engineering proceedings

Proceeding Paper

Treatment of Agro-Industrial Wastewaters by Coagulation-Flocculation-Decantation and Advanced Oxidation Processes—A literature Review †

Nuno Jorge [1,2,*], Carolina Santos [2], Ana R. Teixeira [2], Leonilde Marchão [2], Pedro B. Tavares [2], Marco S. Lucas [2] and José A. Peres [2]

1 Escuela Internacional de Doctorado (EIDO), Campus da Auga, Campus Universitário de Ourense, Universidade de Vigo, As Lagoas, 32004 Ourense, Spain
2 Centro de Química de Vila Real (CQVR), Departamento de Química, Universidade de Trás-os-Montes e Alto Douro (UTAD), Quinta de Prados, 5001-801 Vila Real, Portugal; al66647@utad.eu (C.S.); ritamourateixeira@gmail.com (A.R.T.); leonilde.mar@gmail.com (L.M.); ptavares@utad.pt (P.B.T.); mlucas@utad.pt (M.S.L.); jperes@utad.pt (J.A.P.)
* Correspondence: njorge@uvigo.es

† Presented at the 1st International Electronic Conference on Processes: Processes System Innovation, 17–31 May 2022; Available online: https://sciforum.net/event/ECP2022.

Abstract: The agro-industry has increased over the years as a necessity to supply the needs of the population in regard to food and drink. This increase has led to the significant production of agro-industrial wastewaters characterized by a high content of organic matter, polyphenols, suspended solids, and turbidity, making these wastewaters dangerous if released into the environment without proper treatment. In this work, recent findings concerning the feasibility of coagulation–flocculation–decantation (CFD) and advanced oxidation processes (AOPs) for the treatment of agro-industrial wastewaters were collected and reviewed. More specifically, the mechanisms, limitations, operational conditions, and relevance of the different treatment processes for wastewater treatment and reuse are discussed. As a result, it was concluded that CFD processes and AOPs could be performed either separately or combined to achieve high efficiency in agro-industrial wastewater treatment.

Keywords: advanced oxidation processes (AOPs); coagulation–flocculation–decantation (CFD); photo-Fenton; sulfate radical-based AOP; ozone-based AOP

check for updates

Citation: Jorge, N.; Santos, C.; Teixeira, A.R.; Marchão, L.; Tavares, P.B.; Lucas, M.S.; Peres, J.A. Treatment of Agro-Industrial Wastewaters by Coagulation-Flocculation-Decantation and Advanced Oxidation Processes—A literature Review. *Eng. Proc.* **2022**, *19*, 33. https://doi.org/10.3390/ECP2022-12665

Academic Editor: Antoni Sánchez

Published: 30 May 2022

1. Introduction

One of the world's largest *L* sources of pollution is the agroindustry, which can be defined as a set of economic activities, including the production, processing or industrialization, and commercialization of agricultural and forestry products, either for food or non-food purposes [1,2]. In Mediterranean countries, most of the agroindustry is centered on the production of olive oil and wine (Figure 1); however, several other products are worthy of mention: coffee, dairy, palm oil, and pulp mill. These activities are the biggest soil, water, and energy consumers in the agro-industrial sector, generating significant volumes of solid materials and wastewaters with important polluting characteristics [2,3]. Considering the high volumes generated and the high organic content that these wastewaters have, it is necessary to apply technologies that are effective. Most studies focus their research on single compounds which are easier to degrade; however, these types of wastewaters are much harder to treat. Therefore, the main goal of this review is to summarize and discuss recent methodologies designed to reduce the organic carbon and polyphenols from agro-industrial wastewaters. The most relevant scientific articles used for this review were selected using Web of Science, Scopus, and Google Scholar databases.

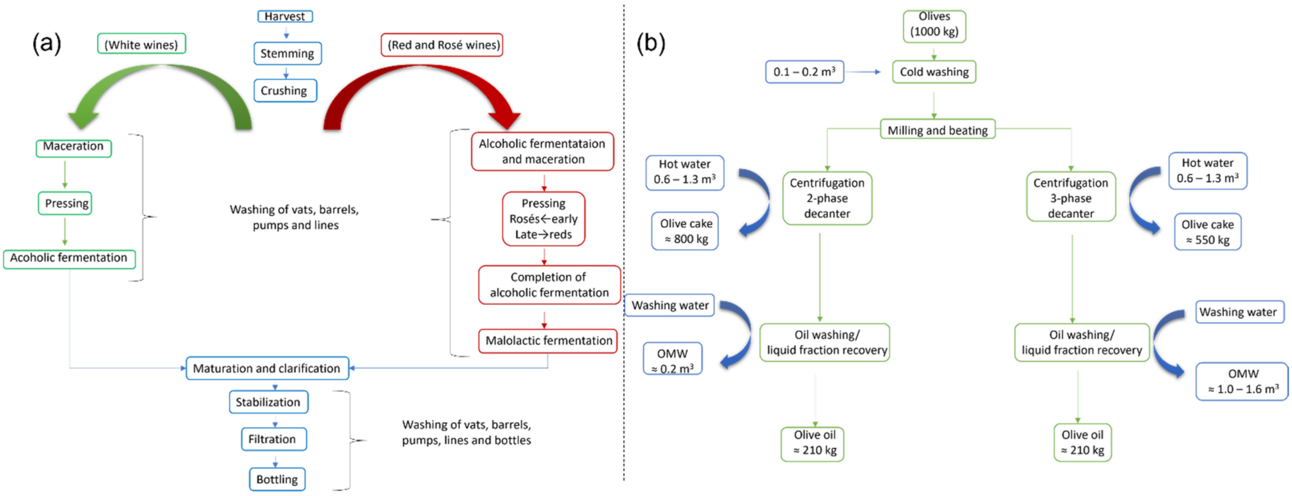

Figure 1. Flow diagram of (**a**) winemaking, (**b**) Two and three phase olive oil production scheme.

2. Coagulation-Flocculation-Decantation Process

To treat agro-industrial wastewater, the physical-chemical process of coagulation–flocculation–decantation (CFD) can be applied. In the coagulation process, small suspended colloids in water are destabilized after diminishing their surface charges by the addition of coagulants with an opposite charge; then, the destabilized particles aggregate and settle down, accelerating particle aggregation further and improving settlement efficiency (Figure 2). Polymeric flocculants with flexible long-chain conformations are sometimes fed after the coagulation as coagulant aids. These polymeric flocculants act as bridges that adsorb and connect various colloidal particles in water to form large flocs that can be effectively removed by sedimentation [4]. In accordance with Howe et al. [5], to obtain particle destabilization, several mechanisms are applied: (1) compression of the electrical double layer, in which if ions are added into the solution, then the electroneutrality can be achieved in a shorter distance; (2) adsorption and charge neutralization, in which particles are destabilized by adsorption of ions or polymers with opposed charge; (3) adsorption and interparticle bridging, in which the polymer remains extended into the solution and continuously adsorbs on remaining surface sites of other particles, and therefore creating a "bridge" between particle surfaces that originates a larger particle that can settle more efficiently; (4) enmeshment in a precipitate, or "sweep floc", which occurs when large concentrations of coagulant are applied. The iron and aluminum generate precipitates that are insoluble, and the particles become entrapped in the amorphous precipitates.

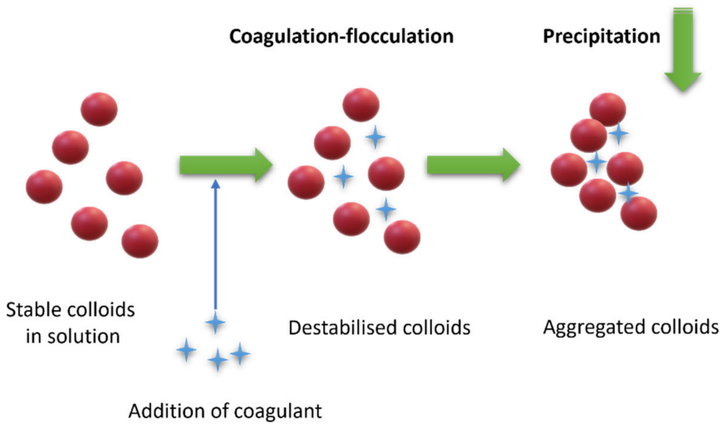

Figure 2. Coagulation-flocculation-decantation scheme.

In order to attain a more economically sustainable, environmentally friendly, and viable production, research interest has been directed towards the evaluation and use of unconventional protein sources, particularly from plant products such as seeds, leaves, and other agricultural by-products. In the work of Dkhissi et al. [6], a plant-based coagulant was applied for the treatment of vegetable oil refinery wastewater, achieving a high removal of turbidity, chemical oxygen demand (COD), and color.

3. Advanced Oxidation Processes (AOP)

Conventional treatment methods have been reported to be inefficient for agro-industrial wastewater treatment, considering that some contaminants are recalcitrant to some degree [7]. Advanced oxidation processes (AOP) can be applied as an alternative or a complement treatment to degrade these recalcitrant compounds. The AOPs generate extremely reactive hydroxyl radicals ($HO^{\bullet}$) radicals that are responsible for the degradation of pollutants in the wastewater. These $HO^{\bullet}$ radicals attack the organic molecules rapidly and non-selectively [8]. The AOPs can be divided according to the oxidant used: hydroxyl radical-based AOP (HR-AOP), sulfate-radical-based AOP (SR-AOP), and ozone-based AOP.

3.1. HR-AOPs

3.1.1. Photo-Fenton Process

The photo-Fenton process is an improvement of the Fenton process, due to the application of the "near-UV to visible region" of light, up to 600 nm, to improve $HO^{\bullet}$ radical production (Equation (1)) [9]. Two additional reactions take place in the photo-Fenton process: (1) photoreduction of Fe^{3+} to Fe^{2+} ions (Equation (2)) [10] and (2) hydrogen peroxide photolysis via shorter wavelengths (Equation (3)) [11], as follows:

$$Fe^{3+} + H_2O + hv \rightarrow Fe^{2+} + HO^{\bullet} + H^{+} \tag{1}$$

$$Fe(HO)^{2+} + hv \rightarrow Fe^{2+}\ HO^{\bullet};\ \lambda < 580\ \text{nm} \tag{2}$$

$$H_2O_2 + hv \rightarrow 2HO^{\bullet};\ \lambda < 310\ \text{nm} \tag{3}$$

Conventional UV-C lamps (primarily mercury lamps) present several problems: overheating, short lifetime, low photonic efficiency, and environmentally-unfriendly properties. LED lights appear to be a viable alternative since they present longer lifetimes, lower energy consumption, higher efficiency, do not overheat, and are less harmful to the environment [12].

3.1.2. Ultrasound-Fenton Process

In recent years, some extensive research on the use of the ultrasound-Fenton (US-Fenton) process for the treatment of water and wastewater has been performed. With the application of ultrasound, a lot of microscopic bubbles that are called cavities are produced. They are formed among water molecules while they gradually become greater. Next, with severe destruction, an application of pressure, and a high temperature, according to Equation (4), water molecules are broken apart, and consequently, hydroxyl radicals are produced [13]. By combining the US with Fenton processes, the production of more hydroxyl ions by the degradation of H_2O_2 (Equation (5)) and the regeneration of Fe^{2+} (Equation (6)) can be observed, as follows:

$$H_2O + US \rightarrow HO^{\bullet} + HO^{-} \tag{4}$$

$$H_2O_2 + US \rightarrow 2HO^{\bullet} \tag{5}$$

$$FeHO_2^{2+} + US \rightarrow Fe^{2+} + HO_2^{\bullet} \tag{6}$$

The application of HR-AOPs is a very efficient process for agro-industrial wastewater treatment. In the work of Velegraki and Mantzavinos [14], a pilot-scale solar Fenton process was applied to the treatment of winery wastewater in a CPC photocatalytic reactor under natural solar irradiation. The results showed that the photo-Fenton process utilizing solar energy is highly efficient in the mineralization and detoxification of real winery wastewater, and the final wastewater exhibited very low toxicity using an *A. fischeri* test as toxicity bioassay.

3.2. SR-AOPs

The interest in persulfate began in earnest around 2000–2002 when work on persulfate began to appear regularly in conference proceedings and in presentations at major remediation meetings [15]. There are two types of sources to obtain the sulfate radical ($SO_4^{\bullet-}$): (1) peroxymonosulphate (HSO_5^-; PMS), which is the active ingredient of triple potassium salt, $2KHSO_5 \bullet KHSO_4 \bullet K_2SO_4$, with the appearance of a white, solid powder. It is stable when the pH is less than 6 or 12. When the pH is 9, it shows poor stability where half of the HSO_5^- decomposes to SO_5^{2-}. PMS can be easily dissolved in water, with a solubility of >250 g L^{-1}. Its water solution is acidic. It has an asymmetrical structure, and the distance of the O–O bond is 1.453 Å. The bond energy is estimated to be in the range of 140–213.3 kJ/mol. (2) persulfate (PS), which is a colorless or white crystal and has high stability. It can be easily dissolved in water, with a solubility of 730 g L^{-1}. The water solution of PS is acidic. It has a symmetrical structure, and the distance of the O–O bond is 1.497 Å, and its bond energy is 140 kJ/mol [16]. Persulfate activation can be achieved by heat, UV radiation, or metal ions, as observed in Equations (7)–(9) [17]:

$$S_2O_8^{2-} \rightarrow 2SO_4^{\bullet-} \tag{7}$$

$$S_2O_8^{2-} + hv \rightarrow 2SO_4^{\bullet-} \tag{8}$$

$$S_2O_8^{2-} + M^n \rightarrow M^{n+1} + SO_4^{\bullet-} + SO_4^{2-} \tag{9}$$

The application of SR-AOPs was shown to be very effective in the treatment of agro-industrial wastewaters. For example, in the work of Domingues et al. [18], the application of PS/Fe^{2+} in the treatment of OMW achieved a total polyphenols removal of 63%.

3.3. Ozone-Based AOPs

In 1840, Schönbein discovered ozone, and by 1872, the chemical structure of ozone (O_3) was finally confirmed as a triatomic oxygen molecule. Later in 1886, de Meritens found that ozone could be used as a germicide for the sterilization of polluted water, and after a few years of pilot tests at water treatment plants in Paris, ozone was first used for water treatment (and used continuously) in Nice, France, in 1906 for drinking water disinfection [19]. Ozone is an unstable gas with a characteristic penetrating odor, which is partially soluble in water. Ozone is also a powerful oxidant with a redox potential of 2.07 V in an alkaline solution. Therefore, O_3 is able to oxidize a lot of inorganic and organic substances [20]. The application of ozone has proven to be effective for agro-industrial wastewater treatment. In the work of Jorge et al. [21], a winery's wastewater was previously treated by the CFD process, achieving a COD removal of 48.0%. With the application of ozonation, the COD removal increased to 60.7%; thus, the combination of CFD with ozonation was shown to be synergistic.

4. Conclusions

The agro-industry has been shown to be very important for the development of populations and must be capable of responding to the need to provide food and to develop the economy of the countries. However, it is concluded that the increase in these industries leads to the production of large volumes of wastewater with a high content of organic matter, total polyphenols, and suspended solids. Therefore, to guarantee the safety of the environment and its ecosystems, it is necessary to apply the necessary treatment processes. Following the literature indications, it can be stated that the coagulation–flocculation–

decantation and advanced oxidation processes can be applied singly or combined to achieve maximum efficiency in wastewater treatment. Thus, it is concluded:

1. The CFD process employs coagulants of different origin (metallic, oenology, or plant-based) and employs different mechanisms simultaneously. Several reviews show that the application of plant-based coagulants has a similar efficiency to metallic coagulants, with lower costs and reduced environmental contamination;
2. The HR-AOPs are dependent on parameters, such as the concentration of H_2O_2, Fe^{2+}, and pH. It is concluded that the application of UV radiation and ultrasound increases the efficiency of the Fenton process. The literature review shows that HR-AOPs are effective in the removal of organic matter from agro-industrial wastewater, reducing the toxicity to lower levels;
3. The SR-AOPs are activated by several mechanisms (thermal activation, alkaline activation, radiation activation, and transition metal ions and metal oxide activation). The literature review shows that PMS and PS have similar effects on the removal of organic matter from agro-industrial wastewater. The results also show the high efficiency of SR-AOPs for the removal of total polyphenols;
4. The ozonation process is enhanced under different conditions (alkaline solution, addition of H_2O_2, radiation, and catalyst) with the production of $HO^{\bullet}$ radicals. The literature review shows that the application of the ozonation process has a high efficiency for the removal of organic carbon and total polyphenols from agro-industrial wastewater.

In summary, the CFD process and AOPs show great potential for the treatment of agro-industrial wastewater treatment, with further research directed toward the reuse of the wastewater for irrigation purposes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ECP2022-12665/s1.

Author Contributions: Conceptualization, N.J., C.S., A.R.T. and L.M.; methodology, N.J.; software, N.J.; validation, N.J., P.B.T., M.S.L. and J.A.P.; formal analysis, N.J.; investigation, N.J., A.R.T. and L.M.; resources, N.J.; data curation, N.J.; writing—original draft preparation, N.J., A.R.T. and L.M.; writing—review and editing, N.J. and J.A.P.; visualization, N.J., P.B.T., M.S.L. and J.A.P.; supervision, M.S.L. and J.A.P.; project administration, J.A.P.; funding acquisition, J.A.P. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are grateful for the financial support of the Project AgriFood XXI, operation nº NORTE-01-0145-FEDER-000041, and to the Fundação para a Ciência e a Tecnologia (FCT) for the financial support provided to CQVR through UIDB/00616/2020. Ana R. Teixeira also thanks the FCT for the financial support provided through the doctoral scholarship UI/BD/150847/2020.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Rosete, A.R. Property, access, exclusion: Agribusiness venture agreements in the Philippines. *J. Rural Stud.* **2020**, *79*, 65–73. [CrossRef]
2. Martinez-Burgos, W.J.; Sydney, E.B.; Medeiros, A.B.P.; Magalhães, A.I.; de Carvalho, J.C.; Karp, S.G.; Vandenberghe, L.P.D.S.; Letti, L.A.J.; Soccol, V.T.; Pereira, G.V.D.M.; et al. Agro-industrial wastewater in a circular economy: Characteristics, impacts and applications for bioenergy and biochemicals. *Bioresour. Technol.* **2021**, *341*, 125795. [CrossRef] [PubMed]
3. Amor, C.; Marchão, L.; Lucas, M.S.; Peres, J.A. Application of Advanced Oxidation Processes for the Treatment of Recalcitrant Agro-Industrial Wastewater: A Review. *Water* **2019**, *11*, 205. [CrossRef]
4. Lee, C.S.; Robinson, J.; Chong, M.F. A review on application of flocculants in wastewater treatment. *Process Saf. Environ. Prot.* **2014**, *92*, 489–508. [CrossRef]

5. Howe, K.J.; Hand, D.W.; Crittenden, J.C.; Trussell, R.R.; Tchobanoglous, G. *Principles of Water Treatment*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2012; ISBN 978-0-470-40538-3.
6. Dkhissi, O.; El Hakmaoui, A.; Souabi, S.; Chatoui, M.; Jada, A.; Akssira, M. Treatment of vegetable oil refinery wastewater by coagulation-flocculation process using the cactus as a bio-flo c culant. *J. Mater. Environ. Sci.* **2018**, *9*, 18–25. [CrossRef]
7. Lucas, M.S.; Mouta, M.; Pirra, A.; Peres, J.A. Winery wastewater treatment by a combined process: Long term aerated storage and Fenton's reagent. *Water Sci. Technol.* **2009**, *60*, 1089–1095. [CrossRef] [PubMed]
8. Bethi, B.; Sonawane, S.H.; Bhanvase, B.A.; Gumfekar, S.P. Nanomaterials-based advanced oxidation processes for wastewater treatment: A review. *Chem. Eng. Process. Process Intensif.* **2016**, *109*, 178–189. [CrossRef]
9. Moncayo-Lasso, A.; Pulgarin, C.; Benítez, N. Degradation of DBPs' precursors in river water before and after slow sand filtration by photo-Fenton process at pH 5 in a solar CPC reactor. *Water Res.* **2008**, *42*, 4125–4132. [CrossRef] [PubMed]
10. Faust, B.C.; Hoigné, J. Photolysis of Fe (III)-hydroxy complexes as sources of OH radicals in clouds, fog and rain. *Atmos. Environ. Part A Gen. Top.* **1990**, *24*, 79–89. [CrossRef]
11. Pouran, S.R.; Aziz, A.A.; Daud, W.M.A.W. Review on the main advances in photo-Fenton oxidation system for recalcitrant wastewaters. *J. Ind. Eng. Chem.* **2015**, *21*, 53–69. [CrossRef]
12. Rodríguez-Chueca, J.; Ferreira, L.C.; Fernandes, J.R.; Tavares, P.B.; Lucas, M.S.; Peres, J.A. Photocatalytic discolouration of Reactive Black 5 by UV-A LEDs and solar radiation. *J. Environ. Chem. Eng.* **2015**, *3*, 2948–2956. [CrossRef]
13. Rahmani, A.R.; Mousavi-Tashar, A.; Masoumi, Z.; Azarian, G. Integrated advanced oxidation process, sono-Fenton treatment, for mineralization and volume reduction of activated sludge. *Ecotoxicol. Environ. Saf.* **2018**, *168*, 120–126. [CrossRef] [PubMed]
14. Velegraki, T.; Mantzavinos, D. Solar photo-Fenton treatment of winery effluents in a pilot photocatalytic reactor. *Catal. Today* **2015**, *240*, 153–159. [CrossRef]
15. Siegrist, R.L.; Crimi, M.L.; Simpkin, T.J. *In Situ Chemical Oxidation for Groundwater Remediation*; Golden, C., Ed.; Springer International Publishing: New York, NY, USA, 2011; ISBN 9781441978257.
16. Wang, J.; Wang, S. Activation of persulfate (PS) and peroxymonosulfate (PMS) and application for the degradation of emerging contaminants. *Chem. Eng. J.* **2018**, *334*, 1502–1517. [CrossRef]
17. Chueca, J.J.R.; Amor, C.; Silva, T.; Dionysiou, D.D.; Puma, G.L.; Lucas, M.; Peres, J. Treatment of winery wastewater by sulphate radicals: HSO5−/transition metal/UV-A LEDs. *Chem. Eng. J.* **2017**, *310*, 473–483. [CrossRef]
18. Domingues, E.; Silva, M.J.; Vaz, T.; Gomes, J.; Martins, R.C. Persulfate Process Activated by Homogeneous and Heteroge-neous Catalysts for Synthetic Olive Mill Wastewater Treatment. *Water* **2021**, *13*, 3010. [CrossRef]
19. Rice, R.G.; Robson, C.M.; Miller, G.W.; Hill, A.G. Uses of ozone in drinking water treatment. *J.-Am. Water Work. Assoc.* **1981**, *73*, 44–57. [CrossRef]
20. Wang, J.; Chen, H. Catalytic ozonation for water and wastewater treatment: Recent advances and perspective. *Sci. Total Environ.* **2020**, *704*, 135249. [CrossRef] [PubMed]
21. Jorge, N.; Teixeira, A.R.; Matos, C.C.; Lucas, M.S.; Peres, J.A. Combination of Coagulation–Flocculation–Decantation and Ozonation Processes for Winery Wastewater Treatment. *Int. J. Environ. Res. Public Health* **2021**, *18*, 8882. [CrossRef] [PubMed]