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Bibliometric Analysis of Nanostructured Anodes for Electro-Oxidative Wastewater Treatment

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Abstract: Last decade, a growing emphasis on developing sustainable and environmentally friendly technologies for electro-oxidative wastewater treatment has catalyzed innovation and spurred research efforts worldwide. Researchers may explore the use of renewable energy sources to drive electrochemical processes, as well as the development of eco-friendly electrode materials for wastewater treatments. The integration of nanostructured anodes into the electrolytic system for wastewater treatment has led to significant advancements in the removal of pollutants via electro-oxidation. Despite the great number of research articles related to the development and use of nanostructured anodes for electro-oxidative wastewater treatment, to our knowledge, no bibliometric analysis has been published in this domain. Therefore, this work presents a bibliometric study of publications on the designated theme, retrieved from the Web of Science Core Collection database, which were published over the last decade. The visual and network analysis of co-authorship among authors, organizations, countries, co-citation of authors, citation of documents and sources, as well as the co-occurrence of author keywords was performed using two compatible pieces of scientometric software, namely VOSviewer (version 1.6.18) and CiteSpace (version 6.2.R4). From 2013 to 2023, there has been a gradual increase in the number of publications regarding the development and use of nanostructured anodes for electro-oxidative wastewater treatment. It suggests a steady advancement in this field. The People's Republic of China emerges as the most productive country, and it is a leader in international collaborations. Also, the United States of America, South Korea, and European Union countries have significant impacts on the research in this domain. The development and application of nanostructured materials for urea electro-oxidation is a main and prospective research theme. This bibliometric analysis allowed for the visualization of the present landscape and upcoming trends in this research field, thereby facilitating future collaborative research endeavors and knowledge exchange.

Keywords: nanostructured anode; wastewater treatment; electro-oxidation; bibliometric analysis

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1. Introduction

One of the crucial environmental problems worldwide is the growth of waterbody pollution via organic and inorganic contaminants arising from anthropogenic activity. With the intention of enhancing the quality of water, it is necessary to apply available and developing technologies for wastewater purification prior to receiving the recipient. A few treatment technologies have been proposed, such as adsorption [1–4], photocatalysis [5–8], biological treatment [9], and membrane filtration [10–12]. However, each tested treatment has a number of negative aspects (such as the high cost of technology, handling and storage of used chemicals, etc.,) for their widespread application. Electro-oxidation is a promising green technology that may be applied to remove organic pollutants from wastewater and reduce their toxicity with minimum operational and capital investments. Also, this environmentally sustainable technology is eco-friendly due to it utilizing electrons as "clean" reagents. Additionally, it is both safe and exceptionally effective at eliminating a variety of pollutants. It is based on the electrochemical generation of reactive oxygen species (very powerful oxidizing species), such as the hydroxyl radical (•OH) at the anode surface which is then able to destroy organic pollutants partially, or lead to their total mineralization to carbon dioxide, inorganic ions, and water. The mineralization efficiencies are influenced by various factors, including the concentration of organic pollutants, the type of supporting electrolyte (e.g., sodium sulfate, sodium chloride), pH values of the electrolyte, the configuration of the electrochemical reactor, electrolysis regime, current density, and the nature of the electrode's material. They should have good electrochemical properties (high electrode surface area, high oxygen evolution potential-OEP, and high electroconductivity), catalytic activity, stability, and satisfactory service life. Since the material nature determines their performance, it has an indirect impact on the mechanism and efficiency, as well as the total cost of the process. Earlier studies [13–19] have tested graphite and pure metal anodes, dimensionally stable anodes (DSA), BDD electrodes, and sub-stoichiometric titanium oxide electrodes for the electro-oxidative degradation of organic pollutants. Nevertheless, each of these electrodes manifests various limitations that constrain their widespread application. The latest trends in electrode design are related to the synthesis and preparation of nanostructure anodes, and their application for electro-oxidative wastewater treatment. It is well-known that nanostructuring causes the structure and morphological material modification (as an increase in the number of active sites), which has an impact on the electrochemical characteristics and performance of electrodes, including improving the electrical conductivity and electrode electrocatalytic activity. Also, due to structure modification, the rate of anode reaction as a primarily limiting step in the overall rate of electro-oxidative treatment increases. To date, numerous researchers have investigated the synthesis, preparation, and application of nanostructured anodes for electro-oxidative wastewater treatment targeting a range of organic pollutants, such as phenolic compounds, antibiotics, organic dyes, bisphenol A, pharmaceuticals, and urea [20–42]. Various types of carbon nanomaterial-based electrodes have been mostly studied. These include carbon nanotube (CNT) and carbon multiwalled carbon nanotube (MWCNT) in graphene nanoforms, heteroatom-doped CNT, metal-doped CNT, nanostructured BDD anode (e.g., porous diamond, diamond nanowire, etc.,) heteroatom and metal oxide-based electrodes, metal or metal oxide-based nanostructured anode, and metal oxide–carbon nanocomposite electrodes.

Bibliometric analysis is a mathematical and statistical method used to explore and analyze the research evolution of a specific topic, providing a clearer comprehension of the research trend, progress, and emerging scientific interests [43]. Recently, a number of researchers have utilized bibliometric techniques in the field of wastewater treatment technologies. Some of these studies have focused on industrial wastewater treatments [44], while others have explored sulfate-rich wastewater pollution control technologies [45], ultrasound-assisted technologies for degradation of organic pollutants [46], electrochemical advanced oxidation processes (EAOPs) using biochar [47], and Fenton oxidation for water remediation [48]. Despite the increasing importance of nanomaterials in environmental treatment technology, a comprehensive bibliometric examination of the research progress about the development and applications of nanostructured anodes for electro-oxidative wastewater treatment remains unexplored. This study aimed to fill this knowledge gap through a thorough bibliometric analysis. Consequently, this paper aimed to provide a detailed and systematic overview of potential and trends in developing nanomaterials and applications of nanostructured anodes in electro-oxidative wastewater treatment from 2013 to 2023. In contrast to traditional review articles which typically employ literature searches to explicate important concepts and advancements within a given field, the present study adopted a distinctive methodological approach. It centered on data-driven analysis of crucial metric parameters, encompassing institutions, publications, countries, funding institutions, authors, journals, references, and keywords extracted from articles. In this way, research productivity, contribution, and collaboration within the research community were traced. Also, the key research hotspots which define directions for future prospective research within the investigated field were summarized. It was expected that this scientific research has provided valuable insights which assists researchers in tracing the diverse field of research topics, assimilating the latest developments, understanding leading themes, and uncovering research hotspots within a given field by encompassing both substantive dimensions. Overall, the future direction of research into electro-oxidative wastewater treatment with nanostructured anodes appears to be dynamic and interdisciplinary, with opportunities for innovation, collaboration, and the development of sustainable solutions to address global water pollution challenges.

2. Materials and Methods

The Web of Science Core Collection (WoSCC), as the world's most extensive scientific database, was used for data searching and acquisition. The following search criteria, keywords, and Boolean operators were: ("nanostructured*" OR "nano" OR "nanostructure*" OR "nano dimension*" OR "nanocomposite*" OR "nanoparticle*" OR "nanotube*" OR "nanoplate*" OR "nanoarray*" OR "nanosheet*" OR "nanowall*" OR "nanorod*" OR "nanowire*" OR "nanoribbon*") (Topic) AND ("electrochemical oxidation" OR "anode oxidation" OR "electro-oxidative degradation" OR "electro-oxidation*" OR "electrooxidation" OR "electrocatalytic oxidation*" OR "electro-catalytic oxidation") (Topic) AND ("waste-water" OR "waste water" OR "aquatic medium" OR "wastewater*" OR "real wastewater*" OR "syntetic electrolyte*" OR "landfill leachate" OR "sewage") (Topic) NOT ("bio-electrocatalityc" OR "sonoelectrochemical" OR "photocatalytic" OR "photoassisted" OR "photoelectrocatalytic" OR "photo-electrocatalytic" OR "ion exchange" OR "microbial" OR "catalyst for hydrogen" OR "sonocatalytic" OR "bacteria") (Topic) NOT ("detection*" OR "sensor*") (Topic). Timespan: 1 January 2013 to 30 September 2023 (Publication Date).

After imposing language restrictions limited to English and specifying article types to include only articles and reviews, a comprehensive set of 543 documents, published from 1 January 2013 to 30 September 2023, were extracted from the WoSCC, and used for bibliometric data analysis. To ensure data integrity and to minimize the risk of document alterations during the WoSCC database updating process, the data exportation was completed within a single day.

Bibliometric tools were employed to analyze the data records from various perspectives. A comprehensive examination of the topic involved analyzing keywords, authors, institutions, journals, references, and citations within the gathered dataset. The application of bibliometric methods proved highly advantageous for conducting quantitative analyses of the academic literature. The presentation of statistical data from the extensive academic literature was achieved via the utilization of bibliometric software such as CiteSpace (version 6.2.R4) and VOSviewer (version 1.6.18). Figures were employed to visually represent data related to institutes, authors, and keywords, wherein each node denotes institutes, authors, or keywords, and the node size corresponds to the number of publications. Interconnections between nodes are depicted by lines, with the thickness of the line indicative of the frequency of connections.

3. Results and Discussion

3.1. Publications Trends, Cited and Co-Cited Journals

The number of published articles over the past decade reflects trends in the research on the application of nanostructured materials for wastewater treatment via electrochemical oxidation. In total, 556 papers were obtained through a search using the WoSCC databases (including English (551), Chinese (3), and Russian (2) languages). Among these publications were 518 research articles, 30 review articles and others (e.g., 14 proceeding papers, seven early access papers and one letter). For further consideration, only research articles (515, 94.8%) and review articles (28, 5.1%) in English (a total 543 publications) were considered. According to the WOS categorization, 24.6% of the total articles were published in the research category of Engineering Chemical, 23.2% in Environmental Sciences, 22.2% in Electrochemistry, 21.3% in Chemistry Physical, 20.0% in Engineering Environmental, and 14.0% in Materials Science Multidisciplinary.

Figure 1A shows the annual and cumulative number of publications from the period of January 2013 to September 2023. A noticeable trend in recent years is the increasing number of publications on investigations of nanostructured materials and electrochemical oxidation processes for wastewater treatment, with this trend expected to continue during 2023. This implies that nanomaterials for research on electro-oxidative wastewater treatment are receiving significant attention from researchers. The highest numbers of new publications were observed in 2017 and 2021, while the lowest number of articles was recorded in 2023, likely because data for the entire year of 2023 was not included (only nine months). In terms of paper types, particularly focusing on review and research articles, the data revealed a consistent upward trend in the number of long research articles over the specified period (see Figure 1B). The number of review articles, which are designed for researchers seeking fundamental knowledge about the subject, was significantly lower compared to long research articles (Figure 1B). This observation suggested a close correlation between the total number of publications and the cumulative number of long research publications. As can be seen in Figure 1C, there was a positive correlation between the number of cited papers and the years since publication. The majority of total citations predominantly originated from citations of long research articles. The number of citations for review papers was notably lower, likely attributable to their comparatively smaller production.

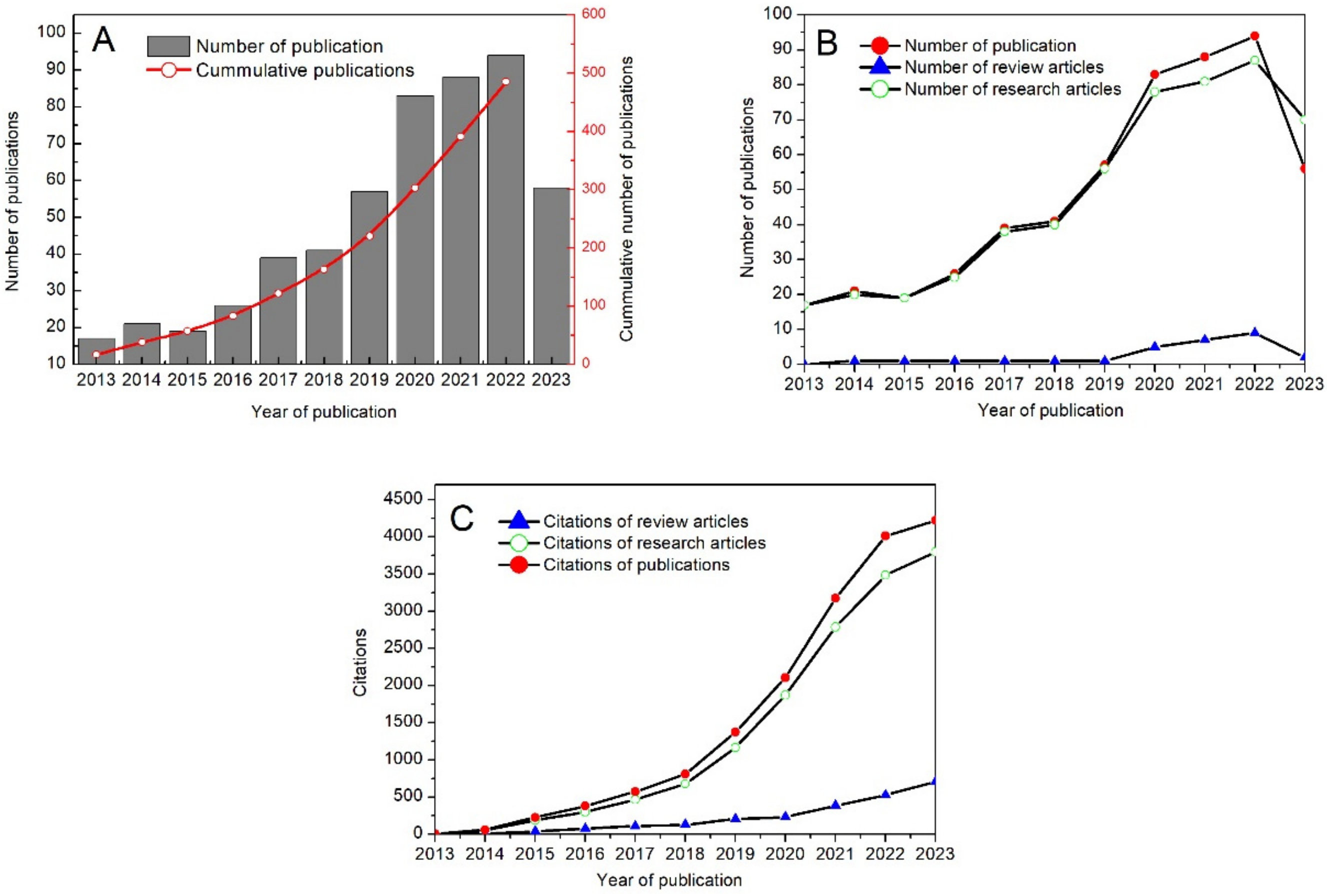

Figure 1. (**A**) number of publications, (**B**) type of paper and, (**C**) citations of publications concerning nanostructured materials in electro-oxidative wastewater treatment by year. Note: the red curve presents the cumulative percentage of publications each year.

The 543 articles were published in 154 journals and the results of the top 10 journals are presented in Table 1. The journals with the highest number of publications relevant to the scope of the above research were Electrochimica Acta, Chemosphere, Chemical Engineering, and the Journal of Separation and Purification Technology. Additionally, Electrochimica Acta had the largest number of citations (1999) and co-citations (2354), suggesting that this journal makes exceptional contributions to this field.

Table 1. Top 10 cited and co-cited journals.

10 Most Cited Journals							10 Most Co-Cited Journals				
No.	**Journal**	**Documents**	**Citations Counts**	**IF (2022)**	**h Index**	**WOS Category**	**Journal**	**Co-Citations Counts**	**IF (2022)**	**h Index**	**WOS Category**
1	Electrochimica Acta	43	1999	6.6	263	Electrochemistry (8/30)	Electrochimica acta	2354	6.6	263	Chemical Engineering (miscellaneous) (Q1); Electrochemistry (Q1)
2	Journal of Environmental Chemical Engineering	12	1263	7.7	107	Engineering, Chemical (16/141) Engineering, Environmental (12/55	Chemical Engineering Journal	1572	15.1	280	Engineering, Chemical (5/141) Engineering, Environmental (3/55)
3	Chemical Engineering Journal	26	1036	15.1	280	Engineering, Chemical (5/141) Engineering, Environmental (3/55)	Environmental Science and Technology	1210	11.4	456	Engineering, Environmental (7/55) Environmental Sciences (19/274)
4	Chemosphere	36	1017	8.8	288	Environmental Sciences (30/274)	Journal of Hazardous Materials	1195	13.6	329	Engineering, Environmental (4/55), Environmental Sciences (10/274)
5	Applied Catalysis. B: Environmental	12	886	22.1	301	Chemistry, Physical (6/161), Engineering, Chemical (3/141), Engineering, Environmental (1/55)	Applied Catalysis. B: Environmental	1172	22.1	301	Chemistry, Physical (6/161), Engineering, Chemical (3/141), Engineering, Environmental (1/55)
6	Separation and Purification Technology	26	504	8.6	191	Engineering, Chemical (12/141)	Chemosphere	1096	8.8	288	Environmental Sciences (30/274)
7	Journal of Electroanalytical Chemistry	17	477	4.5	167	Chemistry, Analytical (18/86), Electrochemistry (12/30)	Water Research	1000	12.8	354	Engineering, Environmental (6/55) Environmental Sciences (13/274) Water Resources (1/103)
8	Journal of Materials Chemistry A	5	428	11.9	270	Chemistry, Physical (24/161), Energy & Fuels (11/117), Materials Science, Multidisciplinary (32/342)	Separation and Purification Technology	719	8.6	191	Engineering, Chemical (12/141)

Table 1. *Cont.*

10 Most Cited Journals							10 Most Co-Cited Journals				
No.	**Journal**	**Documents**	**Citations Counts**	**IF (2022)**	**h Index**	**WOS Category**	**Journal**	**Co-Citations Counts**	**IF (2022)**	**h Index**	**WOS Category**
9	Journal of Hazardous Materials	16	376	13.6	329	Engineering, Environmental (4/55), Environmental Sciences (10/274)	Journal of Electroanalytical Chemistry	634	4.5	167	Chemistry, Analytical (18/86), Electrochemistry (12/30)
10	Journal of Power Sources	8	367	9.2	339	Chemistry, Physical (36/161) Electrochemistry (4/30) Energy & Fuels (21/117) Materials Science, Multidisciplinary (59/342)	Journal of Materials Chemistry A	503	11.9	270	Chemistry, Physical (24/161), Energy & Fuels (11/117), Materials Science, Multidisciplinary (32/342)

The co-citation source visualization was carried out on 205 journals that were cited more than 15 times using VOSviewer. As presented in Figure S1, the journals were grouped into five clusters based on their disciplines. The blue cluster consists of 54 journals related to research from the electrochemical aspect, the red cluster (74 journals) indicates the aspect of chemistry and chemical engineering, the yellow cluster (17 journals) refers to environmental sciences, the pink cluster (three journals) focuses on catalysis and the green cluster (57 journals) relates to a citing journal with the aspect of materials science.

3.2. Countries' Contribution

Figure 2 presents a co-authorship network map among countries where the investigation of using nanostructure anodes for wastewater treatment via electrochemical oxidation is an important field of study. It consists of 54 nodes and 121 links which represent relationships among them. According to node sizes which reflect the number of country publications, the People's Republic of China was the most productive country (345 papers), followed by the United States of America (USA) (51), South Korea (29), India (29), and Iran (27) (for addition information see Tables S1 and S2). The distribution of colors inside the nodes represents published publications per year. The purple ring outside the node relates to the centrality of a specific country. An escalation in centrality, as indicated by the thickness of the purple ring, signifies a rise in the level of collaboration between a particular country and others, thereby increasing their influence within the academic domain. In this case, the highest centrality was exhibited by the People's Republic of China (0.69), indicating their extensive collaboration with authors from other countries in research on nanostructured electro-oxidative technology. Following China are South Korea (0.23), Great Britain (marked as England in CiteSpace software- version 6.2.R4) (0.21), Italy (0.19), and the USA (0.17).

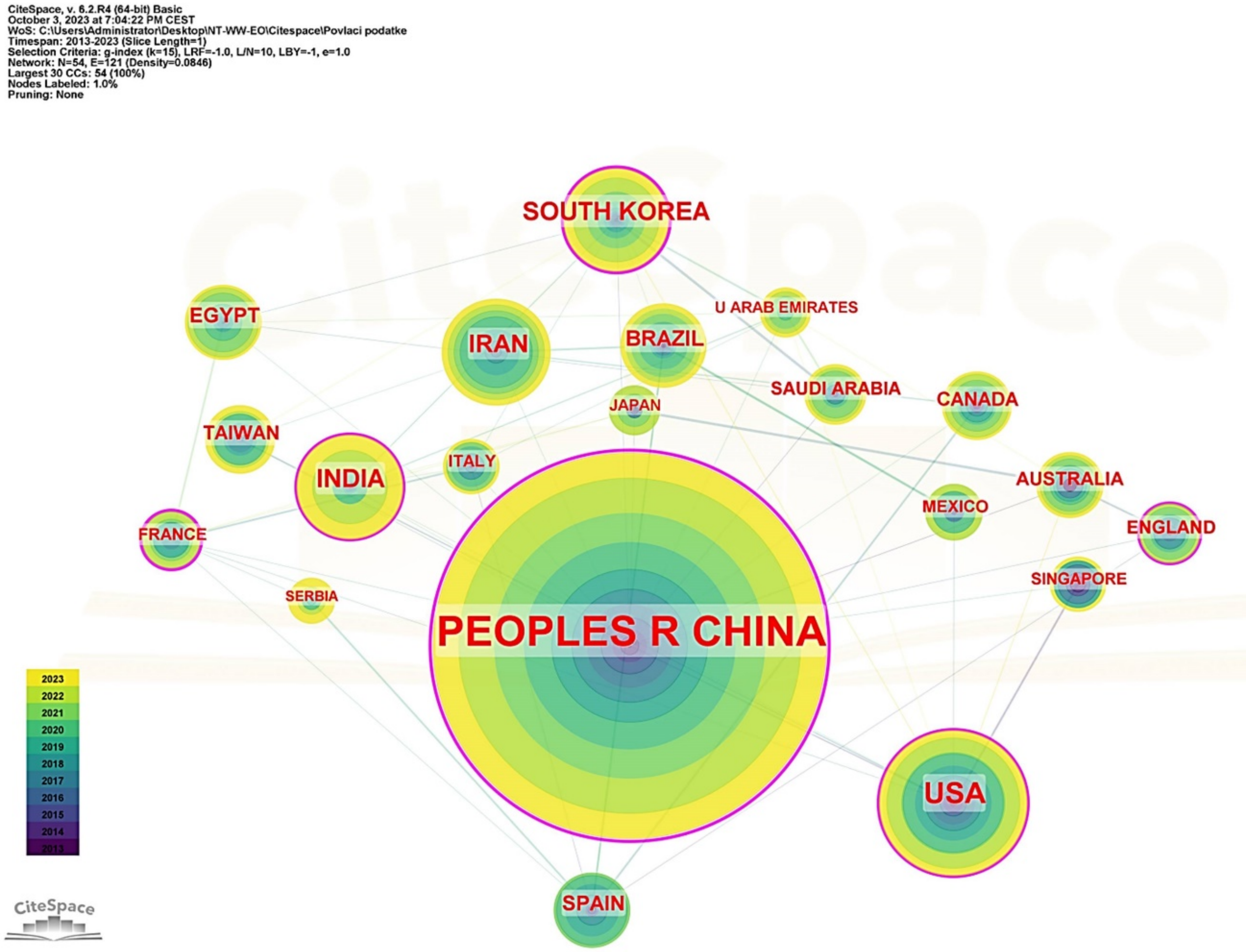

Figure 2. CiteSpace network of countries that research nanostructured electro-oxidative technology.

It is interesting to note that Great Britain and France showed significant cooperation in the investigated field, although their productivity was not at the top (production 7 and 7, centrality 0.21 and 0.09, respectively, see Table S1). The quality of their publications has a significant effect on the scientific community (detailed in Tables S1 and S2). This is supported by the fact that France was second ranked among ten countries in average citation per document (55.25). The first place belonged to Singapore (75.57) and the third to India (47.52). The publications of these countries have impressed the scientific community, although their numbers may not be exceedingly high. On the other hand, China had a lower average citation per document (29.09) which implied the necessity for further improvement in their research about the application of nanomaterials for electro-oxidative wastewater treatment in order to attract the attention of scientists worldwide.

3.3. The Contributions of Institutions

The contributions of institutions were also analyzed and visualized using CiteSpace, which involved extracting information about institutions and their associated collaboration through published articles. The institutions that frequently appeared in scientific publications related to the research area are presented in the network map and table (refer to Figure 3 and Table S3). Based on the node size, it can be observed that the most productive institutions were from the People's Republic of China, with the Chinese Academy of Sciences having the highest publication count (22) followed by Tianjin University (publication count 19). Additionally, the Chinese Academy of Sciences (centrality 0.12), the Egyptian Knowledge Bank (EKB) (centrality 0.09), and Zhejiang University (centrality 0.05) demonstrated the highest centrality, pointing to their central role in the research and development of nanomaterials for electro-oxidative wastewater treatment.

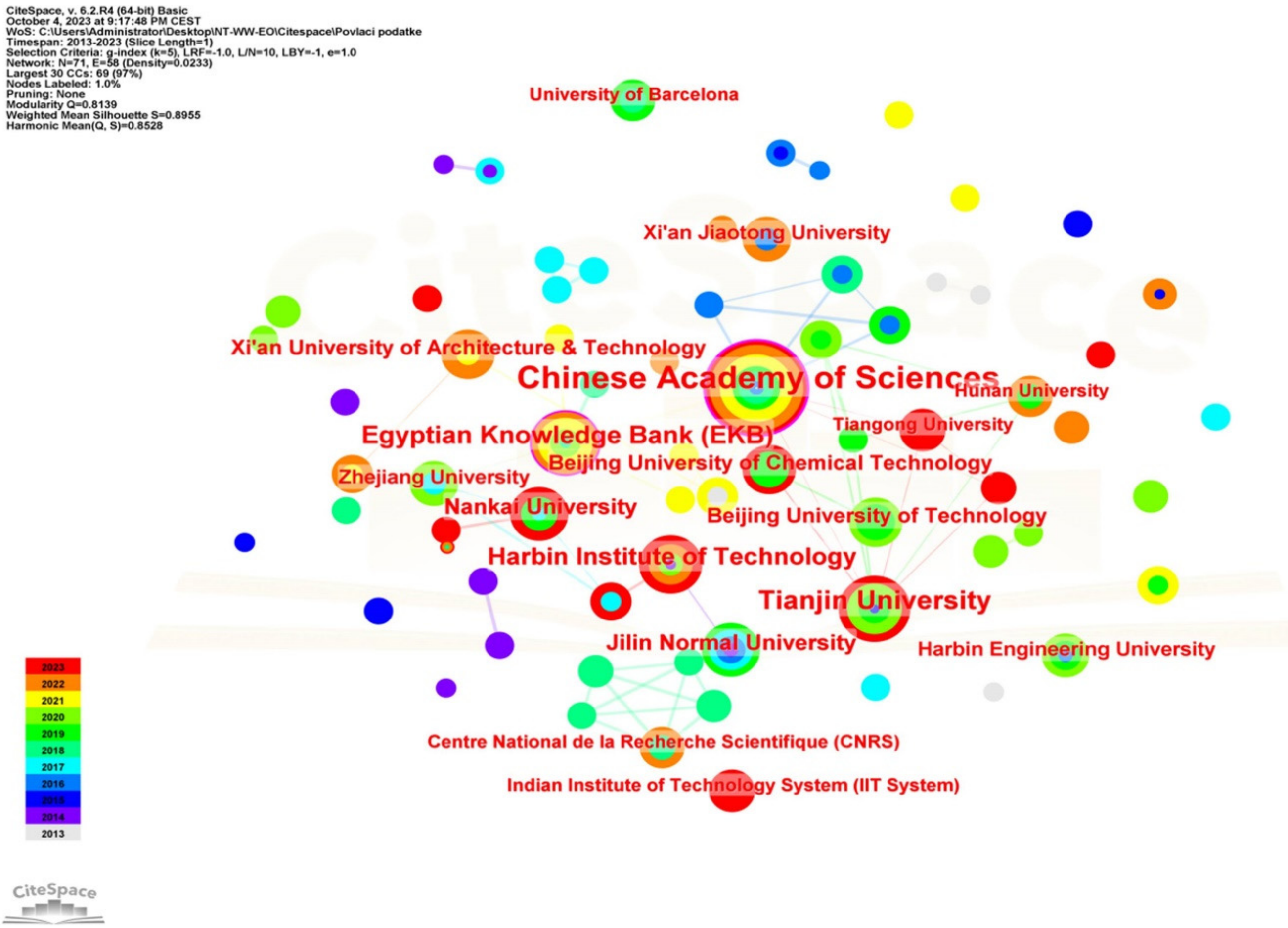

Figure 3. The network of institutions that research nanostructured electro-oxidative technology.

3.4. Contributions of Authors and Reference

3.4.1. Co-Citation Author and Co-Citation Reference

In order to identify authors who had two or more articles which were cited by another article at the same time, the co-citation analysis was performed. Based on the size of the nodes and their centrality shown on the co-citation network map (Figure 4A), Carlos A. Martınez-Huitle from the Chemistry Department at the University of Ferrara, Italy had the highest number of co-citations (139) and centrality (0.37). This indicated that he had the most significant influence on the research topic. Following this was Paniza M. (number co-citation 117, centrality 0.17), Wang Y. (number co-citation 63, centrality 0.28), and Wang D. (number co-citation 27, centrality 0.24). On the other hand, authors with the highest citation burst in the last decade is presented in Figure 4B.

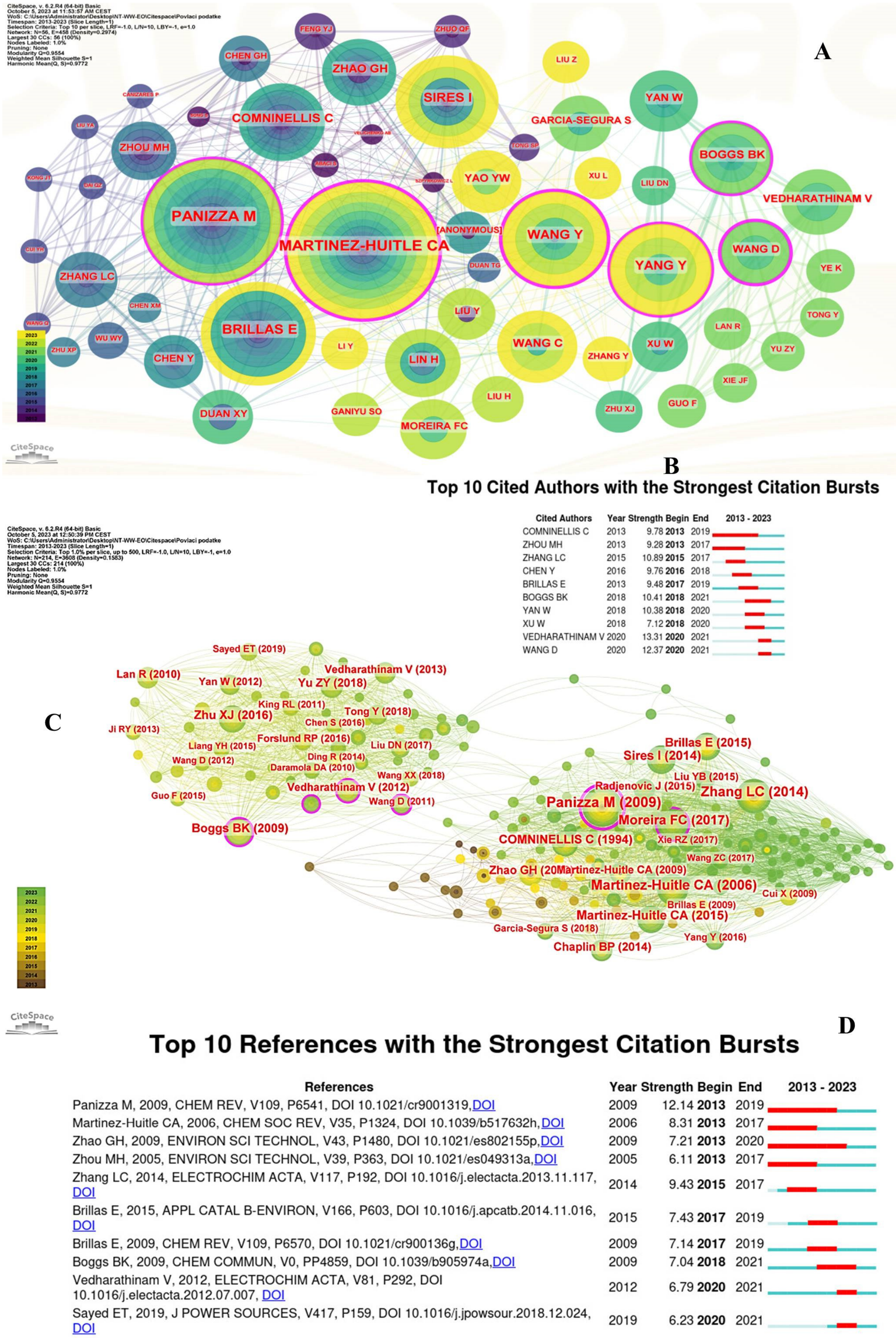

Figure 4. Co-citation network map (**A**) author, (**B**) top 10 authors, (**C**) co-citation reference, and (**D**) top 10 co-citation references [31,49–57].

3.4.2. Co-Citation Reference

The influence of a published article on the investigated research area was estimated via co-citation reference analysis. As can be seen in Figure 4C, the network map of co-citation reference consists of 214 nodes and 3608 links. The largest node is related to the most co-cited reference by Paniza (2009) [49] which had a citation count of 85. The second largest node corresponds to Martnez-Huitle CA (2006) [50] (citation count of 66), followed by Zhang LC (2014) [51] (citation count of 61), and Boggs (2009) [52] (citation count of 40). This indicated their strong connection with other nodes and their interesting influence on future articles. The list of references with the highest citation burst is presented in Figure 4D.

Among the top 10 authors or references co-cited, the first-ranked authors Cominelis and Vantharathiam are leading researchers who have made enormous contributions to the explanations of the mechanisms of electrochemical oxidation. In the references with the highest number of co-citations by Paniza [49] and Martinez [50], otherwise, (close associates of Comninellis), Comininelis is cited as the one who explained the anodic material influence on the mechanism degradation of the organic pollutants using electrochemical oxidation. On the other hand, Vedharathinam [53] in the article from 2012 first described the mechanism of urea electro-oxidation on an Ni anode. It obtained the greatest number of co-citations, which pointed out the highest impact of this article on the scientific community in the field of urea electro-oxidation. Nevertheless, the co-cited analysis results pointed to the two key aspects of the nanomaterials-based electrode application, for urea oxidation and generally, for electrochemical oxidation of organic molecules. Moreover, most of these publications are highly cited review articles, which are suitable for researchers who wish to gain a basic knowledge of the theme. Also, it was noted that a small number of recent publications had a higher co-citation count, probably due to the shorter time framework (last ten years).

3.5. Co Authorship, Cited Author, and Cited Reference

Co-authorship analysis determined the most productive authors in the field of applications of nanostructure anodes for wastewater treatment via electrochemical oxidation. This analysis was conducted by employing the VOSviewer (version 1.6.18) and CiteSpace (version 6.2.R4) software. The results are presented in the form of a network map (see Figure S2) and a table (refer to Table S4). As can be seen in Figure S2, the author's network consists of 98 nodes and 102 links. The node symbolizes the author. Their size indicates the article number of each author. The weight of the line between authors represents their co-authors. The different colors of the node and link correspond to years in the previous decade. Chang Limin, Duan Xiaoyue, and Xu Li were the most productive authors with the highest number of published papers (publications number nine, for both). However, their average citation number per document (39.78, 37.44, and 37.44, respectively) was smaller compared to that of Cao Dianxue (93.17), Ye Ke (93.17), Cheng Kui (82.4), and Wang Guiling (82.4) (see Table S4). Consequently, the articles authored by these individuals achieved a greater impact on the scientific community, regardless of Chang Limin, Duan Xiaoyue, and Xu Li's productivity.

The most cited articles were pragmatic indexes that pointed to current actuality and the hotspot of research in the scientific field [58]. The top 10 highly cited articles are presented in Table 2. It was established, via analysis of cited publications, that the research related to nanostructured anodes, and their application for organic pollutants removal from wastewater using electro-oxidation, were constantly hot research fields, which is grouped into five clusters (see Figure 5). Apart from review articles about electro-oxidation, which were the most cited, such as articles by Babuponnusami (2014) [59], and Rashid (2021) [60] (grey cluster), most papers provided the following new perspectives on the use and development of nanomaterials: (i) as electrocatalysts for fuel cells and the production of hydrogen via urea electro-oxidation from urea-rich wastewater (red cluster); (ii) as anodes, i.e., dimensionally stable anodes (DSA), or metal oxide electrodes doping with metals or mixing with metal- and carbon-based nanomaterials for electro-oxidation organic contaminant (green cluster); (iii) for electrocatalytic filtration membrane (blue cluster); (iv) as an electrode for the electro-oxidation of ammonia (orange cluster); and (v) as an electrode for electro-Fenton degradation (grey cluster).

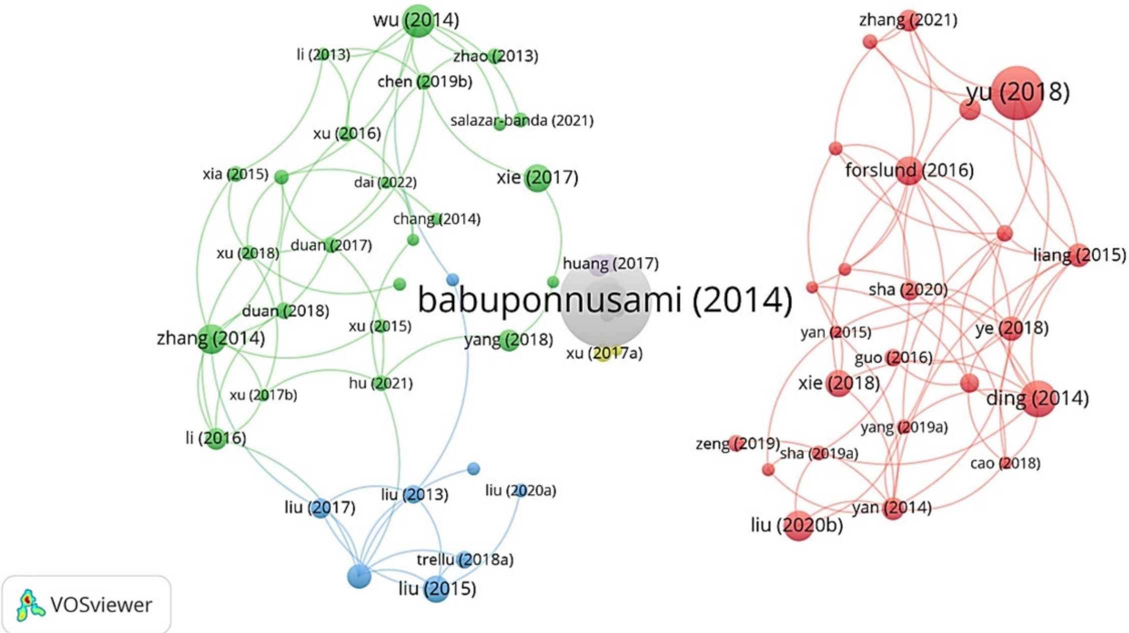

Figure 5. VOSviewer network map of cited publications with min. 50 citations.

The red cluster consists of cited publications, with the main focus of the research relating to the development of nanostructured Ni-based anodes. Among the twenty top articles, eight publications focused on the development and investigation of nanostructured Ni-based electrocatalysts for urea electro-oxidation. The studied frameworks mainly used mesoporous spinel $NiCo_2O_4$ nanostructures [61], $NiSe_2$ nanoparticle/NiO nanosheet [62], nanostructured $LaNiO_3$ perovskite electrocatalyst [63], amorphous nickel–iron-layered double-hydroxide nanosheet [64], $NiMoO_4{\cdot}xH_2O$ nanosheet arrays on Ni foam [65], nickel nanowires [66], leaf-like nickel–cobalt bimetal phosphides [67], and nitrogen dopants in nickel nanoparticles-embedded carbon nanotubes [24].

The references in the green cluster are related to the synthesis and investigation of the structural, morphological, and electrochemical characteristics of nanostructured dimensionally stable (DSA), or metal oxide anodes (such as PbO_2, SnO_2, TiO_2) for electro-oxidation of organic contaminants, primarily dyes and antibiotics. The highest number of citations (citation count 199) was the reference by Zhang et al. [51], who investigated the effect of introducing carbon nanotubes into Ti/SnO_2-Sb electrodes. Also, about ten references in this cluster were related to the improvement of electrocatalytic characteristic nanostructured PbO_2 anode compared to traditional PbO_2 anode (such as higher electrochemical activity and longer service lifetime). These included the following types of electrodes: PbO_2 electrodes with a graphene nanosheet [68] and graphene nanoplatelets interlayer [69], a carbon nanotube and Bi co-doped PbO_2 electrodes (CNT-Bi-PbO_2) [27], a hydroxyl multi-wall carbon nanotube-modified nanocrystalline PbO_2 anode (MWNTs-OH-PbO_2) [25], Fe- and Ce-doped Ti/TiO_2 nanotube (TNTs)/PbO_2 anodes [70,71], and a sulfur-doped TiO_2 nanotube array as a conductive interlayer of a PbO_2 anode [72].

The remaining three clusters were constituted only of a few members. Therefore, the set search conditions in VOSviewer (minimum 50 citations) may indicate the limited importance of these themes in the examined research field. The blue cluster collects the references to describe the electro-oxidation of organic pollutants via reactive electrochemical membranes. According to Gao et al. [73] this process can be enhanced using carbon nanotubes. The most cited reference of the orange cluster was the nickel–copper hydroxide nanowires on carbon fiber cloth for efficient electro-oxidation of ammonia [74]. In the grey cluster, besides the review article by Babuponnusami [59], the article with the title "An integrated catalyst of Pd supported on magnetic Fe_3O_4 nanoparticles: Simultaneous production of H_2O_2 and Fe^{2+} for efficient electro-Fenton degradation of organic contaminants" was the most cited reference [75]. Although among the most cited papers there were also some review articles; many papers offer a fresh perspective on the utilization and advancement of nanomaterials.

Table 2. Top 10 Cited references.

No.	Document	Title	Journal	Citations	Links
1	Babuponnusami (2014) [59]	A review on Fenton and improvements to the Fenton process for wastewater treatment	Journal of Environmental Chemical Engineering **2014**, *2*, 557–572	1133	1
2	Yu (2018) [76]	Ni-Mo-O nanorod-derived composite catalysts for efficient alkaline water-to-hydrogen conversion via urea electrolysis	Energy & Environmental Science **2018**, *11*, 1890–1897	491	29
3	Ding (2014) [61]	Facile synthesis of mesoporous spinel $NiCo_2O_4$ nanostructures as highly efficient electrocatalysts for urea electro-oxidation	Nanoscale **2014**, *6*, 1369–1376	268	21
4	Wu (2014) [77]	Recent development of mixed metal oxide anodes for electrochemical oxidation of organic pollutants in water	Applied Catalysis A: General **2014**, *480*, 58–78	235	23
5	Rashid (2021) [60]	A state-of-the-art review on wastewater treatment techniques: the effectiveness of adsorption method	Environmental Science and Pollution Research **2021**, *28*, 9050–9066	224	0
6	Liu (2020b) [62]	Efficient synergism of $NiSe_2$ Nanoparticle/NiO nanosheet for energy-relevant water and urea electrocatalysis	Applied Catalysis B: Environmental **2020**, *276*, 119165	205	6
7	Zhang (2014a) [51]	Preparation of Ti/SnO_2-Sb electrodes modified by carbon nanotube for anodic oxidation of dye wastewater and combination with nanofiltration	Electrochimica Acta **2014**, *117*, 192–201	199	46
8	Forslund (2016) [63]	Nanostructured $LaNiO_3$ Perovskite Electrocatalyst for Enhanced Urea Oxidation	ACS Catalysis **2016**, *6*, 5044–5051	187	23
9	Xie (2017) [78]	Electrochemical oxidation of ofloxacin using a TiO_2-based SnO_2-Sb/polytetrafluoroethylene resin-PbO_2 electrode: Reaction kinetics and mass transfer impact	Applied Catalysis B: Environmental **2017**, *203*, 515–525	179	18
10	Xie (2018) [64]	Partially Amorphous Nickel-Iron Layered Double Hydroxide Nanosheet Arrays for Robust Bifunctional Electrocatalysis	Journal of Materials Chemistry A **2018**, *6*, 16121–16129	174	15

3.6. Keywords

The article's keywords point to understanding the research topics and issues in a specific field. Generally, it provides key guidelines about content and the article's subject to interest the readers and the scientific community. A keyword's occurrence network analysis and cluster map analysis, including the author's keyword, keyword plus, and an abstract of publications during last decade, was performed using the CiteSpace software (version 6.2.R4).

The network co-occurrence map of keywords presented in Figure 6A consists of 289 nodes which represent the keywords number. The size of each node relates to the co-occurring frequencies of its keywords. The nodes with the highest frequencies were synonymous words for electrochemical oxidation (182) and electro-oxidation (121) which were difficult to avoid using the indicated software. The other keywords were degradation (138), oxidation (120), removal (114), nanoparticle (80), waste-water treatment (82), and carbon nanotube (39). The colors in the node refer to the years in which certain keyword appears. As can be seen in Figure 6, some of these nodes, such as electro-oxidation, degradation, and oxidation, are marked with a purple ring, which implies their good centrality (0.11 and 0.1, 0.1, respectively), and consequently, had the most significance in the research field. These words are prominent and define a large research field which can be observed from several aspects, starting from the mechanism, kinetics, and use of electrodes. For that reason, their occurrence and high centrality were expected. On the other hand, the words nanoparticle, carbon nanotubes, and nanosheets showed a slightly lower centrality (centrality 0.07, 0.06 and 0.04, respectively, see Table S5) since they referred only to the specific part of research about electrochemical oxidation, i.e., research and development of new anodic nanomaterials. According to this, it can be accepted as a significant hotspot in the research field.

The idea of the cluster map analysis was to find the main hotspots via CiteSpace software and to compare them with the hotspots which were predicted with reference citation and co-citation analysis. The general criterion of cluster analysis via CiteSpace were the values of modularity (Q) and silhouette (S). They defined the extent of specific topics reflected by clusters in the researched area. If the Q is near to 1 (0.4 to 0.8 are acceptable), the clusters are clearly defined. On the other hand, if the S is near to 1 (above 0.6 is reasonable), it points to the high level of confidence in the way of grouping nodes. The main research topics on the application of nanostructured materials for electro-oxidative wastewater treatment were defined by the cluster's title (see Figure 6B).

The largest cluster denoted (#0) relates to direct urea fuel cells and consists of 66 members and has a silhouette value of 0.769. This cluster framework draws together various keywords such as electro-oxidation (121), electrocatalytic oxidation (54), and catalysts (45). This current topic was in agreement with the hotspot suggested via citation and co-citation analysis. Therefore, the articles explicitly referred to developing and investigating bifunctional electrocatalysts that would be significantly beneficial for the electrocatalytic oxidation of urea-rich wastewater, as for direct urea fuel cells or hydrogen production at the same time. The following bifunctional electrocatalyst was designed by integrating the following materials: cobalt nitride (CoN) and nickel hydroxide ($Ni(OH)_2$) on nickel foam [79], NiCo-layered double hydroxide/hydroxide nanosheet heterostructures [80], NiCo bimetal organic frames [81], asok-like Ni-NiO-Mo0.84Ni0.16/NF hybrids synthesized via hydrothermal and calcination methods [82], rosette-like MoS_2/Ni_3S_2/NiFe-layered double hydroxide/nickel foam (LDH/NF) [83], a catalyst system of $NiSe_2$ nanoparticle/NiO nanosheet [62], reduced graphene oxide-supported nickel tungstate nanocomposites [84], SnO decorated with NiO nanocrystal [85], V_2O_3 nanosheet anchored N-doped-carbon encapsulated Ni heterostructure [86], and nickel–cobalt bimetal phosphide as a bifunctional electrocatalyst [67].

The second cluster (#1) with 49 members and a silhouette value of 0.728, is labelled as a PbO_2 electrode. The most cited members in this cluster were degradation (138), oxidation (120), and wastewater (105). It included articles which related to the fabrication and electrocatalytic application for pollutant (due, antibiotic, phenol compounds, etc.,) removal from wastewaters. During this process, researchers used new PbO_2-based anodes that were doped with metals or carbon nanomaterials. These included Fe/C-doped lead dioxide-modified anodes [87], PbO_2 electrode with a graphene nanosheet interlayer [68], PbO_2 with a graphene nanorod anode [30], titanium dioxide nanotubes/cerium-doped lead dioxide (TiO_2-NTs/Ce-PbO_2) anode [33], CeO_2-ZrO_2/TiO_2/CNT anode [26], and PbO_2 nanocrystals via incorporation of Y_2O_3 nanoparticles [32]. The topic partially matched the green clusters of the citation analysis.

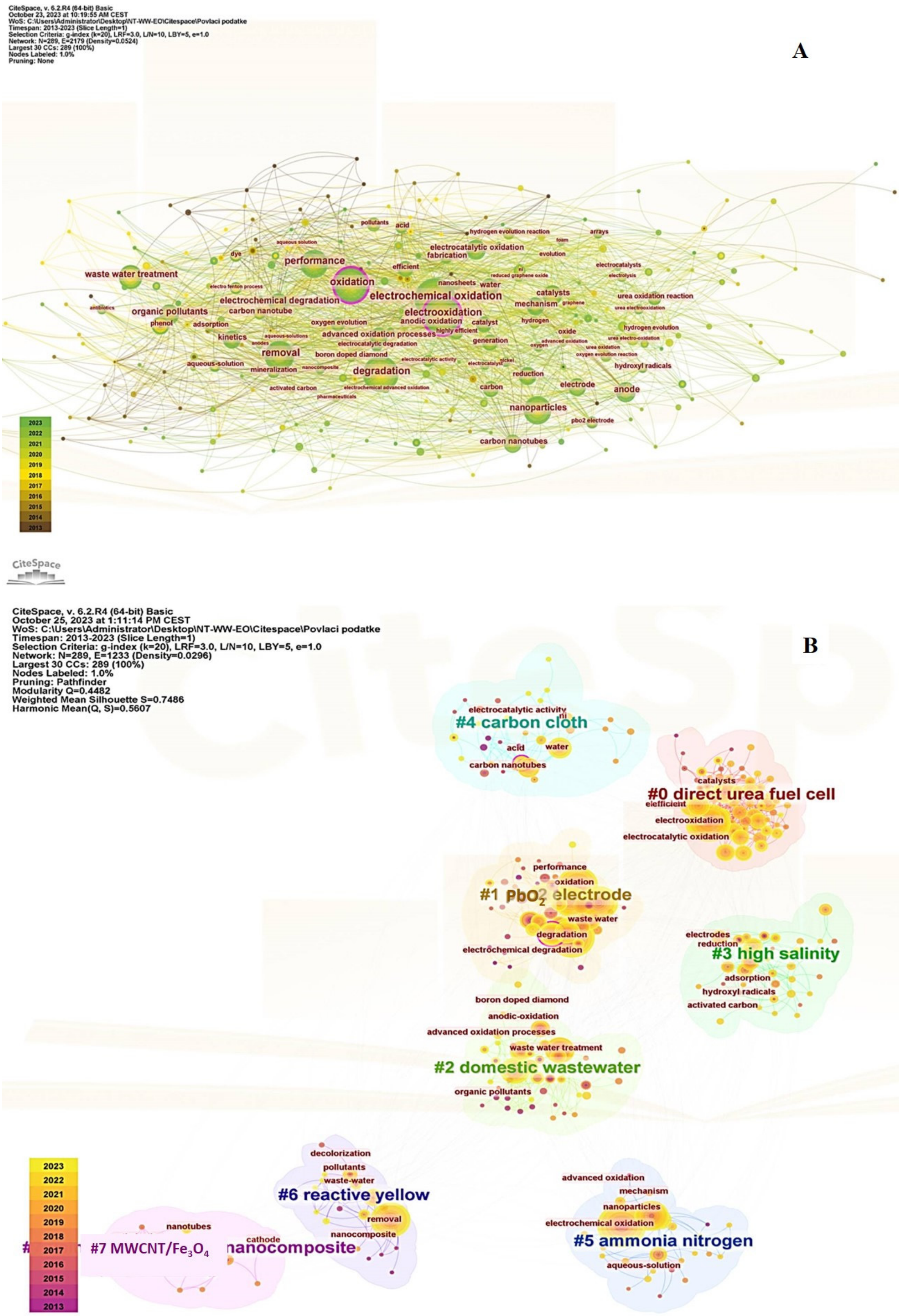

Figure 6. (**A**) The network co-occurrence map of keywords and (**B**) cluster map analysis.

The third cluster with a silhouette value of 0.744, consists of 82 wastewater treatments, 71 organic pollutants, and 49 advanced oxidation processes as the most cited members which related to the domestic wastewater treatment via the electrochemical method. In order to treat domestic wastewater, researchers in this cluster proposed using boron-doped diamond and nanostructured amorphous carbon electrodes [23] and nanostructured electrodes such as TiO_2 nanotube arrays (TiO_2-NTA) with an La-PbO_2 layer on a Ti surface [28].

The clusters labelled as #4 (CARBON CLOTH), Cluster #5 (AMMONIA NITROGEN), Cluster #6 (REACTIVE YELLOW), Cluster #7 (USING MWCNTS-FE_3O_4 NANOCOMPOSITE) had fewer members (33, 25, 23, and 13) than the previous clusters and higher silhouette values (0.769, 0.808, 0.699, and 0.856, respectively). The exception was Cluster #5, which had a high level of confidence in the way of grouping nodes. It is interesting to point out that the most commonly cited words directly referring to nanomaterials were carbon nanotubes (36), nanoparticles (80), and nanotubes (7). The major citing articles from Clusters 4 and 5 were published by Zhong, C (2013.0) [88] and Wen-wu, Liu (2014.0) [89], and they did not refer to using nanomaterials for electro-oxidative treatment wastewater. The articles were related to the electrochemical degradation of tricyclazole in aqueous solutions using Ti/SnO_2-Sb/PbO_2 anodes and a treatment of pretreated coking wastewater via flocculation, alkali out, air stripping, and three-dimensional electrocatalytic oxidation with parallel plate electrodes, respectively. On the other hand, articles by Sharan, S (2023.0) [90] and Pourzamani, H (2018.0) [29] with the highest citation score within Clusters 6 and 7, directly described the development of three-dimensional networks of Zn-oxide nanorods assisted with PbO_2/Pb electrodes for the electrochemical oxidation of methylene blue in an aqueous phase and the application of the three-dimensional electro-Fenton process using the MWCNTs-Fe_3O_4 nanocomposite for the removal of diclofenac.

The chronology of co-occurrence keywords from 2013 to 2023 is presented in the timeline map (Figure S3). The node position corresponds to years of publication, the line colors indicate that the word belongs to the cluster, and the lines which connect nodes point to co-occurring links. It is important to note that nodes associated to keywords with the prefix "nano" (such as nanosheet, nanocomposites, nanowires, nanoparticles, and nanotubes) were present in all of these clusters across different years. These keywords were significant for our evaluation of research fields.

3.7. Retrospection on Bibliometric Results

In general, articles on the application of nanomaterials for electro-oxidative wastewater treatment have increased progressively from 2013 to 2023. As the country with the largest number of publications, China is one of the top sources of publishing institutions, which implies their important contributions to this field. China, South Korea, and the United States were the top three countries in terms of the application of nanomaterials for electro-oxidative wastewater treatment. Multiple cooperation networks were established among various countries and institutions, suggesting that the implementation of nanostructured materials is constantly being explored and confirmed. This underscored the potential prosperity of new nanomaterials in the future. Among the top 10 cited or co-cited journals, the first-ranked journal, Electrochimica Acta, is a leading journal that has a great reputation in this field. The highest number of studies about nanostructured materials for electro-oxidative wastewater treatment published in electrochemical and environmental journals was comparable, which suggests a wide variety of options for the choice of journal submissions in the future.

Nanostructured materials play a key role in improving the performance of anodes for electro-oxidative wastewater treatment including urea electrolysis, advancing science, and changing technological practice towards green and renewable sources on the broadest possible scale. The incredibly good agreement of the bibliometric analysis results revealed the hotspot of research themes through two programs and different types of analysis (analysis of co-citations, citations, and cluster keywords). This undoubtedly led to the use of nanomaterials in two key fields, for electro-oxidation of urea, and for electro-oxidation of phenols, dyes, and antibiotics.

Five of the top 10 cited and co-cited publications were related to urea electrolysis. The reason behind this could be attributed to ecologically acceptable technologies for wastewater treatment and energy production which are the solution to the energy crisis, the actual problem of the 21st century. Urea is an indisputable natural energy resource that reaches the environment mostly as a by-product of mammalian protein metabolism. Also, it is well known that the increasing presence of urea in the environment has a positive effect on the development of agriculture, but it leads to the pollution of water resources at the same time. Urea enters to the human environment through municipal wastewater, as well as through wastewater from textile industries, pharmaceutical industries, and fertilizer manufacturing plants. According to estimates, about 240 Mt of urea is released into the environment per day (for comparison, fossil fuel production is only 0.5 Mt per day) [91]. Disposal of untreated water loaded with urea can lead to serious environmental problems due to its transformation into highly toxic ammonia and carbon dioxide, which is the main cause of the greenhouse effect. In order to prevent the emergence of global pollution problems and to improve water quality, it is necessary to develop environmentally acceptable and economically profitable technologies for purifying industrial and communal wastewaters before discharging them into the recipient. The application of conventional methods such as adsorption, biological methods, and chemical oxidation is limited by the storage problems of the used material and chemicals. Prospective technologies, such as electro-oxidation, can be applied to remove urea and produce clean hydrogen energy at the same time, (through the following reaction: $CO(NH_2)_2 + H_2O \rightarrow 3H_2 + N_2 + CO_2$) from wastewater without generating additional waste and chemical pollution, with minimal need for human resources and capital investment.

The main problem of their intensive application is the very slow oxidation reaction of urea, which can be eliminated by improving the characteristics of existing or newly synthesized nano-based electrocatalysts. It is well-known that the anode material has an influence on the kinetics and mechanism of electrochemical oxidation, as well as the efficiency of urea oxidation. This is explained by the decisive impact of the material's structure, the morphology of the physicochemical properties, and the electrochemical performance of the electrodes. For that reason, the anodes are regarded as the electrolytic system's key component, in terms of process efficiency and costs. It is desirable for electrodes used in electro-oxidation processes to show satisfactory electrochemical characteristics, to be catalytically active, stable during use, and to have a long working life. In the initial investigations of urea decomposition, RuO_2–SnO_2–TiO_2, BDD, TiO_2–RuO_2, Ti/IrO_2, (Ti/Pt, Ti/(Pt–Ir), Ti/RuO_2, Ti/(RuO_2–TiO_2), Ti/(RuO_2–TiO_2–IrO_2), Ti/(Ta_2O_5–IrO_2), SnO_2–Sb, and BiOx/TiO_2 anodes were used [92]. The complete oxidation was only achieved using the BDD electrode. In early studies, the use of noble metals or their oxides as anodes (such as platinum) was proposed which showed high electrical conductivity and excellent electrocatalytic activity. However, a high price and low mechanical strength is a limiting factor for their application. Due to low cost, high corrosion resistance, and higher electrocatalytic activity compared to Pt, Ir, Rh, the metal nickel and nickel-based materials (such as their oxides, hydroxides, phosphides, and sulfides) are good electrocatalysts for urea electro-oxidation. The main problem is the degradation of the Ni catalyst (i.e., deactivation of the catalytic surface) during electrolysis, which leads to a decline in current density and the blocking of the urea electro-oxidation. To solve this problem, the nanostructure/morphology and chemical composition must be adjusted. This affects the regulation of the electronic configuration of electrocatalysts by increasing the surface area and active sites on the catalyst, which leads to faster electron transfer and a reduction in surface blockage. Consequently, their performance and the kinetic properties of water and urea electrolysis are improved. In the first period, simple nano-structured forms of Ni-based electrocatalysts such as nanowires, nanosheets, nanoribbons, and nanotubes were investigated. Later, two- or three-dimensional nanosheet materials which had a high surface area and numerous active sites for the anodic process were also tested. The nickel–cobalt, NiMo and nickel–iron nanocompounds showed both better electrical conductivity and rate of electron transfer compared to pure Ni, and thus, they had a tendency to reduce the potential of urea oxidation reaction (UOR). However, most of the current catalysts must be immobilized on anode surfaces using a polymer binder (like Nafion or polytetrafluoroethylene (PTFE) prior to use. It can result in decreased catalytic activity, due to a rise in the series resistance, a blocking of active sites, and inhibit diffusion. The most cited articles [80–82], were trying to solve this problem by introducing materials with high specific surface area and perfect electrical conductivity such as nickel foam (NF), so called a binder-free catalytic electrode. For instance, Yan et al. [80] synthesized a NiCo-layered double hydroxide/hydroxide (NiCo LDH/NiCo$(OH)_2$) microsphere formed of ultrasmall nanosheets on Ni foam via chemical solution method. Due to abundant active sites on NiCo LDH-NiCo$(OH)_2$ interfaces and the introduction of Co-ions, the electrical conductivity and catalytic performance toward UOR were improved. The obtained onset potential was 0.29 V vs. Hg/HgO. Wei et al. [81] synthesized NiCo bimetal organic frames in situ on nickel foam (NiCo MOF/NF) via a solvothermal method. Electrochemical measurement of synthesized electrocatalyst displayed an ultra-low UOR potential of 1.280 V vs. RHE at 10 mA cm^{-2} in 1.0 M KOH. Also, the NiMo-based bifunctional catalysts were favorable for UOR due to their acceptable catalytic activities. Compared to the ever-reported NiMo-based catalysts, the better electrochemical performance for UOR was obtained by Xu et al. [82] using asok-like Ni-NiO-Mo0.84Ni0.16 on NF (low potentials of 1.33 V at 50 mA cm^{-2} for UOR and kept the current density at 250 mA cm^{-2} for 60 h). The nanosheet's and nanorod's morphological forms of this catalyst inevitably enabled a large surface area, and thus better electrocatalytic activity. Another cited study [65] was based on 3D preparations of a binder-free catalytic electrode, such as growing the $NiMoO_4xH_2O$ nanosheet arrays on Ni foam ($NiMoO_4$ NAs/NF). Compared to Ni$(OH)_2$ NAs/NF, the (NiMoO4 NAs/NF) anodes had a higher catalytic activity and stability. The specific current density was enhanced by 4.2 times (830 mAcm^{-2} at 0.5 V at a scan rate of 10 mV). Also, electrocatalysts based on nanostructured nickel–iron compounds were studied due to their high earth abundance, low cost, and relatively high activity. The theoretical and experimental results suggested that the Ni:Fe ratio is key for the OER and UOR activity. Therefore, Xie et al. [64] developed partially amorphous NiFe LDH nanosheet arrays with native Ni^{3+} ions and an optimal Ni:Fe ratio. The current density of UOR for this electrocatalyst at 1.8 V (vs. RHE) was 1.6 mA cm^{-2} and was 2.4 times higher in comparison to crystalline catalysts. Also, the nanoparticle–nanosheet catalyst system, such as the $NiSe_2$ nanoparticle/NiO nanosheet catalyst, due to coupling effects, led to a unique heterostructure (with increased active sites and a high amount of intrinsic Ni^{3+} ions), and the synergism effect enhanced the catalytic activity, stability, and accelerated the kinetics of the reaction [62].

Secondly, based on the analysis of the most-cited publications, it can be assumed that the enlarged number of active sites, and thus the faster kinetics of urea electro-oxidation, can be achieved via the synthesis of Ni-based nanocompounds with heteroatoms (such as P, S, and N). For instance, Sha et al. [67] used the hydrothermal-phosphating treatment method for the synthesis of a leaf thorn-like (2D nanosheets supporting 1D nanowires) NiCoP on carbon cloth (NiCoP/CC) with excellent electrocatalytic activity toward HER and UOR (a cell voltage (1.42 V) was 160 mV less than the voltage of its urea-free counterpart, at a current density of 10 mA cm^{-2} and a durability of about 30 h). Also, Zhang and Yang [24] integrated nickel nanoparticles into nitrogen-doped carbon nanotubes (Ni@NCNT) via the carbonization of a nickel precursor and a dicyandiamide at 700 °C. The nitrogen dopants decreased the CO_2 poisoning effect by reducing the binding strength of CO_2 species and active sites on one hand, and stimulated the in situ conversion of Ni^{3+} species to ease UOR electrocatalysis on the other hand. As a result, the electrocatalytic current density for Ni@NCNT in 1 M KOH electrolyte was 3.8-fold higher than commercial Pt/C (45.8 mA cm^{-2} compared to 11.8 mA cm^{-2}).

Four of the top 10 cited and co-cited publications were related to the application of nanostructured dimensionally stable (DSA), or metal oxide anodes (such as PbO_2, SnO_2, TiO_2) for electro-oxidation of organic contaminants, primarily, phenol compounds, dye, and antibiotics. It is well-known that dimensionally stable anode (DSA), such as PbO_2, SnO_2, TiO_2, due to characteristics such as high stability, durability, good corrosion resistance, and low cost of synthesis, were considered as good candidates for the electrochemical oxidation of pollutants. On the other hand, poor electric conductivity of pure SnO_2, or toxicity of PbO_2 restricted their application in the field of electrochemical oxidation technology. This problem can be solved by reducing the grain size to the nanometer dimension and doping with metal nanoparticles or carbon-based nanomaterial. It is well-known that the antimony-doped tin dioxide electrodes (SnO_2-Sb) showed excellent electrocatalytic performance for most organic contaminant electrochemical oxidation. However, the short service life and durability of the Ti/Sb–SnO_2 anode were limiting factors for their commercial applications. A significant annulation of these disadvantages was achieved by Zhang et al. [51], who stood out with a higher number of citations (199). They introduced carbon nanotube into Ti/SnO_2-Sb electrodes and prolonged the service lifetime of the Ti/SnO_2-Sb-CNT electrode by 4.8 times compared to the Ti/SnO_2-Sb electrode without the CNT modification. On the other hand, there was a very good agreement between the results of VOSviewer citation analysis and CiteSpace keyword cluster analysis about publications which referred to the synthesis, design, and investigation of electrocatalytic characteristics of a nanostructured PbO_2 anode. In order to diminish the cost and to enhance the electrocatalytic activity of metal–metal oxide electrodes, the most cited articles proposed introducing carbon-based materials such as CNT and MWCNT. Therefore, Duan et al. [68] reported the preparation of graphene nanosheet interlayers (marked as GNS-PbO_2) with combinations of electrophoretic deposition and electro-deposition technologies with larger electrochemically active surface area, stronger OH degradation of 2-chlorophenols, and longer service lifetime (107.9 h), compared to traditional PbO_2 electrodes. Also, better electro-catalytic oxidation of p-nitrophenols was exhibited using carbon nanotube and Bi co-doped PbO_2 electrodes (CNT-Bi-PbO_2) synthesized using thermal deposition and electrodeposition technologies by Chang et al. [27]. The result of citate analyses showed that nanostructured anodes synthesized via a combination of both the PbO_2 with TiO_2 nanotube and doping with some other metal ions (such as Fe^{3+}, Bi^{3+}), were very attractive in last ten years too. The increase in electrocatalytic activity and the rise in corrosion resistance of the electrode was achieved using cerium-doped Ti/nanoTiO_2/PbO_2 [71]. Jiang et al. [70] achieved a significantly improved electrode performance, and thus the better degradation of p-nitrophenol using Fe-doped Ti/TiO_2 nanotube/PbO_2 anode synthesized via ectrodeposition.

In pursuit of achieving the objective of "ideal electro-oxidation," researchers in recent years have focused on developing novel, advanced electrode materials with high surface areas, exceptional efficiency, and stability under oxidative conditions. Numerous studies have demonstrated the significant impact of the anode material on both degradation efficiency and the mechanism of electrochemical oxidation [42,93,94] Nevertheless, gaining a deeper understanding of the degradation process, including whether complete mineralization occurs or if intermediate species are formed, requires the identification and quantification of organic pollutants and their by-products across different media. To monitor the mineralization of organic compounds, researchers employ methods such as determining total organic carbon (TOC) and/or measuring chemical oxygen demand (COD) or biological oxygen demand (BOD) [95–97]. Additionally, analytical techniques such as electrospray ionization-mass spectroscopy (ESI-MS), liquid chromatography-mass spectroscopy (LC-MS), gas chromatography-mass spectroscopy (GC-MS), ultra-performance liquid chromatography (UPLC) with photodiode array (PDA) detector, and the matrix-assisted laser desorption ionization-time of flight (MALDI-TOF) method were utilized for detecting intermediates [30,42,95,96,98]. Finally, it is desirable to assess the toxicity after the removal of organic compounds.

4. Conclusions

This study presents an integrative approach to review participation and connectivity within the scientific community in terms of contributions of countries, institutions, authors, journals, references, and directions of research about the applications of nanostructured materials for electro-oxidative wastewater treatment. The trends, state, and evolution in this field were summarized. Since 2013, the number of publications about the use of nanostructured materials for electro-oxidative wastewater treatment has slowly grown, implying that this field is steadily improving. The People's Republic of China was the most productive country with numerous prominent institutions and researchers. The United States of America, South Korea, and countries in the European Union showed the key impact of the research in this area. The main theme that has attracted the attention of researchers and could remain crucial in the future is the development and use of nanostructured materials for urea electro-oxidations. Therefore, these results provide a starting point for further research in the field of developing and the application of nanostructured anode for urea electrochemical oxidation. The main benefit of the proposed approach was to provide useful and valuable information that should help researchers find the most relevant journals, articles, and hotspot themes and to find scientists for research collaboration.

5. Future Directions

Based on the text provided, the future direction of research in the field of electro-oxidative wastewater treatment with nanostructured anodes seems to be promising and multifaceted. Here are some potential directions:

- Advanced Nanostructured Materials: researchers may focus on developing novel nanostructured materials with enhanced properties for electro-oxidative wastewater treatment. These materials could offer improved efficiency, durability, and selectivity in pollutant removal.
- Integration of Nanotechnology: further integration of nanotechnology into the electrolytic systems could lead to more efficient and cost-effective wastewater treatment processes. This might involve exploring new methods for fabricating nanostructured anodes and optimizing their performance in real-world applications.
- Multidisciplinary Collaborations: given the international collaboration observed in the bibliometric analysis, future research efforts could involve multidisciplinary collaborations between researchers from different countries and institutions. This collaborative approach can foster innovation and accelerate progress in the field.
- Focus on Urea Electro-oxidation: since the analysis identified urea electro-oxidation as a main research theme, future studies may delve deeper into this area. This could involve investigating the electrochemical mechanisms involved in urea oxidation, optimizing electrode materials for urea removal, and exploring potential applications in various industries, such as agriculture and wastewater treatment.
- Environmental Protection and Sustainable Ecological Engineering: there could be a growing emphasis on developing sustainable and environmentally friendly technologies for electro-oxidative wastewater treatment. Researchers may explore the use of renewable energy sources, such as solar energy, to drive electrochemical processes, as well as the development of eco-friendly electrode materials.
- Data Analysis and Visualization Tools: continued advancements in bibliometric analysis tools, such as VOSviewer and CiteSpace, could enable researchers to gain deeper insights into research trends, collaboration networks, and emerging topics in the field. This could facilitate more informed decision-making and strategic planning for future research endeavors.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16103982/s1, Table S1. The results of the analysis of countries' contributions using CiteSpace; Table S2. The results of the analysis of countries' contributions using VOSviewer; Table S3. The results from analyzing the contributions of institutions using CiteSpace;

Table S4. Co-authorship and citations of authors in the field nanostructured electrooxidative technology; Table S5. Keyword network summary table; Figure S1. The journal co-citation network map; Figure S2. Co-authorship network map; Figure S3. Timeline map.

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References

1. Jagadeesh, N.; Sundaram, B. Adsorption of Pollutants from Wastewater by Biochar: A Review. *J. Hazard. Mater. Adv.* **2023**, *9*, 100226. [CrossRef]
2. Ajala, O.A.; Akinnawo, S.O.; Bamisaye, A.; Adedipe, D.T.; Adesina, M.O.; Okon-Akan, O.A.; Adebusuyi, T.A.; Ojedokun, A.T.; Adegoke, K.A.; Bello, O.S. Adsorptive Removal of Antibiotic Pollutants from Wastewater Using Biomass/Biochar-Based Adsorbents. *RSC Adv.* **2023**, *13*, 4678–4712. [CrossRef] [PubMed]
3. Karim, A.R.; Danish, M.; Alam, M.G.; Majeed, S.; Alanazi, A.M. A Review of Pre- and Post-Surface-Modified Neem (Azadirachta Indica) Biomass Adsorbent: Surface Functionalization Mechanism and Application. *Chemosphere* **2024**, *351*, 141180. [CrossRef] [PubMed]
4. Xia, Y.; Zuo, H.; Lv, J.; Wei, S.; Yao, Y.; Liu, Z.; Lin, Q.; Yu, Y.; Yu, W.; Huang, Y. Preparation of Multi-Layered Microcapsule-Shaped Activated Biomass Carbon with Ultrahigh Surface Area from Bamboo Parenchyma Cells for Energy Storage and Cationic Dyes Removal. *J. Clean. Prod.* **2023**, *396*, 136517. [CrossRef]
5. Mishra, S.; Sundaram, B. A Review of the Photocatalysis Process Used for Wastewater Treatment. *Mater. Today Proc.* **2023**. [CrossRef]
6. Wang, Z.; Wang, H.; Shi, P.; Qiu, J.; Guo, R.; You, J.; Zhang, H. Hybrid Organic Frameworks: Synthesis Strategies and Applications in Photocatalytic Wastewater Treatment—A Review. *Chemosphere* **2024**, *350*, 141143. [CrossRef] [PubMed]
7. Patra, R.; Dash, P.; Panda, P.K.; Yang, P.-C. A Breakthrough in Photocatalytic Wastewater Treatment: The Incredible Potential of g-C3N4/Titanate Perovskite-Based Nanocomposites. *Nanomaterials* **2023**, *13*, 2173. [CrossRef] [PubMed]
8. Mei, J.; Gao, X.; Zou, J.; Pang, F. Research on Photocatalytic Wastewater Treatment Reactors: Design, Optimization, and Evaluation Criteria. *Catalysts* **2023**, *13*, 974. [CrossRef]
9. Song, Q.; Chen, X.; Hua, Y.; Chen, S.; Ren, L.; Dai, X. Biological Treatment Processes for Saline Organic Wastewater and Related Inhibition Mechanisms and Facilitation Techniques: A Comprehensive Review. *Environ. Res.* **2023**, *239*. [CrossRef]
10. Ma, Z.; Chang, H.; Liang, Y.; Meng, Y.; Ren, L.; Liang, H. Research Progress and Trends on State-of-the-Art Membrane Technologies in Textile Wastewater Treatment. *Sep. Purif. Technol.* **2024**, *333*. [CrossRef]
11. Lin, H.; Zhang, M. Advanced Membrane Technologies for Wastewater Treatment and Recycling. *Membranes* **2023**, *13*, 558. [CrossRef] [PubMed]
12. Ma, R.; Li, J.; Zeng, P.; Duan, L.; Dong, J.; Ma, Y.; Yang, L. The Application of Membrane Separation Technology in the Pharmaceutical Industry. *Membranes* **2024**, *14*, 24. [CrossRef] [PubMed]
13. Sivodia, C.; Sinha, A. Assessment of Graphite Electrode on the Removal of Anticancer Drug Cytarabine via Indirect Electrochemical Oxidation Process: Kinetics & Pathway Study. *Chemosphere* **2020**, *243*, 125456. [CrossRef] [PubMed]
14. Ramalho, A.M.Z.; Martínez-Huitle, C.A.; da Silva, D.R. Application of Electrochemical Technology for Removing Petroleum Hydrocarbons from Produced Water Using a DSA-Type Anode at Different Flow Rates. *Fuel* **2010**, *89*, 531–534. [CrossRef]
15. Santos, I.D.; Dezotti, M.; Dutra, A.J.B. Electrochemical Treatment of Effluents from Petroleum Industry Using a Ti/RuO_2 Anode. *Chem. Eng. J.* **2013**, *226*, 293–299. [CrossRef]

16. Da Silva, R.G.; Neto, S.A.; De Andrade, A.R. Electrochemical Degradation of Reactive Dyes at Different DSA®Compositions. *J. Braz. Chem. Soc.* **2011**, *22*, 126–133. [CrossRef]
17. Panizza, M.; Cerisola, G. Applicability of Electrochemical Methods to Carwash Wastewaters for Reuse. Part 1: Anodic Oxidation with Diamond and Lead Dioxide Anodes. *J. Electroanal. Chem.* **2010**, *638*, 28–32. [CrossRef]
18. Martínez-Huitle, C.A.; De Battisti, A.; Ferro, S.; Reyna, S.; Cerro-López, M.; Quiro, M.A. Removal of the Pesticide Methamidophos from Aqueous Solutions by Electrooxidation Using Pb/PbO_2, Ti/SnO_2, and Si/BDD Electrodes. *Environ. Sci. Technol.* **2008**, *42*, 6929–6935. [CrossRef]
19. Ganiyu, S.O.; Oturan, N.; Raffy, S.; Cretin, M.; Esmilaire, R.; van Hullebusch, E.; Esposito, G.; Oturan, M.A. Sub-Stoichiometric Titanium Oxide (Ti_4O_7) as a Suitable Ceramic Anode for Electrooxidation of Organic Pollutants: A Case Study of Kinetics, Mineralization and Toxicity Assessment of Amoxicillin. *Water Res.* **2016**, *106*, 171–182. [CrossRef]
20. Zhang, J.; Huang, S.; Ning, P.; Xin, P.; Chen, Z.; Wang, Q.; Uvdal, K.; Hu, Z. Nested Hollow Architectures of Nitrogen-Doped Carbon-Decorated Fe, Co, Ni-Based Phosphides for Boosting Water and Urea Electrolysis. *Nano Res.* **2022**, *15*, 1916–1925. [CrossRef]
21. Pourzamani, H.; Mengelizadeh, N.; Hajizadeh, Y.; Mohammadi, H. Electrochemical Degradation of Diclofenac Using Three-Dimensional Electrode Reactor with Multi-Walled Carbon Nanotubes. *Environ. Sci. Pollut. Res.* **2018**, *25*, 24746–24763. [CrossRef] [PubMed]
22. Ghanbarlou, H.; Pedersen, N.L.; Simonsen, M.E.; Muff, J. Nitrogen-Doped Graphene Iron-Based Particle Electrode Outperforms Activated Carbon in Three-Dimensional Electrochemical Water Treatment Systems. *Water* **2020**, *12*, 3121. [CrossRef]
23. Daghrir, R.; Drogui, P.; Tshibangu, J.; Delegan, N.; El Khakani, M.A. Electrochemical Treatment of Domestic Wastewater Using Boron-Doped Diamond and Nanostructured Amorphous Carbon Electrodes. *Environ. Sci. Pollut. Res.* **2014**, *21*, 6578–6589. [CrossRef] [PubMed]
24. Zhang, Q.; Kazim, F.M.; Ma, S.; Qu, K.; Li, M.; Wang, Y.; Hu, H.; Cai, W.; Yang, Z. Nitrogen Dopants in Nickel Nanoparticles Embedded Carbon Nanotubes Promote Overall Urea Oxidation. *Appl. Catal. B Environ.* **2021**, *280*, 119436. [CrossRef]
25. Xu, Z.; Liu, H.; Niu, J.; Zhou, Y.; Wang, C.; Wang, Y. Hydroxyl Multi-Walled Carbon Nanotube-Modified Nanocrystalline PbO_2 Anode for Removal of Pyridine from Wastewater. *J. Hazard. Mater.* **2017**, *327*, 144–152. [CrossRef] [PubMed]
26. Duan, P.; Gao, S.; Li, X.; Sun, Z.; Hu, X. Preparation of CeO_2-ZrO_2 and Titanium Dioxide Coated Carbon Nanotube Electrode for Electrochemical Degradation of Ceftazidime from Aqueous Solution. *J. Electroanal. Chem.* **2019**, *841*, 10–20. [CrossRef]
27. Chang, L.; Zhou, Y.; Duan, X.; Liu, W.; Xu, D. Preparation and Characterization of Carbon Nanotube and Bi Co-Doped PbO_2 Electrode. *J. Taiwan Inst. Chem. Eng.* **2014**, *45*, 1338–1346. [CrossRef]
28. Sun, Z.; Ni, Y.; Wu, Y.; Yue, W.; Zhang, G.; Bai, J. Electrocatalytic Degradation of Methyl Orange and 4-Nitrophenol on a Ti/TiO_2-NTA/La-PbO_2 Electrode: Electrode Characterization and Operating Parameters. *Environ. Sci. Pollut. Res.* **2023**, *30*, 6262–6274. [CrossRef] [PubMed]
29. Pourzamani, H.; Hajizadeh, Y.; Mengelizadeh, N. Application of Three-Dimensional Electrofenton Process Using MWCNTs-Fe_3O_4 Nanocomposite for Removal of Diclofenac. *Process Saf. Environ. Prot.* **2018**, *119*, 271–284. [CrossRef]
30. Savić, B.G.; Stanković, D.M.; Živković, S.M.; Ognjanović, M.R.; Tasić, G.S.; Mihajlović, I.J.; Brdarić, T.P. Electrochemical Oxidation of a Complex Mixture of Phenolic Compounds in the Base Media Using PbO_2-GNRs Anodes. *Appl. Surf. Sci.* **2020**, *529*, 147120. [CrossRef]
31. Zhao, G.; Cui, X.; Liu, M.; Li, P.; Zhang, Y.; Cao, T.; Li, H.; Lei, Y.; Liu, L.; Li, D. Electrochemical Degradation of Refractory Pollutant Using a Novel Microstructured TiO_2 Nanotubes/Sb-Doped SnO_2 Electrode. *Environ. Sci. Technol.* **2009**, *43*, 1480–1486. [CrossRef]
32. Yu, S.; Hao, C.; Li, Z.; Zhang, R.; Dang, Y.; Zhu, J.J. Promoting the Electrocatalytic Performance of PbO_2 Nanocrystals via Incorporation of Y_2O_3 Nanoparticles: Degradation Application and Electrocatalytic Mechanism. *Electrochim. Acta* **2021**, *369*, 137671. [CrossRef]
33. Li, Q.; Zhang, Q.; Cui, H.; Ding, L.; Wei, Z.; Zhai, J. Fabrication of Cerium-Doped Lead Dioxide Anode with Improved Electrocatalytic Activity and Its Application for Removal of Rhodamine B. *Chem. Eng. J.* **2013**, *228*, 806–814. [CrossRef]
34. Sreekanth, T.V.M.; Prasad, K.; Yoo, J.; Kim, J.; Yoo, K. CuO-SnO_2 Nanocomposites: Efficient and Cost-Effective Electrocatalysts for Urea Oxidation. *Mater. Lett.* **2023**, *353*, 10–13. [CrossRef]
35. Li, D.; Tang, J.; Zhou, X.; Li, J.; Sun, X.; Shen, J.; Wang, L.; Han, W. Electrochemical Degradation of Pyridine by Ti/SnO_2-Sb Tubular Porous Electrode. *Chemosphere* **2016**, *149*, 49–56. [CrossRef] [PubMed]
36. Wang, H.; Lu, L.; Subramanian, P.; Ji, S.; Kannan, P. Co, Fe-Ions Intercalated $Ni(OH)_2$ Network-like Nanosheet Arrays as Highly Efficient Non-Noble Catalyst for Electro-Oxidation of Urea. *Int. J. Hydrogen Energy* **2021**, *46*, 34318–34332. [CrossRef]
37. Ðuričić, T.; Prosen, H.; Kravos, A.; Mićin, S.; Kalčíková, G.; Malinović, B.N. Electrooxidation of Phenol on Boron-Doped Diamond and Mixed-Metal Oxide Anodes: Process Evaluation, Transformation By-Products, and Ecotoxicity. *J. Electrochem. Soc.* **2023**, *170*, 023503. [CrossRef]
38. Audino, F.; Arboleda, J.; Petrovic, M.; Cudinach, R.G.; Pérez, S.S. Pharmaceuticals Removal by Ozone and Electro-Oxidation in Combination with Biological Treatment. *Water* **2023**, *15*, 3180. [CrossRef]
39. Vinayagam, V.; Palani, K.N.; Ganesh, S.; Rajesh, S.; Akula, V.V.; Avoodaiappan, R.; Kushwaha, O.S.; Pugazhendhi, A. Recent Developments on Advanced Oxidation Processes for Degradation of Pollutants from Wastewater with Focus on Antibiotics and Organic Dyes. *Environ. Res.* **2024**, *240*, 117500. [CrossRef] [PubMed]

40. Rajoria, S.; Vashishtha, M.; Sangal, V.K. Electroplating Wastewater Treatment by Electro-Oxidation Using Synthesized New Electrode: Experimental, Optimization, Kinetics, and Cost Analysis. *Process Saf. Environ. Prot.* **2024**, *183*, 735–756. [CrossRef]
41. Magdaleno, A.L.; Brillas, E.; Garcia-Segura, S.; dos Santos, A.J. Comparison of Electrochemical Advanced Oxidation Processes for the Treatment of Complex Synthetic Dye Mixtures. *Sep. Purif. Technol.* **2024**, *345*, 127295. [CrossRef]
42. Simić, M.D.; Savić, B.G.; Ognjanović, M.R.; Stanković, D.M.; Relić, D.J.; Aćimović, D.D.; Brdarić, T.P. Degradation of Bisphenol A on SnO_2-MWCNT Electrode Using Electrochemical Oxidation. *J. Water Process Eng.* **2023**, *51*, 103416. [CrossRef]
43. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to Conduct a Bibliometric Analysis: An Overview and Guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [CrossRef]
44. Mao, G.; Hu, H.; Liu, X.; Crittenden, J.; Huang, N. A Bibliometric Analysis of Industrial Wastewater Treatments from 1998 to 2019. *Environ. Pollut.* **2021**, *275*, 115785. [CrossRef] [PubMed]
45. Ding, M.; Zeng, H. A Bibliometric Analysis of Research Progress in Sulfate-Rich Wastewater Pollution Control Technology. *Ecotoxicol. Environ. Saf.* **2022**, *238*, 113626. [CrossRef] [PubMed]
46. Wang, L.; Luo, D.; Hamdaoui, O.; Vasseghian, Y.; Momotko, M.; Boczkaj, G.; Kyzas, G.Z.; Wang, C. Bibliometric Analysis and Literature Review of Ultrasound-Assisted Degradation of Organic Pollutants. *Sci. Total Environ.* **2023**, *876*, 162551. [CrossRef] [PubMed]
47. Jiang, H.; Chen, H.; Duan, Z.; Huang, Z.; Wei, K. Research Progress and Trends of Biochar in the Field of Wastewater Treatment by Electrochemical Advanced Oxidation Processes (EAOPs): A Bibliometric Analysis. *J. Hazard. Mater. Adv.* **2023**, *10*, 100305. [CrossRef]
48. Usman, M.; Ho, Y.-S. A Bibliometric Study of the Fenton Oxidation for Soil and Water Remediation. *J. Environ. Manag.* **2020**, *270*, 110886. [CrossRef] [PubMed]
49. Panizza, M.; Cerisola, G. Direct And Mediated Anodic Oxidation of Organic Pollutants. *Chem. Rev.* **2009**, *109*, 6541–6569. [CrossRef] [PubMed]
50. Martínez-Huitle, C.A.; Ferro, S. Electrochemical Oxidation of Organic Pollutants for the Wastewater Treatment: Direct and Indirect Processes. *Chem. Soc. Rev.* **2006**, *35*, 1324–1340. [CrossRef] [PubMed]
51. Zhang, L.; Xu, L.; He, J.; Zhang, J. Preparation of Ti/SnO_2-Sb Electrodes Modified by Carbon Nanotube for Anodic Oxidation of Dye Wastewater and Combination with Nanofiltration. *Electrochim. Acta* **2014**, *117*, 192–201. [CrossRef]
52. Boggs, B.K.; King, R.L.; Botte, G.G. Urea Electrolysis: Direct Hydrogen Production from Urine. *Chem. Commun.* **2009**, 4859. [CrossRef] [PubMed]
53. Vedharathinam, V.; Botte, G.G. Understanding the Electro-Catalytic Oxidation Mechanism of Urea on Nickel Electrodes in Alkaline Medium. *Electrochim. Acta* **2012**, *81*, 292–300. [CrossRef]
54. Zhou, M.; Dai, Q.; Lei, L.; Ma, C.A.; Wang, D. Long life modified lead dioxide anode for organic wastewater treatment: Electrochemical characteristics and degradation mechanism. *Environ. Sci. Technol.* **2005**, *39*, 363–370. [CrossRef]
55. Brillas, E.; Martínez-Huitle, C.A. Decontamination of wastewaters containing synthetic organic dyes by electrochemical methods. An updated review. *Appl. Catal. B:Environ.* **2015**, *166*, 603–643. [CrossRef]
56. Brillas, E.; Sirés, I.; Oturan, M.A. Electro-Fenton process and related electrochemical technologies based on Fenton's reaction chemistry. *Chem.Rev.* **2009**, *109*, 6570–6631. [CrossRef] [PubMed]
57. Sayed, E.T.; Eisa, T.; Mohamed, H.O.; Abdelkareem, M.A.; Allagui, A.; Alawadhi, H.; Chae, K.J. Direct urea fuel cells: Challenges and opportunities. *J. Power Sources* **2019**, *417*, 159–175. [CrossRef]
58. Jiang, M.; Qi, Y.; Liu, H.; Chen, Y. The Role of Nanomaterials and Nanotechnologies in Wastewater Treatment: A Bibliometric Analysis. *Nanoscale Res. Lett.* **2018**, *13*, 233. [CrossRef] [PubMed]
59. Babuponnusami, A.; Muthukumar, K. A Review on Fenton and Improvements to the Fenton Process for Wastewater Treatment. *J. Environ. Chem. Eng.* **2014**, *2*, 557–572. [CrossRef]
60. Rashid, R.; Shafiq, I.; Akhter, P.; Iqbal, M.J.; Hussain, M. A State-of-the-Art Review on Wastewater Treatment Techniques: The Effectiveness of Adsorption Method. *Environ. Sci. Pollut. Res.* **2021**, *28*, 9050–9066. [CrossRef] [PubMed]
61. Ding, R.; Qi, L.; Jia, M.; Wang, H. Facile Synthesis of Mesoporous Spinel $NiCo_2O_4$ Nanostructures as Highly Efficient Electrocatalysts for Urea Electro-Oxidation. *Nanoscale* **2014**, *6*, 1369–1376. [CrossRef]
62. Liu, Z.; Zhang, C.; Liu, H.; Feng, L. Efficient Synergism of $NiSe_2$ Nanoparticle/NiO Nanosheet for Energy-Relevant Water and Urea Electrocatalysis. *Appl. Catal. B Environ.* **2020**, *276*, 119165. [CrossRef]
63. Forslund, R.P.; Mefford, J.T.; Hardin, W.G.; Alexander, C.T.; Johnston, K.P.; Stevenson, K.J. Nanostructured $LaNiO_3$ Perovskite Electrocatalyst for Enhanced Urea Oxidation. *ACS Catal.* **2016**, *6*, 5044–5051. [CrossRef]
64. Xie, J.; Qu, H.; Lei, F.; Peng, X.; Liu, W.; Gao, L.; Hao, P.; Cui, G.; Tang, B. Partially Amorphous Nickel–Iron Layered Double Hydroxide Nanosheet Arrays for Robust Bifunctional Electrocatalysis. *J. Mater. Chem. A* **2018**, *6*, 16121–16129. [CrossRef]
65. Liang, Y.; Liu, Q.; Asiri, A.M.; Sun, X. Enhanced Electrooxidation of Urea Using $NiMoO_4 \cdot xH_2O$ Nanosheet Arrays on Ni Foam as Anode. *Electrochim. Acta* **2015**, *153*, 456–460. [CrossRef]
66. Yan, W.; Wang, D.; Diaz, L.A.; Botte, G.G. Nickel Nanowires as Effective Catalysts for Urea Electro-Oxidation. *Electrochim. Acta* **2014**, *134*, 266–271. [CrossRef]
67. Sha, L.; Yin, J.; Ye, K.; Wang, G.; Zhu, K.; Cheng, K.; Yan, J.; Wang, G.; Cao, D. The Construction of Self-Supported Thorny Leaf-like Nickel-Cobalt Bimetal Phosphides as Efficient Bifunctional Electrocatalysts for Urea Electrolysis. *J. Mater. Chem. A* **2019**, *7*, 9078–9085. [CrossRef]

68. Duan, X.; Zhao, C.; Liu, W.; Zhao, X.; Chang, L. Fabrication of a Novel PbO_2 Electrode with a Graphene Nanosheet Interlayer for Electrochemical Oxidation of 2-Chlorophenol. *Electrochim. Acta* **2017**, *240*, 424–436. [CrossRef]
69. Dai, J.; Feng, H.; Shi, K.; Ma, X.; Yan, Y.; Ye, L.; Xia, Y. Electrochemical Degradation of Antibiotic Enoxacin Using a Novel PbO_2 Electrode with a Graphene Nanoplatelets Inter-Layer: Characteristics, Efficiency and Mechanism. *Chemosphere* **2022**, *307*, 135833. [CrossRef]
70. Jiang, Y.; Hu, Z.; Zhou, M.; Zhou, L.; Xi, B. Efficient Degradation of P-Nitrophenol by Electro-Oxidation on Fe Doped Ti/TiO_2 Nanotube/PbO_2 Anode. *Sep. Purif. Technol.* **2014**, *128*, 67–71. [CrossRef]
71. Xu, M.; Wang, Z.; Wang, F.; Hong, P.; Wang, C.; Ouyang, X.; Zhu, C.; Wei, Y.; Hun, Y.; Fang, W. Fabrication of Cerium Doped Ti/NanoTiO_2/PbO_2 Electrode with Improved Electrocatalytic Activity and Its Application in Organic Degradation. *Electrochim. Acta* **2016**, *201*, 240–250. [CrossRef]
72. Yang, C.; Shang, S.; Li, X. Fabrication of Sulfur-Doped TiO_2 Nanotube Array as a Conductive Interlayer of PbO_2 Anode for Efficient Electrochemical Oxidation of Organic Pollutants. *Sep. Purif. Technol.* **2021**, *258*, 118035. [CrossRef]
73. Gao, G.; Pan, M.; Vecitis, C.D. Effect of the Oxidation Approach on Carbon Nanotube Surface Functional Groups and Electrooxidative Filtration Performance. *J. Mater. Chem. A* **2015**, *3*, 7575–7582. [CrossRef]
74. Xu, W.; Lan, R.; Du, D.; Humphreys, J.; Walker, M.; Wu, Z.; Wang, H.; Tao, S. Directly Growing Hierarchical Nickel-Copper Hydroxide Nanowires on Carbon Fibre Cloth for Efficient Electrooxidation of Ammonia. *Appl. Catal. B Environ.* **2017**, *218*, 470–479. [CrossRef]
75. Luo, M.; Yuan, S.; Tong, M.; Liao, P.; Xie, W.; Xu, X. An Integrated Catalyst of Pd Supported on Magnetic Fe_3O_4 Nanoparticles: Simultaneous Production of H_2O_2 and Fe^{2+} for Efficient Electro-Fenton Degradation of Organic Contaminants. *Water Res.* **2014**, *48*, 190–199. [CrossRef] [PubMed]
76. Yu, Z.Y.; Lang, C.C.; Gao, M.R.; Chen, Y.; Fu, Q.Q.; Duan, Y.; Yu, S.H. Ni-Mo-O Nanorod-Derived Composite Catalysts for Efficient Alkaline Water-to-Hydrogen Conversion: Via Urea Electrolysis. *Energy Environ. Sci.* **2018**, *11*, 1890–1897. [CrossRef]
77. Wu, W.; Huang, Z.H.; Lim, T.T. Recent Development of Mixed Metal Oxide Anodes for Electrochemical Oxidation of Organic Pollutants in Water. *Appl. Catal. A Gen.* **2014**, *480*, 58–78. [CrossRef]
78. Xie, R.; Meng, X.; Sun, P.; Niu, J.; Jiang, W.; Bottomley, L.; Li, D.; Chen, Y.; Crittenden, J. Electrochemical Oxidation of Ofloxacin Using a TiO_2-Based SnO_2-Sb/Polytetrafluoroethylene Resin-PbO_2 Electrode: Reaction Kinetics and Mass Transfer Impact. *Appl. Catal. B Environ.* **2017**, *203*, 515–525. [CrossRef]
79. Cheng, Y.; Liao, F.; Dong, H.; Wei, H.; Geng, H.; Shao, M. Engineering CoN/$Ni(OH)_2$ Heterostructures with Improved Intrinsic Interfacial Charge Transfer toward Simultaneous Hydrogen Generation and Urea-Rich Wastewater Purification. *J. Power Sources* **2020**, *480*, 229151. [CrossRef]
80. Yan, X.; Hu, Q.-T.; Wang, G.; Zhang, W.-D.; Liu, J.; Li, T.; Gu, Z.-G. NiCo Layered Double Hydroxide/Hydroxide Nanosheet Heterostructures for Highly Efficient Electro-Oxidation of Urea. *Int. J. Hydrogen Energy* **2020**, *45*, 19206–19213. [CrossRef]
81. Wei, D.; Tang, W.; Ma, N.; Wang, Y. NiCo Bimetal Organic Frames Derived Well-Matched Electrocatalyst Pair for Highly Efficient Overall Urea Solution Electrolysis. *J. Alloys Compd.* **2021**, *874*, 159945. [CrossRef]
82. Xu, Q.; Qian, G.; Yin, S.; Yu, C.; Chen, W.; Yu, T.; Luo, L.; Xia, Y.; Tsiakaras, P. Design and Synthesis of Highly Performing Bifunctional Ni-NiO-MoNi Hybrid Catalysts for Enhanced Urea Oxidation and Hydrogen Evolution Reactions. *ACS Sustain. Chem. Eng.* **2020**, *8*, 7174–7181. [CrossRef]
83. He, M.; Hu, S.; Feng, C.; Wu, H.; Liu, H.; Mei, H. Interlaced Rosette-like MoS_2/Ni_3S_2/NiFe-LDH Grown on Nickel Foam: A Bifunctional Electrocatalyst for Hydrogen Production by Urea-Assisted Electrolysis. *Int. J. Hydrogen Energy* **2020**, *45*, 23–35. [CrossRef]
84. Wang, Y.; Liu, G. Reduced Graphene Oxide Supported Nickel Tungstate Nano-Composite Electrocatalyst for Anodic Urea Oxidation Reaction in Direct Urea Fuel Cell. *Int. J. Hydrogen Energy* **2020**, *45*, 33500–33511. [CrossRef]
85. Gopi, S.; Al-Mohaimeed, A.M.; Elshikh, M.S.; Yun, K. Facile Fabrication of Bifunctional SnO–NiO Heteromixture for Efficient Electrocatalytic Urea and Water Oxidation in Urea-Rich Waste Water. *Environ. Res.* **2021**, *201*, 111589. [CrossRef]
86. Qian, G.; Chen, J.; Luo, L.; Zhang, H.; Chen, W.; Gao, Z.; Yin, S.; Tsiakaras, P. Novel Bifunctional V_2O_3 Nanosheets Coupled with N-Doped-Carbon Encapsulated Ni Heterostructure for Enhanced Electrocatalytic Oxidation of Urea-Rich Wastewater. *ACS Appl. Mater. Interfaces* **2020**, *12*, 38061–38069. [CrossRef]
87. El Aggadi, S.; Kerroum, Y.; El Hourch, A. Elaboration and Characterization of Fe/C-Doped Lead Dioxide-Modified Anodes for Electrocatalytic Degradation of Reactive Yellow 14. *J. Appl. Electrochem.* **2023**, *53*, 109–119. [CrossRef]
88. Zhong, C.; Wei, K.; Han, W.; Wang, L.; Sun, X.; Li, J. Electrochemical Degradation of Tricyclazole in Aqueous Solution Using Ti/SnO_2-Sb/PbO_2 Anode. *J. Electroanal. Chem.* **2013**, *705*, 68–74. [CrossRef]
89. Wen-wu, L.; Xiu-ping, W.; Xue-yan, T.; Chang-yong, W. Treatment of Pretreated Coking Wastewater by Flocculation, Alkali out, Air Stripping, and Three-Dimensional Electrocatalytic Oxidation with Parallel Plate Electrodes. *Environ. Sci. Pollut. Res.* **2014**, *21*, 11457–11468. [CrossRef]
90. Sharan, S.; Khare, P.; Shankar, R.; Tyagi, A.; Khare, A. Development of 3D Network of Zn-Oxide Nanorods Assisted with PbO_2/Pb Electrode for Electrochemical Oxidation of Methylene Blue in Aqueous Phase. *J. Taiwan Inst. Chem. Eng.* **2023**, *144*, 104739. [CrossRef]
91. Rollinson, A.N.; Jones, J.; Dupont, V.; Twigg, M.V. Urea as a Hydrogen Carrier: A Perspective on Its Potential for Safe, Sustainable and Long-Term Energy Supply. *Energy Environ. Sci.* **2011**, *4*, 1216. [CrossRef]

92. Urbańczyk, E.; Sowa, M.; Simka, W. Urea Removal from Aqueous Solutions—A Review. *J. Appl. Electrochem.* **2016**, *46*, 1011–1029. [CrossRef]
93. Aćimović, D.; Vasić Anićijević, D. Electrooxidative Removal of Organophosphates—A Combined Experimental and Theoretical Approach. In *Organophosphates: Detection, Exposure and Occurrence. Volume 1: Impact on Health and the Natural Environment*; Lazarević-Pašti, T., Ed.; Nova Science Publishers: New York, NY, USA, 2022; Volume 1, pp. 215–250. ISBN 9781685076528.
94. Han, Q.; Wang, M.; Sun, F.; Yu, B.; Dong, Z.; Li, P.; Luo, J.; Li, M.; Jin, X.; Dai, Z. Effectiveness and Degradation Pathways of Bisphenol A (BPA) Initiated by Hydroxyl Radicals and Sulfate Radicals in Water: Initial Reaction Sites Based on DFT Prediction. *Environ. Res.* **2023**, *216*. [CrossRef] [PubMed]
95. Biswas, B.; Goel, S. Electrocoagulation and Electrooxidation Technologies for Pesticide Removal from Water or Wastewater: A Review. *Chemosphere* **2022**, *302*, 134709. [CrossRef] [PubMed]
96. Li, J.; Wang, H.; Reddy, N.; Zhu, Z.; Zheng, J.; Wang, W.; Liu, B.; Hu, C. MOFFeCo/B-CN Composites Achieve Efficient Degradation of Antibiotics in a Non-Homogeneous Concurrent Photocatalytic-Persulfate Activation System. *Sci. Total Environ.* **2023**, *858*, 159795. [CrossRef] [PubMed]
97. Xiao, H.; Xu, F.; Chen, J.; Hao, Y.; Guo, Y.; Zhu, C.; Luo, S.; Jiang, B. Electrogenerated Oxychlorides Induced Overlooked Negative Effects on Electro-Oxidation Wastewater Treatment in Terms of over-Evaluated COD Removal Efficiency and Biotoxicity. *J. Hazard. Mater.* **2023**, *456*, 131667. [CrossRef] [PubMed]
98. Ječmenica Dučić, M.; Krstić, A.; Zdolšek, N.; Aćimović, D.; Savić, B.; Brdarić, T.; Vasić Anićijević, D. Low-Cost Graphene-Based Composite Electrodes for Electrochemical Oxidation of Phenolic Dyes. *Crystals* **2023**, *13*, 125. [CrossRef]