Electrocoagulation as a Possible Treatment for Wastewater Contaminated with Microplastics - A Review

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Abstract. Microplastics (MPs) have arisen as an omnipresent pollutant that damages the aquatic ecosystem, raising serious concerns. It has become a massive challenge since MPs have the ability to biomagnify and thereby harm human health, biodiversity, aquatic species, and the environment. Therefore, innovative technologies are needed to efficiently remove MPs. Membrane technologies can be quite effective in the removal of MPs. Furthermore, hybrid membrane techniques such as advanced oxidation processes (AOPs), membrane fouling, electrochemical processes, and adsorption processes can be used to improve efficiency. Electrocoagulation is considered an effective wastewater treatment technique for MPs removal, with the advantages of low cost, independence of chemicals, and ease of operation. The main aim of this work is to demonstrate the potential of electrocoagulation to remove MPs from wastewater and provide an overview of the sources and toxicity of MPs found in wastewater. This study also evaluates various physical, chemical, and biological treatment methods for removing MPs from wastewater.

1 Introduction

In the span of nearly seventy years, the volume of plastic manufactured worldwide surged dramatically, jumping from 1.7 million tons in the 1950s to 361 million tons by 2019 [1]. The ubiquity of plastic in common products, such as bags and lenses, coupled with large-scale production, widespread use, and inadequate disposal practices, has substantially fueled the problem of waste. This scenario has precipitated the rise of microplastics (MPs) [1-5]. Consequently, it's crucial to explore the efficacy of existing treatment methodologies in eliminating microplastics.

Microplastics, characterized by their tiny size of less than 5 mm, manifest in diverse compositions, forms, structures, and surfaces, becoming significant pollutants in the environment. It is estimated that by 2060, microplastics will constitute 13.2% of the global plastic waste accumulation [6-8]. These minute particles pose a threat to marine life, birds, terrestrial animals, soil-dwelling organisms, and humans, as they are found in air, water, soil, household dust, and food products.

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Microplastics enter aquatic ecosystems through various pathways, including household wastewater, sewage effluent, runoff from plastic production facilities, and the breakdown of larger plastic debris. Additionally, road dust containing materials like tire particles, bitumen, and road paint contributes to microplastic pollution as it makes its way from freshwater systems into the ocean [9-12].

In the last ten years, there has been a surge in studies focusing on the dangers of microplastics and methods for their removal, identifying microplastics as a crucial carrier for contaminants such as heavy metals and drugs. A range of remediation techniques has demonstrated effectiveness, including mechanical filtration, biologically based solutions like constructed wetlands and membrane bioreactors (MBR), and chemical approaches such as electrocoagulation (EC), as well as photo- and electro-Fenton processes. Hybrid systems combining these methods have also yielded positive outcomes [13-18].

Microplastics, due to their stability and resistance to degradation, present a significant risk to environmental and biological well-being. They are recognized as a critical global environmental challenge, on par with issues such as climate change and ozone depletion [1, 19-22]. The quest for efficient methods to eliminate microplastics from water bodies is becoming increasingly urgent. Among various strategies, electrocoagulation (EC) technology stands out as a promising solution for the removal of microplastics, offering benefits such as high effectiveness, straightforward implementation, and minimal sludge generation [16, 23-31].

This study aims to examine the efficiency, underlying mechanisms, and key determinants affecting the elimination of microplastics in wastewater treatment using electrocoagulation (EC). It endeavors to investigate the origins, presence, and harmful effects of microplastics, while showcasing the capabilities of electrocoagulation. Additionally, it will assess a spectrum of physical, chemical, and biological approaches for removing microplastics from wastewater, providing a comprehensive evaluation of their effectiveness.

2 Microplastics

Microplastics have emerged as a significant environmental concern due to their chemical resilience and ability to permeate various ecosystems, garnering considerable public interest owing to their ubiquitous nature and potential hazards [32]. These particles, defined by their size of less than 5 mm, are derived from synthetic organic polymers. Their composition spans a range of common polymers like polyethylene, acrylics, polyamides (including nylon), polyesters, polypropylene, and polystyrene, in addition to specific industrial polymers, with polyethylene being notably predominant [6]. Exhibiting a plethora of shapes and forms, including fibers, films, foams, fragments, and spheres, microplastics infiltrate environmental mediums from terrestrial to marine and aerial systems, underscoring their pervasive distribution [6].

2.1 Sources and toxicity of MPs

Microplastics (MPs) are categorized according to their origins. Primary MPs are deliberately produced small-scale particles found in products such as preproduction pellets, abrasive blasting materials, and cosmetics [6]. Conversely, secondary MPs originate from the breakdown of larger plastic items in both terrestrial and aquatic settings, including disposed plastics, fishing gear, urban runoff, and sewage outputs [6].

The persistence of MPs in natural environments is attributed to their durability, resistance to biological degradation, and ease of transport, leading to their accumulation. This accumulation poses a risk as aquatic life often ingests these particles, resulting in

digestive and health complications [1]. Furthermore, the substantial surface area and hydrophobic characteristics of MPs enable them to bind with various pollutants, leading to compounded environmental contamination. MPs act as vectors for transporting hazardous substances into food webs, thereby amplifying human exposure to detrimental chemicals, reducing nutritional quality, and facilitating the transmission of diseases. Fig. 1 provides a visual summary of the pathways through which MPs originate, spread, and exert toxic effects on living beings.

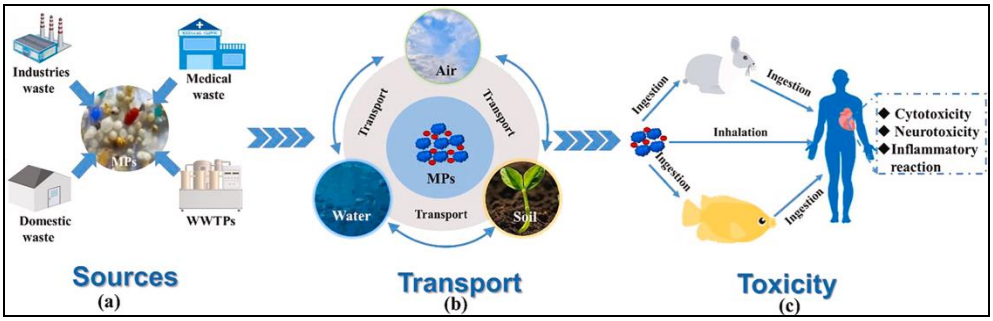

Fig. 1. Schematic representation of sources, transport, and toxicity of MPs on living organisms [1]

2.2 Treatment techniques applied for MPs removal

Microplastics (MPs) have been detected in both treated wastewater and drinking water, leading to a surge in research aimed at evaluating the efficiency of traditional treatment approaches and the development of novel, more effective strategies. While conventional treatments have demonstrated significant effectiveness in removing MPs, there is a consensus on the need for integration with advanced technologies to achieve optimal removal rates [33].

In response to the challenge of MPs, an array of purification techniques has been introduced, spanning physical, chemical, and biological methods, tailored to the specific nature of the treatment. The last decade has seen a heightened focus on the study of microplastics, particularly their role as carriers for a variety of pollutants such as heavy metals, chemical additives, surfactants, antibiotics, pesticides, and pharmaceuticals [13].

Among the methods employed, filtration stands out as the premier physical strategy for MP removal. On the biological front, systems such as Constructed Wetlands (CWs) and Membrane Bioreactors (MBR) have proven effective. Chemical treatments, including Electrocoagulation (EC), standard coagulation, and advanced oxidation processes like photo- and electro-Fenton, have also yielded promising outcomes. Moreover, hybrid systems combining technologies like MBR with Ultrafiltration/Reverse Osmosis (UF/RO), coagulation with subsequent ozonation, Granulated Activated Carbon (GAC), and filtration, as well as CWs-based hybrid models, have demonstrated significant efficacy [13]. Table 1 showcases a variety of MP removal techniques along with their effectiveness.

Table 1. Performance of treatment techniques applied for MPs removal [4].

Technique	Performance
Membrane bioreactor	>99%
Activated sludge	98%
Rapid sand filtration	97.1%
Dissolved air flotation	95%
Electrocoagulation	>90%

Constructed wetlands	88%

3 Application of electrocoagulation on MPs removal

Electrocoagulation (EC) is a comprehensive approach to wastewater treatment that merges the mechanisms of flocculation, flotation, and electrochemical reactions [34]. This method is recognized for its cost efficiency, low energy consumption, and capacity for automated operations, functioning as a chemical coagulation process that produces coagulants on-site through the oxidation of an anode, typically composed of aluminum or iron.

The design of a standard EC system includes multiple electrolytic cells outfitted with cathodes and anodes, which may be crafted from identical or varied materials [13]. These cells are connected to an external direct current (DC) supply, which facilitates the electrolysis of metal anodes, leading to the generation of metal cations and hydroxide ions [34]. Aluminum and iron serve as the preferred materials for sacrificial electrodes due to their excellent coagulation capabilities. The metal ions released during this process combine with hydroxyl ions to create metal hydroxide coagulants. These coagulants effectively disperse emulsions and capture suspended microplastics, resulting in the formation of a sludge layer [9]. At the cathode, gas production occurs, causing the lighter flocs to rise to the surface of the water, thereby enhancing the removal of contaminants through the EC technique [34]. Figure 2 depicts the operational mechanism of EC.

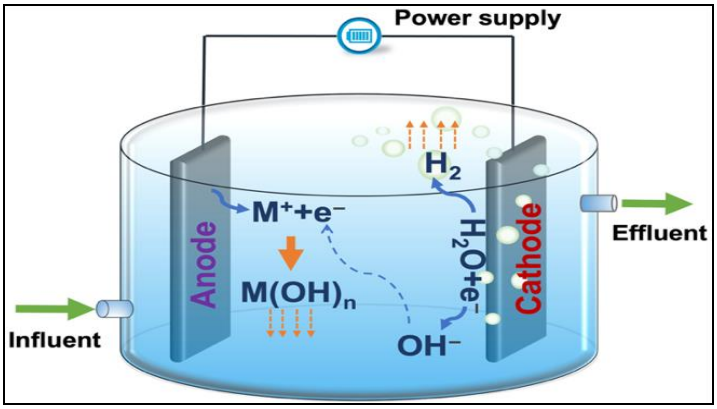

Fig. 2. Schematic diagram of the electrocoagulation process [8].

3.1 MPs removal via EC in contrast to alternative chemical approaches

The coagulation approach is adept at extracting microplastics (MPs) from wastewater, aggregating them into larger flocs via charge neutralization, adsorptive bridging, and entrapment. The success of this method hinges on factors such as the MPs' surface characteristics, size, the dosage and type of coagulant used, though the pH level of the wastewater can significantly influence the process's efficiency, posing limitations on its practical application [34].

Electrocoagulation (EC) provides several advantages over traditional physicochemical treatments, such as effective separation of organic compounds, maintenance of pH levels without chemical additives, lower operational costs, diminished environmental impact, and straightforward automation. EC also generates gas bubbles that aid in the aggregation of pollutants into larger, more stable flocs, capable of capturing even tiny colloidal particles [35]. However, challenges such as the passivation of the cathode, the need for frequent

anode replacement, post-treatment requirements due to elevated metal ion concentrations, increased energy costs, and sludge management issues persist [35].

Photocatalytic (PC) degradation offers a promising route for MP treatment, yet it is not without its complications, including limitations in effectiveness measurement, concerns over the catalyst's environmental impact post-use, and dependence on external light sources. Current evaluation methods, focusing on weight reduction, primarily reflect the adsorption efficiency of MPs on the catalyst, overlooking the broader environmental ramifications and the economic burden of light dependency in PC processes.

In comparison to alternative chemical treatments like photocatalysis (PC) and electro-Fenton (EF), EC stands out for its cost-effectiveness and adaptability, performing under diverse conditions such as varying salinity and pH levels. This is in contrast to PC, which exhibits sensitivity to specific environmental parameters [35]. While other techniques like PC, EF, microbial electrolysis cells (MEC), and microbial fuel cells may offer superior treatment for organically polluted water through bio-electrochemical processes or leveraging chemicals and light, EC maintains a competitive edge in versatility. Table 2 outlines the findings from various studies on the removal rates of MPs from wastewater via the EC process.

3.2 Summary of MPs removal efficiencies by EC

Electrocoagulation (EC) has proven to be a highly efficient technique for the extraction of microplastics from wastewater. Research has delved into the capabilities of an electrochemical setup designed for the concurrent elimination of microplastics during wastewater treatment [36]. This investigation evaluated several variables, including applied voltage, solution pH, treatment duration, electrolyte concentration, electrode arrangement, and the use of a perforated anode. The findings highlighted that the EC approach achieved a microplastic removal rate of 100%, significantly surpassing the effectiveness of standard secondary and tertiary wastewater treatment methods, which ranged between 2% and 81.6%.

Additional studies have scrutinized the EC method's capacity to purge microplastics from wastewater, employing both synthetic mixtures and authentic samples for analysis [37]. Experiments with synthetic solutions adjusted to pH levels of 4 and 7, alongside current densities of 2.88 and 8.07 mA/cm², registered microplastic removal efficiencies of at least 99%. When applied to genuine wastewater samples, the technique demonstrated a microplastic removal efficiency of 96.5%.

Research focused on the deployment of an interpenetrating bipolar plate electrocoagulation (IBPE) reactor aimed at extracting a variety of contaminants from the secondary effluent of wastewater treatment facilities [38]. The findings revealed that the reactor was highly effective in eliminating both heavy metals and microplastics, achieving removal efficiencies of 95.16% and 97.5%, respectively. With operational costs pegged at 0.91 USD per liter, the IBPE reactor presents a viable, eco-friendly solution for the concurrent eradication of microplastics and heavy metals, mitigating risks to aquatic life and human health. The study positions the IBPE method as a sustainable approach to purifying wastewater treatment plant effluents.

In another investigation into the efficacy, underlying mechanisms, and critical factors influencing the removal of microplastics in wastewater treatment via electrocoagulation (EC), findings indicated that aluminum-based anodes outperformed iron counterparts in microplastic removal, securing rates exceeding 80% [39]. The study identified the ideal EC conditions as an electrolyte concentration of 0.05 M, a pH of 7.2, an applied voltage density of 10 V, and the use of an aluminum anode. The research advocates for further exploration

into reactor design enhancements to refine the process, facilitating its application and scalability from lab settings to full-scale sewage treatment operations.

An examination of a specially designed electrocoagulation (EC) reactor, when applied to both synthetic and actual laundry wastewater, demonstrated the technique's efficacy in reducing microplastic pollution [40]. Nonetheless, the EC process was observed to alter the physical and chemical structure of microplastic polymers, causing them to degrade, fragment, or disintegrate, which could result in the creation of smaller, potentially more hazardous nanoplastic fragments. This finding challenges the previously held view of EC's effectiveness, indicating that it might inadvertently contribute to further degradation and fragmentation of microplastics.

Separately, a study delved into the efficiency of an electrochemical setup in concurrently eliminating microplastics and benzyldimethyldodecylammonium chloride (DDBAC) from both potable and wastewater systems [41]. This research scrutinized several parameters, including the applied voltage, pH levels, processing time, electrolyte concentration, electrode arrangement, and the incorporation of a perforated anode. Upon evaluating the cost and energy implications, the method emerged as a viable commercial option for the targeted removal of DDBAC and microplastic compounds from water and wastewater environments.

This research focused on assessing the efficacy of electrocoagulation (EC) for extracting polyamide microplastics from wastewater. Utilizing a setup with an iron anode and an aluminum cathode (Fe-Al), the study achieved a notable removal rate of 96.82% within 120 minutes [32]. It underscored EC's capability to significantly reduce microplastic pollution in wastewater and provided valuable engineering insights for refining operational settings to enhance treatment outcomes. The findings underscore the potential of EC in advancing wastewater purification efforts.

In a separate inquiry, microplastics present in the industrial discharge from the cooling water system of a food packaging manufacturer were scrutinized [42]. By employing the Box Behnken Design (BBD) for optimization, the EC technique reached a microplastic removal efficiency of 99%. The study identified the optimal conditions as a pH of 6.74, a current density of 3.16 mA cm^-2, and a treatment time of 13.58 minutes. Demonstrating EC's high efficiency and cost-effectiveness for microplastic remediation in industrial effluents, the research highlighted the importance of pinpointing the most advantageous EC operational parameters to boost removal efficiency, particularly in the context of upscaling to full-scale treatment facilities.

Table 2. Summary of microplastics removal rates using electrocoagulation.

Water matrix	Microplastic	Operating parameters	Removal rate (%)	Ref.
Domestic wastewater	Polyethylene Polyvinylchloride	Electrode pair Al-Fe, pH 7, current density 20 $A.m^{-2}$, reaction time 10 min	100	[36]
Synthetic wastewater	Polyethylene Polypropylene Polyvinylchloride	Initial MPs concentration 25 mg/L, Al plates, batch reactor, initial pH 4, current density 2.88 mA/cm^2, treatment time 90 min	98.5	[37]
Municipal WWTP	Polyethylene Polypropylene Polyvinylchloride	Initial MPs concentration 25 mg/L, Al plates, batch reactor, initial pH 4, current density 2.88 mA/cm^2, treatment time 90 min	96.5	
Secondary effluent of WWTP	Polyethylene	Current density 12 $mA.cm^{-2}$, initial pH 6, reaction time 20 min, Al plates, IBPE reactor	97.5	[38]

Synthetic domestic wastewater	Polyethylene Polymethylmethacrylate Cellulose acetate Polypropylene	Initial MPs concentration 0.5 g/L, electrolyte (Na_2SO_4) concentration 0.05 M, pH 7.2, voltage density 10 V, Al as anode, Cu as cathode, reaction time 4 h	93.2 91.7 98.2 98.4	[39]
Synthetic wastewater	Polyethylene terephthalate Polypropylene LDPE Polyamide	Fe as anode, Stainless steel as cathode, 23 ◦C, 15V, 1.0 A, initial pH 8.38	94 89 91 86	[40]
Laundry wastewater	Polyethylene terephthalate Polyamide Acrylic copolymer Ethylene acrylic acid copolymer Polyethylene propylene diene	Fe as anode, Stainless steel as cathode, 23 ◦C, 15V, 1.0 A, initial pH 8.38	89 - 91 70 - 75 78 - 79 75 - 86 80	
Synthetic wastewater	Polystyrene	Initial concentration 20 mg/L, pH 7.4, reaction time 80 min, electrolyte (Na_2SO_4) concentration 0.05 M, voltage 12.59 V, four Fe electrodes,	82.5	[41]
Synthetic wastewater	Polyamide	120 min of electrolysis, combination of Fe–Al electrode, plate spacing of 2.5 cm, applied voltage of 10 V, initial pH 7, electrolyte concentration 0.02 mol/L.	96.82	[32]
Food packaging industry wastewater	Microplastics	pH 6.74, current density 3.16 $mA.cm^{-2}$, treatment time 13.58 min.	99	[42]

4 Conclusion

This comprehensive review delves into the origins and toxic impacts of microplastics (MPs) on aquatic ecosystems and living beings, offering a broad perspective on the array of wastewater treatment technologies employed for MP mitigation. It evaluates different MP management strategies, discussing their effectiveness, benefits, and drawbacks.

The document emphasizes electrocoagulation (EC) as an effective and eco-friendly approach for MP removal from wastewater. It provides an in-depth look at EC's benefits and challenges, its underlying principles, and the operational variables influencing its performance, including a compilation of MP removal efficiencies achieved through the EC method.

Despite EC's effectiveness in addressing MP pollution, it faces operational challenges such as the regular need to replace sacrificial anodes, the risk of cathode passivation, and the associated costs of high energy consumption. Addressing these issues requires the exploration of more durable anode materials and further research into operational adjustments that can mitigate cathode passivation, enhancing the overall efficacy and sustainability of the EC process.

References

1. F. Liu, C. Zhang, H. Li, N.-A.O. Offiong, Y. Bi, R. Zhou, and H. Ren, Chemical Engineering Journal, **456**, 141078 (2023).
2. A. Bourjila, F. Dimane, M. Ghalit, M. Taher, S. Kamari, Y. El Hammoudani, I. Achoukhi, and K. Haboubi, Water Cycle, **4**, 104-119 (2023).
3. Y. El Hammoudani, F. Dimane, K. Haboubi, A. Bourjila, C. Benaissa, I. Achoukhi, and C. Haboubi, Environmental Engineering & Management Journal (EEMJ), **22**, (2023).
4. I. Achoukhi, Y. El Hammoudani, F. Dimane, K. Haboubi, A. Bourjila, C. Haboubi, C. Benaissa, A. Elabdouni, and H. Faiz, Journal of Ecological Engineering, **24**, 12-31 (2023).
5. Y. El Hammoudani, F. Dimane, K. Haboubi, C. Benaissa, L. Benaabidate, A. Bourjila, I. Achoukhi, M. El Boudammoussi, H. Faiz, and A. Touzani, Desalination and Water Treatment, 100190 (2024).
6. S. Sharma, S. Basu, N.P. Shetti, M.N. Nadagouda, and T.M. Aminabhavi, Chemical Engineering Journal, **408**, 127317 (2021).
7. Y. Fernine, N. Arrousse, R. Haldhar, C.J. Raorane, S.-C. Kim, F. El Hajjaji, M.E. Touhami, M. Beniken, K. Haboubi, and M. Taleb, Journal of the Taiwan Institute of Chemical Engineers, **140**, 104556 (2022).
8. A. Ait Mansour, B. El-Haitout, R.J. Adnin, H. Lgaz, R. Salghi, H.-s. Lee, M.R. Alhadeethi, M. Messali, K. Haboubi, and I.H. Ali, Metals, **13**, 797 (2023).
9. M.B. Ahmed, M.S. Rahman, J. Alom, M.S. Hasan, M. Johir, M.I.H. Mondal, D.-Y. Lee, J. Park, J.L. Zhou, and M.-H. Yoon, Science of the Total Environment, **775**, 145793 (2021).
10. A.E. Abdouni, S. Bouhout, I. Merimi, B. Hammouti, and K. Haboubi, Caspian Journal of Environmental Sciences, **19**, 423-429 (2021).
11. A. Elabdouni, K. Haboubi, N. Bensitel, S. Bouhout, K. Aberkani, and M.S. El Youbi, Moroccan Journal of Chemistry, **10**, 191-202 (2022).
12. A. Elabdouni, K. Haboubi, I. Merimi, and M. El Youbi, Materials Today: Proceedings, **27**, 3145-3150 (2020).
13. M. Bodzek and A. Pohl, Archives of Environmental Protection, **48**, (2022).
14. M. Elazzouzi, K. Haboubi, M. Elyoubi, and A. El Kasmi, ES Energy & Environment, **5**, 66-74 (2019).
15. M. Elazzouzi, K. Haboubi, M.S. Elyoubi, and A. El Kasmi, Arabian Journal of Chemistry, **14**, (2021).
16. C. Benaissa, A. Rossi, B. Bouhmadi, Y. El Hammoudani, and F. Dimane. Assessment of the physicochemical and bacteriological quality of water source and a well in Bakoya aquifer, northern Morocco. in E3S Web of Conferences. 2024. EDP Sciences.
17. F. Dimane and Y. El Hammoudani, Materials Today: Proceedings, **45**, 7742-7746 (2021).
18. O. Saadi, N. Nouayti, A. Nouayti, F. Dimane, and K. Elhairechi, Groundwater for Sustainable Development, **14**, 100639 (2021).
19. M. El bastrioui, K. Haboubi, A. Chetouani, B. Hammouti, and A. Nandiyanto, Moroccan Journal of Chemistry, **10**, 10-4 (2022) 851-860 (2022).
20. K. Andaloussi, H. Achtak, C. Nakhcha, K. Haboubi, and M. Stitou, Moroccan Journal of Chemistry, **9**, 9-3 (2021) 513-529 (2021).
21. A. Salhi, A. Elyoussfi, I. Azghay, A. El Aatiaoui, H. Amhamdi, M. El Massaoudi, M. Ahari, A. Bouyanzer, S. Radi, and S. El barkany, Inorganic Chemistry Communications, **152**, (2023).
22. H.E. Hassouni, A. Elyousfi, F. Benhiba, N. Setti, A. Romane, T. Benhadda, A. Zarrouk, and A. Dafali, Inorganic Chemistry Communications, **143**, 109801 (2022).

23. A. Abouabdallah, Y. El Hammoudani, F. Dimane, K. Haboubi, K. Rhayour, and C. Benaissa, Ecological Engineering and Environmental Technology, **24**, 170-182 (2023).
24. C. Benaissa, B. Bouhmadi, A. Rossi, and Y. El Hammoudani. Hydro-chemical and bacteriological Study of Some Sources of Groundwater in the GHIS-NEKOR and the BOKOYA Aquifers (AL HOCEIMA, MOROCCO). in Proc of The 4th Edition of International Conference on Geo-IT and Water Resources. 2020.
25. C. Benaissa, B. Bouhmadi, A. Rossi, Y. El Hammoudani, and F. Dimane, Ecological Engineering & Environmental Technology, **23**, 31-44 (2022).
26. S. Bouhout, K. Haboubi, A. El Abdouni, Y. El Hammoudani, C. Haboubi, F. Dimane, I. Hanafi, and M.S. Elyoubi, Journal of Ecological Engineering, **24**, (2023).
27. S. Bouhout, K. Haboubi, Y.E. Hammoudani, A.E. Abdouni, C. Haboubi, F. Dimane, I. Hanafi, and M.S. Elyoubi, Ecological Engineering and Environmental Technology, **25**, 22-45 (2024).
28. Y. El Hammoudani and F. Dimane, Environ. Eng. Res., **0**, 0 (2020).
29. Y. El Hammoudani and F. Dimane, Environ. Chall., **5**, 1-8 (2021).
30. Y. El Hammoudani, F. Dimane, and H. El Ouarghi, Environmental Engineering and Management Journal, **20**, 995-1002 (2021).
31. A. Touzani, Y. El Hammoudani, F. Dimane, M. Tahiri, and K. Haboubi, Ecological Engineering & Environmental Technology, **25**, 57-69
32. Y. Hu, L. Zhou, J. Zhu, and J. Gao, Journal of Water Process Engineering, **51**, 103417 (2023).
33. S.F. Ahmed, N. Islam, N. Tasannum, A. Mehjabin, A. Momtahin, A.A. Chowdhury, F. Almomani, and M. Mofijur, Chemosphere, **347**, 140648 (2024).
34. B. Cui, H. Rong, T. Tian, D. Guo, L. Duan, F. Nkinahamira, P. Ndagijimana, W. Yan, and R. Naidu, Environmental Research, 118416 (2024).
35. Y. Mao, Y. Zhao, and S. Cotterill, Water, **15**, 1455 (2023).
36. C. Akarsu, H. Kumbur, and A.E. Kideys, Water Science and Technology, **84**, 1648-1662 (2021).
37. D. Elkhatib, V. Oyanedel-Craver, and E. Carissimi, Separation and Purification Technology, **276**, 118877 (2021).
38. R. Xu, Z. Yang, Y. Niu, D. Xu, J. Wang, J. Han, and H. Wang, Separation and Purification Technology, **290**, 120905 (2022).
39. M. Shen, Y. Zhang, E. Almatrafi, T. Hu, C. Zhou, B. Song, Z. Zeng, and G. Zeng, Chemical Engineering Journal, **428**, 131161 (2022).
40. K. Senathirajah, R. Kandaiah, L. Panneerselvan, C. Sathish, and T. Palanisami, Environmental Pollution, **334**, 122159 (2023).
41. A. Mahmoudnia, N. Mehrdadi, M. Baghdadi, and G. Moussavi, Environmental Science and Pollution Research, **30**, 66195-66208 (2023).
42. M. Sezer, M. Isgoren, S. Veli, E. Topkaya, and A. Arslan, Chemosphere, **352**, 141314 (2024).