Bibliometric Analysis of Global Research Progress on Electrochemical Degradation of Organic Pollutants

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Research Article

Keywords: Electrochemical oxidation, Organic contaminants, Electrode materials, Bibliometric study, Scientific production, Environment pollution.

Posted Date: October 19th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-926153/v1>

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Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on March 19th, 2022. See the published version at <https://doi.org/10.1007/s11356-022-19534-y>.

Abstract

As a result of anthropogenic action, an increasing amount of toxic organic compounds has been released into the environment. These pollutants have adverse effects on human health and wildlife, which has motivated the development of different types of technologies for the treatment of effluents and contaminated environments. The electrochemical degradation of organic pollutants has attracted the interest of research centers around the world for its environmental compatibility, high efficiency and affordable cost. In the present study, a bibliometric analysis was performed using the Web of Science database in order to assess the progress of publications related to electrochemical degradation of organic pollutants between the years 2001 and 2021. The data retrieved showed a significant increase in publications related to the topic in the last 20 years. *Electrochimica Acta* was the magazine responsible for the largest number of publications (230, 7.22%). The studies mainly included the areas of chemistry, engineering and electrochemistry. China with a total of 1004 (31.49%) publications dominated research in this area, followed by Spain (282, 8.85%) and Brazil (255, 8.00%). The institutions with the highest number of contributions were the University of Castilla-la Mancha and the Chinese Academy of Sciences, and the most productive authors were Rodrigo MA and Martines-Huitle CA. The results of this study provide important references and information on possible research directions for future investigations on electrochemical degradation of organic pollutants.

Introduction

The expansion of industry and agricultural production, together with the accelerated population growth, led the world to a critical scenario regarding the presence of organic pollutants in the environment. These contaminants include pesticides, pharmaceuticals, personal care products, endocrine disruptors, dyes, aromatic and phenolic compounds (Lu and Astruc 2020). Many of these substances represent a risk to ecosystems and human health due to their high toxicity (Alharbi et al. 2018). Thus, the development of efficient and economically viable technologies for the degradation of these pollutants becomes urgent.

Recently, many efforts have been made to develop technologies for removing organic pollutants. The techniques commonly employed involve physical adsorption (Zhang et al. 2021), biological degradation (Cheng et al. 2021), photocatalysis (Matora et al. 2021) and advanced oxidation processes (Ma et al. 2021). Among these techniques, electrochemical oxidation or anodic oxidation has stood out for its environmental compatibility, high efficiency, affordable cost, simple automation and ability to degrade a wide variety of pollutants (Clematis and Panizza 2021; Jiang et al. 2021).

The electrochemical oxidation of organic compounds can occur through two different ways: direct anodic oxidation and indirect oxidation. In the case of direct oxidation, the transfer of charges between the anodic surface and the compound to be oxidized takes place directly without the involvement of other substances. In indirect oxidation, the electrochemical generation of oxidizing species occurs, which act as intermediaries for charge transfer between the anode and the organic compound (Martínez-Huitle and Panizza 2018). The choice of the process to be used depends on the characteristics of the anode material and operating conditions. The electrode materials used have a fundamental influence on the efficiency and selectivity of the anodic oxidation process. Thus, in recent years, many studies have focused on the preparation and application of different types of anodic materials for use in electro-oxidation processes of organic pollutants, among which Pt, metallic oxides (RuO_2 , IrO_2 , PbO_2 , SnO_2 , etc.) and carbon-based materials (He et al. 2019).

Some high-quality reviews have recently evaluated electrochemical oxidation processes for degradation of organic compounds (Clematis and Panizza 2021; Garcia-Segura et al. 2018; Hu et al. 2021; Jiang et al. 2021; Titchou et al. 2021). However, these reviews were not dedicated to analyzing the topic from a bibliometric perspective. Over the years, bibliometrics has become a popular means to classify bibliographic data and create representative summaries of the results obtained, this was driven by the rapid evolution of computers and the internet that allow for great ease in accessing and analyzing data (Cancino et al. 2017). Bibliometric analysis is a method used to analyze large amounts of scientific data. Through mathematical and statistical techniques, it allows you to follow the progress of publications on a given topic and simultaneously identify global trends and gaps in a research area. This provides researchers and organizations with guidance regarding the needs and objectives of future research (Donthu et al. 2021; Zhao et al. 2020).

In the present study, a bibliometric analysis of scientific publications on the electrochemical degradation of organic pollutants was carried out. The main objectives of this bibliometric analysis were: (1) Evaluate the advances in the research of different materials used as catalysts; (2) Analyze the historical and current growth of literature related to electrochemical degradation of organic pollutants; (3) Identify the main countries, authors and journals that contribute to the advancement of the theme. This document contributes to the field of research concerning the electro-oxidation of organic pollutants in many respects, as it provides researchers with an understanding of the current state of research and development on the topic, helps to identify the authors, institutions and countries with the greatest potential for conduct and share research on degradation of organic pollutants. Furthermore, it allows researchers to be more aware of the main challenges in this area of research when making decisions about which topics will be studied.

Methodology

The main collection of the Web of Science (WoS) database was used to retrieve scientific publications related to the topic. The Web of Science is one of the most trusted and widely used bibliographic databases for bibliometric analysis (Singh et al. 2021), offering comprehensive coverage of excellent publications in general academic fields, ease of access, and advanced search and filtering features. The Web of Science database was chosen because, compared to other databases, it had the highest number of publications on the subject. The following keywords were used, in English, in the aforementioned database, related to the electrochemical degradation of organic pollutants: ("electrochemical degradation" OR "electrochemical oxidation" OR "electrocatalytic oxidation" OR "anodic oxidation") AND ("organic pollutants" OR "volatile organic compounds" OR PAH OR pesticides OR phenol*). The search was carried out on August 9, 2021, applying a chronological filter considering the publications in the timeframe of 2001 and 2021. Only publications in the English language were searched, the search field was limited to "title", "abstract" and "keyword". VOSviewer 1.6.17 software was used for analysis of cooperation networks and keyword co-occurrences.

Results

Annual publications and growth trend

The search carried out in the Web of Science obtained a total of 3188 publications on the electro-oxidation of organic pollutants with an average of 31.8 citations per document. Among these, the majority were research articles (2946, 92.41%) followed by event proceedings (214, 6.71%), reviews (147, 4.61%), early access (15,

0.471%), meeting summaries (5, 0.157%), book Chaps. (2, 0.063%), editorials (1, 0.031%) and retraction publication (1, 0.031%). As can be seen in Fig. 1, during the period evaluated there was a growing interest in research related to the electrochemical degradation of organic pollutants, initially with 55 publications in 2001 up to a significant number of 308 scientific studies published on the subject in 2020, which corresponds to an average growth rate of 9.30%. In general, few exceptions to this growth trend were observed, specifically in the years 2006, 2010 and 2016 the number of publications was lower compared to previous years. In the year 2021, up to the time of data research (August/09/2021), 156 studies on the subject had already been published. To assess the correlation between the number of documents and the year (data from 2021 were not included) the polynomial model was applied. A good fit of the polynomial curve to the increasing trend of publications was observed and a high coefficient of determination was obtained ($R^2 = 0.9681$). This result suggests that in the coming years, annual publications on this topic will continue to grow. The continued interest in the electrochemical degradation of organic contaminants, indicated by the increase in the number of publications, can be attributed to different factors, such as: population growth and high demand; commitment to reduce environmental contamination; and importance of electrochemical methods as effective tools for removing organic pollutants.

Analysis of publications by subject area and source

The electrochemical degradation of organic pollutants included 51 thematic areas of the Web of Science. As shown in Fig. 2, the analysis of the results showed that the recovered documents mainly belonged to the chemistry area (1133, 35.54%). In the recovered literature, the areas of engineering (1045, 32.78%), electrochemistry (840, 26.35%), environmental sciences and ecology (793, 24.88%), and materials science (320, 10.04%) also stand out. Due to the assignment of journals to different subject categories, the total percentage of research areas is greater than 100%.

In total, 595 journals participated in research publications on electrochemical degradation of organic pollutants. Table 1 shows the 15 sources with the highest number of publications, representing 42.91% of all publications. The journal with the most publications was *Electrochimica Acta* (230, 7.22%), followed by *Chemosphere* (141, 4.42%), *Journal of Hazardous Materials* (141, 4.42%), *Journal of Electroanalytical Chemistry* (122, 3.83%) and *Chemical Engineering Journal* (107, 3.36%). The list of the top 15 sources includes six journals in the field of electrochemistry, while the remaining journals are in the areas of environmental chemistry, environmental science, catalysis, chemical engineering and hydrology. Six of the leading journals are from the Netherlands, four from the UK, two from the USA and Germany, respectively, and one from Serbia. Furthermore, it is important to mention that among the journals on the list, 8 have an impact factor greater than 6.000, of which *Applied Catalysis B Environmental* has the highest impact factor (19.503).

Analysis of publications by country

A total of 93 different countries participated in research publications on the electrochemical degradation of organic pollutants. The geographic distribution of the retrieved documents is shown in Fig. 3, and the fifteen countries with the highest research production and the highest number of citations are shown in Table 2. In the period evaluated, China is notably the country with the highest number of publications (1004, 31.49%), followed by Spain (282, 8.85%), Brazil (255, 8.00%), India (192, 6.02%) and USA (189, 5.93%), which complete the top five. When evaluating the number of citations by country, some changes in ranking are observed. Among the top five, China ($n = 26398$) and Spain ($n = 18497$) still occupy the top two positions, however, Italy ($n = 14288$) and France

(n = 10276) appear, respectively, as third and fourth place, followed by Brazil (n = 7901). Switzerland, which occupies the seventh position in relation to the total number of citations (n = 4978), has the highest average of citations per document (146.41).

Academic cooperation between countries and institutions is a very important practice for the production and dissemination of scientific knowledge. Figure 4 shows the academic collaboration network among the 30 most productive countries. In this figure the nodes represent the different countries, the lines connecting the nodes indicate cooperation between countries, and the line thickness is proportional to the strength of the cooperation. China is the country with the highest number of publications in collaboration with other countries (n = 149), followed by Spain (n = 143), France (n = 107), USA (n = 105) and Brazil (n = 87). Despite occupying the first position, only 14.84% of all publications in China were in collaboration with other countries, which corresponds to the lowest rate among highly productive countries. For example, France cooperated with other countries in 65.24% of its publications, for the USA this percentage was 55.56%, for Italy 50.96% and for Spain 50.70%. Therefore, it is important that China, which is the country with the most research in the area of electrochemical degradation of organic pollutants, intensify its academic cooperation with other countries. The analysis of academic cooperation also revealed that the USA has the most diverse collaboration network, having collaborated on publications with 41 different countries. In this aspect, also stand out Spain (37), Italy (31), France (30) and China (29). Spain and Brazil are the countries that most cooperate with each other (46 publications), besides them an intense academic cooperation was verified between China and the USA (41 publications).

Analysis of publications by institutions and authors

Figure 5 shows the 20 institutions with the most publications between 2001 and 2021. A total of 1947 institutions contributed to the 3188 publications retrieved. The most productive institution was the Universidad de Castilla-La Mancha, which published 91 documents, followed by the Chinese Academy of Sciences (89), the Center National de la Recherche Scientifique CNRS (77), the University of São Paulo (70) and the Federal University of Rio Grande do Norte (69). In addition, 5 of the 15 most productive institutions were from China, the other 10 institutions are spread across 6 countries.

The authors with the most publications on electrochemical degradation of organic pollutants are shown in Table 3. A total of 8017 researchers participated in publications on the subject between 2001 and 2021. Researcher Rodrigo MA appears with the highest number of publications (92, 2.886%), followed by Martinez-Huitle CA (78, 2.447%), Canizares P (74, 2.321%), Oturan MA (69, 2.164%), Saez C (64, 2.008%). Another important parameter to be considered is the number of citations, in this case Panizza M leads the list with a total number of 7860 citations, Rodrigo MA was the second with the most citations (7139), followed by Oturan MA, Brillas E and Cerisola G who had a total of 7041, 6184 and 5834 citations, respectively.

Most cited publications

Table 4 shows the most cited publications on electrochemical degradation of organic pollutants. Among the 10 most cited publications there are 9 review articles and only 1 research article. Spain and Italy are the countries with the highest number of publications among the most cited, each of these countries collaborated in 5 publications belonging to this list. The journals with the most publications among the 10 most cited were Chemical Reviews (n = 2) and Critical Reviews in Environmental Science and Technology (n = 2). The study by Panizza and Cerisola (2009) was the most cited publication, with 1434 citations. In this review, the authors

discuss important aspects of the mechanisms and materials used in direct and mediated anode processes for the oxidation of organic pollutants, as well as reviewing performance indicators used to assess the progress and efficiency of electrochemical treatments. The study by Marselli et al. (2003), the only research article among the 10 most cited, presented evidence of the electrogeneration of hydroxyl radicals during electrolysis in the boron-doped diamond (BDD) electrode. The high number of citations generated by this publication can be attributed to the great interest in the use of BDD electrodes for the electro-oxidation of organic pollutants, due to the excellent characteristics of this material, such as high stability, high starting potential for the evolution of O₂ and properties of weak adsorption.

Keywords analysis

The keywords of a scientific article reflect the general themes of the study. Thus, by analyzing the frequency and co-occurrence of keywords, it is possible to identify important topics and trends in a particular field of research (Li et al. 2009; Zhang et al. 2010). In this study, the VOSviewer 1.6.17 software was used to assess the frequency and co-occurrence of keywords. Terms with similar meaning and different spelling were combined, such as "electrooxidation" and "electro-oxidation", "hydroxyl radical" and "hydroxyl radicals". In all, 5694 keywords were found in publications related to electrochemical degradation of organic pollutants. The vast majority of these keywords had only one (4323, 75.9%) or two (611, 10.7%) occurrences, while 283 (5.0%) keywords had more than 5 occurrences. Table 5 shows the keywords with the highest number of occurrences in different periods. Between 2001 and 2021, the most frequent keywords were "electrochemical oxidation" (482), "phenol(s)" (261), "boron-doped diamond" (183), "electrooxidation" (180) and "hydroxyl radical(s)" (172). By analyzing the ranking of the most frequent keywords in different periods, search trends can be noticed. For example, the keyword "electro-Fenton" between the years 2001–2007 has the 15th highest frequency, between 2008–2014 it appears in the 7th position and between 2015–2021 it appears in the 4th position, which indicates a growing interest in the process electro-Fenton for degradation of organic pollutants. An important increase in occurrences was also observed for the term "water treatment", which occupied the 22nd position in 2001–2007 and rose to the 11th position in 2015–2021. "Advanced oxidation processes" also appears as an emerging topic moving from 30th position in 2001–2007 to 14th position in 2015–2021.

Figure 6 shows the co-occurrence network map of the most frequent keywords in publications related to the topic. Each keyword is represented by a node and the lines connecting the nodes indicate co-occurrence between the keywords. Node size is proportional to the number of links keywords have, and line thickness is proportional to the number of co-occurrences between two keywords. For the construction of the map, keywords with at least 20 occurrences were selected, which resulted in 57 keywords. "Electrochemical oxidation" has the highest number of links with other keywords as it is the most frequent word, which reflects its central position in this research field. Thicker lines are observed between the words "electrochemical oxidation" and "boron-doped diamond" (53 co-occurrences), "electrochemical oxidation" and "phenol(s)" (50 co-occurrences), "electrochemical oxidation" and "wastewater treatment" (49 co-occurrences), which indicates that these themes are frequently addressed in the studies together. There is also a relevant co-occurrence between the keywords "hydroxyl radical" and "electro-Fenton", "anodic oxidation" and "electro-Fenton", "electrochemical oxidation" and "hydroxyl radical", therefore, these combinations are focuses in research on the degradation of organic pollutants.

Author keywords with strong correlation were grouped into five clusters indicated by different colors. Among these clusters, three main groups were observed, defined by the number of keywords contained. Cluster 1 (red

color) is the largest group and has 25 keywords, focusing on the electrochemical oxidation applied to the degradation of phenolic compounds, adding the terms "electrochemical oxidation", "electrochemical degradation", "oxidation", "phenol", "phenolic compounds", "chlorophenol", "boron-doped diamond electrode", "PbO₂", etc. Cluster 2 (green color) has 14 keywords, mainly related to the application of combined techniques and advanced oxidative processes for degradation of organic pollutants, this group includes the keywords "anodic oxidation", "mineralization", "electro-Fenton", "photoelectro-fenton", "photoelectrocatalysis", "advanced oxidation process", etc. Cluster 3 (blue color) has 12 keywords, and involves the electro-oxidation of organic pollutants focusing mainly on the use of boron-doped diamond anodes, among the keywords belonging to this group are "electro-oxidation", "electrolysis", "organic pollutant", "wastewater", "pesticide", "boron-doped diamond", among others.

Discussion

The retrieved data point to a considerable expansion of technologies for the electrochemical oxidation of organic pollutants in the last 20 years. The analysis of the publications found shows that a great deal of attention was given to the investigation of efficient anode materials for the degradation of organic pollutants.

Electrode materials used in the electrochemical degradation process

Active anodes (anodes with low oxygen evolution potential), mainly Pt, graphite, IrO₂ and RuO₂, have been widely used in studies on the oxidation of organic compounds due to their high electrocatalytic activity and good chemical stability (Li et al. 2009; Mahmoudi et al. 2020). However, these materials generally allow only partial oxidation of organic compounds. Thus, non-active anodes (anodes with high potential for oxygen evolution) have been appointed as ideal anodes because they favor the complete oxidation of organic pollutants to CO₂ (Panizza and Cerisola 2009).

Among the non-active anodes, the most used are boron-doped diamond (BDD), SnO₂ and PbO₂. On the other hand, these materials also have their disadvantages, for example, the BDD electrode has a high cost, which limits its practical application. Pure SnO₂ electrodes have high resistance to charge transfer and the use of the PbO₂ electrode presents the risk of lead leaching, which raises environmental concerns considering the high toxicity and bioaccumulation of lead (Jiang et al. 2021). In view of these issues, alternative materials in addition to different types of modifications and preparation methods were evaluated in order to obtain better performance.

The results obtained in different studies showed that a very effective way to improve the degradation performance is through the application of materials on a nanometric scale. For example, nanostructured BDD electrodes (nanopores, nanowires) showed improved electrocatalytic activity compared to conventional BDD electrodes (Lee et al, 2017; Shi et al. 2020). Several types of nanocomposites and metallic nanoparticles have shown to be promising materials for the electrochemical oxidation of organic pollutants. In the study by Espinoza et al. (2020) a mixture of RuO₂ and IrO₂ nanoparticles was successfully applied for oxamic acid mineralization. MnFe₂O₄ nanoparticles used for tetracycline degradation were able to remove 86.23% of the pollutant after 60 min of treatment (Tang et al. 2021). The nanocomposite formed by poly(vinylidene fluoride-co-hexafluoropropylene) aerogel decorated with RuO₂ nanoparticles (PVDF HFP_RuO₂), produced by supercritical

drying, showed a relevant purification performance in the treatment of effluents (Sarno et al. 2021). The benefit of using nanomaterials is mainly associated with their high surface area and high catalytic activity.

It was demonstrated that the material used as a support has a fundamental influence on the performance of the electrode, as the use of an adequate support can provide better stability, improvement of the active sites on the surface, lower resistance to charge transfer and greater surface area. Ti is a material commonly used as a substrate for the electrodeposition of metallic elements and metallic oxides due to its high chemical stability, high mechanical strength, wide electrochemical potential windows and low cost (Ansari et al. 2020; Tang et al. 2021). Furthermore, TiO_2 nanotubes used as an intermediate layer can improve the adhesion between the substrate and the catalytic layer, and thus improve the electrocatalytic activity and stability of the electrodes (Wu et al. 2019; Xu et al. 2020). The development of anodes based on carbonaceous materials such as carbon fibers (Pereira et al. 2020), single-walled carbon nanotubes (CNTs) (Liu et al. 2021), multi-walled carbon nanotubes (MWCNTs) (Zhu et al. 2021), graphene (Savić et al. 2021) and reduced graphene oxide (rGO) (Hamous et al. 2021) provided very promising results. In the study conducted by Chen et al. (2021) $\text{rGO@Ti/SnO}_2\text{-Sb}$ composite electrodes showed significantly improved electrocatalytic oxidation activity for degradation of the fluoroquinolone antibiotic norfloxacin due to rGO coupling. Xia et al. (2021) showed that the multilayer CNT-PbO_2 anode has better efficiency for isoniazid removal compared to the pure PbO_2 electrode.

Among the strategies used to improve electrocatalytic performance is the introduction of doping elements. In the case of PbO_2 and SnO_2 electrodes, doping with F, Bi, Fe, Ni, Co, Sb, Al, Pd, Yb, Ce, La, Gd, among other elements (Ferreira et al. 2020; Yao et al. 2020), managed to further improve the performance for electrochemical degradation of organic pollutants. For example, the addition of nickel metal to the $\text{Ti/SnO}_2\text{-Sb-Ni}$ electrode generated a more compact and uniform surface compared to the $\text{Ti/SnO}_2\text{-Sb}$ electrode, in addition to improving the oxidation performance for mineralization of the chloramphenicol compound (Li et al. 2021). The Cu-doped PbO_2 electrode showed 98.4% combustion efficiency for amoxicillin degradation in wastewater, while for the non-doped PbO_2 electrode this value was 65.6% (Hu et al., 2020).

Important strategies to improve the degradation process

In addition to the nature of the anode material, another crucial factor for the efficiency of electrochemical oxidation is the operating conditions. To obtain better mineralization efficiency, the influence of factors such as temperature, pH, type and concentration of the supporting electrolyte, current density and concentration of organic pollutants must be carefully analyzed and the optimal conditions for carrying out the degradation process must be determined (Jiang et al. 2021).

The use of hybrid and sequential processes, in which electrochemical oxidation is combined with other techniques for a more efficient removal of pollutants, emerges as a very promising field and presents remarkable results (Hu et al. 2021). Among the methods usually applied in conjunction with electrocatalysis are Fenton's reaction, photocatalysis, ozonization, membrane filtration, adsorption, ultrasound, UV irradiation and biological treatment (Chen et al. 2019). In general, the combination of these methods with electrochemical oxidation has a synergistic effect causing an increase in the oxidative capacity of the process (Dewil et al. 2017). For example, Ren et al. (2021) obtained a degradation rate of 95.03% of the malachite green organic dye using an electrochemical system combined with ultrasound, while using only the electrochemical method the degradation rate was 83.91%. In the research carried out by Barrera et al. (2021) a sequential treatment combining electro-

oxidation and gamma irradiation achieved 100% efficiency for degradation of nonylphenol ethoxylate 10 (NP₁₀EO), in addition to reducing treatment time by 80%.

Conclusions And Perspectives

In this article a historical mapping and current trends related to the process of electrochemical degradation of organic pollutants were carried out. From 2001 to 2021, a total of 3188 documents related to the topic were published in scientific journals indexed in the Web of Science database. A significant increase in publications was observed in the last twenty years and the interest in this area should keep growing due to the efficiency of electrochemical methods and high demand. China dominated this field of research and presented a remarkably higher number of publications compared to other countries. It is important for other countries to be more interested in the subject considering that organic pollutants are a global problem. Bibliometric analysis also indicated that the most productive authors were Rodrigo MA, Martinez-Huitle CA, and Canizares P. The authors' favorite journals were *Electrochimica Acta*, *Chemosphere*, and *Journal of Hazardous Materials*. Electrochemical oxidation, phenol(s), boron-doped diamond, electro-oxidation and hydroxyl radical(s) are the most frequent keywords in publications and indicate the main focus and direction of current research in this research area.

Following the content analysis, it was possible to verify that the electrochemical degradation process of organic pollutants presents itself as a promising technique for mineralization of pollutants. Anode materials are critical to process efficiency and great strides have been made in the construction of high-performance catalysts. However, further development is still needed to obtain more stable anodes with better electrocatalytic performance. The adoption of strategies such as doping, surface modification and nanostructured construction can effectively improve anode efficiency. Another factor to be considered is the cost, investigations involving simple fabrication techniques and with non-precious metals can help to enable large-scale application.

The experimental parameters of the degradation process (pH, temperature, supporting electrolyte, etc.) need to be carefully evaluated to ensure the best performance of the electrocatalysts. The by-products generated during the electrochemical degradation process must be considered, considering that the incomplete oxidation of organic compounds can lead to the formation of toxic compounds, which is highly undesirable. It is also important that future investigations consider the combined use of electrochemical methods with renewable energies, such as solar energy, wind energy and geothermal energy, in order to obtain a cleaner process at a reduced cost.

Declarations

Ethics approval and consent to participate

The article does not contain any studies with human participants or animal subjects and all the authors named in a manuscript are entitled to the authorship and have approved the final version of the submitted manuscript.

Consent for publication

The article is an original research which has neither been published previously nor submitted to more than one journal for simultaneous consideration.

Availability of data and materials

Data will be made available upon request.

Competing interests

The authors declare no competing interest.

Funding

This study was supported by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - CAPES [PROCAD-AM/SCBA 450 88887.200615/2018-00], Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq [PQ 2017, Proc. 310664/2017-9], Fundação de Amparo à Pesquisa e ao Desenvolvimento Científico e Tecnológico do Maranhão - FAPEMA (Edital UNIVERSAL-01136/17, Termo de Outorga 015759/2017), and Agência Nacional do Petróleo, Gás Natural e Biocombustíveis - ANP [1.029/2016-ANP-007.639 - PMQC].

Authors' contributions

JRNS: Performed the investigation, methodology, writing and editing, and was a major contributor in writing the manuscript.

ICBA: Performed the investigation, methodology, writing and editing, and gave important contribution in writing the manuscript.

EPM: Held scientific orientation, writing and editing.

MALB: Provided fundind, and held scientific orientation, writing and editing.

All authors read and approved the final manuscript.

Acknowledgements

The authors are grateful to CAPES-PROCAD AM (Edital PROCAD AMAZÔNIA 2018 – Line 2; Number SCBA: 88887.200615/2018-00), CNPq (PQ 2017, Proc. 310664/2017-9), and FAPEMA (Proc. Edital UNIVERSAL-01136/17) and ANP (Research Project PMQC/BIOPETRO, No 1.029/2016-ANP-007.639- PMQC), for the financial support and fellowships received.

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Tables

Table 1 Sources with more publications on electrochemical degradation of organic pollutants

Position	Source title	Records	(%)	Impact factor
1	Electrochimica Acta	230	7.22	6.901
2	Chemosphere	141	4.42	7.086
3	Journal of Hazardous Materials	141	4.42	10.588
4	Journal of Electroanalytical Chemistry	122	3.83	4.464
5	Chemical Engineering Journal	107	3.36	13.273
6	International Journal of Electrochemical Science	88	2.76	1.765
7	Separation and Purification Technology	88	2.76	7.312
8	Journal of Applied Electrochemistry	76	2.38	2.800
9	Journal of the Electrochemical Society	76	2.38	4.316
10	Water Research	64	2.01	11.236
11	Applied Catalysis B Environmental	53	1.66	19.503
12	Environmental Science and Pollution Research	51	1.60	4.223
13	Environmental Science & Technology	48	1.51	9.028
14	Water Science and Technology	42	1.32	1.915
15	Electroanalysis	41	1.29	3.223

Table 2 The 15 most productive countries in relation to the total number of publications and citations

Most productive countries				Number of citations per country			
Position	Country	Records	%	Position	Country	Total citations	Avarage citation
1	China	1004	31.49	1	China	26398	26.29
2	Spain	282	8.85	2	Spain	18497	65.59
3	Brazil	255	8.00	3	Italy	14288	92.18
4	India	192	6.02	4	France	10276	62.66
5	USA	189	5.93	5	Brazil	7901	30.98
6	France	164	5.14	6	USA	6137	32.47
7	Italy	155	4.86	7	Switzerland	4978	146.41
8	Iran	120	3.76	8	India	4774	24.86
9	Mexico	98	3.07	9	Turkey	3187	34.64
10	S. Korea	94	2.95	10	Japan	2922	32.11
11	Turkey	92	2.89	11	Portugal	2647	44.86
12	Japan	91	2.85	12	Mexico	2418	24.67
13	Tunisia	81	2.54	13	Canada	2328	29.10
14	Canada	80	2.51	14	Tunisia	2328	28.74
15	Taiwan	68	2.13	15	Iran	2151	17.93

Table 3 Authors with more publications on electrochemical degradation of organic pollutants

	Author	Records	(%)	Total citations	Average citation
1	Rodrigo, M. A.	92	2.886	7139	77.60
2	Martinez-Huitle, C. A.	78	2.447	4434	56.85
3	Canizares, P.	74	2.321	3408	46.05
4	Oturan, M. A.	69	2.164	7041	102.04
5	Saez, C.	64	2.008	2997	46.83
6	Brillas, E.	59	1.851	6184	104.81
7	Oturan, N.	58	1.819	3854	66.45
8	Sirés, I.	40	1.255	4267	106.68
9	Panizza, M.	39	1.223	7860	201.54
10	Zhou, M. H.	36	1.129	1900	52.78
11	Wang, H.	30	0.941	674	22.47
12	Moon, I. S.	29	0.910	538	18.55
13	Wang, Y.	27	0.847	619	22.93
14	Cerisola, G.	26	0.816	5834	224.38
15	Abdelhedi, R.	25	0.784	958	38.32
16	Chung, S. J.	25	0.784	527	21.08
17	Comninellis, C.	25	0.784	4211	168.44

Table 4 Most cited publications on electrochemical degradation of organic pollutants

Position	Title	Author/Year	Citations
1	Direct and mediated anodic oxidation of organic pollutants	Panizza and Cerisola (2009)	1434
2	Electrochemical oxidation of organic pollutants for the wastewater treatment: direct and indirect processes	Martinez-Huitle and Ferro (2006)	1133
3	Electrochemical advanced oxidation processes: today and tomorrow. A review	Sirés et al. (2014)	1012
4	Advanced oxidation processes in water/wastewater treatment: principles and applications. A review	Oturan and Aaron (2014)	971
5	Electrochemical advanced oxidation processes: A review on their application to synthetic and real wastewaters	Moreira et al. (2017)	884
6	Single and coupled electrochemical processes and reactors for the abatement of organic water pollutants: a critical review	Martinez-Huitle et al. (2015)	796
7	Electrogeneration of hydroxyl radicals on boron-doped diamond electrodes	Marselli et al. (2003)	738
8	Advanced oxidation processes for wastewater treatment: formation of hydroxyl radical and application	Wang and Xu (2012)	681
9	Remediation of water pollution caused by pharmaceutical residues based on electrochemical separation and degradation technologies: a review	Sirés and Brillas (2012)	634
10	Application of diamond electrodes to electrochemical processes	Panizza and Cerisola (2005)	618

Table 5 15 most used author keywords in different periods

2001–2007			2008–2014		2015–2021		2001–2021	
P	Keywords	KO	Keywords	KO	Keywords	KO	Keywords	KO
1	Electrochemical oxidation	71	Electrochemical oxidation	173	Electrochemical oxidation	238	Electrochemical oxidation	482
2	Phenol(s)	54	Phenol(s)	118	Electrooxidation	100	Phenol(s)	261
3	Wastewater treatment	36	Boron-doped diamond	71	Boron-doped diamond	94	Boron-doped diamond	183
4	Anodic oxidation	33	Hydroxyl radical(s)	70	Electro-Fenton	92	Electrooxidation	180
5	Oxidation	28	Electrooxidation	58	Phenol(s)	89	Hydroxyl radical(s)	172
6	Cyclic voltammetry	26	Anodic oxidation	57	Anodic oxidation	80	Anodic oxidation	170
7	Hydroxyl radical(s)	23	Electro-Fenton	48	Hydroxyl radical(s)	79	Wastewater treatment	155
8	Electrooxidation	22	Electrochemical degradation	48	Wastewater treatment	74	Electro-Fenton	152
9	Electrocatalysis	22	Wastewater treatment	45	Degradation	49	Cyclic voltammetry	111
10	Electrolysis	18	Cyclic voltammetry	45	Electrochemical degradation	49	Electrochemical degradation	104
11	Boron-doped diamond	18	Mineralization	34	Water treatment	44	Degradation	88
12	Electrochemistry	15	Oxidation	33	Cyclic voltammetry	40	Oxidation	88
13	Wastewater	14	Degradation	30	Electrolysis	39	Electrolysis	80
14	Boron-doped diamond electrode	13	Boron-doped diamond electrode	30	Advanced oxidation process(es)	36	Water treatment	78
15	Electro-Fenton	12	Wastewater	29	Mineralization	35	Boron-doped diamond electrode	77

Figures

Figure 1

Number of publications of research per year on electrochemical degradation of organic pollutants

Figure 2

15 main thematic areas of publications related to electrochemical degradation of organic pollutants

Figure 3

Geographical distribution of documents retrieved from the Web of Science (2001–2021) on electrochemical degradation of organic pollutants. Gray areas on the map represent regions with no documents retrieved

Figure 4

Map of the academic collaboration network among the 30 most productive countries

Figure 5

The 15 institutions with the most publications on electrochemical degradation of organic pollutants between 2001 and 2021

Figure 6

Co-occurrence network of the most frequent author keywords