

## Review

# Bibliometric Study of Electrochemical Advanced Oxidation Processes (EAOPs) for Wastewater Treatment

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**Abstract:** Electrochemical advanced oxidation processes (EAOPs) are at the forefront of scientific research as green technologies aimed at effectively purifying polluted aquatic environments. These methods utilize electrochemical processes to generate reactive oxygen species (ROS), such as the hydroxyl radical ( $\bullet\text{OH}$ ), either on the anode surface or within the bulk solution, which can partially degrade or completely mineralize organic pollutants. The aim of the article is to provide a bibliometric analysis of research articles specifically focused on the application and development of EAOPs in wastewater treatment over the past five years. Utilizing the most extensive database for literature searches, Web of Science Core Collection (WoS), which encompasses 95% of global publications, a total of 649 research articles were retrieved by limiting the search results to words associated with EAOPs in titles, keywords, and abstracts. The bibliometric dataset was then processed using CiteSpace and VOSviewer software. The People's Republic of China is emerging as the country with the highest production in the field, demonstrating a strong commitment to research and a leading role in international cooperation. This leadership is evident through China's substantial contributions to the body of literature and its extensive network of collaborations with researchers worldwide. Meanwhile, Australia, despite producing fewer publications, has achieved a high citation rate, underscoring the significant impact and influence of its research within the scientific community. One of the most promising and extensively studied topics in this field is the electro-Fenton process, which has garnered considerable attention due to its potential applications and remarkable efficiency in various contexts. The bibliometric analysis conducted in this study allowed for a detailed visualization of the currently available literature data and corresponding developing trends. By mapping out the key areas of focus, prominent researchers, influential journals, and collaborative networks, this analysis provides valuable insights. These insights can facilitate future joint research endeavors, enhance collaboration, and promote the sharing of knowledge and best practices among researchers globally.

**Keywords:** EAOPs; wastewater; bibliometric analysis; CiteSpace; VOSviewer



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## 1. Introduction

Water pollution mainly occurs when untreated industrial or domestic wastewater, which contains harmful chemicals and substances, is discharged into water bodies like lakes, ponds, rivers, and reservoirs. This contamination makes the water unsuitable for consumption. This pollution also affects various other uses of the water. Since the survival of humanity and all other life forms on our planet depends on the availability of clean water, the primary research mission is to improve water quality through the development and application of new wastewater purification technologies [1,2]. Initially, conventional methods, including physical (sand filtration), physico-chemical (coagulation/flocculation, precipitation, adsorption using activated charcoal, evaporation), chemical (oxidation, incineration, solvent extraction, membrane separation, membrane bioreactors, electrochemical

treatment, ion exchange) and biological (biodegradation) ones were employed for the decontamination of wastewaters [3–7]. While these methods demonstrate fairly remarkable results regarding the efficiency of pollutant removal, they also have significant drawbacks. Physical methods such as adsorption merely shift pollutants from one location to another without degrading or mineralizing them, unlike EAOPs. Adsorption tends to be more selective and may not effectively address all types of pollutants. Additionally, adsorption can generate secondary waste (spent adsorbent material) that must be disposed of or regenerated, a complex process that is often not economically viable. Chemical methods lead to additional pollution of the environment due to the chemicals used, probable formation of toxic byproducts, and difficulty in targeting specific pollutants without affecting the environment or non-target organisms. However, biological methods, while eco-friendly, necessitate extended periods for biological acclimation and biodegradation, as well as specific conditions for implementation. On the other hand, electrochemical technologies based on the generation of reactive species from water electrolysis (hydrogen evolution occurs on the cathode and oxygen evolution intermediates are generated on the anode surface) have garnered significant attention due to their sustainability potential, high amount of pollutant removal, and the perspectives to reduce the process cost by applying appropriate electrode materials. Besides classical electrochemical separation technologies (such as electrodeposition, electrocoagulation, and electroflotation), scientists have focused on developing EAOPs in order to totally degrade and mineralize organic pollutants, reducing their harmfulness while minimizing the operational cost by using simple and available equipment and avoiding complex procedures.

EAOPs degrade organic pollutants through reactive oxygen species (ROS) like hydroxyl radicals ( $\bullet\text{OH}$ ). These radicals are generated in electrochemical systems by oxidizing water at the anode surface or, to a significantly lesser extent, in the solution bulk. These techniques are typically used as secondary or advanced treatment options, rather than as primary methods. Their importance becomes evident in cases where conventional treatment approaches do not suffice to meet regulatory standards for surface and groundwater quality. This is especially relevant as environmental regulations become increasingly stringent, driven by new policies aimed at reducing levels of pollution in the environment. A notable example of this change is the recent revision of the Urban Wastewater Treatment Directive by the European Commission (Council Directive 91/271/EEC). The revised directive aims to improve water quality by addressing persistent pollution issues originating from municipal wastewater. It includes provisions that mandate polluters to cover the costs of removing micropollutants (such as pesticides, pharmaceuticals, microplasticizers, etc.), and requires EU member states to treat and continuously monitor micropollutants in wastewater. This comprehensive approach highlights the growing potential for applying and developing EAOPs for wastewater treatment to ensure compliance with evolving environmental standards. On the other hand, while EAOPs have significant advantages in treating micropollutants in wastewater, particularly in achieving high removal efficiency, they are generally more expensive compared to other methods such as adsorption, biological treatment, and chemical oxidation. EAOPs require a higher initial investment, but their benefits—including reduced sludge production and minimal use of chemical additives—can offset these initial costs over time. Consequently, EAOPs play a crucial role in supporting zero-waste initiatives, making them an appealing option for future wastewater management. Recent technological advances in EAOPs, such as the development of improved electrode materials and more efficient reactor designs, have substantially lowered their operating costs. Additionally, integrating EAOPs with renewable energy sources holds the potential to create treatment plants with zero or low energy consumption, aligning with global sustainability goals and further enhancing the feasibility of EAOPs as a sustainable wastewater treatment solution.

Numerous EAOPs are discussed in the literature [8–11], such as anodic oxidation (AO) and EAOPs where the oxidizing species are provided from Fenton's reaction. AO is the simplest and most popular process which is extensively used for removing organic

pollutants from textile and dye wastewater [12,13], industry wastewater [14], and slaughterhouse wastewater [15]. In AO, the degradation of organic pollutants can rarely occur directly, through electron transfer from the electrode to organic molecules adsorbed on the anode surface. More frequently, the oxidation proceeds indirectly, via reactive oxygen species formed at the anode. Lately, researchers have focused more on the anodic materials, with the aim to elucidate degradation mechanisms and find optimal degradation performance. Common electrodes used in wastewater treatment include graphite, Pt, PbO<sub>2</sub>, SnO<sub>2</sub>, SnO<sub>2</sub>-Sb, Ti/Pt, Ti/SnO<sub>2</sub>, Ti/PbO<sub>2</sub>, Ti/RuO<sub>2</sub>, TiO<sub>2</sub>, Ti/IrO<sub>2</sub>-TiO<sub>2</sub>, Ti/IrO<sub>2</sub>-RuO<sub>2</sub>-TiO<sub>2</sub>, boron-doped diamond (BDD), and titanium-based boron-doped diamond (BDD/Ti) [16–24]. Additionally, novel anodic materials are expected to be the key factor determining efficiency and cost of future technologies for wastewater treatment. In combination with the cathodic electrogeneration of H<sub>2</sub>O<sub>2</sub>, this type of AO is referred to as anodic oxidation with electrogenerated H<sub>2</sub>O<sub>2</sub> (AO-H<sub>2</sub>O<sub>2</sub>) [8]. Compared to AO, EAOPs based on Fenton reaction chemistry for the degradation of organic pollutants use OH radicals, which are produced in the bulk solution. The most employed and investigated among the EAOPs is the classical electro-Fenton (EF) process, where H<sub>2</sub>O<sub>2</sub> is electrogenerated at the cathode with pure O<sub>2</sub> or air supply, and an iron-based catalyst (Fe<sup>2+</sup>, Fe<sup>3+</sup>, salts or oxides) is added to the effluent [11]. Numerous variants of EF methods have been the subject of research interest [8,11,25–27]. These include proxy-coagulation (PC), photochemically assisted EF (photoelectro-Fenton (PEF), solar photoelectro-Fenton (SPEF), photoelectrochemical electro-Fenton (PEC-EF)), and ultrasound-assisted EF (sonoelectro-Fenton (SEF)). Electrochemical modifications of EF included cathodically generated Fe<sup>2+</sup>, as well as electrochemical and combined Fenton processes with H<sub>2</sub>O<sub>2</sub> added to the solution or produced indirectly (Fered–Fenton, electrochemical peroxidation (ECP), anodic Fenton treatment (AFT)).

Bibliometric analysis employs the methods of mathematics and statistics to assess the quantity, quality and network of scientific activities in a specific research area [28]. Quantitative indicators (such as the number of publications by a researcher, institution, or country) assess the production and volume of scientific results in a particular field. The impact and importance of the research are assessed using quality indicators, including citation counts, journal impact factors, and the h-index. Network analysis examines the relationships among publications through authorship, citations, or keywords, with the goal of delineating the intellectual structure and evolution of a particular research domain [29].

Up to date, several articles dealing with the application of bibliometric studies to the environmental research field have been published by many authors [30–37]. Among these bibliometric studies, our research group has also published a bibliometric analysis on the use of nanostructured anodes for electrooxidative wastewater treatment. However, to the best of the authors' knowledge, a bibliometric analysis of research articles on EAOPs for wastewater treatment technology has not been conducted to date, despite numerous review articles [8,9,30,38–41]. Hence, the aim of this article is to conduct a bibliometric analysis restricted to research articles specifically focused on the application and development of EAOPs in the treatment of wastewater. While both bibliometric analysis and review papers contribute to the scientific understanding of a given topic, they differ in their methodologies and objectives. Unlike a classic review paper, which synthesizes the existing literature to summarize current knowledge and highlight the most important achievements within the target area, bibliometric analysis is a data-driven method that explores and analyzes the research evolution of a particular topic through mathematical and statistical techniques. Therefore, while review papers provide qualitative insights and interpretations of research trends and findings, bibliometric analysis offers quantitative metrics and visualizations to understand the structure and dynamics of scientific knowledge within a field. This bibliometric study makes a significant contribution to research on applying EAOPs to degrade organic pollutants. It offers insights into the current state of research and development, identifies key authors, institutions, and leading countries in this field, and presents findings on pollutant degradation. Additionally, it helps researchers become more aware of the

main challenges in this field, guiding them in making informed decisions about future research topics.

## 2. Materials and Methods

### *Data Collection and Analysis*

Data for this bibliometric analysis were collected from the WoS database, using All Editions. The Topic search options (which include searching titles, abstracts, keywords, and author keywords) were utilized with the terms (“electrochemical advanced oxidation process\*” OR “EAOP\*” OR “anodic oxidation” OR “electrochemical oxidation” OR “electrooxidation” OR “electro-oxidation” OR “electrochemical degradation” OR “electrocatalytical degradation” OR “electro-Fenton” OR “electro Fenton” OR “peroxi-coagulation” OR “photoelectro-Fenton” OR “solar photoelectro-Fenton” OR “photoelectrochemical electro-Fenton” OR “sonoelectro-Fenton” OR “Fered-Fenton” OR “electrochemical peroxidation” OR “anodic Fenton”) (Topic) AND (“waste-water\*” OR “waste water\*” OR “aquatic medium\*” OR “wastewater\*” OR “real wastewater\*” OR “synthetic electrolyte\*” OR “landfill leachate” OR “sewage”) (Topic) AND (“organic pollutant\*” OR “organic contaminant\*”) (Topic) NOT “photocatalytic\*” (Topic). Publications from the past five years, from 1 January 2020 to 19 June 2024, were included. The data were collected on 19 June 2024.

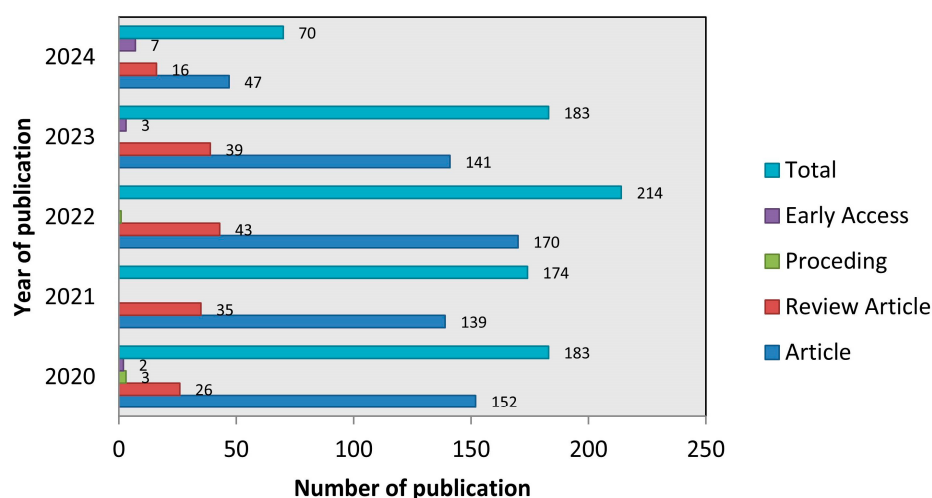
For visualizations and network analysis, we used the CiteSpace (version 6.3.R1) software developed by Dr. Chaomei Chen [42]. It focuses on the visualization and analysis of trends and patterns in the scientific literature. In this paper, it was used to discover the most co-cited articles, journal co-citations, and the evolution of keywords over the past five years.

VOSviewer software (version 1.6.18) was also used in this bibliometric analysis of research on the application of EAOPs for wastewater treatment, focusing mainly on the analysis of co-authorship (countries, organizations, and authors), cited articles, and co-cited authors.

## 3. Results and Discussion

### *3.1. Publications Trends*

Under the set search criteria using the WoS database, 810 papers were published in the last five years. Among these, there were 649 research articles, 159 review articles, 12 early access articles, and 4 proceeding papers. These papers were published in English (805), Chinese (2), Portuguese (1), Spanish (1), and Turkish (1). The distribution by number and type of papers, depending on the year of production, is shown in Figure 1.



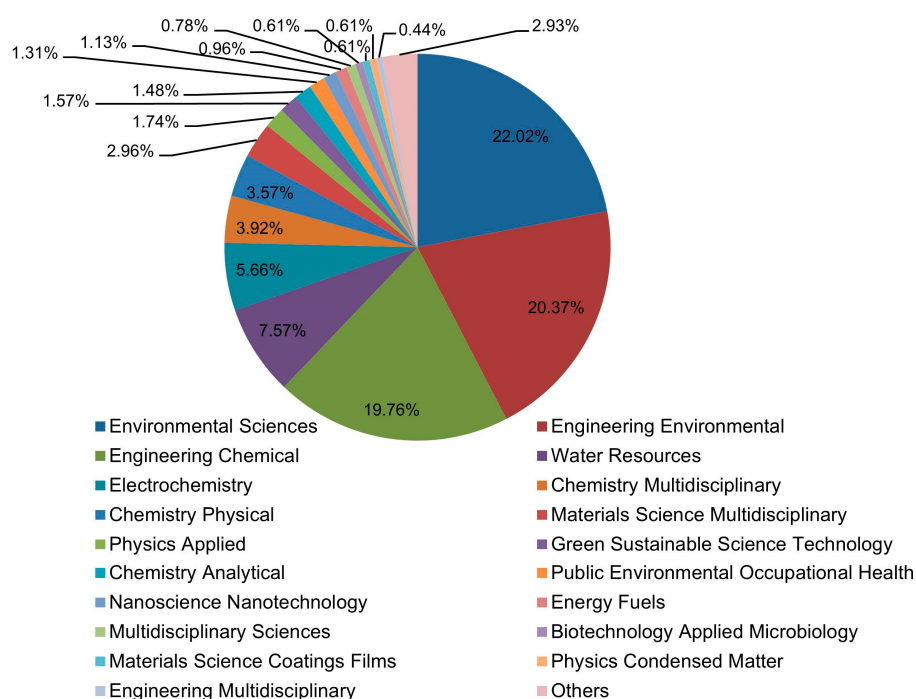
**Figure 1.** The distribution of papers by number and type of article during the last five years.

Over the past five years, approximately 200 papers were published annually, predominantly consisting of articles, followed by review articles. This distribution highlights a

strong focus on original research and thorough literature reviews during that time. The fewest articles were published in 2024, probably because the data does not yet include the entire year of 2024.

In the next sections of this work, the review articles are not included in the bibliometric analysis, focusing solely on research articles in English language. Review papers typically receive a high number of citations because they provide foundational knowledge, which can skew the analysis of the most cited organizations, countries, and other metrics, thereby distorting the actual impact of original research.

In total, 647 research articles are distributed across various subject areas. Environmental sciences, chemistry, and chemical engineering are emerging as the fields most relevant to the topic. Additionally, water resources, electrochemistry, chemistry multidisciplinary, chemistry physical, and materials science multidisciplinary are crucial, as they are directly related to the wastewater treatment, mechanism of degradation–chemical pathway, manufacturing and optimization of reactor, and synthesis and characterization of electrocatalysts used in EAOPs. Figure 2 presents the distribution map of these interconnected subject areas.



**Figure 2.** Distribution of the research articles according to subject area.

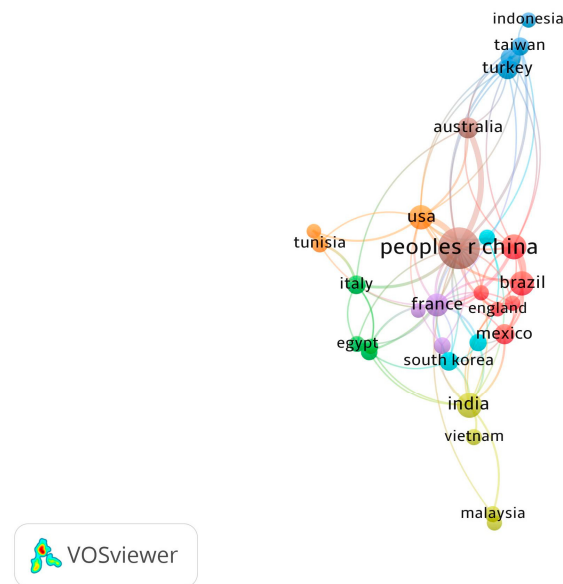
### 3.2. The Collaboration Network Analysis

#### 3.2.1. Co-Authorship Countries

In all, 78 countries worked in the field of EAOPs (78 have at least one publication). To define the most prominent countries, we set a limit of countries with at least five publications and three citations, and 31 countries met this, and this is shown in Figure 3.

There is a scarce network of cooperation between countries in the field of “application of EAOPs for wastewater treatment” research. In the country network collaboration map, larger circles and fonts represent a more significant contribution. The People’s Republic of China (354 publications), India (44 publications), Spain (43 publications), and the USA (40 publications) are the most productive countries in this area. The People’s Republic of China leads with 354 publications, and has the number of citations of 7352 (average citations per document 20.77). On the other hand, Australia, with only 22 publications, has 986 citations (average citations per document 44.82), making it more influential when considering the average citation per document compared to the People’s Republic of China

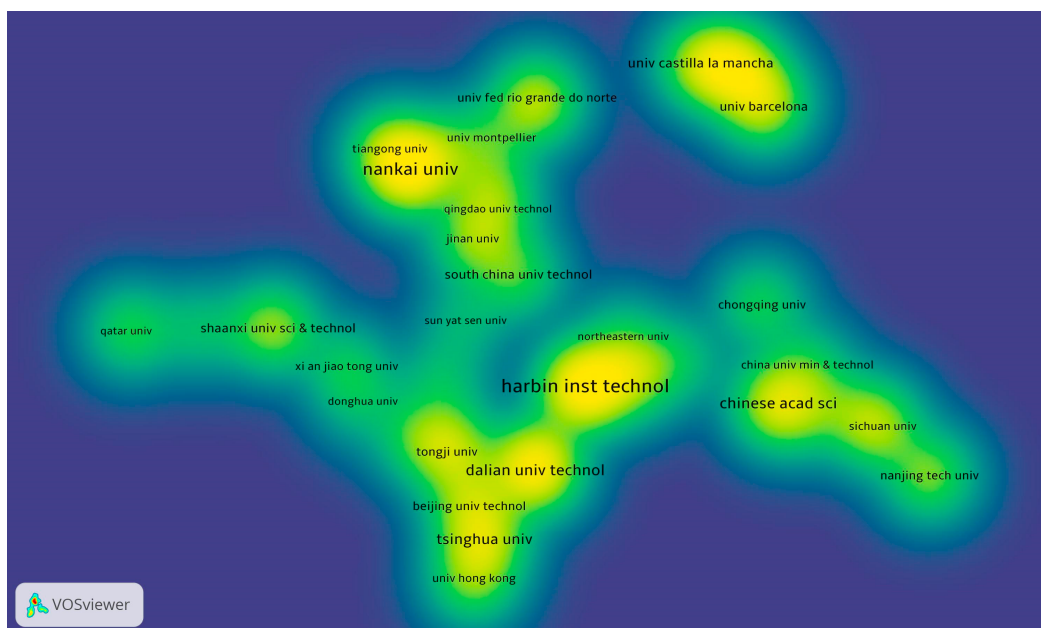
(average citation per document 20.77) and India, Spain, and the USA, which have citations per document 20.14, 19.26, and 18.33, respectively. This indicates that Australia is highly influential, relevant, and impactful in the research area. The lists of the prominent countries based on the number of publications and citations are presented in Supplementary Table S1. Also, the People's Republic of China has the greatest total link strength of 65, indicating extensive collaborations with other countries, particularly with Australia and the USA, as shown by the link thickness.



**Figure 3.** VOSviewer network map of countries.

### 3.2.2. Co-Authorship Organizations

Moreover, 756 organizations published in the field of EAOPs (756 have at least one publication). To define the most prominent organization, we set a limit to organizations with at least five publications and three citations, and 51 organizations met this, and this is shown in Figure 4 and Table S2 of the Supplementary Information.

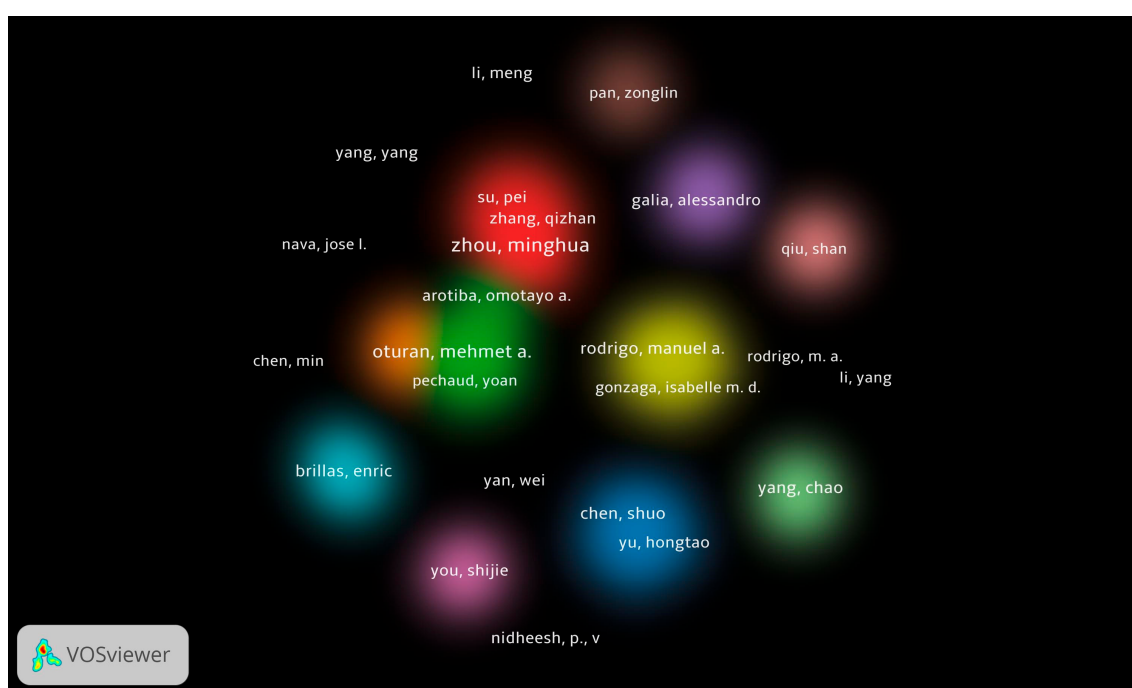


**Figure 4.** Density visualization of institutional cooperation.

The most productive organizations are from the People's Republic of China, such as Harbin Institute of Technology (29 papers), Nankai University (24 papers), and the Chinese Academy of Sciences (18 papers). In terms of average citations per document, which is a key indicator of an organization's research impact, quality, and overall influence on the academic community, the first and second places are occupied by Nankai University (average citations per document: 46.42) and Hunan University (45.70). Additionally, the University of Paris from France and the University of Barcelona from Spain also play a significant role in the field of application of EAOPs for wastewater treatment, with average citations per document of 41.88 and 29.2, respectively.

### 3.2.3. Co-Authorship Authors

Additionally, 2932 authors published in the field of EAOPs (2932 have at least one publication). To define the most prominent author, we set a limit to authors with at least five publications and three citations, and 49 authors met this, and this is shown in Figure 5 and Table S3 of the Supplementary Information.



**Figure 5.** Density visualization of prominent authors.

The identification of the most prominent authors was based on two key metrics: the number of publications and the average number of citations per published document. Together, these metrics provide a comprehensive view of an author's productivity and the impact of their articles. Among the top research contributors, Zhou Minghua leads with 22 publications, followed by Mehmet A. Oturan with 14 publications and Nihal Oturan with 11 publications. These authors are recognized for their extensive research output and consistent contributions to the field. When considering the average citations per document, Xuedong Du stands out with an impressive 111.50 citations per document, indicating that her work is highly influential and frequently referenced. Similarly, Qizhan Zhang, with 72.86 citations per document, and Wangwang Tang, with 51.2 citations per document, demonstrate significant impact on the research community through their studies on the application of EAOPs in wastewater treatment.

### 3.3. Most Cited Articles

To define the most cited articles, a threshold of at least five citations per paper was set. This criterion was met by 419 documents out of a total of 647, after manual elimination

of less significant works. The number of citations an article receives is an important bibliometric indicator of its influence and relevance, and it indicates the direction of future research towards a specific topic within the research area.

The most cited publications presented in Table 1 suggest that the main research topics focus on the development of innovative electrochemical processes, electrocatalysts, and combined treatment methodologies aimed at improving the efficiency and effectiveness of wastewater treatment. For instance, these include the development of new electrocatalysts, the green synthesis of hydrogen peroxide for application in the EF process, the integration of multiple EAOP techniques or their combination with separation technologies, and the use of EAOPs to degrade pollutants with complex chemical structures or a complicated wastewater matrix—wastewaters with complex compositions. These trends highlight ongoing efforts to enhance water treatment technologies, making them more efficient, cost-effective, and environmentally friendly.

**Table 1.** The most cited articles.

| Nb. | Document                  | Title                                                                                                                                                                                            | Journal                                                  | Citations | Links |
|-----|---------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------|-----------|-------|
| 1   | Zhang (2020d) [43]        | Highly efficient electrosynthesis of hydrogen peroxide on a superhydrophobic three-phase interface by natural air diffusion                                                                      | Nature Communications, 11 (2020), 1731                   | 414       | 18    |
| 2   | Chanikya (2021) [44]      | Treatment of dyeing wastewater by combined sulfate radical based electrochemical advanced oxidation and electrocoagulation processes                                                             | Separation and Purification Technology 254 (2021) 117570 | 144       | 5     |
| 3   | Olvera-Vargas (2021) [45] | Electro-Fenton treatment of real pharmaceutical wastewater paired with a BDD anode: Reaction mechanisms and respective contribution of homogeneous and heterogeneous OH                          | Chemical Engineering Journal, 404 (2021), 126524         | 133       | 15    |
| 4   | Du (2020) [46]            | Internal-micro-electrolysis-enhanced heterogeneous electro-Fenton process catalyzed by Fe/Fe <sub>3</sub> C@PC core-shell hybrid for sulfamethazine degradation                                  | Chemical Engineering Journal 398 (2020) 125681           | 119       | 7     |
| 5   | Ghanbari (2020a) [47]     | Efficient treatment for landfill leachate through sequential electrocoagulation, electrooxidation and PMS/UV/CuFe <sub>2</sub> O <sub>4</sub> process                                            | Separation and Purification Technology 242 (2020) 116828 | 115       | 2     |
| 6   | Zhang (2022a) [48]        | Efficient degradation of tetracycline using core-shell Fe@Fe <sub>2</sub> O <sub>3</sub> -CeO <sub>2</sub> composite as novel heterogeneous electro-Fenton catalyst                              | Chemical Engineering Journal 428 (2022) 131403           | 111       | 6     |
| 7   | Zhang (2020a) [49]        | Heterogeneous electro-Fenton using three-dimension NZVI-BC electrodes for degradation of neonicotinoid wastewater                                                                                | Water Research 182 (2020) 115975                         | 102       | 4     |
| 8   | Ghanbari (2021) [50]      | Electrochemical activation of peroxides for treatment of contaminated water with landfill leachate: Efficacy, toxicity and biodegradability evaluation                                           | Chemosphere 279 (2021) 130610                            | 99        | 2     |
| 9   | Nidheesh (2020) [51]      | Electrochemical oxidation of ofloxacin using a TiO <sub>2</sub> -based SnO <sub>2</sub> -Sb/polytetrafluoroethylene resin-PbO <sub>2</sub> electrode: Reaction kinetics and mass transfer impact | Chemosphere 251 (2020) 126437                            | 93        | 4     |

The most cited paper by Zhang (2020d) [43] (citation 414) relates to the development of a superhydrophobic natural air diffusion electrode (NADE), where air spontaneously diffuses to the ORR interface with no aeration needed, providing the highest yield of H<sub>2</sub>O<sub>2</sub> production. This electrode demonstrates significant efficacy in pollutant degradation using

the EF process, achieving complete removal (100% degradation efficiency) of the 2,4-D herbicide (initial concentration of  $100 \text{ mg L}^{-1}$ ) within 90 min. The process also shows remarkable performance in total organic carbon (TOC) removal, reaching 51.5% within 2 h, while maintaining the relatively low energy consumption of  $66.4 \text{ kWh kgTOC}^{-1}$ . In comparison, García et al. [52], who employed a Pt-gas diffusion electrode (Pt/GDE) in their EF process, reported a TOC of 59% for 2,4-D herbicide after 5 h and a significantly higher energy consumption of  $420 \text{ kWh kgTOC}^{-1}$ . Regarding the PEF process, this study achieved an impressive 92.1% removal of phenol ( $100 \text{ mg L}^{-1}$ ) within just 30 min. Conversely, Assumpção's study [53], which also used a Pt/GDE for the PEF process, reported a lower phenol ( $100 \text{ mg L}^{-1}$ ) removal efficiency of 65% over a 2 h period and a TOC removal of only 11%. These results indicate that the PEF process in this study outperforms Alcaraz's method in both removal efficiency and processing speed. A key focus of the investigations in four of the nine cited articles by Chanikya et al. [44] (citation 144), Olivera Vargas et al. [45] (citation 133), Ghanbari (2021) [50] (citation 115), and Nidheesh (2020b) [51] (citation 93) is the integration of EAOPs and electrocoagulation (EC) for treating wastewater. Chanikya et al. [44] conducted a study comparing the performance of two combined processes, sulfate radical-based EAOP followed by EC, and EC followed by EAOP, for treating dyeing wastewater from the field. The setup used a Pt/Ti plate as the anode and an iron plate as the cathode. Sulfate radicals were generated both through the cathodic reduction of persulfate and its activation by ferrous ions. Additionally, pollutant removal was enhanced by anodic oxidation using the Pt/Ti anode and indirect electrochemical oxidation processes. The study found that instantaneous current efficiency improved with increasing persulfate concentration and decreasing chemical oxygen demand (COD) levels. The EAOP followed by EC process proved more effective than EC followed by EAOP, achieving a higher COD reduction of 93.5%, lower specific energy consumption, and reduced sludge generation. Olivera Vargas et al. [45] conducted a detailed study on the combined use of EF and AO processes with BDD anodes for the degradation of organic pollutants in real pharmaceutical wastewater. The research focused on elucidating the exact roles and synergistic effects of hydroxyl radicals and BDD-generated hydroxyl radicals ( $\text{BDD}(\bullet\text{OH})$ ) in this process. The data analysis confirmed the synergistic influence of homogeneous and heterogeneous hydroxyl radicals. Initially, homogeneous  $\bullet\text{OH}$  played a dominant role in the degradation process, effectively breaking down organic pollutants. As the treatment progressed, the  $\text{BDD}(\bullet\text{OH})$  became more influential, driving further mineralization through electron transfer reactions. The study found that the EF-BDD system achieved the highest extent of mineralization, removing 97.1% of total organic carbon (TOC) at a current density of  $4.17 \text{ mA cm}^{-2}$  and with  $0.2 \text{ mM}$  of  $\text{Fe}^{2+}$ . This performance was significantly better compared to the EF system using a dimensionally stable anode (DSA), which did not produce heterogeneous  $\bullet\text{OH}$ . Despite this, the EF-DSA system was also effective in increasing the biodegradability of the effluent, achieving a BOD/COD ratio of 0.68 at a lower operational cost of USD 1.46 per cubic meter in 4 h. Ghanbari (2021) [50] conducted a thorough investigation into a sequential treatment approach for landfill leachate using three distinct processes: EC, electrooxidation (EO), and a sulfate radical-based advanced oxidation process (SR-AOP) involving peroxymonosulfate (PMS), UV light, and  $\text{CuFe}_2\text{O}_4$ . The study meticulously evaluated various parameters for each process, including pH levels, current densities, types of electrodes, catalyst loading, PMS dosage, and reaction time. In the electrocoagulation phase, aluminum (Al) and iron (Fe) electrodes were tested, while in the electrooxidation phase, platinum (Pt), lead dioxide ( $\text{PbO}_2$ ), and graphite electrodes were examined. The findings revealed that Fe electrodes were the most effective for EC, and  $\text{PbO}_2$  electrodes outperformed others in the EO process. The study recorded COD removal efficiencies of 60.0% for EC, 50.0% for EO, and 77.9% for SR-AOP. When these processes were applied sequentially, the removal efficiencies significantly improved, achieving 95.6% for COD, 90.5% for TOC, 91.6% for biochemical oxygen demand (BOD), and 99.8% for ammonia ( $\text{NH}_4\text{-N}$ ). This comprehensive analysis demonstrates the enhanced efficiency of the combined treatment processes in effectively reducing various contaminants in landfill

leachate, highlighting the potential of this sequential approach for improved wastewater treatment. Nidheesh (2020b) [51] conducted an in-depth study on the electrochemical remediation of complex industrial wastewater, focusing on electrocoagulation and indirect electrochemical oxidation processes for the removal of chemical COD and color. The research found that both processes were more efficient at the natural pH of the wastewater. In the electrocoagulation process, it was determined that a monopolar connection was more effective than a bipolar connection. Specifically, the monopolar connection achieved a COD removal efficiency of up to 55% and color removal efficiency of 56%, whereas the bipolar connection resulted in COD and color removal efficiencies of 43% and 48%, respectively. These results were obtained with an applied voltage of 1.5 V over the course of 1 h of electrolysis. For the indirect electrochemical oxidation process, graphite electrodes were used. The study found that this process achieved COD and color removal efficiencies of 55% and 99.8%, respectively, within 1 h of electrolysis conducted at a pH of 7.7, an applied voltage of 4 V, and a sodium chloride (NaCl) concentration of 1 g/L. Overall, the study highlights the effectiveness of electrocoagulation with monopolar connections and indirect EO on graphite electrodes in significantly reducing COD and color in mixed industrial wastewater.

The development of electrocatalysts for heterogeneous EF (hetero-EF) processes is presented in the publications of Du et al. (citation 119) [46] and Zhang (2022a) (citation 102) [49].

Du et al. [46] investigated a hybrid octahedron catalyst consisting of an iron-based nanoparticle core (Fe/Fe<sub>3</sub>C) and a graphitized porous carbon (PC) shell. This novel catalyst was synthesized through a one-pot pyrolysis process using MIL-101(Fe) as a sacrificial template and was applied for the degradation of antibacterial agent sulfamethazine (SMT) via the hetero-EF process. The Fe/Fe<sub>3</sub>C@PC catalyst demonstrated superior performance compared to common heterogeneous catalysts such as Fe<sub>0</sub>, Fe<sub>3</sub>O<sub>4</sub>, and Fe<sub>2</sub>O<sub>3</sub>. This was attributed to the synergistic effects between the Fe/Fe<sub>3</sub>C nanoparticles and the porous carbon shell. The removal efficiency of 10.0 mg L<sup>-1</sup> SMT achieved was 99% within 30 min under an applied current of 25 mA and with a catalyst concentration of  $5.0 \times 10^{-2}$  g L<sup>-1</sup>, using a Ti-RuO<sub>2</sub>/CB-CF anode/cathode and a 200 mL solution at pH 3. In comparison, the study by Barhoumi et al. [54] utilized pyrite as the catalyst, achieving 100% removal of 56 mg L<sup>-1</sup> SMT in 90 min with a higher catalyst concentration of  $2 \times 10^{-2}$  g L<sup>-1</sup>, Pt/CF anode/cathode, at a higher applied current of 100 mA, and 200 mL solution also at pH 3. The Fe/Fe<sub>3</sub>C@PC catalyst in this study demonstrated superior performance by achieving high removal efficiency in a shorter treatment time compared to the pyrite catalyst reported by Barhoumi et al. [54]. The rate constant for SMT degradation using the hetero-EF process increased by about seven times that of the heterogeneous Fenton (hetero-F) process. The study proposed a degradation mechanism for the mineralization of SMT, confirming the crucial contribution of adsorbed hydroxyl radicals (•OH<sub>ads</sub>) in the oxidation process. Density functional theory (DFT) calculations have confirmed the contribution of internal microelectrolysis to the overall efficiency of the hetero-EF process. The Fe/Fe<sub>3</sub>C@PC catalyst also exhibited easy recyclability due to its magnetic properties and could be efficiently recovered via simple thermal treatment in a hydrogen atmosphere. This research underscores the potential of metal-organic framework (MOF)-derived core-shell structured hybrids as ultra-efficient heterogeneous catalysts, promoting their promising utilization in the hetero-EF process for the removal of organic pollutants.

Zhang (2022a) [48] developed a novel hetero-EF catalyst, the core-shell Fe@Fe<sub>2</sub>O<sub>3</sub>-CeO<sub>2</sub> composite, for the effective degradation of tetracycline (TC). The study evaluated the catalytic activity by examining various factors, including input Fe to Ce ratio, catalyst mass, pH, operating current, and aeration. The optimal Fe@Fe<sub>2</sub>O<sub>3</sub>-CeO<sub>2</sub> composite (2:1 Fe/Ce) achieved a TC removal efficiency of 90.7% within 1 h and a mineralization efficiency of 86.9% within 6 h. The study by Luo et al. [55] demonstrated comparable effectiveness, achieving a removal efficiency of 98.1% and a mineralization efficiency of 89.8% after 6 h using Cu-doped Fe@Fe<sub>2</sub>O<sub>3</sub> core-shell nanoparticles (CFF) on nickel foam as the cathode, with a lower initial TC concentration of 20.0 mg L<sup>-1</sup>. Despite these comparable results, the

Fe@Fe<sub>2</sub>O<sub>3</sub>-CeO<sub>2</sub> composite in this study is notable for its superior performance in degrading a higher concentration of TC within the same time frame, underscoring its effectiveness under more challenging conditions. Additionally, the novel catalyst demonstrated good recyclability and stability over successive cycles with minimal metal leaching. The heterogeneous EF process also showed excellent catalytic activity for the degradation of other organic pollutants, including metronidazole, diclofenac sodium, and chloramphenicol. Based on the experimental results and analysis, the study proposed the mechanism of the hetero-EF process with the Fe@Fe<sub>2</sub>O<sub>3</sub>-CeO<sub>2</sub> catalyst and outlined possible TC degradation pathways. These insights into the catalytic reaction process provide valuable information for facilitating the application of this method in treating refractory wastewater.

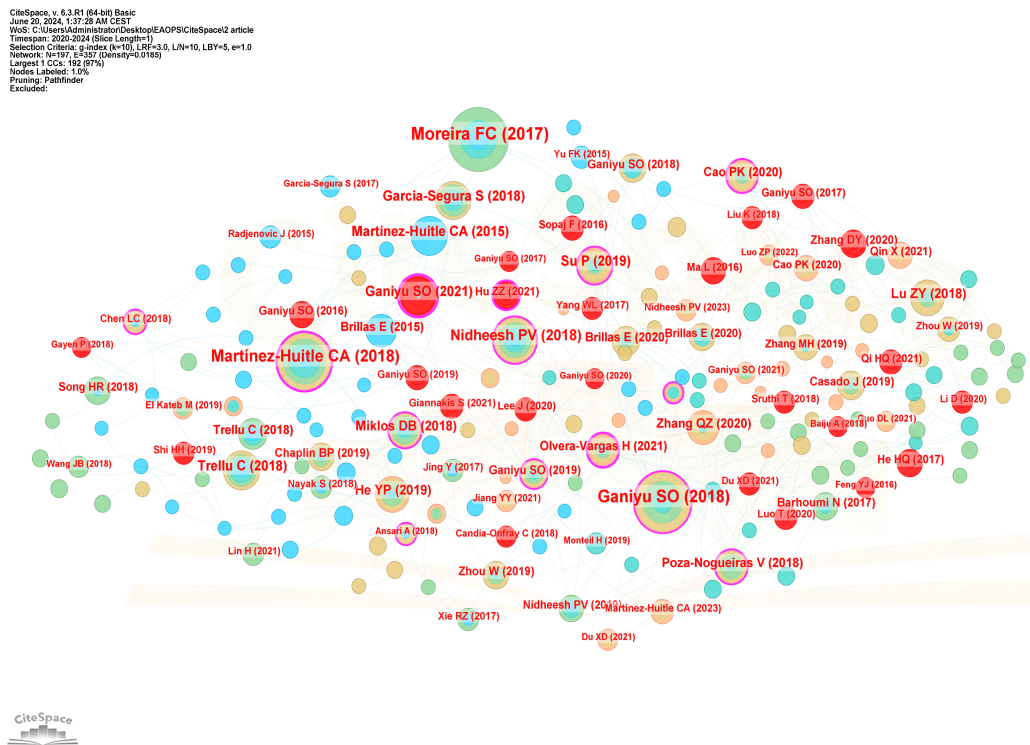
Zhang [49] introduced a novel heterogeneous EF system employing three-dimensional electrodes made of nanoparticle neutral iron supported on a biochar (NZVI-BC), known as the 3D-ICE-EF system. This system was innovatively applied to degrade clothianidin (CLO) wastewater without the need for additional Fenton reagents. The NZVI-BC electrodes in the 3D-ICE-EF system demonstrated excellent adsorption capabilities, concentrating CLO on the electrodes and effectively eliminating it, resulting in a self-cleaning effect. Furthermore, the addition of hydroquinone (HQ) in the system significantly improved the precipitation of iron (Fe(OH)<sub>3</sub>) and enhanced the circular utilization of iron within the Fenton system. One of the key advantages of the 3D-ICE-EF system is its extended pH applicability, allowing the Fenton system to operate efficiently under alkaline conditions. The increased acidity of the electrolyte was found to be the primary factor contributing to the high degradation efficiency of CLO, especially at a starting pH of 9.0. The degradation performance of the system was further enhanced by increasing the current intensity and air flow rate. Seven plausible mechanisms for CLO degradation were identified within the 3D-ICE-EF system. The examination of the toxicity of the degradation byproducts indicated a significant reduction in toxicity levels, showcasing the system's effectiveness in not only degrading CLO but also in mitigating its ecological impact.

### 3.4. Co-Citation Network Analysis

#### 3.4.1. Document Co-Citation Network

In bibliometric analysis, document co-citation refers to the frequency with which two documents are cited together by other documents, highlighting their relationship within a field of study. Co-citation networks help researchers identify principal research trends and select appropriate research problems by revealing the key literature and emerging trends. Figure 6A, generated by CiteSpace, illustrates the document co-citation network, comprising 197 nodes which represent references co-cited and 353 co-citation links spanning the last five years. The density of the research field network is 0.0165. The largest node in the network is associated with the most co-cited reference by Moreira F.C. (2017) [8], which has a citation count of 82. The second largest node is attributed to Ganiyu S.O. (2018) [56], with 74 citations, followed by Martinez-Huitle CA (2018) [57], with 66 citations. These nodes indicate a strong connection with other references and demonstrate significant influence on subsequent research. By analyzing co-citation documents, grouping documents into clusters was completed. The keyword terms and LSI weighting algorithm were used to label the clusters. All silhouette scores are above 0.8, indicating reliable cluster quality. The largest 10 clusters are detailed in Table S4 and Figure S1 in the Supplementary Information. Each cluster represents a subfield or a specific topic area within the broader research field. Documents within the same cluster are more closely related to each other than to documents in other clusters.

The references with the highest citation bursts are shown in Figure 6B. It is well-known that in bibliometric analysis, a “citation burst” refers to a rapid increase in the number of citations an article receives over a specific period, indicating a surge of interest from the academic community. It is used for identifying influential research and understanding the dynamics of scientific progress.



(A)

Top 10 References with the Strongest Citation Bursts

| References                                                                             | Year | Strength | Begin | End  | 2020 - 2024 |
|----------------------------------------------------------------------------------------|------|----------|-------|------|-------------|
| Ganiyu SO, 2016, WATER RES, V106, P171, DOI 10.1016/j.watres.2016.09.056, DOI          | 2016 | 3.55     | 2020  | 2021 | <div></div> |
| Ma L, 2016, ELECTROCHIM ACTA, V200, P222, DOI 10.1016/j.electacta.2016.03.181, DOI     | 2016 | 3.31     | 2020  | 2021 | <div></div> |
| Sopaj F, 2016, APPL CATAL B-ENVIRON, V199, P331, DOI 10.1016/j.apcatb.2016.06.035, DOI | 2016 | 3.07     | 2020  | 2021 | <div></div> |
| Ganiyu SO, 2019, SEP PURIF TECHNOL, V208, P142, DOI 10.1016/j.seppur.2018.03.076, DOI  | 2019 | 2.83     | 2020  | 2021 | <div></div> |
| He HQ, 2017, CRIT REV ENV SCI TEC, V47, P2100, DOI 10.1080/10643389.2017.1405673, DOI  | 2017 | 3.43     | 2021  | 2022 | <div></div> |
| Ganiyu SO, 2017, J MATER CHEM A, V5, P3655, DOI 10.1039/c6ta09100h, DOI                | 2017 | 2.97     | 2021  | 2022 | <div></div> |
| Qi HQ, 2021, CHEM ENG J, V403, P0, DOI 10.1016/j.cej.2020.126270, DOI                  | 2021 | 2.92     | 2022  | 2024 | <div></div> |
| Luo T, 2020, CHEM ENG J, V382, P0, DOI 10.1016/j.cej.2019.122970, DOI                  | 2020 | 2.69     | 2022  | 2024 | <div></div> |
| Giannakis S, 2021, CHEM ENG J, V406, P0, DOI 10.1016/j.cej.2020.127083, DOI            | 2021 | 2.69     | 2022  | 2024 | <div></div> |
| Zhang DY, 2020, CHEM ENG J, V383, P0, DOI 10.1016/j.cej.2019.123184, DOI               | 2020 | 2.62     | 2022  | 2024 | <div></div> |

(B)

Figure 6. (A) Document co-citation network and (B) top 10 articles with the strongest citation bursts [55,56,58–65].

The article with the strongest burst is about a novel sub-stoichiometric titanium oxide ( $\text{Ti}_4\text{O}_7$ ) as a suitable ceramic anode for the electrooxidation of organic pollutants, and it was published in 2016 by Ganiyu et al. [58]. In 2020 to 2021, several major studies validate its findings, leading to a sudden spike in citations. This burst indicates that the article has attracted considerable attention and points to the future interest of the scientific community in the synthesis and application of  $\text{Ti}_4\text{O}_7$  in the electrooxidative treatment of organic pollutants.

During the period from 2020 to 2021, the main co-citation bursts included articles by Ma [59] and Sopaj [60]. Ma [59] designed a highly energy-efficient flow-through electro-Fenton reactor for the oxidation of methylene blue (MB) from aqueous solution, using a perforated DSA as the anode and graphite felt modified by carbon black and polytetrafluoroethylene (PTFE) as the cathode for the in situ generation of  $\text{H}_2\text{O}_2$ . Sopaj [60] investigated

the role of different anode materials on the electrochemical oxidation and mineralization of the antibiotic SMT, testing materials such as Pt, BDD, DSA, Ti/RuO<sub>2</sub>-IrO<sub>2</sub>, and graphite felt (GF). Articles by He [61] and Ganiyu [62], published in 2017, experienced a strong burst of co-citations from 2021 to 2022, indicating their relevance in the period as review papers.

Additionally, articles by Qi [63], Luo [55], Giannakis [64], and Zhang [65], published in 2021 and 2020, respectively, exhibited a strong burst of co-citations from 2022 to 2024. Qi [63] etched a graphite felt (EGF) using an in situ CoOX etching process, where EGF was used as a cathode to degrade diuron in the electro-Fenton process. Luo [55] investigated the mechanism, degradation pathway, and efficiency of TC degradation in an aqueous environment using a novel hetero-EF process. For this process, as the cathode catalyst used was a Cu-doped Fe@Fe<sub>2</sub>O<sub>3</sub> core-shell nanoparticles system (CFF) which was loaded on nickel foam. The CFF was synthesized through a simple two-step reduction and aging process. Zhang [65] explored selective H<sub>2</sub>O<sub>2</sub> production on N-doped porous carbon derived from the direct carbonization of metal-organic frameworks for the electro-Fenton mineralization of antibiotics. Herein, nitrogen-doped porous carbon (NPC) was synthesized via the direct calcination of a nitrogen-containing metal-organic framework.

### 3.4.2. Author Co-Citation Network

Author co-citation networks can find the most contributing authors in a specific field of application of EAOPs for wastewater treatment. Because CiteSpace only considers the first author in the analysis of author co-citation, it defaults to using the abbreviation of the author's full name, which can cause the emergence of authors with the same name, especially in Chinese scholars. Therefore, this study adopts VOSviewer to analyze the network of author co-citation.

The minimum number of citations of an author is set up at 20, and 215 authors of 14,562 meet the threshold.

In the network map of co-citation of authors presented in Figure 7, each node represents an author, with the size of the node indicating the frequency of their co-citations. Prominent authors such as Brillas E. and Geniyu S. are represented by larger nodes, indicating their significant contributions and high citation counts (co-citations of 374 and 332, respectively). Following these are Martínez-Huitle (288), Panizza M (271), and Nidheesh (252). The list of co-cited authors is presented in Table S5 in the Supplementary Information.

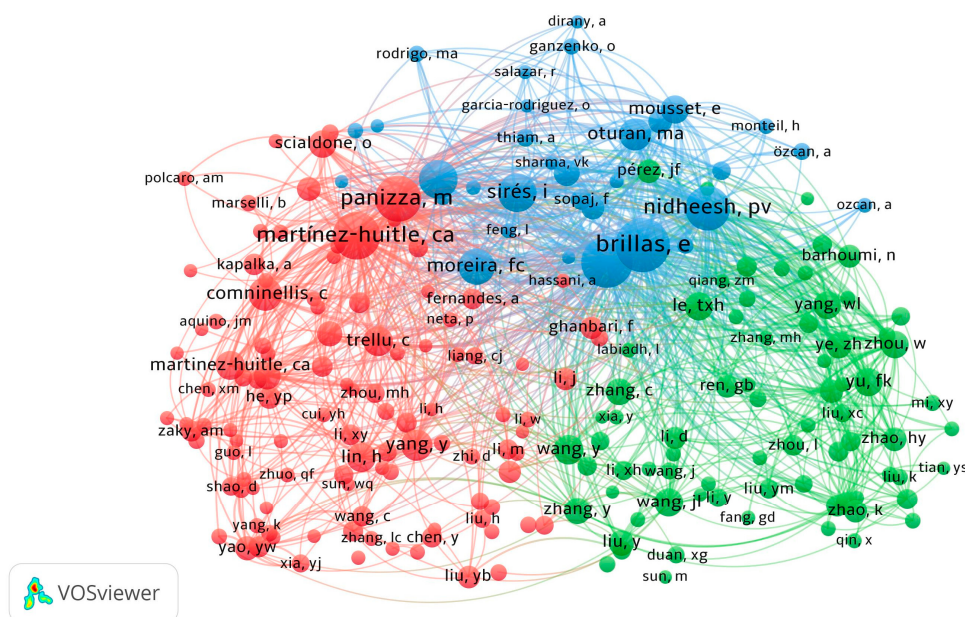
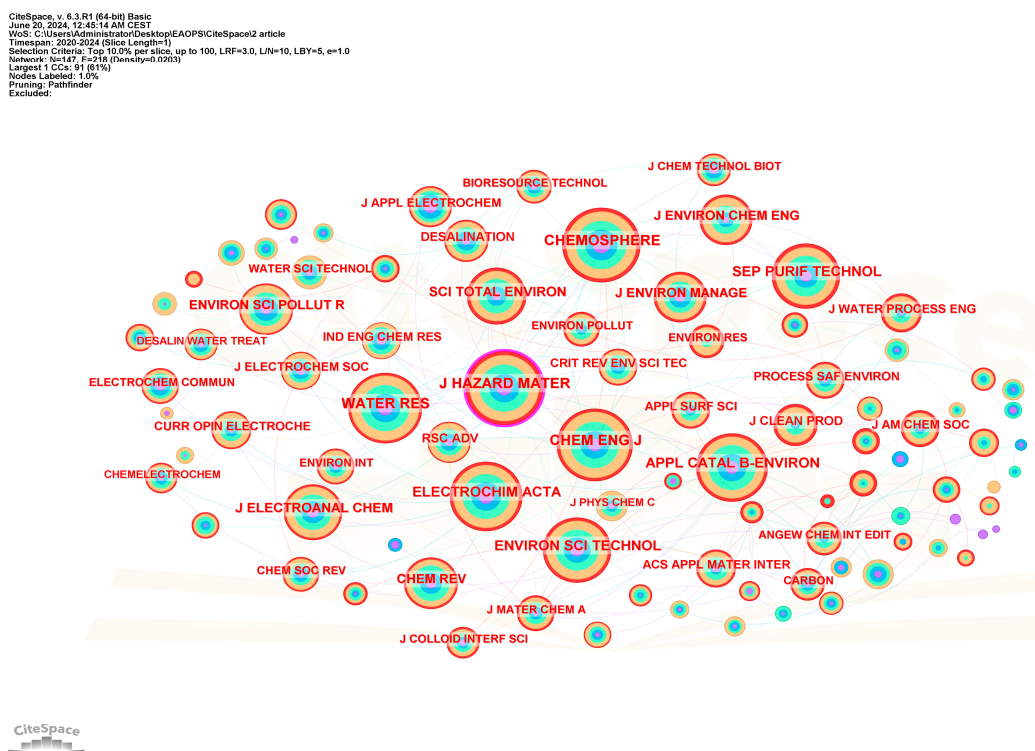


Figure 7. The network map of co-citation of authors.

### 3.4.3. Journal Co-Citation Analysis

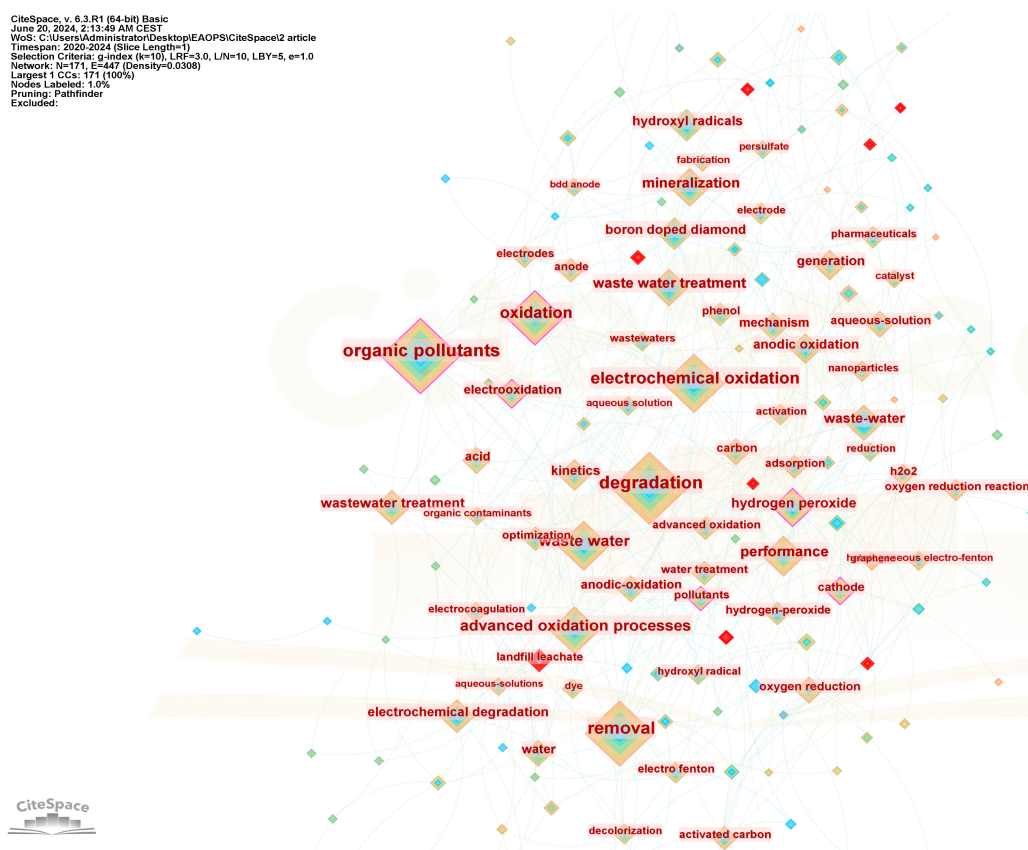
In the network map of co-cited journals (see Figure 8) analyzing application of EAOPs for wastewater treatment, *Chemosphere* appears as a large node, indicating it is the most frequently cited journal in the dataset. Also, *Journal of Hazard Materials* has a large-sized node with a high centrality (indicated by a purple ring), meaning it plays a crucial role in connecting EAOPs research with broader environmental research fields. *Water research*, *Chem Eng J*, *Electrochimica acta*, *App catal B environ*, and *Environmental sci technolog* are medium-sized nodes, showing they are also frequently cited but less so than *Chemosphere*.



**Figure 8.** The network map of co-cited journals.

### 3.5. Keywords Analysis

The network co-occurrence map of keywords depicted in Figure 9 comprises 171 nodes, each representing a unique keyword. The size of each node corresponds to the frequency of co-occurrence of its respective keyword with others in the analyzed dataset. Larger nodes indicate keywords that co-occur more frequently. The purple line outside the node relates to the centrality of a specific keyword, i.e., its importance. The keyword “degradation” appears as the largest node, indicating it is the most frequently occurring keyword in the dataset. Other significant nodes include keywords like “electrochemical oxidation”, “removal”, and “advanced oxidation process”. Also, the keyword “organic pollutants” has a large-sized node and high centrality (shown with a purple ring). This suggests that it is the most frequent keyword, and it plays a crucial role in connecting different research themes within EAOPs research.



**Figure 9.** The network co-occurrence map of keywords.

### 3.6. Past and Future Research Trends of EAOP Based on Bibliometric Analysis

The application of EAOPs in wastewater treatment has garnered significant interest from the scientific community due to the effectiveness of these processes. Citation and co-citation analyses reveal that research on wastewater treatment using EAOPs has primarily focused on EF and AO processes, along with their integration with separation techniques like EC. Translating laboratory efficiencies to industrial-scale applications requires addressing several critical factors. Successful scaling involves overcoming the disadvantages outlined in Table 2, including optimizing the technique through the careful selection of anode (which impacts to the generation of reactive species like hydroxyl radicals ( $\bullet\text{OH}$ ), which can be tailored to improve selectivity towards specific pollutants) and cathode materials (influences the production of reducing agents such as hydrogen peroxide ( $\text{H}_2\text{O}_2$ ), which also affects selectivity), and fine-tuning the electrolytic medium can alter pH and ionic strength, impacting the reactivity and stability of the radicals generated. Additionally, operational parameters such as applied current and temperature must be meticulously adjusted to enhance selectivity and overall degradation efficiency. Numerous studies [4,10,26,66] underscore these challenges and highlight the importance of these optimizations in enhancing performance in practical applications.

Table 2. Basic EAOP technologies.

| Technology       | Advantages                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Disadvantages                                                                                                                                                                                                                                                                                                                                  | Safety                                                                                                                                                                                                                                                                                                                                                                                                                |
|------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Anodic oxidation | <ul style="list-style-type: none"> <li>• High efficiency of degradation and mineralization for various chemical contaminants, and adaptability to different wastewater types;</li> <li>• Applicable across a broad pH range;</li> <li>• Without additional external chemicals, as oxidants are produced on site;</li> <li>• The operation is straightforward, requiring only simple and easy-to-use equipment;</li> <li>• Produces minimal or no sludge, reducing waste;</li> <li>• Offers a diverse selection of electrode materials, allowing for customization based on specific pollutants or types of wastewater.</li> </ul> | <ul style="list-style-type: none"> <li>• Electrode materials can degrade over time, increasing maintenance and replacement costs;</li> <li>• High electrode production costs lead to significant expenses;</li> <li>• Elevated energy consumption increases operational costs;</li> <li>• May generate harmful byproducts.</li> </ul>          | <ul style="list-style-type: none"> <li>• Electrical Safety: Risks include electric shocks and short circuits due to high voltages;</li> <li>• Chemical Generation: May produce hazardous byproducts like chlorine species, requiring careful handling.</li> </ul>                                                                                                                                                     |
| Electro-Fenton   | <ul style="list-style-type: none"> <li>• High efficiency in removing a wide range of organic pollutants, including those hard to treat with conventional methods;</li> <li>• Produces H<sub>2</sub>O<sub>2</sub> on site and requires less iron (which is continuously and rapidly regenerated as Fe<sup>2+</sup> at the cathode), minimizing the need for external chemical handling and storage.</li> </ul>                                                                                                                                                                                                                     | <ul style="list-style-type: none"> <li>• The process can be expensive due to the costs of electricity, electrodes, and reagents;</li> <li>• Acidic pH is necessary, requiring acidification and requalification of the aqueous matrix;</li> <li>• Produces iron sludge as a byproduct, which requires proper disposal or treatment.</li> </ul> | <ul style="list-style-type: none"> <li>• Chemical Handling: Necessitates careful handling and storage of chemicals, especially hydrogen peroxide and ferrous salts, to ensure safety and prevent accidental exposure or reactions.</li> <li>• Electrochemical Cells: Presents a risk of electrical hazards, such as shocks or short circuits, if not managed with proper safety protocols and precautions.</li> </ul> |

In EAOPs, the degradation of pollutants is monitored using various methods to assess the effectiveness of the treatment and ensure the complete removal or transformation of contaminants. Commonly used methods include TOC analysis, COD, and biological oxygen demand (BOD) [67,68]. To confirm the efficiency of EAOPs, liquid chromatography and gas chromatography, often coupled with mass spectrometry, are frequently employed. Additionally, microbial and toxicity tests are crucial for providing insights into the overall effectiveness of the degradation process. There are also many other methods used for these purposes, such as electrochemical measurements, kinetic calculations, ion chromatography, etc. [69–71]. The choice of monitoring technique depends on the specific pollutant whose degradation is being assessed. Also, during the degradation of chlorinated organic pollutants, it is important to consider that the byproducts formed can sometimes be more toxic than the original compounds. Therefore, thorough monitoring during the treatment and a toxicological evaluation after treatment are essential. EAOP methods can be effective

in such cases, as they are designed to meet these requirements and address the potential formation of hazardous byproducts [72–74].

AO, a key technology in EAOPs, removes contaminants from wastewater through electrode reactions. It is classified into direct oxidation, where pollutants are oxidized by electron transfer from the electrode to adsorbed organic molecules on the anode surface, and indirect oxidation, which involves oxidation via free radical species like  $\bullet\text{OH}$ , chlorine, (per)bromate, persulfate, ozone, hydrogen peroxide, and percarbonate generated on the anode surface. According to a literature review [24,75], direct oxidation is rare and inefficient, making indirect oxidation the predominant mechanism in EAOPs.

During AO, the selection of an electrolyte (considering its composition and concentration) and the conditions under which the process occurs (pH and temperature) are crucial. The electrode is a key component, requiring specific electrochemical characteristics such as good electrical conductivity, catalytic activity, high oxygen evolution reaction (OER), sufficient surface area, and reliable stability and durability. Commonly used anodic electrodes include boron-doped diamond electrodes, DSA, graphite, and pure metal anodes. Emerging trends in electrode design include the development of novel sub-stoichiometric titanium oxide anodes, such as  $\text{Ti}_4\text{O}_7$ , incorporating nanostructures (such as metal oxide, carbon) and doping with metals into the anode [58,68,76–78].

Research conducted before 2020 [18,79–87] extensively investigated DSAs such as  $\text{PbO}_2$  and  $\text{SnO}_2$  due to their high stability, good corrosion resistance, and low synthesis cost. These were considered promising candidates for electrochemical pollutant oxidation. Researchers aimed to address the short lifetime of the anodes and the poor electrical conductivity of pure  $\text{SnO}_2$  by reducing the grain size to the nanometer scale and doping the anodes with metal nanoparticles or carbon-based nanomaterials. Significant progress was achieved with antimony-doped tin dioxide ( $\text{SnO}_2\text{-Sb}$ ) electrodes [88–90], which showed excellent electrocatalytic performance for the AO of organic pollutants. However, the commercial application of  $\text{Ti/Sb-SnO}_2$  anodes remained limited due to their short lifespan and limited durability.

In the past five years, research has shifted towards the synthesis and application of metal oxide anodes doped with non-metals or metals, primarily rare earth elements. For example: Eu-doped  $\text{PbO}_2$  electrodes [91],  $\text{Ti/Sb}_2\text{O}_3\text{-SnO}_2/\text{Er-PbO}_2$  anodes [92], sulfur-doped  $\text{TiO}_2$  nanotube Arrays ( $\text{S-TiO}_2$  NTA) [93], indium-doped  $\text{PbO}_2$  electrodes [94].

Overall, the increasing number of research articles indicates a strong interest in advancing EF processes as sustainable and efficient methods for environmental remediation [95,96]. The EF process utilizes electrochemical processes to accelerate the generation of  $\bullet\text{OH}$  through the Fenton reaction. In general, the EF process is classified into four categories based on the addition or formation of Fenton's reagent within the system. In the first method, hydrogen peroxide and ferrous ions are generated electrochemically. Hydrogen peroxide is produced using a sacrificial anode, while ferrous ions are generated at an oxygen-sparging cathode. In the second method, hydrogen peroxide is introduced externally while ferrous ions are generated from a sacrificial anode, while the third method involves adding ferrous ions externally, with hydrogen peroxide being produced on oxygen-sparging cathodes. Finally, in the fourth method, hydroxyl radicals are generated in an electrolytic cell by adding Fenton's reagent ( $\text{Fe}^{2+}$ ,  $\text{H}_2\text{O}_2$ ) [71]. Simultaneously, ferrous ions are regenerated through the reduction of ferric ions on the cathode [25]. Also, EF processes can be categorized into two types based on the physical nature of the catalyst: homogeneous EF (homo-EF) and hetero-EF processes. In the homo-EF process, soluble forms of iron are utilized as the catalyst source, while in hetero-EF processes, solid catalysts serve as the iron source [97,98]. While homo-EF is still widely used for wastewater treatment, hetero-EF is emerging as a more efficient technique. This is due to its ability to operate over a wider pH range, more easily separate the catalyst from the aqueous phase after EF treatment, reduce or eliminate the generation of iron sludge, as well as improve catalyst durability and reproducibility. Cathode materials play a crucial role in EF processes, significantly influencing the synthesis of  $\text{H}_2\text{O}_2$  and  $\bullet\text{OH}$ . The efficiency of

H<sub>2</sub>O<sub>2</sub> production heavily relies on the specific type of cathode materials employed. Initially, the cathode materials consisted primarily of carbon-based materials without metals (carbon black, carbon felt, carbon sponge, carbon nanotubes, graphene oxide, and metal-free carbon materials doped with heteroatoms, such as N, F, S, P, B) and conventional iron-based catalysts [97,99–102]. Although carbon materials offer numerous advantages such as excellent electrical conductivity, appropriate porosity, chemical durability, accessibility, eco-friendliness, and cost-effectiveness, they are prone to oxidative decomposition. This phenomenon affects metal-free carbon materials and diminishes the effectiveness of hetero-EF reactions. However, with the development of metal catalyst-carbon materials, alloy catalyst-carbon materials, and transition metal single-atom catalyst-carbon materials, scientists have managed to overcome these shortcomings [103–106].

The bibliometric analysis indicates that the most frequently cited research highlights integrating combined treatment methodologies, such as AO and EF, with EC. These combined approaches are seen as crucial for enhancing the efficiency and effectiveness of wastewater treatment, guiding future EAOP research.

On the other hand, EAOP technologies often face the challenge of high energy consumption, which increases the overall cost of the process (see Table 2). A promising solution is integrating them with renewable energy sources such as solar, wind, and biomass. By powering EAOP reactors with these renewable sources, it is possible to enhance sustainability, lower operating costs, and minimize environmental impact [107]. Recent advancements have focused on developing and evaluating innovative solar-based wastewater purification methods. Among these, the SPEF process has garnered significant interest due to its high efficiency in degrading organic pollutants [108–113]. This approach can be implemented in two main ways: (1) direct solar treatment, where pollutants are degraded directly by solar energy in a photoreactor, and indirect solar treatment, where solar energy is used to generate electricity that powers the electrochemical treatment system. Bioenergy, derived from biological and organic sources collectively known as “biomass,” represents another form of renewable energy. Biomass materials contain stored chemical energy that can be converted into electricity either through direct combustion or via microbial fuel cells (MFCs). Recent research on MFCs [114–118] suggests that they are a promising alternative for integration with EAOP methods, offering the potential for both pollutant degradation and green hydrogen generation. While Souza’s work [107] on using wind-powered BDD electrochemical oxidation for treating wastewater contaminated with the pesticide 2,4-D is well recognized, recent studies on utilizing wind energy as a power source in this context have been limited and deserve further investigation.

Future Research Directions for EAOPs:

- Development of Electrode Materials

Future research should prioritize the synthesis and characterization of new electrode materials, for both the anode and cathode. The focus for anode development should be on enhancing the generation of ROS, while advancements in cathode materials should aim to increase the production of hydrogen peroxide. Investigating materials beyond the traditionally studied options could lead to the discovery of electrodes with superior stability, better corrosion resistance, and lower synthesis costs.

- Optimization of the EF process

Given its promising applications and effectiveness, further investigations into the EF process are essential. Research should aim to optimize operational parameters such as current density, pH, and catalyst dosage to enhance pollutant degradation rates while minimizing energy consumption. By creating detailed kinetic models, we can predict how factors like electrode material, reaction conditions, and pollutants affect reaction rates. This understanding will help optimize operational settings and improve EAOP system design for greater efficiency and lower costs.

- Integration with Other Treatment Technologies

Combining EAOPs with other wastewater treatment methods—such as photocatalysis, biological treatments, adsorption techniques, and separation technologies like EC and electroflocculation—could result in more comprehensive and efficient systems. Studies should explore the synergistic effects and practical feasibility of such integrated approaches.

- Mechanism Studies and ROS Generation

Detailed mechanistic studies are crucial for understanding the pathways of ROS generation and their interactions with various organic pollutants. Employing advanced analytical techniques to elucidate these mechanisms will improve process efficiency and efficacy.

- The Integration and Adaptation of EAOPs

EAOPs are effective for treating domestic and urban industrial wastewater by breaking down contaminants and meeting high treatment standards. They produce powerful oxidizers like hydroxyl radicals, which help treat complex wastewater. In agriculture, EAOPs can handle runoff and pesticide residues, supporting more sustainable practices.

- Scalability and Industrial Applications

Research should address the challenges associated with scaling up EAOPs from laboratory settings to industrial applications. This includes designing reactors capable of handling larger volumes of wastewater and conducting pilot-scale studies to evaluate performance under real-world conditions. Combining computational fluid dynamics with experimental data will yield more precise predictions and improve the scalability of laboratory findings to industrial applications.

- Environmental Impact and Sustainability

Investigating the environmental impact and sustainability of EAOPs is vital. Life cycle assessments and environmental impact analyses should be conducted to ensure that these technologies are environmentally friendly and do not lead to unintended negative consequences.

- Economic Feasibility and Cost Reduction

Efforts should be made to reduce the overall cost of EAOPs by optimizing material usage, improving energy efficiency, and developing cost-effective catalysts. Economic feasibility analyses can help identify the most viable approaches for widespread adoption.

By pursuing these research directions, the scientific community can continue to advance the development and application of EAOPs, contributing to the effective purification of polluted aquatic environments and promoting sustainable water management practices globally.

#### 4. Conclusions

This research article utilized bibliometric analysis of the WoS database, along with CiteSpace (version 6.3 R1) and VOSviewer (version 1.6.18) software, for visualizations and network analysis. The article aims to fill a gap by conducting bibliometric analysis focused on research articles about EAOPs used in wastewater treatment published between January 2020 and June 2024. Unlike review papers that synthesize the literature qualitatively, bibliometric analysis uses statistical methods to explore research trends quantitatively. This study identifies key authors, institutions, and countries in the field, provides insights into pollutant degradation, and highlights research challenges to guide future studies. Based on the bibliometric analysis over the past five years, it is evident that the annual publication rate of approximately 200 papers underscores a robust emphasis on original research and comprehensive literature reviews within the field of EAOPs for industrial wastewater treatment. The predominant publication type was articles, followed by review articles, indicating a balanced exploration of new findings and critical assessments of existing knowledge.

The People's Republic of China led in productivity, supported by numerous prominent institutions and researchers. Significant contributions were also made by institutions such as the University of Paris in France and the University of Barcelona in Spain, highlighting their key impact in this research area.

While the People's Republic of China stands out with the highest number of publications, it does not have as high a citation rate per publication as Australia. This higher average citation rate indicates Australia's significant influence and impact in the field, surpassing that of China and other leading countries with higher publication numbers but weaker citation impact per publication.

Citation and co-citation analyses reveal that research on wastewater treatment using EAOPs has mainly concentrated on EF and AO methods, as well as their integration with separation techniques like EC. These findings lay a foundational framework for further investigation into the development and application of these techniques in industrial wastewater treatment. Accordingly, the most cited publications highlight that key research areas include advancing innovative electrochemical processes. These trends include the development of novel electrocatalysts, the eco-friendly synthesis of hydrogen peroxide for use in the EF process, the integration of various EAOP techniques or their combination with separation technologies, and the application of EAOPs for degrading pollutants with complex chemical structures or challenging wastewater matrices. Such trends underscore ongoing efforts to advance water treatment technologies, aiming to make them more efficient, cost-effective, and environmentally sustainable.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/coatings14081060/s1>, Table S1. The lists of the prominent countries. Table S2. The list of prominent organizations using VOSviewer. Table S3. The list of prominent authors using VOSviewer. Table S4. Clusters of documents co-citations analysis. Table S5. The list of co-cited authors. Figure S1. The cluster of co-citation document analysis network map.

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