secondary effluent by anodic oxidation with a boron-doped diamond anode as tertiary treatment. *J. Hazard. Mater.* **283**, 551–557.
- Gernjak, W., Krutzler, T., Glaser, A., Malato, S., Caceres, J., Bauer, R. & Fernández-Alba, A. R. 2003 Photo-Fenton treatment of water containing natural phenolic pollutants. *Chemosphere* **50** (1), 71–78.
- Gernjak, W., Maldonado, M. I., Malato, S., Caceres, J., Krutzler, T., Glaser, A. & Bauer, R. 2004 Pilot-plant treatment of olive mill wastewater (OMW) by solar TiO₂ photocatalysis and solar photo-Fenton. *Solar Energy* **77** (5), 567–572.
- Gernjak, W., Krutzler, T. & Bauer, R. 2007 Photo-Fenton treatment of olive mill wastewater applying a combined Fenton/flocculation pretreatment. *J. Solar Energy Eng.* **129** (1), 53–59.
- Ghanbari, F., Moradi, M., Mehdipour, F. & Gohari, F. 2016 Simultaneous application of copper and pbo2 anodes for electrochemical treatment of olive oil mill wastewater. *Desal. Water Treat.* **57** (13), 5828–5836.
- Giannis, A., Kalaitzakis, M. & Diamadopoulos, E. 2007 Electrochemical treatment of olive mill wastewater. *J. Chem. Technol. Biotechnol.* **82** (7), 663–671.
- Ginni, M., Kumar, S. A., Banu, R. J. & Yeom, I. T. 2017 Synergistic photodegradation of pulp and paper mill wastewater by combined advanced oxidation process. *Desalin. Water Treat.* **68**, 160–169.
- Ginos, A., Manios, T. & Mantzavinos, D. 2006 Treatment of olive mill effluents by coagulation–flocculation–hydrogen peroxide oxidation and effect on phytotoxicity. *J. Hazard. Mater.* **133** (1–3), 135–142.
- Giordano, G., Perathoner, S., Centi, G., De Rosa, S., Granato, T., Katovic, A., Siciliano, A., Tagarelli, A. & Tripicchio, F. 2007 Wet hydrogen peroxide catalytic oxidation of olive oil mill wastewaters using Cu-zeolite and Cu-pillared clay catalysts. *Catal. Today* **124** (3–4), 240–246.

- Glaze, W. H., Kang, J. W. & Chapin, D. H. 1987 The chemistry of water treatment processes involving ozone, hydrogen peroxide and ultraviolet radiation. *Ozone Sci. Eng.* **9**, 335–352.
- Gökkuş, Ö., Yıldız, N., Koparal, A. S. & Yıldız, Y. Ş. 2018 Evaluation of the effect of oxygen on electro-Fenton treatment performance for real textile wastewater using the taguchi approach. *Int. J. Environ. Sci. Technol.* **15** (2), 449–460.
- Gomec, C. Y., Erdim, E., Turan, I., Aydin, A. F. & Ozturk, I. 2007 Advanced oxidation treatment of physico-chemically pretreated olive mill industry effluent. *J. Environ. Sci. Health B* **42** (6), 741–747.
- Gomes, H. T., Figueiredo, J. L. & Faria, J. L. 2007 Catalytic wet air oxidation of olive mill wastewater. *Catal. Today* **124** (3–4), 254–259.
- Gonçalves, M. R., Marques, I. P. & Correia, J. P. 2012 Electrochemical mineralization of anaerobically digested olive mill wastewater. *Water Res.* **46** (13), 4217–4225.
- González-González, A. & Cuadros, F. 2015 Effect of aerobic pretreatment on anaerobic digestion of olive mill wastewater (OMWW): an ecoefficient treatment. *Food Bioprod. Process.* **95**, 339–345.
- Gopu, C., Gao, L., Volpe, M., Fiori, L. & Goldfarb, J. L. 2018 Valorizing municipal solid waste: waste to energy and activated carbons for water treatment via pyrolysis. *J. Anal. Appl. Pyrolysis* **133**, 48–58.
- Gotsi, M., Kalogerakis, N., Psillakis, E., Samaras, P. & Mantzavinos, D. 2005 Electrochemical oxidation of olive oil mill wastewaters. *Water Res.* **39** (17), 4177–4187.
- Gudiña, E. J., Rodrigues, A. I., de Freitas, V., Azevedo, Z., Teixeira, J. A. & Rodrigues, L. R. 2016 Valorization of agro-industrial wastes towards the production of rhamnolipids. *Bioresour. Technol.* **212**, 144–150.
- Gümüş, D. & Akbal, F. 2016 Comparison of Fenton and electro-Fenton processes for oxidation of phenol. *Process Saf. Environ. Prot.* **103**, 252–258.
- Hamad, H., Bassyouni, D., El-Ashtouky, E. S., Amin, N. & El-Latif, M. A. 2018 Electrocatalytic degradation and minimization of specific energy consumption of synthetic azo dye from wastewater by anodic oxidation process with an emphasis on enhancing economic efficiency and reaction mechanism. *Ecotoxicol. Environ. Saf.* **148**, 501–512.
- Hanafi, F., Assobhei, O. & Mountadar, M. 2010 Detoxification and discoloration of Moroccan olive mill wastewater by electrocoagulation. *J. Hazard. Mater.* **174** (1–3), 807–812.
- Hashim, K. S., Shaw, A., Al Khaddar, R., Pedrola, M. O. & Phipps, D. 2017 Iron removal, energy consumption and operating cost of electrocoagulation of drinking water using a new flow column reactor. *J. Environ. Manage.* **189**, 98–108.
- Hassan, M., Zhao, Y. & Xie, B. 2016 Employing TiO₂ photocatalysis to deal with landfill leachate: current status and development. *Chem. Eng. J.* **285**, 264–275.
- Hassan, M., Pous, N., Xie, B., Colprim, J., Balaguer, M. D. & Puig, S. 2017 Employing microbial electrochemical technology-driven electro-Fenton oxidation for the removal of recalcitrant organics from sanitary landfill leachate. *Bioresour. Technol.* **243**, 949–956.
- Hodaifa, G., Ochando-Pulido, J. M., Rodriguez-Vives, S. & Martinez-Ferez, A. 2013 Optimization of continuous reactor at pilot scale for olive-oil mill wastewater treatment by Fenton-like process. *Chem. Eng. J.* **220**, 117–124.
- Hodaifa, G., Agabo, C., Moya, A. J., Pacheco, R. & Mateo, S. 2015 Treatment of olive oil mill wastewater by UV-light and UV/H₂O₂ system. *Int. J.* **1**, 46–53.
- Huang, L. Z., Zhang, Y., Hu, X. M., Hansen, H. C. B., Pedersen, S. U. & Daasbjerg, K. 2018 Energy-harvesting bio-electrodehalogenation for sustainable wastewater treatment. *Electrochim. Acta* **290**, 38–45.
- Iboukhoulef, H., Amrane, A. & Kadi, H. 2013 Microwave-enhanced Fenton-like system, Cu (II)/H₂O₂, for olive mill wastewater treatment. *Environ. Technol.* **34** (7), 853–860.
- Iboukhoulef, H., Amrane, A. & Kadi, H. 2016 Removal of phenolic compounds from olive mill wastewater by a Fenton-like system H₂O₂/Cu (II) – thermodynamic and kinetic modeling. *Desal. Water Treat.* **57** (4), 1874–1879.
- Inan, H., Dimoglo, A., Şimşek, H. & Karpuzcu, M. 2004 Olive oil mill wastewater treatment by means of electro-coagulation. *Separ. Purif. Technol.* **36** (1), 23–31.
- International Olive Council (IOC) 2016 *Market newsletter* 110. November 2016.
- Iskander, S. M., Novak, J. T. & He, Z. 2019 Reduction of reagent requirements and sludge generation in Fenton's oxidation of landfill leachate by synergistically incorporating forward osmosis and humic acid recovery. *Water Res.* **151**, 310–317.
- Israilides, C. J., Vlyssides, A. G., Mourafeti, V. N. & Karvouni, G. 1997 Olive oil wastewater treatment with the use of an electrolysis system. *Bioresour. Technol.* **61** (2), 163–170.
- Jaafarzadeh, N., Takdastan, A., Jorfi, S., Ghanbari, F., Ahmadi, M. & Barzegar, G. 2018 The performance study on ultrasonic/Fe₃O₄/H₂O₂ for degradation of azo dye and real textile wastewater treatment. *J. Mol. Liq.* **256**, 462–470.
- Jeguirim, M., Chouchène, A., Réguillon, A. F., Trouvé, G. & Le Buzit, G. 2012 A new valorisation strategy of olive mill wastewater: impregnation on sawdust and combustion. *Resour. Conserv. Recycl.* **59**, 4–8.
- Joshi, S. M. & Gogate, P. R. 2019 Treatment of landfill leachate using different configurations of ultrasonic reactors combined with advanced oxidation processes. *Separ. Purif. Technol.* **211**, 10–18.
- Jum'h, I., Abdelhay, A., Al-Taani, H., Telfah, A., Alnaief, M. & Rosiwal, S. 2017 Fabrication and application of boron doped diamond BDD electrode in olive mill wastewater treatment in Jordan. *J. Water Reuse Desal.* **7** (4), 502–510.
- Justino, C., Marques, A. G., Duarte, K. R., Duarte, A. C., Pereira, R., Rocha-Santos, T. & Freitas, A. C. 2010 Degradation of phenols in olive oil mill wastewater by biological, enzymatic, and photo-Fenton oxidation. *Environ. Sci. Pollut. Res.* **17** (3), 650–656.
- Kajitvichyanukul, P., Lu, M. C., Liao, C. H., Wirojanagud, W. & Koottatep, T. 2006 Degradation and detoxification of

- formaline wastewater by advanced oxidation processes. *J. Hazard. Mater.* **135** (1–3), 337–343.
- Kallel, M., Belaid, C., Boussahel, R., Ksibi, M., Montiel, A. & Elleuch, B. 2009a Olive mill wastewater degradation by Fenton oxidation with zero-valent iron and hydrogen peroxide. *J. Hazard. Mater.* **163** (2), 550–554.
- Kallel, M., Belaid, C., Mechichi, T., Ksibi, M. & Elleuch, B. 2009b Removal of organic load and phenolic compounds from olive mill wastewater by Fenton oxidation with zero-valent iron. *Chem. Eng. J.* **150** (2), 391–395.
- Kaplan, F., Hesenov, A., Gözmen, B. & Erbatur, O. 2011 Degradations of model compounds representing some phenolics in olive mill wastewater via electro-Fenton and photoelectro-Fenton treatments. *Environ. Technol.* **32** (7), 685–692.
- Karunakaran, C. & Anilkumar, P. 2007 Semiconductor-catalyzed solar photooxidation of iodide ion. *J. Mol. Catal. A Chem.* **265** (1–2), 153–158.
- Kavitha, V. & Palanivelu, K. 2016 Degradation of phenol and trichlorophenol by heterogeneous photo-Fenton process using Granular Ferric Hydroxide[®]: comparison with homogeneous system. *Int. J. Environ. Sci. Technol.* **13** (3), 927–936.
- Kestioğlu, K., Yonar, T. & Azbar, N. 2005 Feasibility of physico-chemical treatment and advanced oxidation processes (AOPs) as a means of pretreatment of olive mill effluent (OME). *Process Biochem.* **40** (7), 2409–2416.
- Khaled, B., Wided, B., Béchir, H., Elimame, E., Mouna, L. & Zied, T. 2015 Investigation of electrocoagulation reactor design parameters effect on the removal of cadmium from synthetic and phosphate industrial wastewater. *Arab. J. Chem.* **1523** (1), 1–13.
- Khataee, A., Gholami, P. & Vahid, B. 2016 Heterogeneous sono-Fenton-like process using nanostructured pyrite prepared by Ar glow discharge plasma for treatment of a textile dye. *Ultrason. Sonochem.* **29**, 213–225.
- Khatri, I., Singh, S. & Garg, A. 2018 Performance of electro-Fenton process for phenol removal using Iron electrodes and activated carbon. *J. Environ. Chem. Eng.* **6** (6), 7368–7376.
- Khoufi, S., Aouissaoui, H., Penninckx, M. & Sayadi, S. 2004 Application of electro-Fenton oxidation for the detoxification of olive mill wastewater phenolic compounds. *Water Sci. Technol.* **49** (4), 97–102.
- Khoufi, S., Aloui, F. & Sayadi, S. 2006 Treatment of olive oil mill wastewater by combined process electro-Fenton reaction and anaerobic digestion. *Water Res.* **40** (10), 2007–2016.
- Khoufi, S., Feki, F. & Sayadi, S. 2007 Detoxification of olive mill wastewater by electrocoagulation and sedimentation processes. *J. Hazard. Mater.* **142** (1–2), 58–67.
- Kıpçak, E. & Akgün, M. 2018 Biofuel production from olive mill wastewater through its Ni/Al₂O₃ and Ru/Al₂O₃ catalyzed supercritical water gasification. *Renew. Energy* **124**, 155–164.
- Klidi, N., Clematis, D., Delucchi, M., Gadri, A., Ammar, S. & Panizza, M. 2018 Applicability of electrochemical methods to paper mill wastewater for reuse. Anodic oxidation with BDD and tirusno₂ anodes. *J. Electroanal. Chem.* **815**, 16–23.
- Körbahti, B. K. & Turan, K. M. 2016 Evaluation of energy consumption in electrochemical oxidation of acid violet 7 textile dye using Pt/Ir electrodes. *J. Turk. Chem. Soc. A Chem.* **3** (3), 75–92.
- Kotronarou, A., Mills, G. & Hoffmann, M. R. 1991 Ultrasonic irradiation of p-nitrophenol in aqueous solution. *J. Phys. Chem.* **95** (9), 3630–3638.
- Kotsou, M., Kyriacou, A., Lasaridi, K. & Pilidis, G. 2004 Integrated aerobic biological treatment and chemical oxidation with Fenton's reagent for the processing of green table olive wastewater. *Process Biochem.* **39** (11), 1653–1660.
- Kotta, E., Kalogerakis, N. & Mantzavinou, D. 2007 The effect of solids on the electrochemical treatment of olive mill effluents. *J. Chem. Technol. Biotechnol.* **82** (5), 504–511.
- Krystynik, P., Kluson, P. & Tito, D. N. 2015 Water treatment process intensification by combination of electrochemical and photochemical methods. *Chem. Eng. Process. Process. Intens.* **94**, 85–92.
- Kul, S., Boncukcuoğlu, R., Yilmaz, A. E. & Fil, B. A. 2015 Treatment of olive mill wastewater with electro-oxidation method. *J. Electrochem. Soc.* **162** (8), 41–47.
- Kumar, S. & Sharma, C. 2017 Synthesis, characterization and application of CuOCeO₂ nanocatalysts in wet air oxidation of industrial wastewater. *J. Environ. Chem. Eng.* **5** (4), 3914–3921.
- Kumari, M. & Saroha, A. K. 2018 Performance of various catalysts on treatment of refractory pollutants in industrial wastewater by catalytic wet air oxidation: a review. *J. Environ. Manage.* **228**, 169–188.
- Kusic, H., Koprivanac, N. & Bozic, A. L. 2006 Minimization of organic pollutant content in aqueous solution by means of AOPs: UV-and ozone-based technologies. *Chem. Eng. J.* **123** (3), 127–137.
- Kyriacou, A., Lasaridi, K. E., Kotsou, M., Balis, C. & Pilidis, G. 2005 Combined bioremediation and advanced oxidation of green table olive processing wastewater. *Process Biochem.* **40** (3–4), 1401–1408.
- Lafi, W. K., Shannak, B., Al-Shannag, M., Al-Anber, Z. & Al-Hasan, M. 2009 Treatment of olive mill wastewater by combined advanced oxidation and biodegradation. *Separ. Purif. Technol.* **70** (2), 141–146.
- Lafi, W. K., Al-Anber, M., Al-Anber, Z. A., Al-shannag, M. & Khalil, A. 2010 Coagulation and advanced oxidation processes in the treatment of olive mill wastewater (OMW). *Desal. Water Treat.* **24** (1–3), 251–256.
- Landeros, C. R., Díaz, C. E. B., Chaves, A. A. & Morales, G. R. 2017 Evaluation of a coupled system of electro-oxidation and ozonation to remove the pesticide Thiodan[®] 35 CE (endosulfan) in aqueous solution. *Fuel* **198**, 91–98.
- Leal, J. F., Neves, M. G. P., Santos, E. B. & Esteves, V. I. 2018 Use of formalin in intensive aquaculture: properties, application and effects on fish and water quality. *Rev. Aquac.* **10** (2), 281–295.
- Leris, I., Kalogianni, E., Tsangaris, C., Smeti, E., Laschou, S., Anastasopoulou, E., Vardakas, L., Kapakos, Y. & Skoulikidis,

- N. T. 2019 Acute and sub-chronic toxicity bioassays of olive mill wastewater on the Eastern mosquitofish *Gambusia holbrooki*. *Ecotoxicol. Environ. Saf.* **175**, 48–57.
- Lester, Y., Avisar, D., Gozlan, I. & Mamane, H. 2011 Removal of pharmaceuticals using combination of UV/H₂O₂/O₃ advanced oxidation process. *Water Sci. Technol.* **64** (11), 2230–2238.
- Leszczyński, J. 2018 Treatment of landfill leachate by using Fenton and photo-Fenton processes. *J. Ecol. Eng.* **19** (5), 194–199.
- Li, J., Zhao, L., Qin, L., Tian, X., Wang, A., Zhou, Y., Meng, L. & Chen, Y. 2016 Removal of refractory organics in nanofiltration concentrates of municipal solid waste leachate treatment plants by combined Fenton oxidative-coagulation with photo-Fenton processes. *Chemosphere* **146**, 442–449.
- Li, D., Guo, X., Song, H., Sun, T. & Wan, J. 2018 Preparation of RuO₂-TiO₂/Nano-graphite composite anode for electrochemical degradation of ceftriaxone sodium. *J. Hazard. Mater.* **351**, 250–259.
- Li, H., Zhang, H., Long, J., Zhang, P. & Chen, Y. 2019 Combined Fenton process and sulfide precipitation for removal of heavy metals from industrial wastewater: bench and pilot scale studies focusing on in-depth thallium removal. *Front. Environ. Sci. Eng.* **13** (4), 49–64.
- Lima, M. J., Silva, C. G., Silva, A. M., Lopes, J. C., Dias, M. M. & Faria, J. L. 2017 Homogeneous and heterogeneous photo-Fenton degradation of antibiotics using an innovative static mixer photoreactor. *Chem. Eng. J.* **310**, 342–351.
- Liu, S., Lim, M., Fabris, R., Chow, C., Drikas, M. & Amal, R. 2010 Comparison of photocatalytic degradation of natural organic matter in two Australian surface waters using multiple analytical techniques. *Org. Geochem.* **41** (2), 124–129.
- Liu, W. H., Zhang, C. G., Gao, P. F., Liu, H., Song, Y. Q. & Yang, J. F. 2017a Advanced treatment of tannery wastewater using the combination of UASB, SBR, electrochemical oxidation and BAF. *J. Chem. Technol. Biotechnol.* **92** (3), 588–597.
- Liu, Y., Wu, D., Chen, M., Ma, L., Wang, H. & Wang, S. 2017b Wet air oxidation of fracturing flowback fluids over promoted bimetallic Cu-Cr catalyst. *Catal. Commun.* **90**, 60–64.
- Longhi, P., Vodopivec, B. & Fiori, G. 2001 Electrochemical treatment of olive oil mill wastewater. *Annal. Chim.* **91** (3–4), 169–174.
- Lu, H., Zhu, Z., Zhang, H., Zhu, J., Qiu, Y., Zhu, L. & Küppers, S. 2016 Fenton-like catalysis and oxidation/adsorption performances of acetaminophen and arsenic pollutants in water on a multimetal Cu-Zn-Fe-LDH. *ACS Appl. Mater. Interfaces* **8** (38), 25,343–25,352.
- Lucas, M. S. & Peres, J. A. 2009a Removal of COD from olive mill wastewater by Fenton's reagent: kinetic study. *J. Hazard. Mater.* **168** (2), 1253–1259.
- Lucas, M. S. & Peres, J. A. 2009b Treatment of olive mill wastewater by a combined process: Fenton's reagent and chemical coagulation. *J. Environ. Sci. Health A* **44** (2), 198–205.
- Lucas, M. S., Peres, J. A. & Puma, G. L. 2010 Treatment of winery wastewater by ozone-based advanced oxidation processes (O₃, O₃/UV and O₃/UV/H₂O₂) in a pilot-scale bubble column reactor and process economics. *Separ. Purif. Technol.* **72** (3), 235–241.
- Lucas, M. S., Beltrán-Heredia, J., Sanchez-Martin, J., Garcia, J. & Peres, J. A. 2013 Treatment of high strength olive mill wastewater by Fenton's reagent and aerobic biological process. *J. Environ. Sci. Health A* **48** (8), 954–962.
- Lutterbeck, C. A., Machado, Ê. L. & Kümmerer, K. 2015 Photodegradation of the antineoplastic cyclophosphamide: a comparative study of the efficiencies of UV/H₂O₂, UV/Fe²⁺ + /H₂O₂ and UV/TiO₂ processes. *Chemosphere* **120**, 538–546.
- Mackulak, T., Nagyová, K., Faberová, M., Grabic, R., Koba, O., Gál, M. & Birošová, L. 2015 Utilization of Fenton-like reaction for antibiotics and resistant bacteria elimination in different parts of WWTP. *Environ. Toxicol. Pharmacol.* **40** (2), 492–497.
- Madani, M., Aliabadi, M., Nasernejad, B., Kermanj Abdulrahman, R., Yalili Kilic, M. & Kestioglu, K. 2015 Treatment of olive mill wastewater using physico-chemical and Fenton processes. *Desal. Water Treat.* **53** (8), 2031–2040.
- Madhavan, J., Grieser, F. & Ashokkumar, M. 2010 Combined advanced oxidation processes for the synergistic degradation of ibuprofen in aqueous environments. *J. Hazard. Mater.* **178** (1–3), 202–208.
- Makhotkina, O. A., Kuznetsova, E. V. & Preis, S. V. 2006 Catalytic detoxification of 1, 1-dimethylhydrazine aqueous solutions in heterogeneous Fenton system. *Appl. Catal. B Environ.* **68** (3–4), 85–91.
- Malik, S. N., Ghosh, P. C., Vaidya, A. N., Waindeskar, V., Das, S. & Mudliar, S. N. 2017 Comparison of coagulation, ozone and ferrate treatment processes for color, COD and toxicity removal from complex textile wastewater. *Water Sci. Technol.* **76** (5), 1001–1010.
- Malvestiti, J. A., Fagnani, E., Simão, D. & Dantas, R. F. 2018 Optimization of UV/H₂O₂ and ozone wastewater treatment by the experimental design methodology. *Environ. Technol.* **40** (15), 1910–1922.
- Maragkaki, A. E., Vasileiadis, I., Fountoulakis, M., Kyriakou, A., Lasaridi, K. & Manios, T. 2018 Improving biogas production from anaerobic co-digestion of sewage sludge with a thermal dried mixture of food waste, cheese whey and olive mill wastewater. *Waste Manage.* **71**, 644–651.
- Marcelino, R. B., Leão, M. M., Lago, R. M. & Amorim, C. C. 2017 Multistage ozone and biological treatment system for real wastewater containing antibiotics. *J. Environ. Manage.* **195**, 110–116.
- Markou, V., Kontogianni, M. C., Frontistis, Z., Tekerlekopoulou, A. G., Katsaounis, A. & Vayenas, D. 2017 Electrochemical treatment of biologically pre-treated dairy wastewater using dimensionally stable anodes. *J. Environ. Manage.* **202**, 217–224.
- Martins, R. C., Silva, A. M., Castro-Silva, S., Garção-Nunes, P. & Quinta-Ferreira, R. M. 2010 Adopting strategies to improve

- the efficiency of ozonation in the real-scale treatment of olive oil mill wastewaters. *Environ. Technol.* **31** (13), 1459–1469.
- Mazellier, P. & Bolte, M. 1997 Iron (III) promoted degradation of 2, 6-dimethylphenol in aqueous solution. *Chemosphere* **35** (10), 2181–2192.
- Mekki, A., Dhoubi, A., Feki, F. & Sayadi, S. 2008 Assessment of toxicity of the untreated and treated olive mill wastewaters and soil irrigated by using microbioassays. *Ecotoxicol. Environ. Saf.* **69** (3), 488–495.
- Mendez, J. O., Melian, J. H., Arana, J., Rodriguez, J. D., Diaz, O. G. & Pena, J. P. 2015 Detoxification of waters contaminated with phenol, formaldehyde and phenol-formaldehyde mixtures using a combination of biological treatments and advanced oxidation techniques. *Appl. Catal. B Environ.* **163**, 63–73.
- Meng, X., Khoso, S. A., Wu, J., Tian, M., Kang, J., Liu, H., Zhang, Q., Sun, W. & Hu, Y. 2019 Efficient COD reduction from sulfide minerals processing wastewater using Fenton process. *Minerals Eng.* **132**, 110–112.
- Mert, B. K., Yonar, T., Kiliç, M. Y. & Kestioglu, K. 2010 Pre-treatment studies on olive oil mill effluent using physicochemical, Fenton and Fenton-like oxidations processes. *J. Hazard. Mater.* **174** (1), 122–128.
- Mestankova, H., Parker, A. M., Bramaz, N., Canonica, S., Schirmer, K., Von Gunten, U. & Linden, K. G. 2016 Transformation of Contaminant Candidate List (CCL3) compounds during ozonation and advanced oxidation processes in drinking water: assessment of biological effects. *Water Res.* **93**, 110–120.
- Michael, I., Panagi, A., Ioannou, L. A., Frontistis, Z. & Fatta-Kassinos, D. 2014 Utilizing solar energy for the purification of olive mill wastewater using a pilot-scale photocatalytic reactor after coagulation-flocculation. *Water Res.* **60**, 28–40.
- Miklos, D. B., Remy, C., Jekel, M., Linden, K. G., Drewes, J. E. & Hübner, U. 2018 Evaluation of advanced oxidation processes for water and wastewater treatment – A critical review. *Water Res.* **139**, 118–131.
- Millán, M., Rodrigo, M. A., Fernández-Marchante, C. M., Cañizares, P. & Lobato, J. 2019 Powering with solar energy the anodic oxidation of wastewater polluted with pesticides. *ACS Sustain. Chem. Eng.* **7** (9), 8303–8309.
- Minh, D. P., Gallezot, P. & Besson, M. 2006 Degradation of olive oil mill effluents by catalytic wet air oxidation: 1. Reactivity of p-coumaric acid over Pt and Ru supported catalysts. *Appl. Catal. B Environ.* **63** (1–2), 68–75.
- Minh, D. P., Aubert, G., Gallezot, P. & Besson, M. 2007a Degradation of olive oil mill effluents by catalytic wet air oxidation: 2-Oxidation of p-hydroxyphenylacetic and p-hydroxybenzoic acids over Pt and Ru supported catalysts. *Appl. Catal. B Environ.* **73** (3–4), 236–246.
- Minh, D. P., Gallezot, P. & Besson, M. 2007b Treatment of olive oil mill wastewater by catalytic wet air oxidation: 3. Stability of supported ruthenium catalysts during oxidation of model pollutant p-hydroxybenzoic acid in batch and continuous reactors. *Appl. Catal. B Environ.* **75** (1–2), 71–77.
- Minh, D. P., Gallezot, P., Azabou, S., Sayadi, S. & Besson, M. 2008 Catalytic wet air oxidation of olive oil mill effluents: 4. Treatment and detoxification of real effluents. *Appl. Catal. B Environ.* **84** (3–4), 749–757.
- Minière, M., Boutin, O. & Soric, A. 2018 Evaluation of degradation and kinetics parameters of acid orange 7 through wet air oxidation process. *Can. J. Chem. Eng.* **96** (11), 2450–2454.
- Miralles-Cuevas, S., Darowna, D., Wanag, A., Mozia, S., Malato, S. & Oller, I. 2017 Comparison of UV/H₂O₂, UV/S₂O₈²⁻, solar/Fe (II)/H₂O₂ and solar/Fe (II)/S₂O₈²⁻ at pilot plant scale for the elimination of micro-contaminants in natural water: an economic assessment. *Chem. Eng. J.* **310**, 514–524.
- Mohanakrishna, G., Abu-Reesh, I. M. & Al-Raoush, R. I. 2018 Biological anodic oxidation and cathodic reduction reactions for improved bioelectrochemical treatment of petroleum refinery wastewater. *J. Clean. Prod.* **190**, 44–52.
- Munir, H. M. S., Feroze, N., Ikhlaq, A., Kazmi, M., Javed, F. & Mukhtar, H. 2019 Removal of colour and COD from paper and pulp industry wastewater by ozone and combined ozone/UV process. *Desal. Water Treat.* **137**, 154–161.
- Nagata, Y., Nakagawa, M., Okuno, H., Mizukoshi, Y., Yim, B. & Maeda, Y. 2000 Sonochemical degradation of chlorophenols in water. *Ultrason. Sonochem.* **7** (3), 115–120.
- Najjar, W., Azabou, S., Sayadi, S. & Ghorbel, A. 2009 Screening of Fe–BEA catalysts for wet hydrogen peroxide oxidation of crude olive mill wastewater under mild conditions. *Appl. Catal. B Environ.* **88** (3–4), 299–304.
- Nasr, B., Ahmed, B. & Abdellatif, G. 2004 Fenton treatment of olive oil mill wastewater–applicability of the method and parameters effects on the degradation process. *J. Environ. Sci.* **16** (6), 942–944.
- Naumczyk, J. H. & Kucharska, M. A. 2017 Electrochemical treatment of tannery wastewater – Raw, coagulated, and pretreated by AOPs. *J. Environ. Sci. Health A* **52** (7), 649–664.
- Nidheesh, P. V., Gandhimathi, R. & Ramesh, S. T. 2013 Degradation of dyes from aqueous solution by Fenton processes: a review. *Environ. Sci. Pollut. Res.* **20** (4), 2099–2132.
- Nieto, L. M., Hodaifa, G., Vives, S. R., Casares, J. G., Driss, S. B. & Grueso, R. 2009 Treatment of olive-mill wastewater from a two-phase process by chemical oxidation on an industrial scale. *Water Sci. Technol.* **59** (10), 2017–2027.
- Nieto, L. M., Hodaifa, G., Vives, S. R. & Casares, J. A. 2010 Industrial plant for olive mill wastewater from two-phase treatment by chemical oxidation. *J. Environ. Eng.* **136** (11), 1309–1313.
- Nieto, L. M., Hodaifa, G., Rodríguez, S., Giménez, J. A. & Ochando, J. 2011 Degradation of organic matter in olive-oil mill wastewater through homogeneous Fenton-like reaction. *Chem. Eng. J.* **173** (2), 503–510.
- Niu, H., Zheng, Y., Wang, S., Zhao, L., Yang, S. & Cai, Y. 2018 Continuous generation of hydroxyl radicals for highly efficient elimination of chlorophenols and phenols catalyzed by heterogeneous Fenton-like catalysts yolk/shell Pd@ Fe₃O₄@ metal organic frameworks. *J. Hazard. Mater.* **346**, 174–183.

- Ochando-Pulido, J. M., Pimentel-Moral, S., Verardo, V. & Martinez-Ferez, A. 2017 A focus on advanced physico-chemical processes for olive mill wastewater treatment. *Separ. Purif. Technol.* **179**, 161–174.
- Oliviero, L., Barbier Jr., J. & Duprez, D. 2003 Wet air oxidation of nitrogen-containing organic compounds and ammonia in aqueous media. *Appl. Catal. B Environ.* **40** (3), 163–184.
- Olvera-Vargas, H., Oturan, N., Oturan, M. A. & Brillas, E. 2015 Electro-Fenton and solar photoelectro-Fenton treatments of the pharmaceutical ranitidine in pre-pilot flow plant scale. *Separ. Purif. Technol.* **146**, 127–135.
- Oturan, M. A. & Aaron, J. J. 2014 Advanced oxidation processes in water/wastewater treatment: principles and applications. A review. *Crit. Rev. Environ. Sci. Technol.* **44** (23), 2577–2641.
- Oumar, D., Patrick, D., Gerardo, B., Rino, D. & Ihsen, B. S. 2016 Coupling biofiltration process and electrocoagulation using magnesium-based anode for the treatment of landfill leachate. *J. Environ. Manage.* **181**, 477–483.
- Ovejero, G., Sotelo, J. L., Martínez, F., Melero, J. A. & Gordo, L. 2001 Wet peroxide oxidation of phenolic solutions over different iron-containing zeolitic materials. *Ind. Eng. Chem. Res.* **40** (18), 3921–3928.
- Oz, N. A. & Uzun, A. C. 2015 Ultrasound pretreatment for enhanced biogas production from olive mill wastewater. *Ultrason. Sonochem.* **22**, 565–572.
- Oz, Y. B., Mamane, H., Menashe, O., Cohen-Yaniv, V., Kumar, R., Kruh, L. I. & Kurzbaum, E. 2018 Treatment of olive mill wastewater using ozonation followed by an encapsulated acclimated biomass. *J. Environ. Chem. Eng.* **6** (4), 5014–5023.
- Padovani, G., Pintucci, C. & Carlozzi, P. 2013 Dephenolization of stored olive-mill wastewater, using four different adsorbing matrices to attain a low-cost feedstock for hydrogen photo-production. *Bioresour. Technol.* **138**, 172–179.
- Palaniandy, P., Abdul Aziz, H. B., Feroz, S., Amr, A. & Salem, S. 2016 Evaluating photo-degradation of COD and TOC in petroleum refinery wastewater by using TiO₂/ZnO photocatalyst. *Water Sci. Technol.* **74** (6), 1312–1325.
- Pan, C., Troyer, L. D., Catalano, J. G. & Giammar, D. E. 2016 Dynamics of chromium (VI) removal from drinking water by iron electrocoagulation. *Environ. Sci. Technol.* **50** (24), 13502–13510.
- Panizza, M. & Cerisola, G. 2006 Olive mill wastewater treatment by anodic oxidation with parallel plate electrodes. *Water Res.* **40** (6), 1179–1184.
- Papaphilippou, P. C., Yiannapas, C., Politi, M., Daskalaki, V. M., Michael, C., Kalogerakis, N., Mantzavinos, D. & Fatta-Kassinos, D. 2013 Sequential coagulation-flocculation, solvent extraction and photo-Fenton oxidation for the valorization and treatment of olive mill effluent. *Chem. Eng. J.* **224**, 82–88.
- Papastefanakis, N., Mantzavinos, D. & Katsaounis, A. 2010 DSA electrochemical treatment of olive mill wastewater on Ti/RuO₂ anode. *J. Appl. Electrochem.* **40** (4), 729–737.
- Paredes, C., Bernal, M. P., Cegarra, J. & Roig, A. 2002 Bio-degradation of olive mill wastewater sludge by its co-composting with agricultural wastes. *Bioresour. Technol.* **85** (1), 1–8.
- Park, J. S., Her, N. G. & Yoon, Y. 2011 Sonochemical degradation of chlorinated phenolic compounds in water: effects of physicochemical properties of the compounds on degradation. *Water Air Soil Pollut.* **215** (1–4), 585–593.
- Paucar, N. E., Kim, I., Tanaka, H. & Sato, C. 2019 Effect of O₃ dose on the O₃/UV treatment process for the removal of pharmaceuticals and personal care products in secondary effluent. *Chem. Eng.* **3** (2), 1–17.
- Penteado, E. D., Fernandez-Marchante, C. M., Zaiat, M., Gonzalez, E. R. & Rodrigo, M. A. 2017 Influence of carbon electrode material on energy recovery from winery wastewater using a dual-chamber microbial fuel cell. *Environ. Technol.* **38** (11), 1333–1341.
- Petrier, C., Lamy, M. F., Francony, A., Benahcene, A., David, B., Renaudin, V. & Gondrexon, N. 1994 Sonochemical degradation of phenol in dilute aqueous solutions: comparison of the reaction rates at 20 and 487 kHz. *J. Phys. Chem.* **98** (41), 10514–10520.
- Pillai, I. M. S. & Gupta, A. K. 2016 Anodic oxidation of coke oven wastewater: multiparameter optimization for simultaneous removal of cyanide, COD and phenol. *J. Environ. Manage.* **176**, 45–53.
- Pliego, G., Zazo, J. A., Pariente, M. I., Rodríguez, I., Petre, A. L., Leton, P. & García, J. 2014 Treatment of a wastewater from a pesticide manufacture by combined coagulation and Fenton oxidation. *Environ. Sci. Pollut. Res.* **21** (21), 12,129–12,134.
- Pourgholi, M., Jahandizi, R. M., Miranzadeh, M., Beigi, O. H. & Dehghan, S. 2018 Removal of dye and COD from textile wastewater using AOP (UV/O₃, UV/H₂O₂, O₃/H₂O₂ and UV/H₂O₂/O₃). *J. Environ. Health Sustain. Dev.* **3** (4), 621–629.
- Priya, S. S., Deshpande, A. & Dwarakanath, R. 2015 Visible light solar photocatalytic degradation of pulp and paper wastewater using dye-sensitized TiO₂. *Int. J. Res. Eng. Technol.* **4**, 2321–2308.
- Ramteke, L. P. & Gogate, P. R. 2015 Treatment of toluene, benzene, naphthalene and xylene (BTNXs) containing wastewater using improved biological oxidation with pretreatment using Fenton/ultrasound based processes. *J. Ind. Eng. Chem.* **28**, 247–260.
- Rasheed, T., Bilal, M., Iqbal, H. M., Shah, S. Z. H., Hu, H., Zhang, X. & Zhou, Y. 2018 TiO₂/UV-assisted rhodamine B degradation: putative pathway and identification of intermediates by UPLC/MS. *Environ. Technol.* **39** (12), 1533–1543.
- Rege, M. A., Bhojani, S. H., Tock, R. W. & Narayan, R. S. 1991 Advanced oxidation processes for destruction of dissolved organics in process wastewater: statistical design of experiments. *Ind. Eng. Chem. Res.* **30** (12), 2583–2586.
- Reis, P. M., Martins, P. J., Martins, R. C., Gando-Ferreira, L. M. & Quinta-Ferreira, R. M. 2018 Integrating Fenton's process and

- ion exchange for olive mill wastewater treatment and iron recovery. *Environ. Technol.* **39** (3), 308–316.
- Rios-Enriquez, M., Shahin, N., Durán-de-Bazúa, C., Lang, J., Oliveros, E., Bossmann, S. H. & Braun, A. M. 2004 Optimization of the heterogeneous Fenton-oxidation of the model pollutant 2, 4-xylydine using the optimal experimental design methodology. *Solar Energy* **77** (5), 491–501.
- Rivas, J., Beltrán, F., Acedo, B. & Gimeno, O. 2000 Two-step wastewater treatment: sequential ozonation-aerobic biodegradation. *Ozone Sci. Eng.* **22** (6), 617–636.
- Rivas, F. J., Beltran, F. J., Frades, J. & Buxeda, P. 2001a Oxidation of p-hydroxybenzoic acid by Fenton's reagent. *Water Res.* **35** (2), 387–396.
- Rivas, F. J., Beltrán, F. J., Gimeno, O. & Acedo, B. 2001b Wet air oxidation of wastewater from olive oil mills. *Chem. Eng. Technol.* **24** (4), 415–421.
- Rivas, F. J., Beltran, F. J., Gimeno, O. & Alvarez, P. 2001c Chemical-biological treatment of table olive manufacturing wastewater. *J. Environ. Eng.* **127** (7), 611–619.
- Rivas, F. J., Beltrán, F. J., Gimeno, O. & Frades, J. 2001d Treatment of olive oil mill wastewater by Fenton's reagent. *J. Agric. Food Chem.* **49** (4), 1873–1880.
- Rivas, F. J., Gimeno, O., Portela, J. R., de la Ossa, E. M. & Beltran, F. J. 2001e Supercritical water oxidation of olive oil mill wastewater. *Ind. Eng. Chem. Res.* **40** (16), 3670–3674.
- Rizzo, L., Lofrano, G., Grassi, M. & Belgiorno, V. 2008 Pre-treatment of olive mill wastewater by chitosan coagulation and advanced oxidation processes. *Separ. Purif. Technol.* **63** (3), 648–653.
- Roshini, P. S., Gandhimathi, R., Ramesh, S. T. & Nidheesh, P. V. 2017 Combined electro-Fenton and biological processes for the treatment of industrial textile effluent: mineralization and toxicity analysis. *J. Hazard. Toxic Radioactive Waste* **21** (4), 04017016.
- Roth, H., Gendel, Y., Buzatu, P., David, O. & Wessling, M. 2016 Tubular carbon nanotube-based gas diffusion electrode removes persistent organic pollutants by a cyclic adsorption-electro-Fenton process. *J. Hazard. Mater.* **307**, 1–6.
- Rubio-Clemente, A., Chica, E. & Peñuela, G. 2019 Evaluation of the UV/H₂O₂ system for treating natural water with a mixture of anthracene and benzo [a] pyrene at ultra-trace levels. *Environ. Sci. Pollut. Res.* **26** (5), 4381–4392.
- Ruzmanova, I., Stoller, M. & Chianese, A. 2013 Photocatalytic treatment of olive mill waste water by magnetic core titanium dioxide nanoparticles. *Chem. Eng* **32**, 2269–2274.
- Saber, A., Mortazavian, S., James, D. E. & Hasheminejad, H. 2017 Optimization of collaborative photo-Fenton oxidation and coagulation for the treatment of petroleum refinery wastewater with scrap iron. *Water Air Soil Pollut.* **228** (8), 1–18.
- Sable, S. S., Panchangam, S. C. & Lo, S. L. 2018 Abatement of clofibrac acid by Fenton-like process using iron oxide supported sulfonated-ZrO₂: efficient heterogeneous catalysts. *J. Water Process Eng.* **26**, 92–99.
- Salgado, J. M., Abrunhosa, L., Venâncio, A., Domínguez, J. M. & Belo, I. 2015 Enhancing the bioconversion of winery and olive mill waste mixtures into lignocellulolytic enzymes and animal feed by *Aspergillus uvarum* using a packed-bed bioreactor. *J. Agric. Food Chem.* **63** (42), 9306–9314.
- Sassi, A. B., Boularbah, A., Jaouad, A., Walker, G. & Boussaid, A. 2006 A comparison of olive oil mill wastewaters (OMW) from three different processes in Morocco. *Process Biochem.* **41** (1), 74–78.
- Schrank, S. G., Gebhardt, W., José, H. J., Moreira, R. F. & Schröder, H. F. 2017 Ozone treatment of tannery wastewater monitored by conventional and substance specific wastewater analyses. *Ozone Sci. Eng.* **39** (3), 159–187.
- Scoma, A., Varela-Corredor, F., Bertin, L., Gostoli, C. & Bandini, S. 2016 Recovery of VFAs from anaerobic digestion of dephenolized olive mill wastewaters by electro dialysis. *Separ. Purif. Technol.* **159**, 81–91.
- Selvabharathi, G., Adishkumar, S., Jenefa, S., Ginni, G., Banu, J. R. & Yeom, I. T. 2016 Combined homogeneous and heterogeneous advanced oxidation process for the treatment of tannery wastewaters. *J. Water Reuse Desal.* **6** (1), 59–71.
- Serna-Galvis, E. A., Botero-Coy, A. M., Martínez-Pachón, D., Moncayo-Lasso, A., Ibáñez, M., Hernández, F. & Torres-Palma, R. A. 2019 Degradation of seventeen contaminants of emerging concern in municipal wastewater effluents by sonochemical advanced oxidation processes. *Water Res.* **154**, 349–360.
- Shokri, A., Mahanpoor, K. & Soodbar, D. 2016 Degradation of Ortho-Toluidine in petrochemical wastewater by Ozonation, UV/O₃, O₃/H₂O₂ and UV/O₃/H₂O₂ processes. *Desal. Water Treat.* **57** (35), 16473–16482.
- Sillanpää, M., Ncibi, M. C. & Matilainen, A. 2018 Advanced oxidation processes for the removal of natural organic matter from drinking water sources: a comprehensive review. *J. Environ. Manage.* **208**, 56–76.
- Silva, T. F., Fonseca, A., Saraiva, I., Boaventura, R. A. & Vilar, V. J. 2016 Scale-up and cost analysis of a photo-Fenton system for sanitary landfill leachate treatment. *Chem. Eng. J.* **283**, 76–88.
- Singh, J., Sharma, S. & Basu, S. 2019a Synthesis of Fe₂O₃/TiO₂ monoliths for the enhanced degradation of industrial dye and pesticide via photo-Fenton catalysis. *J. Photochem. Photobiol. A Chem.* **376**, 32–42.
- Singh, R., Kumar, V., Verma, A., Sobti, A. & Toor, A. P. 2019b Photocatalytic activity of bi-doped TiO₂ for phenol degradation under UV and sunlight conditions. *Sustainable Engineering* **30**, 201–212.
- Sivagami, K., Anand, D., Divyapriya, G. & Nambi, I. 2019 Treatment of petroleum oil spill sludge using the combined ultrasound and Fenton oxidation process. *Ultrason. Sonochem.* **51**, 340–349.
- Soares, P. A., Souza, R., Soler, J., Silva, T. F., Souza, S. M. G. U., Boaventura, R. A. & Vilar, V. J. 2017 Remediation of a synthetic textile wastewater from polyester-cotton dyeing combining biological and photochemical oxidation processes. *Separ. Purif. Technol.* **172**, 450–462.
- Souza, B. M., Cerqueira, A. C., Sant'Anna Jr., G. L. & Dezotti, M. 2011 Oil-refinery wastewater treatment aiming reuse by advanced

- oxidation processes (AOPs) combined with biological activated carbon (BAC). *Ozone Sci. Eng.* **33** (5), 403–409.
- Souza, B. M., Souza, B. S., Guimarães, T. M., Ribeiro, T. F., Cerqueira, A. C., Sant'Anna, G. L. & Dezotti, M. 2016 Removal of recalcitrant organic matter content in wastewater by means of AOPs aiming industrial water reuse. *Environ. Sci. Pollut. Res.* **23** (22), 22,947–22,956.
- Srinivasan, S. V., Mary, G. P. S., Kalyanaraman, C., Sureshkumar, P. S., Balakameswari, K. S., Suthanthararajan, R. & Ravindranath, E. 2012 Combined advanced oxidation and biological treatment of tannery effluent. *Clean Technol. Environ. Pol.* **14** (2), 251–256.
- Strokach, P. P. 1975 The prospects of using anodic dissolution of metal for water purification. *Electrochem. Ind. Process. Biol.* **4**, 55.
- Suzuki, H., Araki, S. & Yamamoto, H. 2015 Evaluation of advanced oxidation processes (AOP) using O₃, UV, and TiO₂ for the degradation of phenol in water. *J. Water Process Engineering* **7**, 54–60.
- Szczuka, A., Berglund-Brown, J. P., Chen, H. K., Quay, A. N. & Mitch, W. A. 2019 Evaluation of a pilot anaerobic secondary effluent for potable reuse: impact of different disinfection schemes on organic fouling of RO membranes and DBP formation. *Environ. Sci. Technol.* **53** (6), 3166–3176.
- Tauber, A., Schuchmann, H. P. & von Sonntag, C. 2000 Sonolysis of aqueous 4-nitrophenol at low and high pH. *Ultrason. Sonochem.* **7** (1), 45–52.
- Tawabini, B. & Makkawi, M. 2018 Remediation of MTBE-contaminated groundwater by integrated circulation wells and advanced oxidation technologies. *Water Sci. Technol.* **18** (2), 399–407.
- Teo, K. C., Xu, Y. & Yang, C. 2001 Sonochemical degradation for toxic halogenated organic compounds. *Ultrason. Sonochem.* **8** (3), 241–246.
- Tran, T. K., Chiu, K. F., Lin, C. Y. & Leu, H. J. 2017 Electrochemical treatment of wastewater: selectivity of the heavy metals removal process. *Int. J. Hydrogen Energy* **42** (45), 27741–27748.
- Trellu, C., Péchaud, Y., Oturan, N., Mousset, E., Huguenot, D., Van Hullebusch, E. D., Esposito, G. & Oturan, M. A. 2016 Comparative study on the removal of humic acids from drinking water by anodic oxidation and electro-Fenton processes: mineralization efficiency and modelling. *Appl. Catal. B Environ.* **194**, 32–41.
- Turnip, A. & Hutagalung, S. S. 2015 Advanced oxidation processes with O₃-UV-H₂O₂ and reverse osmosis controlled PLC for water purification. *Adv. Sci. Lett.* **21** (12), 3635–3638.
- Uğurlu, M. & Kula, İ. 2007 Decolourization and removal of some organic compounds from olive mill wastewater by advanced oxidation processes and lime treatment. *Environ. Sci. Pollut. Res. Int.* **14** (5), 319–325.
- Ukundimana, Z., Omwene, P. I., Gengec, E., Can, O. T. & Kobya, M. 2018 Electrooxidation as post treatment of ultrafiltration effluent in a landfill leachate MBR treatment plant: effects of BDD, Pt and DSA anode types. *Electrochim. Acta* **286**, 252–263.
- Un, U. T., Altay, U., Koparal, A. S. & Oğutveren, U. B. 2008 Complete treatment of olive mill wastewaters by electrooxidation. *Chem. Eng. J.* **139** (3), 445–452.
- Ün, Ü. T., Uğur, S., Koparal, A. S. & Öğütveren, Ü. B. 2006 Electrocoagulation of olive mill wastewaters. *Separ. Purif. Technol.* **52** (1), 136–141.
- Vasconcelos, V. M., Ponce-de-León, C., Nava, J. L. & Lanza, M. R. 2016 Electrochemical degradation of RB-5 dye by anodic oxidation, electro-Fenton and by combining anodic oxidation–electro-Fenton in a filter-press flow cell. *J. Electroanal. Chem.* **765**, 179–187.
- Vassilakis, C., Pantidou, A., Psillakis, E., Kalogerakis, N. & Mantzavinos, D. 2004 Sonolysis of natural phenolic compounds in aqueous solutions: degradation pathways and biodegradability. *Water Res.* **38** (13), 3110–3118.
- Ververi, M. & Goula, A. M. 2019 Pomegranate peel and orange juice by-product as new biosorbents of phenolic compounds from olive mill wastewaters. *Chem. Eng. Process. Process Intens.* **138**, 86–96.
- Víctor-Ortega, M. D., Ochando-Pulido, J. M. & Martínez-Ferez, A. 2016 Performance and modeling of continuous ion exchange processes for phenols recovery from olive mill wastewater. *Process Saf. Environ. Prot.* **100**, 242–251.
- Vilardi, G., Di Palma, L. & Verdone, N. 2018 On the critical use of zero valent iron nanoparticles and Fenton processes for the treatment of tannery wastewater. *J. Water Process Eng.* **22**, 109–122.
- Vlyssides, A. G., Loukakis, H. N., Karlis, P. K., Barampouti, E. M. P. & Mai, S. T. 2004 Olive mill wastewater detoxification by applying pH related Fenton oxidation process. *Fres. Environ. Bull.* **13**, 501–504.
- Wang, F., Van Halem, D. & Van der Hoek, J. P. 2016 The fate of H₂O₂ during managed aquifer recharge: a residual from advanced oxidation processes for drinking water production. *Chemosphere* **148**, 263–269.
- Wang, H., Zhan, J., Yao, W., Wang, B., Deng, S., Huang, J., Yu, G. & Wang, Y. 2018 Comparison of pharmaceutical abatement in various water matrices by conventional ozonation, peroxone (O₃/H₂O₂), and an electro-peroxone process. *Water Res.* **130**, 127–138.
- Wu, C., Zhou, Y., Sun, X. & Fu, L. 2018 The recent development of advanced wastewater treatment by ozone and biological aerated filter. *Environ. Sci. Pollut. Res.* **25** (9), 8315–8329.
- Xiao, R., Wei, Z., Chen, D. & Weavers, L. K. 2014 Kinetics and mechanism of sonochemical degradation of pharmaceuticals in municipal wastewater. *Environ. Sci. Technol.* **48** (16), 9675–9683.
- Xu, Y. 2001 Comparative studies of the Fe³⁺/2+–UV, H₂O₂–UV, TiO₂–UV/vis systems for the decolorization of a textile dye X-3B in water. *Chemosphere* **43** (8), 1103–1107.
- Xu, H., Zhang, D., Xu, Z., Liu, Y., Jiao, R. & Wang, D. 2018a Study on the effects of organic matter characteristics on the residual aluminum and flocs in coagulation processes. *J. Environ. Sci.* **63**, 307–317.
- Xu, P., Xu, H. & Shi, Z. 2018b A novel bio-electro-Fenton process with FeVO₄/CF cathode on advanced treatment of coal gasification wastewater. *Separ. Purif. Technol.* **194**, 457–461.

- Xu, Y., Li, Y. & Hou, Y. 2019 Reducing ultrafiltration membrane fouling during recycled paper mill wastewater treatment using pretreatment technologies: a comparison between coagulation and Fenton. *J. Chem. Technol. Biotechnol.* **94** (3), 804–811.
- Yahlı Kılıç, M., Yonar, T. & Kestioğlu, K. 2013 Pilot-scale treatment of olive oil mill wastewater by physicochemical and advanced oxidation processes. *Environ. Technol.* **34** (12), 1521–1531.
- Yang, Y., Pignatello, J. J., Ma, J. & Mitch, W. A. 2016 Effect of matrix components on UV/H₂O₂ and UV/S₂O₈²⁻ advanced oxidation processes for trace organic degradation in reverse osmosis brines from municipal wastewater reuse facilities. *Water Res.* **89**, 192–200.
- Yang, B., Wei, T., Xiao, K., Deng, J., Yu, G., Deng, S., Li, J., Zhu, C., Duan, H. & Zhuo, Q. 2018 Effective mineralization of anti-epilepsy drug carbamazepine in aqueous solution by simultaneously electro-generated H₂O₂/O₃ process. *Electrochim. Acta* **290**, 203–210.
- Yang, Y., Cao, Y., Jiang, J., Lu, X., Ma, J., Pang, S., Li, J., Liu, Y., Zhou, Y. & Guan, C. 2019 Comparative study on degradation of propranolol and formation of oxidation products by UV/H₂O₂ and UV/persulfate (PDS). *Water Res.* **149**, 543–552.
- Yazdanbakhsh, A., Mehdipour, F., Eslami, A., Maleksari, H. S. & Ghanbari, F. 2015 The combination of coagulation, acid cracking and Fenton-like processes for olive oil mill wastewater treatment: phytotoxicity reduction and biodegradability augmentation. *Water Sci. Technol.* **71** (7), 1097–1105.
- Yehia, F. Z., Eshaq, G., Rabie, A. M., Mady, A. H. & ElMetwally, A. E. 2015 Phenol degradation by advanced Fenton process in combination with ultrasonic irradiation. *Egypt. J. Petrol.* **24** (1), 13–18.
- Yen, H. Y. 2016 Energy consumption of treating textile wastewater for in-factory reuse by H₂O₂/UV process. *Desal. Water Treat.* **57** (23), 10,537–10,545.
- Yousefifar, A., Baroutian, S., Farid, M. M., Gapes, D. J. & Young, B. R. 2017 Fundamental mechanisms and reactions in non-catalytic subcritical hydrothermal processes: a review. *Water Res.* **123**, 607–622.
- Yu, W., Graham, N. J. & Fowler, G. D. 2016 Coagulation and oxidation for controlling ultrafiltration membrane fouling in drinking water treatment: application of ozone at low dose in submerged membrane tank. *Water Res.* **95**, 1–10.
- Zhao, H., Wang, Y., Wang, Y., Cao, T. & Zhao, G. 2012 Electro-Fenton oxidation of pesticides with a novel Fe₃O₄@ Fe₂O₃/activated carbon aerogel cathode: high activity, wide pH range and catalytic mechanism. *Appl. Catal. B Environ.* **125**, 120–127.
- Zhao, Y., Chang, W., Huang, Z., Feng, X., Ma, L., Qi, X. & Li, Z. 2017 Enhanced removal of toxic Cr (VI) in tannery wastewater by photoelectrocatalysis with synthetic TiO₂ hollow spheres. *Appl. Surf. Sci.* **405**, 102–110.
- Zhou, Z., Yang, Y., Li, X., Li, P., Zhang, T., Lv, X., Liu, L., Dong, J. & Zheng, D. 2018 Optimized removal of natural organic matter by ultrasound-assisted coagulation of recycling drinking water treatment sludge. *Ultrason. Sonochem.* **48**, 171–180.

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