Discover Water

Review

Advanced and prospects in phenol wastewater treatment technologies: unveiling opportunities and trends

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Abstract
This study aims to explore technological advances and prospects in phenol treatment by providing a detailed bibliometric survey of wastewater treatment applications, highlighting innovative advances in research. Using the Web of Science database, we identified 79,104 articles from 2003 to 2023, later refined to 1848. The keywords were used for the initial search: "phenol", "wastewater", "degradation", "treatment" and "removal". The bibliographic review details the occurrence of journals, authors, newspapers, countries, institutions, keywords, highly cited articles, and prominent predominant research fields. In particular, the field of "Engineering" was responsible for 32% of the published articles, followed by "Ecology of Environmental Sciences" (25%) and "Chemistry" (12%). In addition, a keyword analysis revealed five major groups of clusters that indicate where the research is progressing. This aspect is crucial for understanding the evolution and perspectives of research interests over time. Therefore, future research in the field should prioritize wastewater treatment and feedstock diversification. This focus is essential to address significant challenges, such as production costs, stability, and durability of treatment processes.

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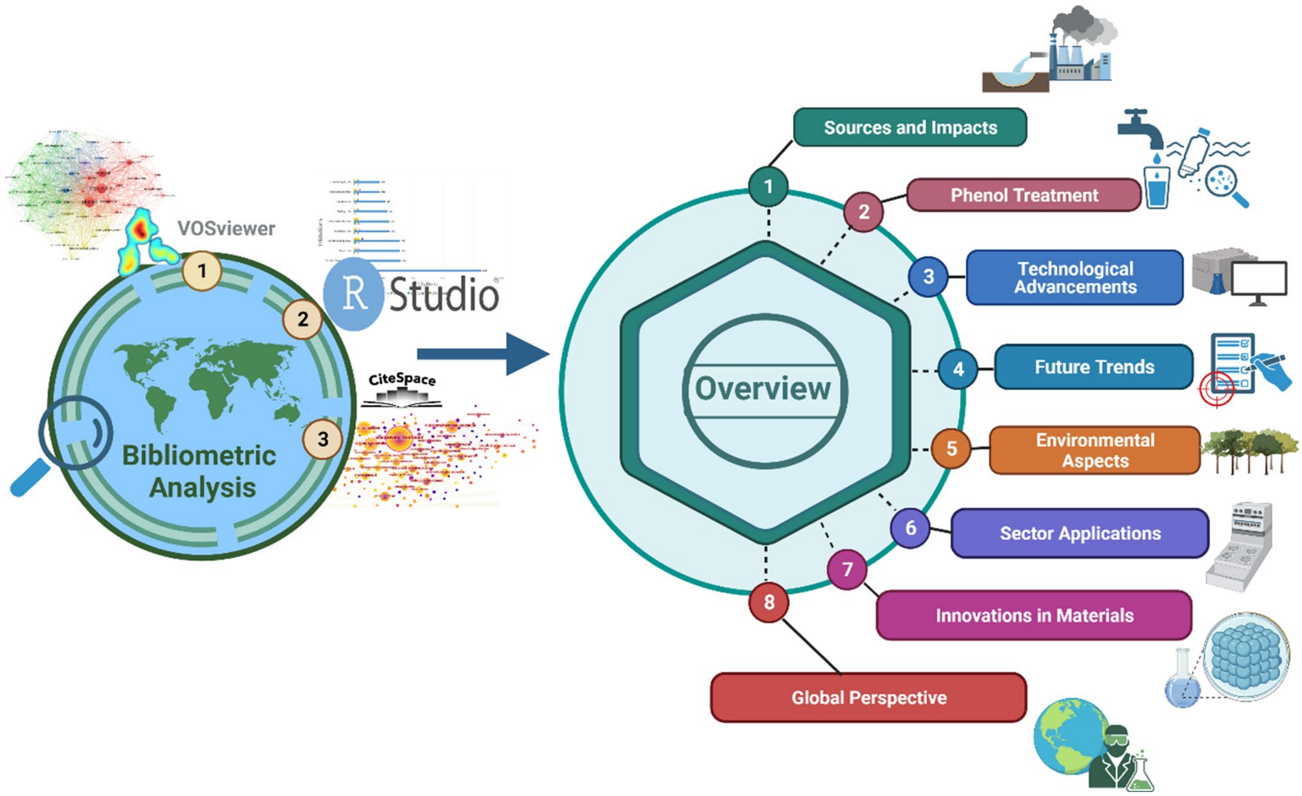
Graphical Abstract



Keywords Phenol · Wastewater · Degradation · Treatment · Removal

1 Introduction

Phenolic compounds are present in wastewater from various industries, including coking, pharmaceutical, petrochemical, and petroleum refining [1]. Industrial wastewater contains multiple organic products, such as phenol, PCBs, cyanide, and heavy metals (including Pb and Cd) and their compounds, originating from different industrial processes [2–4]. Contamination of water bodies with phenols can adversely affect aquatic fauna and flora and threaten the safety of water supplies for human consumption. Phenol and its derivatives, as aromatic pollutants with high toxicity, are widespread and persistent in aquatic environments because of the stability of their benzene structure [5–7].

Eliminating these compounds (e.g., phenol) plays a crucial role, as their presence in industrial and municipal wastewater challenges water quality. Conventional water treatment methods often face difficulties in effectively removing these pollutants, leading to a growing interest in investigating alternative and sustainable approaches [8].

Several methods for the removal of phenolic compounds from wastewater have been documented, including membrane separation and biodegradation [9], electrochemical oxidation of phenol [10, 11], direct osmosis [12], coal-based electrodes [13], ion exchange [14], anaerobic membrane [15, 16], aerobic biodegradation [17], photocatalytic degradation [18], and adsorption [19, 20]. However, these methods are expensive and often best suited for small to medium-scale applications [21]. Out of these methods, adsorption is emerging as a notable and promising solution for phenol removal because of its remarkable efficiency, favourable cost–benefit ratio, and simplified operational and design features compared to other methods [22]. Adsorption is a separation process in which one or more components are attracted to the surface of a solid adsorbent upon contact [23].

The present study aims to explore technological advances and prospects in phenol treatment through a detailed bibliometric survey of wastewater treatment applications, highlighting innovative advances in research. It will consider the primary search parameters, such as authors, journals, research institutions, countries, and keywords. This analysis allows us to answer specific questions about conventional treatment advances, highlighting effectiveness, limitations, and costs. Technological advances, innovations in efficiency, adsorbent materials, and biological processes will also be considered. In the future, the field of phenol treatment should focus on promising directions, identifying research gaps and growth opportunities, environmental, regulatory, and financial feasibility aspects, sectoral applications, and specific challenges in different industries.

2 Methods

2.1 Data analysis

This review was conducted based on previous studies [24–32]. Data were accessed and transferred to a text file for in-depth analysis. This procedure was carried out through "CAFe Access" on the CAPES Journal Portal, accessed on December 1, 2023. The Web of Science (WoS) Core Collection is considered the most reliable citation database in the world because of its verification and extensive data curation [33, 34]. The database was imported into VOSviewer, RStudio V3, and CiteSpace (v.6.2.R6) software to perform a visual, comprehensive bibliometric analysis of all documents in the database [35, 36]. The CiteSpace software performs a structural and temporal analysis of information from documents obtained from WoS, allowing the construction of different networks, such as collaboration networks, author co-citation networks, and bibliographic co-citation networks [37].

The search started with the term "phenol". Subsequently, a second filter was applied based on the range of publication years, covering 2003 to 2023. The choice of the period from 2003 to 2023 was based on the delimitation of the research scope and the availability of relevant data for analysis. The year 2003 was chosen as the starting point, as only 19 publications were recorded, representing a considerably low number within the period investigated. Furthermore, the period up to 2023 allows for a comprehensive analysis of trends and developments in wastewater treatment over two decades. The leading search terms used in the WoS search field were "Phenol", "wastewater", "degradation", "treatment", and "removal", which were included to refine the results further. The search covered a wide range of studies related to phenol wastewater treatment using a search string consisting of these keywords. This selection addressed different aspects of the problem, from the contaminated wastewater's nature to phenol's degradation and removal processes. Together, these keywords provided a comprehensive approach to identifying relevant articles contributing to advancing phenol wastewater treatment technologies. This specific focus on wastewater treatment culminated in the identification of 1848 articles for analysis. This analysis allows us to identify the major trends, contributions, and gaps in this rapidly evolving research field. Figure 1 shows the search criteria used to select the database for the literature search. The present study uses the refined bibliometric dataset to address questions related to bibliometric analysis and provide a comprehensive view of wastewater treatment.

3 Results and discussion

3.1 Advanced bibliometric analysis

3.1.1 Bibliometric analysis of wastewater treatment with phenol over the last 20 years

The WoS search yielded a total of 79,104 articles with the word phenol, which were refined into 1848 articles with the above keywords, of which 1700 articles (92%) were classified as full articles, 110 articles (6%) as proceedings and 38 articles as review articles (2%). The distribution of citations and articles over the 20 years can reflect a research field's leading trends and evolution. Figure 1 shows the total number of citations and publications from 2003 to 2023. Bibliometrics is recognized as an appropriate method for mapping scientific activity in a given field, allowing both qualitative and quantitative assessment of scientific productivity through statistical and mathematical techniques [38].

Figure 2 displays the distribution of publications and citations over 20 years. The first article was published in 2003, stating that fixed film bioreactor technology showed higher removal rates and chemical oxygen demand (COD) removal

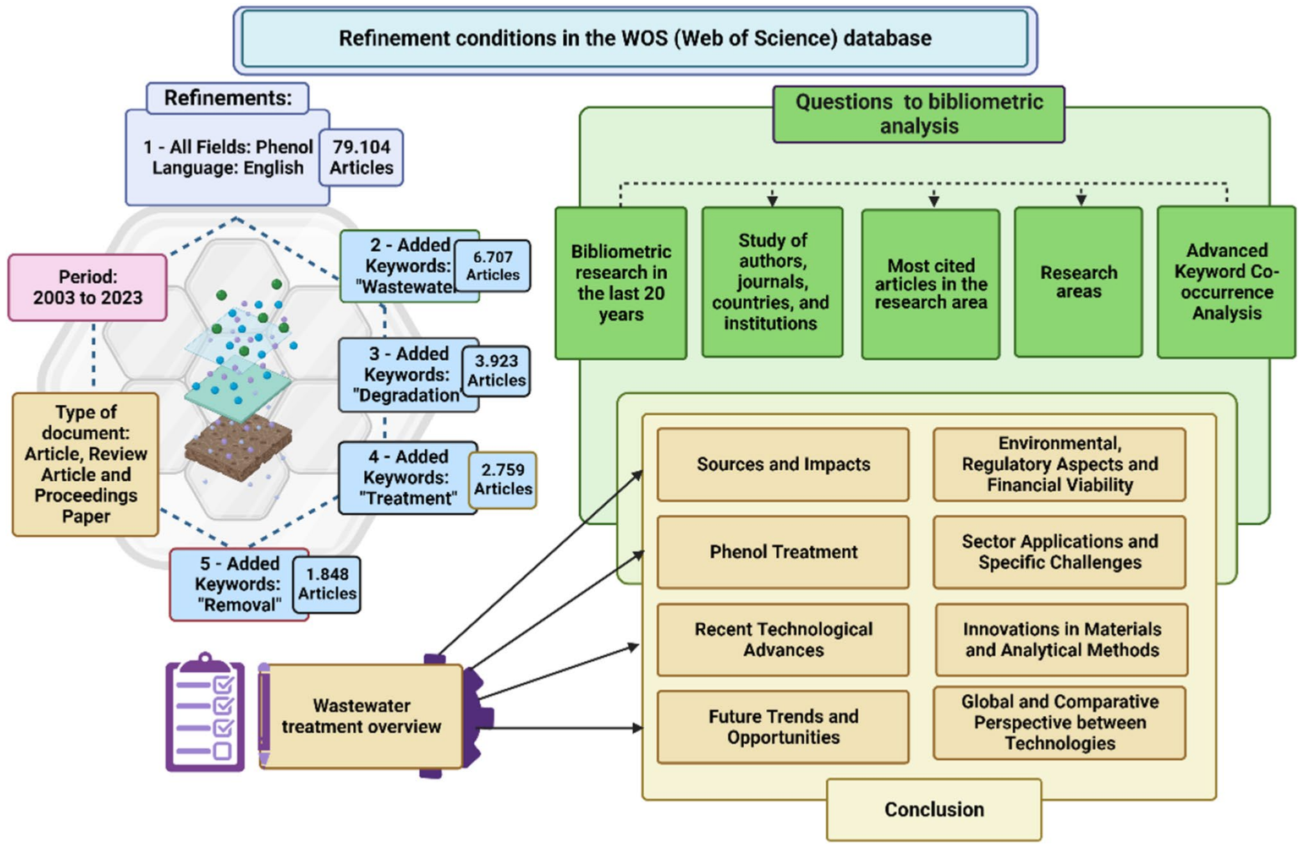


Fig. 1 Refinement conditions for searching in the Web of Science

rates of 85–90% and degradation of almost 100% of phenol from industrial oil refinery effluent [39]. A steady increase in annual publications was observed, with significant growth in the following three years. However, 2007, 2010, 2011, 2016, 2017, 2022, and 2023 showed a slight decrease in publications. A possible reason for the decreasing trend in the years above could be attributed to fluctuations in research prioritization, changes in funding availability, or temporary saturation of the topic, leading to a reorientation of research efforts to other areas or a temporary decrease in the number of publications. The period from 2018 to 2021 was marked by a remarkable and qualitative leap in scientific production, reflected in a significant increase. In particular, 2021 was the peak of publications, with 188 annual publications and more than 10 thousand citations. This scenario indicates that research on wastewater treatment has emerged as a central focus, generating remarkable enthusiasm among scientists.

3.2 Study of authors, journals, countries, and institutions

Table 1 shows the ranking of the ten most cited authors, journals, countries, and institutions in descending order of citation. Data also include the number of publications. Out of 4080 authors identified in this study, statistical analysis shows that the ten most cited authors have accumulated 5120 citations across 44 scientific publications. These results highlight the concentration of citations in a select group of authors. Among them, the three most cited authors were *Dionysios D. Dionysiou* (1149 citations in 2 publications), *K. Palanivelu* (633 citations in 3 publications), and *Nihar Biswas* (464 citations in 2 publications). Notably, they had few publications. Figure 3B shows that the most productive authors, *Minghua Zhou* (424 citations in ten publications) and *Hongjun Han* (316 citations in ten publications), ranked eighth and ninth in Table 1.

Figure 3A shows the leading networks of collaboration clusters among authors who published at least two documents with at least two citations. Again, *Minghua Zhou* and *Hongjun Han* appear to be the most significant authors within their groupings or clusters, represented by the pink and red colours. *Minghua Zhou* (pink cluster) contributes heavily to authors *Xiaoye Lu*, *Jie Yang*, and *Qi Wang*, while *Hongjun Han* (red cluster) contributes heavily to authors *Yuxing Han* and *Wercheng Ma*. The cluster network's node size and link line thickness confirm the results. Although these ten authors are

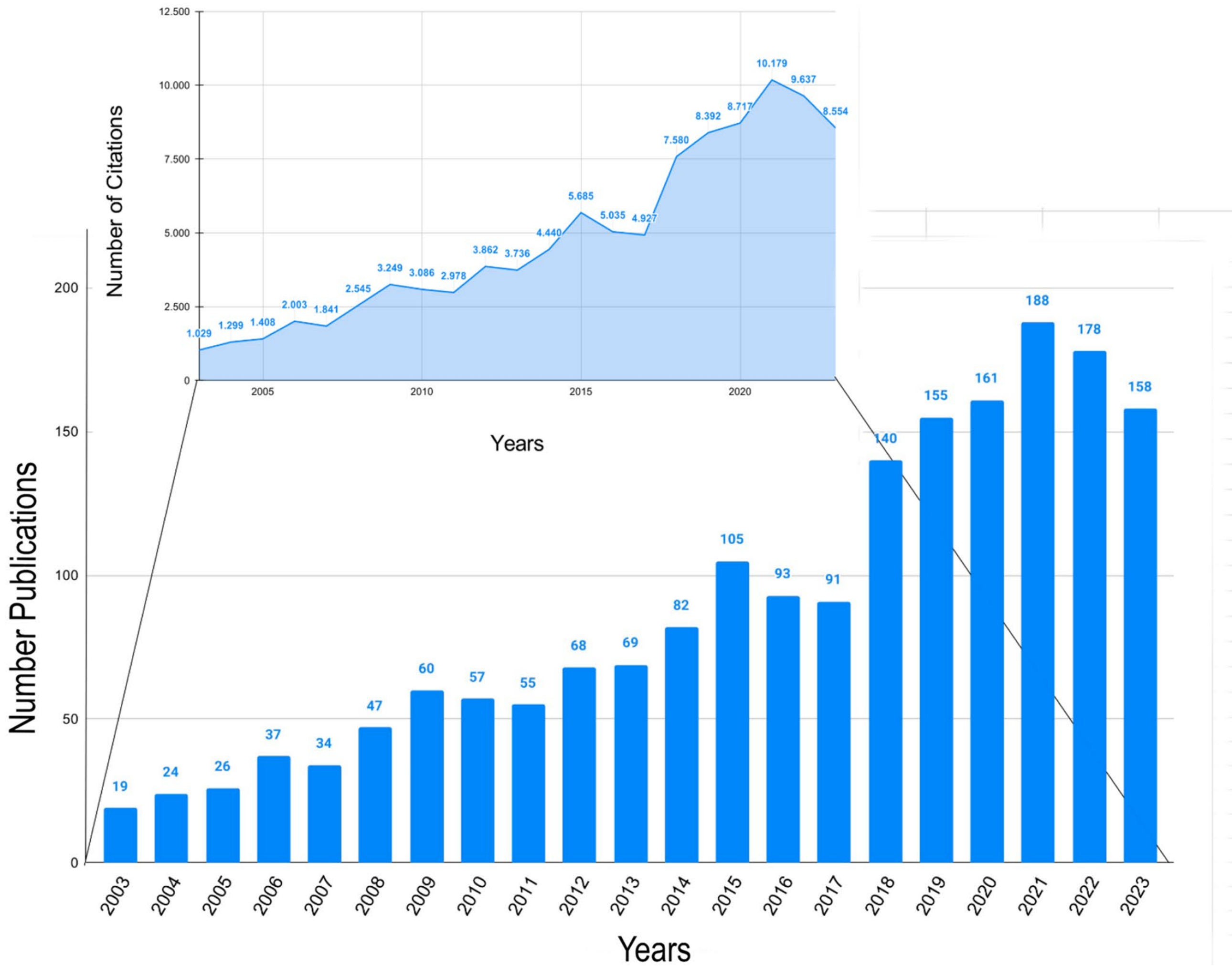


Fig. 2 Distribution of Publications and citations in research on water treatment with phenol from 2003 to 2023

gaining prominence, statistical analysis shows they contribute only 2.38% of the total publications in the field studied. This low representation suggests that, despite the significant influence of these authors, research in the area is diverse, with a wide variety of contributions from different researchers. This can be explained by the fact that the academic community increasingly values the quality of published work over mere quantity since authors with relatively few articles receive many citations in our analysis.

To analyze the journals prepared by VOSviewer, we observed the ten most cited journals out of 368. the journal with the highest number of citations is the Dutch Journal of Hazardous Materials (4229 citations in 54 publications), reaching an average of 78.31 citations per publication. Figure 3C shows the citation dimension of the prominent journals in different clusters (in moss green, blue, purple, and green), in which the Journal of Hazardous Materials appears as central within its cluster (moss green). However, regarding the number of articles published (as seen in Fig. 3D), it is only second to the American journal Desalination and Water Treatment, which had the highest number of publications with 64 publications and 835 citations. Once again, we found that the level of citations is not necessarily related to the number of publications. This depends on several factors, including the journal's impact factor. The impact factor (IF) is an important metric used to measure the recognition of journals in the academic world. In this case, the Journal of Hazardous Materials has an impact factor of 13.6 years (2023), a high value compared to the low value of 1.273 for the impact factor of the journal Desalination and Water Treatment year (2023). However, considering only the impact factor is insufficient to explain a journal's recognition and impact [40, 41]. An example is the Dutch journal Applied Catalysis B-Environmental, which has an impact factor of 22.1 years (2023), the highest in the ranking, but does not appear among the first journals published the most. Factors such as area of research concentration, specific fields of investigation, and places of interest may contribute to the preference for particular journals.

Table 1 Ranking of the ten most published authors, journals, countries, and institutions, classified in descending order of citations, between 2003 and 2023

Ranking		NP	NC
Authors			
1	Dionysiou, Dionysios D	2	1149
2	Palanivelu, K	3	633
3	Biswas, Nihar	2	464
4	Mashhadi, Neda	2	464
5	Taylor, Keith E	2	464
6	Korbahti, Bahadir K	4	462
7	Moussavi, Gholamreza	6	436
8	Zhou, Minghua	10	424
9	Han, Hongjun	10	316
10	Ni, Jinren	3	308
Journals			
1	Journal of Hazardous Materials	54	4229
2	Chemosphere	46	2509
3	Chemical Engineering Journal	37	1648
4	Bioresource Technology	35	1613
5	Applied B-Environmental Catalysis	13	1310
6	Water Research	18	1146
7	Separation and Purification Technology	30	934
8	Desalination and Water Treatment	64	835
9	Environmental Science and Pollution Research	27	621
10	Journal of Water Process Engineering	23	595
Countries			
1	China	1512	11491
2	India	282	2863
3	Iran	280	2781
4	Turkey	124	1535
5	South Korea	87	998
6	Spain	73	1199
7	USA	65	2126
8	Malaysia	58	496
9	Brazil	56	453
10	France	50	663
Institutions			
1	Chinese Acad Sci	25	2154
2	Tarbiat Modares Univ	15	788
3	Anna Univ	12	780
4	Harbin Inst Technol	39	775
5	Tsinghua Univ	13	604
6	Dalian Univ Technol	29	598
7	Peking Univ	7	570
8	Univ Windsor	4	535
9	Indian Inst Technol	16	440
10	Islamic Azad Univ	12	440

Note: *NP* number of publications, and *NC* number of citations

The database analysis also provides information on the region/country of origin indicated by the corresponding authors of the published articles. In Fig. 4A, we can see a network of coloured clusters formed by different countries, grouped according to their degree of collaboration and connected by lines. Among all these countries, represented by "nodes", one node stands out due to its size and the number of connections with other countries. This country is China, which obtained the highest number of publications (1,512, 81.8% of the total) and a significant number of citations (11,491). In Fig. 4B, we confirm these data, and we get India in second (2862 citations and 282 publications) and third place Iran (2781 citations and 280 publications). India had the highest average number of citations per publication among

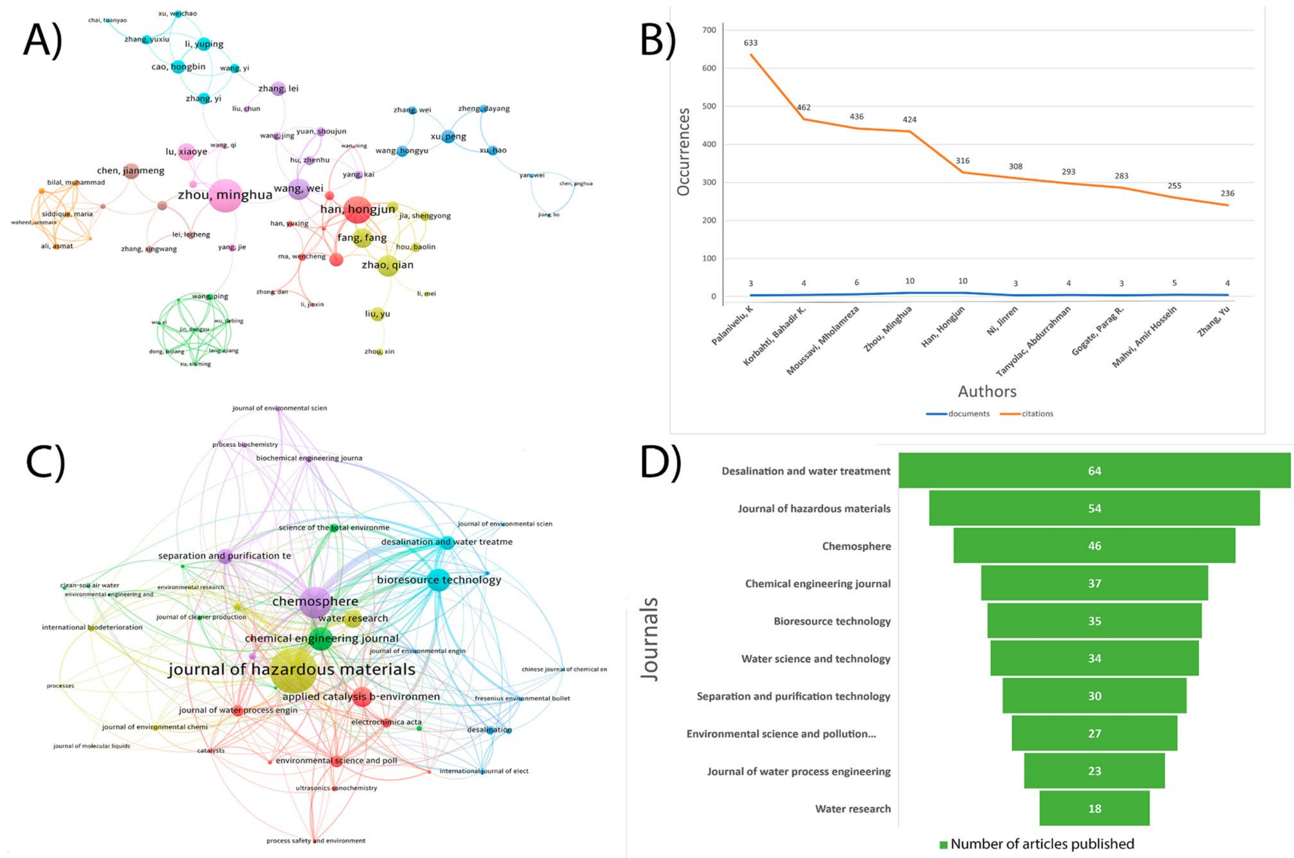


Fig. 3 Bibliometric analysis Collaboration and Publication: **A** Cooperation network between authors, **B** Distribution of publications between authors, **C** Jornals Citation Networks, and **D** the number of Jornals publications

the top three countries. China also stands out in terms of recent publications in the field studied. In Fig. 4C, compared to other countries, the highlighted "node" of China shows, through warm and cold colours, the significant contribution of this country to the number of publications. We also note that the participation of developed countries, such as the US, Spain, and France, indicates that research is not limited to specific regions. Although Asia leads as the continent with the most published and cited titles, other continents also contribute, covering Europe and the Americas, suggesting a global approach to the challenges associated with phenol wastewater treatment. The prominent presence of Asian countries, including China, India, South Korea, and Malaysia, highlights the considerable attention paid to environmental issues in the region. Such issues may be influenced by local needs, the concentration of industries generating phenolic waste, stringent environmental policies, and significant investments in research and development [42, 43].

Figure 5A illustrates the major institutions organized in coloured clusters, highlighting those that are significant in terms of publications and their collaborative relationships. In particular, the Chinese Academy of Sciences, represented by the moss-green "knot", occupies a central position, confirming its leadership in research on phenolic water treatment. Furthermore, the presence of the Indian institution Anna University in the same cluster indicates a close collaboration with the Chinese institution. Based on the affiliation of the corresponding authors, the three most prominent institutions in terms of publications were Chinese, namely the Harbin Institute of Technology, Dalian University of Technology, and the Chinese Academy of Sciences. These institutions contributed 93 publications (5.03% of the total) and accumulated 3,527 citations. The Chinese Academy of Sciences stood out with the highest average number of citations per publication, reaching 86.16. Figure 5B shows the three institutions mentioned above but were not necessarily the first most cited.

3.3 Most cited articles in the research area

Table 2 presents a compilation of the ten most cited articles, arranged in descending order of citations. Analysis of these publications reveals the central themes of the research. Examining the most influential documents makes it possible to

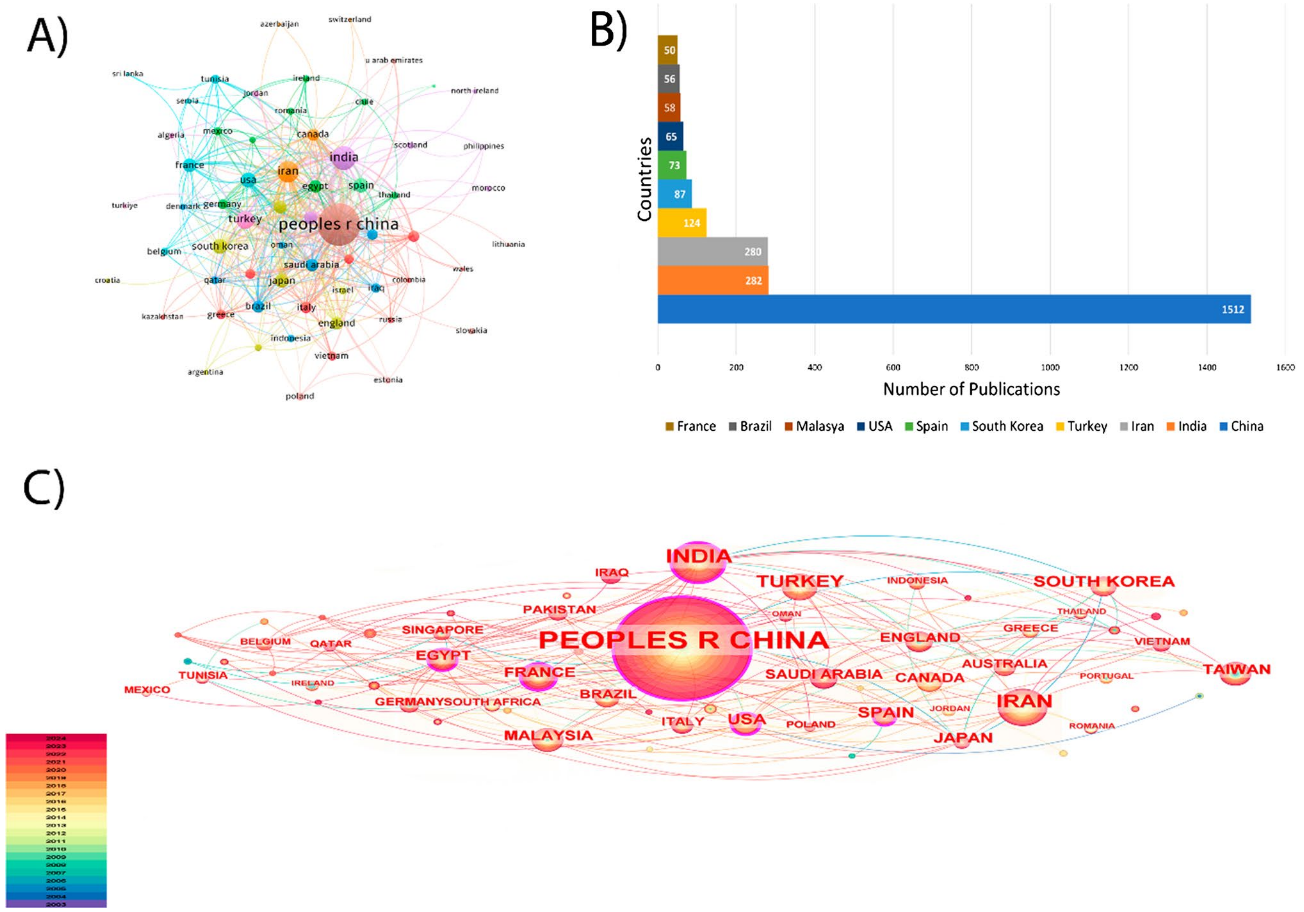


Fig. 4 Country analysis. **A** Visualization of the network map of the countries that most published, composed of at least four published articles, the thickness of the lines in the visualization indicates the strength of the co-authorship links that connect two countries and the most intense nuclei, divided into clusters, illustrate the groups of countries that published more significantly among themselves. **B** Distribution of the 25 countries that published the most in the research area, and **C** Co-authorship analysis among the leading research countries over 20 years

understand the authors' approach to specific content and its direct relevance to the topic under study [35]. The most cited article, "The use of zero-valent iron for groundwater remediation and wastewater treatment: A review, " was published in the Journal of Hazardous Materials in 2014, with 1,144 citations and an average of 104 citations per year to date. The article comprehensively reviews recent advances in zero-valent iron (ZVI), groundwater remediation, and wastewater treatment. The review concludes that there is growing interest in using ZVI to remove various contaminants from groundwater and wastewater, including chlorinated organic compounds, nitroaromatics, arsenic, heavy metals, nitrate, dyes, and phenol [44].

The second article, "Photocatalytic degradation of azo dye acid red 14 in water: investigation of the effect of operational parameters", ranks second with 787 citations, an average of 35.77 citations per year. This paper, published in the Journal of Photochemistry and Photobiology A-Chemistry, is the oldest on the list, dating back to 2003. The authors investigated how the UV/TiO_2 process can be used efficiently to degrade a dye in water, identifying the ideal conditions and factors that influence the effectiveness of the process. Although their main focus is degrading dyes, their findings have valuable implications for treating wastewater containing phenolic compounds. The study highlights the importance of optimising treatment conditions by analyzing operational parameters and the influence of supporting agents, such as hydrogen peroxide. These insights can be applied to the development of phenolic wastewater treatment technologies. The UV/TiO_2 method was found to be effective in degrading acid red 14, with a significantly reduced photodegradation efficiency in the absence of TiO_2 and virtually zero in the absence of UV light. It is also highlighted that the controlled addition of hydrogen peroxide improved the degradation rate. However, at high concentrations, H_2O_2 neutralizes hydroxyl radicals [45].

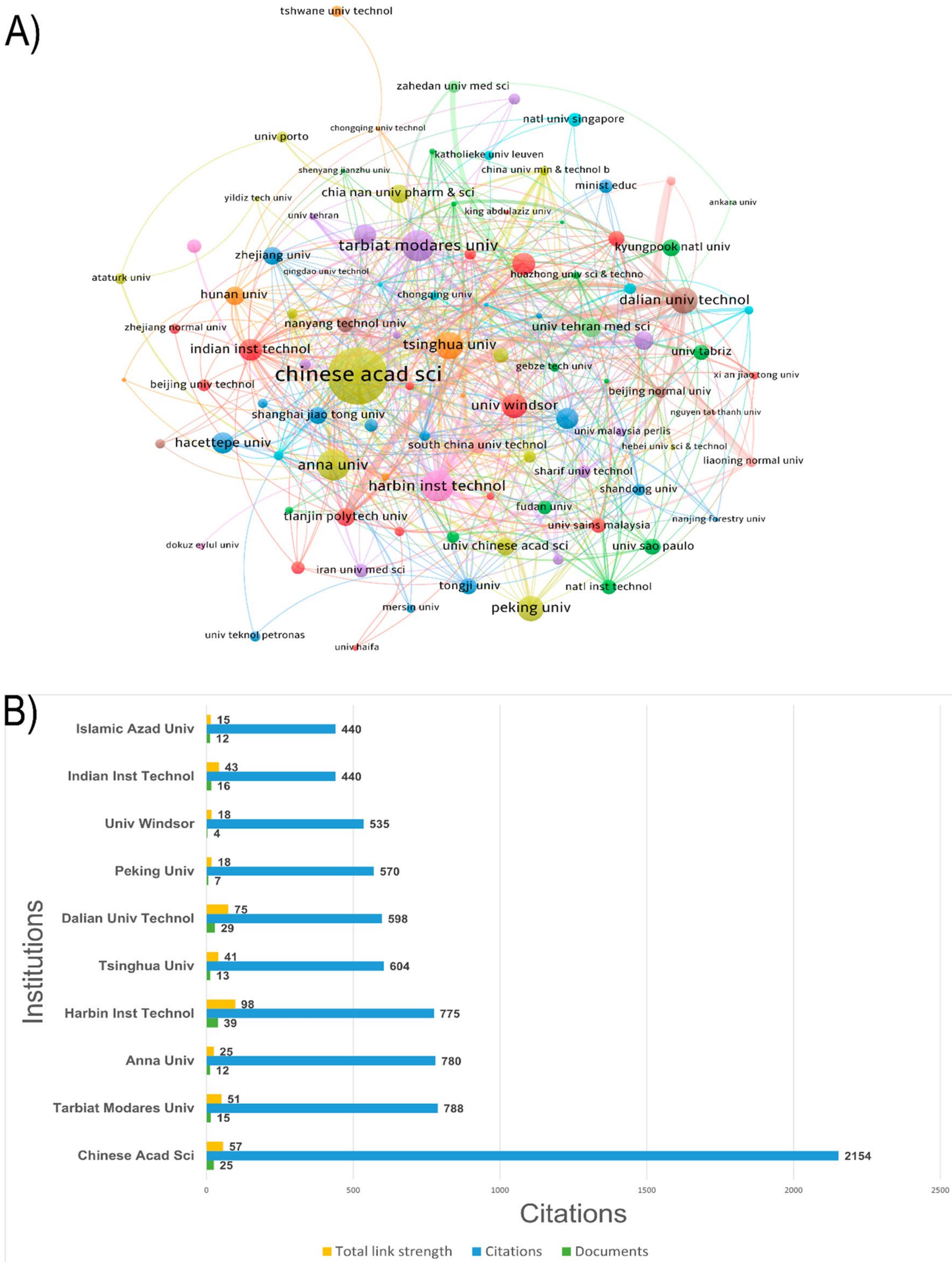


Fig. 5 Institution's visualization network: **A** Publication Network between Institutions **B** Number of obligations per institution

The third most cited article in 2020 was authored by *Dongjie Chen* and collaborators, published in 2020, has 685 citations and an annual average of 137 citations, titled "Photocatalytic degradation of organic pollutants using TiO_2-based photocatalysts: A review". It has provided fundamental information on removing organic pollutants from wastewater effluents. In addition, the study reviewed several critical parameters that affect TiO_2 photocatalytic

Table 2 The most cited works on the use of Phenol

Rank	Title	Authors	Journal	Publication Year	Total citation	Average citation per year	Reference
1	The use of zero-valent iron for groundwater remediation and wastewater treatment: A review	Fu, FL (Fu, Fenglian); Dionysiou, DD (Dionysiou, Dionysios D.); Liu, H (Liu, Hong)	Journal of Hazardous Materials	2014	1144	104	[1]
2	Photocatalytic degradation of azo dye acid red 14 in water: investigation of the effect of operational parameters	Daneshvar, N; Salari, D; Khataee, AR	Journal of Photochemistry And Photobiology A-Chemistry	2003	787	35,77	[2]
3	Photocatalytic degradation of organic pollutants using TiO_2-based photocatalysts: A review	Chen, Dongjie; Cheng, Yanling; Zhou, Nan; Chen, Paul; Wang, Yunpu; Li, Kun; Huo, Shuhao; Cheng, Pengfei; Peng, Peng; Zhang, Renchuang; Wang, Lu; Liu, Hui; Liu, Yuhuan; Ruan, Roger	Journal Of Cleaner Production	2020	685	137	[3]
4	Review on electrical discharge plasma technology for wastewater remediation	Jiang, Bo; Zheng, Jingtang; Qiu, Shi; Wu, Mingbo; Zhang, Qinhui; Yan, Zifeng; Xue, Qingzhong	Chemical Engineering Journal	2014	671	61	[4]
5	The role of ferrous ion in Fenton and photo-Fenton processes for the degradation of phenol	Kavitha, V; Palanivelu, K	Chemosphere	2004	471	22,43	[5]
6	A Short Review of Techniques for Phenol Removal from Wastewater	Villegas, Laura G. Cordova; Mashhadi, Neda; Chen, Miao; Mukherjee, Debjani; Taylor, Keith E.; Biswas, Nihar	Current Pollution Reports	2016	454	50,44	[6]
7	Enhanced photocatalytic removal of phenol from aqueous solutions using ZnO modified with Ag	Vaiano, V.; Matarangolo, M.; Murcia, J. J.; Rojas, H.; Navio, J. A.; Hidalgo, M. C	Applied Catalysis B-Environmental	2018	357	51	[7]
8	Magnetic $CoFe_2O_4$ nanoparticles supported on titanate nanotubes ($CoFe_2O_4$/TNTs) as a novel heterogeneous catalyst for peroxymonosulfate activation and degradation of organic pollutants	Du, Yunchen; Ma, Wenjie; Liu, Pingxin; Zou, Bohua; Ma, Jun	Journal Of Hazardous Materials	2016	355	39,44	[8]
9	Treatment technologies for petroleum refinery effluents: A review	Diya'uddeen, Basheer Hasan; Daud, Wan Mohd Ashri Wan; Aziz, A. R. Abdul	Process Safety And Environmenta	2011	326	23,29	[9]
10	Iron-copper bimetallic nanoparticles embedded within ordered mesoporous carbon as effective and stable heterogeneous Fenton catalyst for the degradation of organic contaminants	Wang, Yanbin; Zhao, Hongying; Zhao, Guohua	Applied Catalysis B-Environmental	2015	318	31,8	[10]

degradation, such as dopant/catalyst concentration, particle size, pH adjustment, and substrate selection. It highlighted the importance of these factors for the future commercialization of TiO_2 photocatalysis [46]. This study contributes to the advancement of scientific knowledge. It offers information directly contributing to advancing and understanding wastewater treatment technologies containing phenols. It provides valuable insights for researching and developing more effective methods of treating contaminated water with phenols.

3.4 Research areas

Figure 6A outlines the essential research areas that have attracted the attention of researchers in the advancement of phenol-containing wastewater treatment from 2003 to 2023. In analysing selected articles from the WoS database, Engineering (32%) and Environmental Sciences Ecology (25%) stand out as the two predominant areas, accounting for 57% of the total with 1687 published papers. Chemistry follows with 12%, corresponding to 347 records, and water resources with 11%, corresponding to 321 publications. The field of biotechnology and applied microbiology contributes 6%, represented by 184 publications. The last five fields, Materials Science (4%), Energy Fuels (3%), Science Technology Other Topics

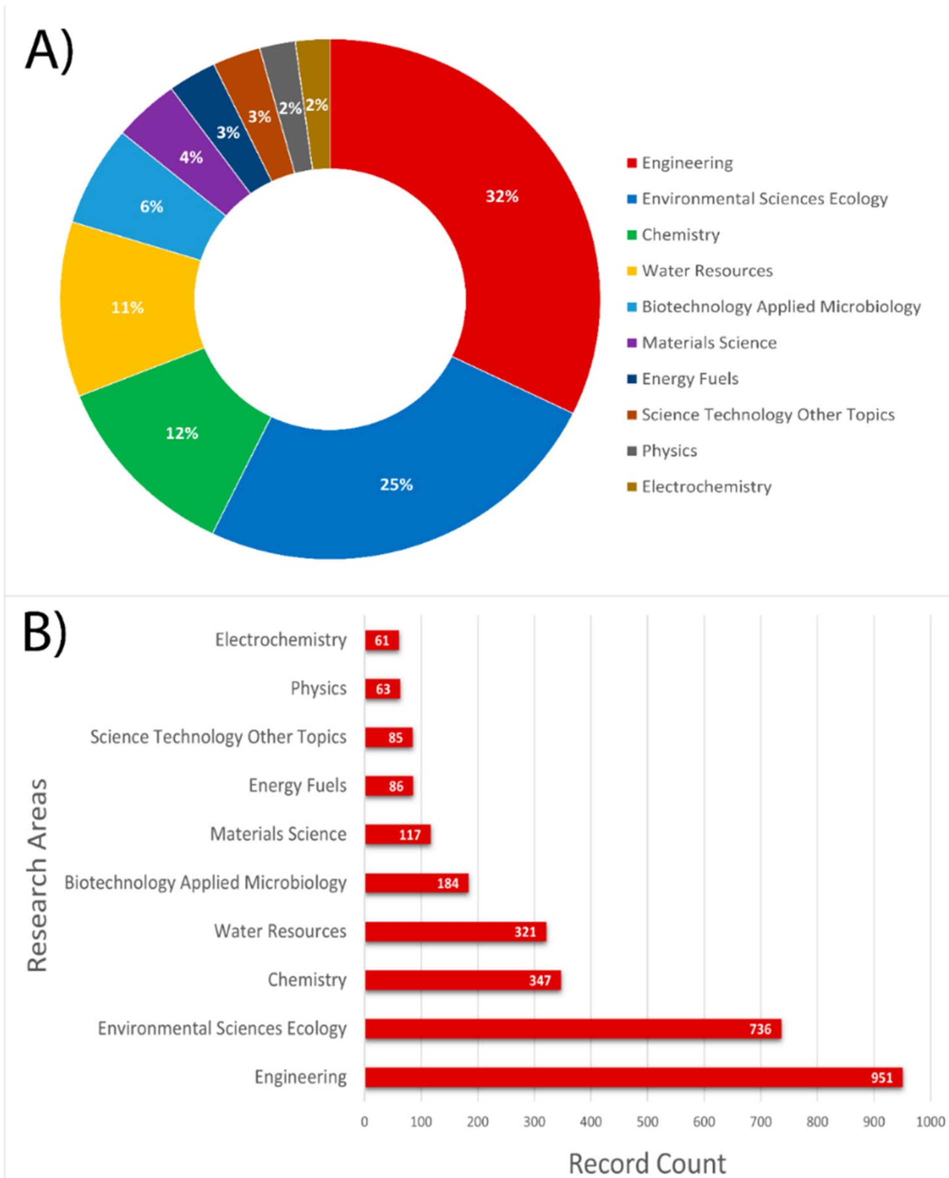


Fig. 6 Main areas of research **A** Percentage distribution of records by research areas. **B** top 10 research areas

(3%), Physics (2%), and Electrochemistry (2%), account for a total of 412 publications. This distribution highlights the multidisciplinary approach to address the challenges of efficiently treating phenol-contaminated waters [47–49].

In addition, Fig. 6B complements this analysis by clearly visualising the relative differences between the top 10 highlighted areas and the number of publications in ascending order. This information provides a comprehensive overview of the regions. It demonstrates the active involvement of the academic community in addressing the environmental challenges associated with the presence of phenol in wastewater. The diversity of disciplines not only underscores the complexity of the problem but also opens up promising opportunities for developing advanced oxidation technologies. Some methods include using photocatalysis, cavitation, hydrogen peroxide, and combinations of these techniques to optimize phenol degradation more efficiently and sustainably within the same project [50–56].

3.5 Advanced keyword co-occurrence analysis

Keyword co-occurrence analysis plays an essential role in research development. This procedure allows it to visualize knowledge networks and relationships between concepts and identify emerging scientific literature trends [57, 58].

Table 3 shows the 20 keywords in ranking order and the total link strength in the analyzed articles. "Phenol" (568 citations), "degradation" (529 citations), and "removal" (413 citations) are the most prominent keywords and are the same topics of this analysis. "Biodegradation" (212 citations), "oxidation" (210 citations), and "effluent treatment" (146 citations) follow in fourth, fifth, and sixth place, respectively. Among the 3946 keywords analyzed, 383 met VOSviewer's accuracy criteria, considering a minimum of 5 occurrences per keyword in our search. This bibliometric analysis of the predominant connections and relationships between the most searched keywords in the investigated articles [59].

Figure 7A displays a map of the visualization network where the keywords are organized into three broad clusters, each identified by a different colour, highlighting those with the highest frequency of participation. The red cluster stands out notably, highlighting the keywords "phenol", "degradation", and "removal", interconnected with other areas, representing the most significant cluster related to the research topic. The second highlighted cluster, identified by green, encompasses waste treatment and the "archeous solution". Then, in the third cluster, represented by yellow, the keywords "electrochemical oxidation" and "organic pollutants" stand out. The blue colour is centred on "oxidation" and "adsorption" and is integrated with the red cluster. The "kinetic" is highlighted in purple and is in the centre of the red and green cluster, indicating that a more significant number of connections between words implies a more extensive or closer cluster. This visual representation provides a clear view of the associations and groupings of the analyzed keywords.

Figure 7B shows the frequency of keywords within the four years in clusters of different colours, indicating the year of publication. The research projections are from 2020 to 2023. The keywords "phenol", "degradation", and "removal" have the most significant clusters, emerging as a central focus in 2020. Furthermore, these keywords may be correlated with others within the same research area. Figure 7C shows the frequency of the top 10 most cited keywords from 2019 to 2023. Degradation stands out as the most prominent word, with a total of 2151 occurrences, with an average of 430.2 over these five years, indicating that the search for these keywords is predominantly associated with the field of environmental research, especially in studies related to the treatment of contaminated water and industrial waste. These keywords are often found in articles that explore methods and technologies for dealing with pollutants in aquatic environments.

Table 3 Top 20 most relevant keywords in the field of wastewater treatment with Phenol

Rank	Keywords	NOs	TLS	Rank	Keywords	NOs	TLS
1	Phenol	568	4175	11	Aqueous-solution	90	737
2	Degradation	529	3862	12	electrochemical oxidation	74	574
3	Removal	413	3129	13	phenol degradation	71	499
4	biodegradation	212	1588	14	activated carbon	68	588
5	oxidation	210	1602	15	tio2	67	519
6	wastewater treatment	146	1091	16	waste-water treatment	67	538
7	adsorption	140	1115	17	photocatalytic degradation	65	506
8	kinetics	133	1054	18	advanced oxidation processes	57	450
9	performance	131	977	19	hydrogen-peroxide	57	497
10	waste-water	117	887	20	organic pollutants	55	461

Note: *NO* number of occurrences; *TLS* total link strength

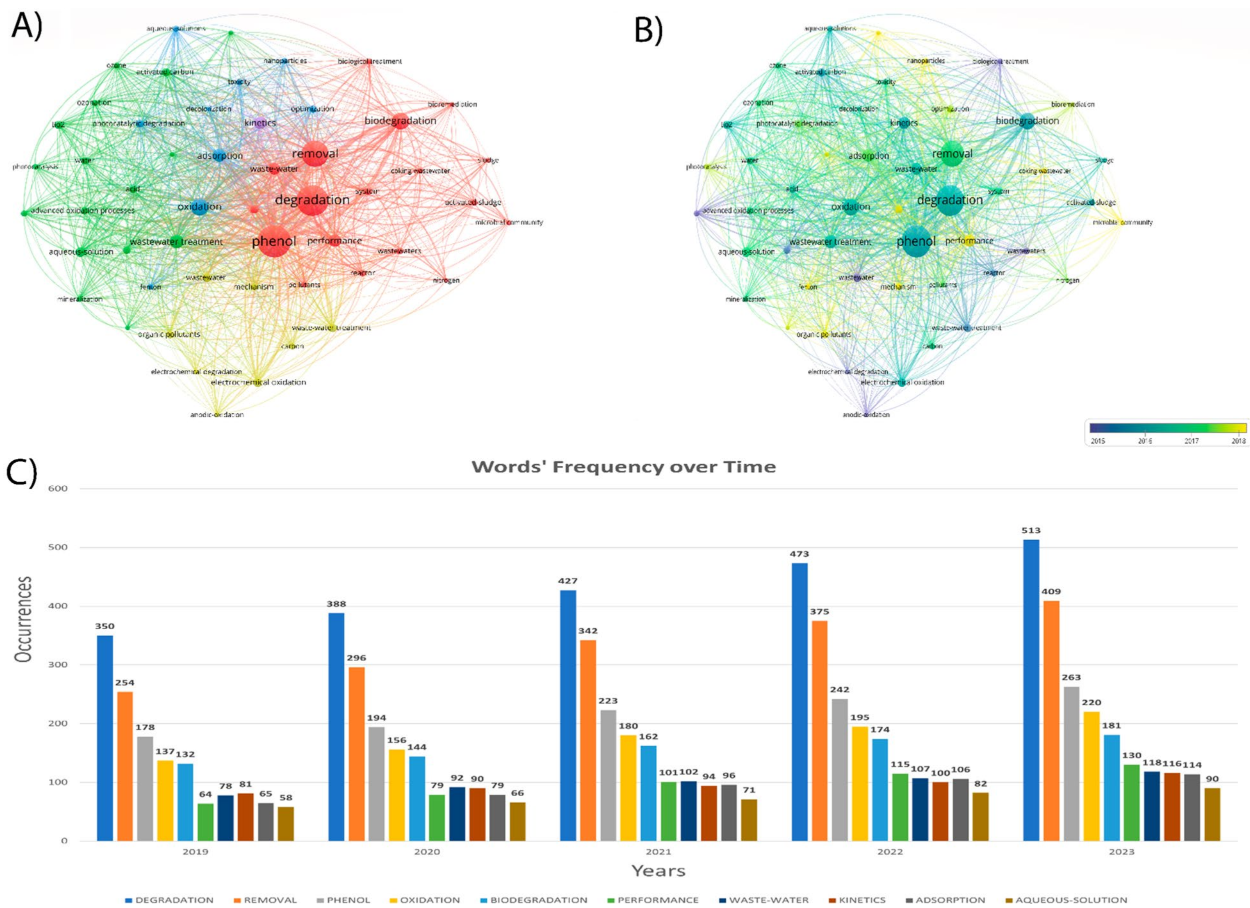


Fig. 7 Visualization map generated by VOSviewer. **A** Cluster map of the main keywords. **B** Average annual word publication map. **C** Occurrence of words over the last five years

Table 4 was created to present the three most significant clusters identified in Fig. 7A, containing the frequency of cited keywords based on 383 articles that meet the limit of five publications. Topics such as wastewater treatment, organic pollutant degradation processes, and removal methods are recurrent in this context, reflecting the predominant interest in environmental research.

Meanwhile, a graphical representation constructed from the analysis using CiteSpace software is presented in Fig. 8A, characterized as a comprehensive bibliometric analysis tool, where 458 keywords and 851 occurrences were identified among the articles in the database data. From January 2004 to January 2024, the top 43 keywords were highlighted. Figure 8A shows them. Therefore, the keyword "wastewater treatment" was the most explicit, being used in more than 57 articles, directly highlighting the greater incidence of studies on wastewater treatment. This may be due to the lack of adequate treatment of these industrial wastes or the current environmental urgency to minimize damage to the ecological system. Keywords such as "biological treatment" (17 occurrences), "phenol degradation" (26 occurrences), and "electrochemical oxidation" (35 occurrences) stand out in the scenario as exciting possibilities for solving this general problem. Biological treatment is one of the most accepted by environmentalists because it is based on using live bacteria that assimilate pollutants (such as organic matter) and thus purify wastewater. Nevertheless, a consolidated trend can be identified regarding future research for wastewater treatment, where some of the strategies above will be the most prominent on research platforms.

In addition, Fig. 8B displays a distribution graph on the timeline of the keywords of the ten main clusters in this research area. Among the main clusters, the term wastewater treatment is at the centre, which explains its centrality to work. The other clusters are directly related to the central term, juxtaposed with the tools for solving the central problem under analysis. The concepts of electrochemistry and biological treatment are the most obvious, confirming themselves once again as promising possibilities for adequate wastewater treatment. The formation of four clusters

Table 4 Grouping of keyword clusters obtained by VOSviewer

Cluster	Colours	Items	Main keywords
1	Red	30	Anaerobic Degradation, Anaerobic Digestion, Anaerobic Treatment, Bacteria, Biomass, Chlorella-Vulgaris, Coke Wastewater, Degradation, Immobilization, Impact, Membrane Microbial Community, Nitrification, Nitrogen, molasses, optimization, Phenol, Phenol Biodegradation, Phenolic Compounds microflora, performance, ph., reactor, response surface, sludge, starch, substrate, substrate concentration, sucrose, temperature, and waste
2	Green	28	Antibiotics, Catalytic Decomposition, Contaminants, chemical oxidation, chemical oxygen demand, chlorella-vulgaris, chlorophenols, Degradation, Electrochemical, Hydrogen Peroxide, Nanocomposites, Organic Pollutants, Particles, aromatic-hydrocarbons, polymerization, Process, pretreatment products, pseudomonas putida, pseudomonas-aeruginosa, pseudomonas-putida, pulp, pyridine quinoline, radicals, rate constants, reaction kinetics, reactor, Water, Zero-Valent Iron
3	yellow	26	Anode, Catalyst oxidation, Coagulation, Electrochemical Degradation, Electrochemical Oxidation, Fenton Process, In-Situ, Optimization, Oxygen, Polymerization, Removal, sulfamethoxazole, sulfate, sulfate radical, sulfate radicals, surface, surface waters, system, systems, technologies, technology, temperature, textile wastewater, Wastewater's oxidation
1	Blue	20	Air Oxidation, Biodegradation, Biodegradation Pathway, Decomposition, discoloration, decolorization, decomposition, degradation Detoxification, Disinfection, Environment, Formaldehyde, Nonylphenol, Saline Wastewater, Solar Photocatalysis, Surface Waters, Toxicity, Treatment-Plant, Waste treatment and Zeolite
1 and 2	Purple	12	2,4-Dichlorophenol, 4-Chlorophenol, Activated carbon, Aqueous-Solutions, Biodegradability, Biodegradation Kinetics, Biological Treatment, Chlorophenols, Combination, Extraction, Phenolic Wastewater, Oxidation

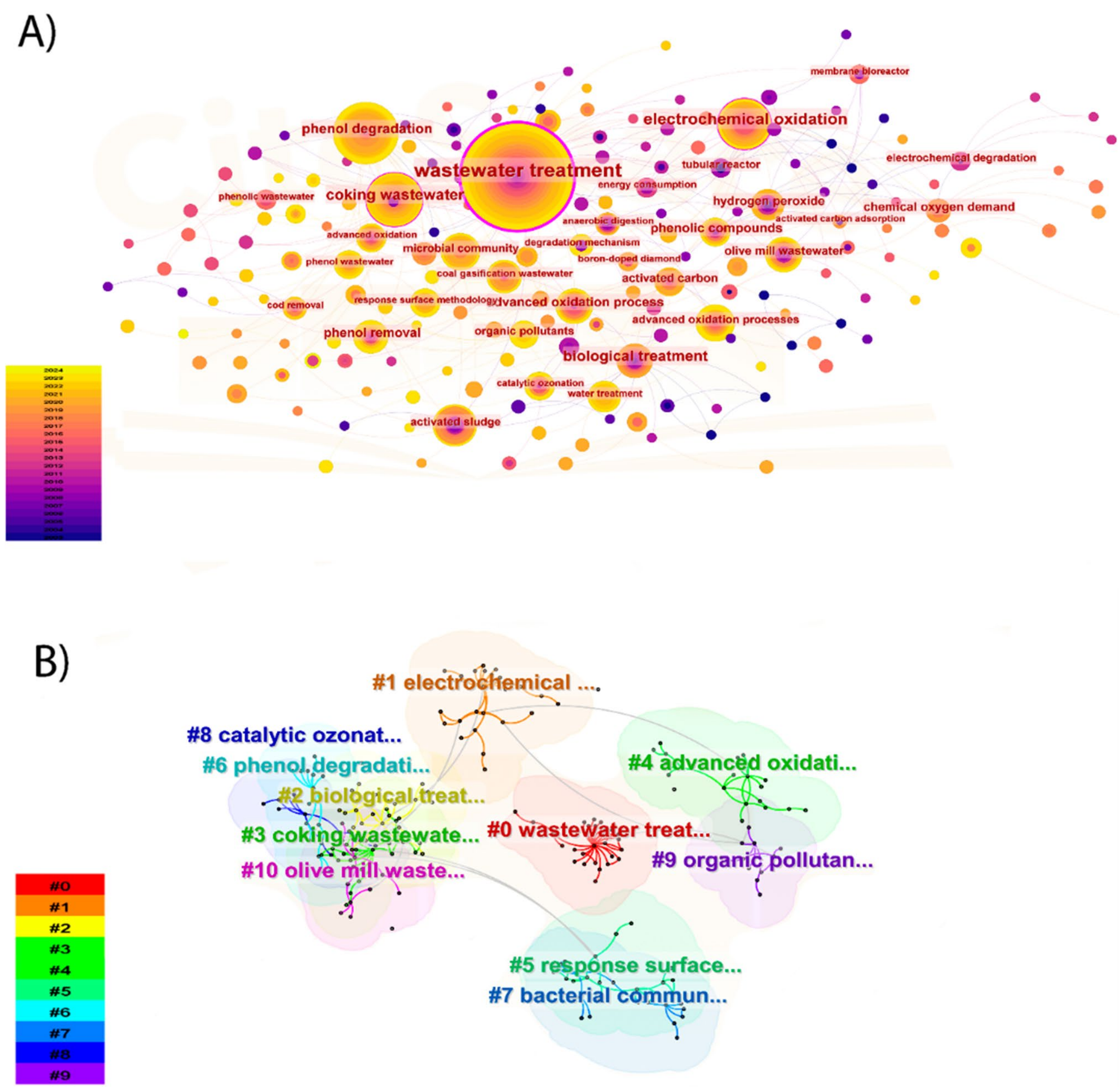


Fig. 8 Visualization map generated by CiteSpace. **A** Cluster cloud. **B** Keyword timeline distribution of the top 10 clusters in the search area

around the wastewater treatment process can also be seen. One of these four clusters directly relates to five essential concepts: catalysis, phenol degradation, biological treatment, coking wastewater, and olive oil mill wastewater. The promising possibilities for wastewater treatment can be seen once again. Thus, the emphasis on the other critical points of the research review is reaffirmed.

Next, Fig. 9 displays a timeline view of the articles studied from January 2013 to mid-January 2024, in which we observe the most important keywords for each main keyword, that is, words that indicate the lines to be studied. Therefore, the central keyword #0 is "wastewater treatment", which is related to the issue of the efficiency of the process of removal/treatment of phenol from wastewater, as the world is going through an attempt to minimize the industrial impact on the planet. In Cluster #1 (Electrochemical Oxidation), aspects related to efficiency in wastewater treatment. The oxidation process via electrochemistry of pollutants can effectively oxidize many inorganic and organic contaminants. In 2013 and 2019, the concentration of work publications was highest. In Cluster #2 (Biological

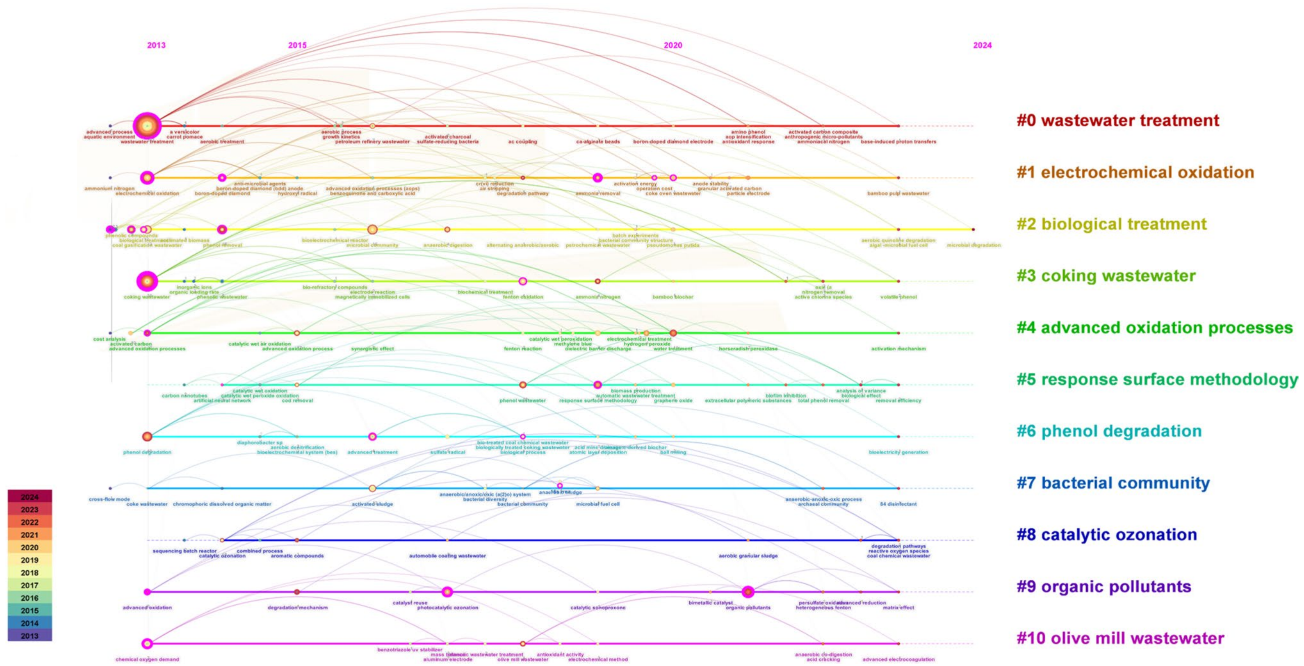


Fig. 9 Temporal representation of keywords from 2003 to 2024, generated through CiteSpace

Treatment), research is conducted on using organic materials such as enzymes and bacteria to purify wastewater. In 2014 and 2017, the concentration of work publications was highest. In Cluster #3 (Wastewater Coking), the highest concentration of publications was in 2013 and 2018. The coking of wastewater presents itself as a promising and efficient alternative to wastewater treatment.

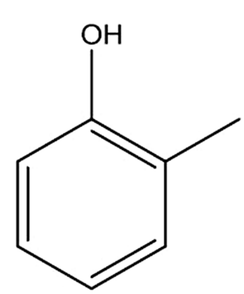
4 Specific research topics

4.1 Sources and impacts of phenol in wastewater

Phenol, an organic molecule, has one or more hydroxyl groups (OH) attached to one or more of its aromatic rings (Fig. 10). Phenol is a chemical used in many industrial processes, including the manufacture of resins, plastics, insecticides, and pharmaceuticals [60]. Any living organism, including humans, animals, and plants, can be at risk from phenol waste released into the environment [61].

The presence of phenol in wastewater occurs in two ways: naturally and as a result of human activity [62]. The decomposition of dead plants and animals indicates natural occurrence [63], whereas disposal by industry, agriculture, municipal solid waste, and household waste indicates anthropogenic activity. Phenol is also produced as a by-product of petroleum refining [64]. Due to its widespread use and improper disposal, the chemical is often detected in wastewater, making it critical to investigate the sources (Fig. 11) and assess the impact of the substance on the aquatic ecosystem and its interaction with the environment.

Fig. 10 Chemical structure of phenol



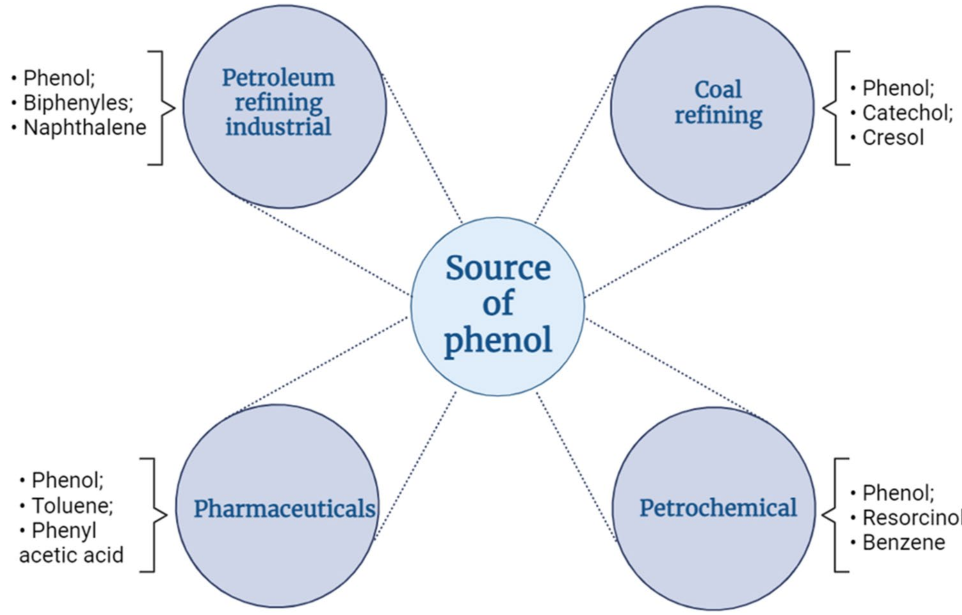


Fig. 11 Sources of phenol of anthropogenic origin

The material is classified as a priority pollutant by the National Pollutant Release Inventory (NPRI) and the US Environmental Protection Agency (USEP) [65]. This is because phenol is exceptionally hazardous and highly reactive, even at low doses[66]. Consequently, interacting with aquatic life disrupts organisms' metabolism, subsequently impacting their developmental processes [67]. Therefore, the release of phenol into the environment is restricted by international regulatory authorities. The USEP sets a strict water purity standard that limits the amount of phenol at the water's surface to 1 ppb [68]. In addition, these species die when exposed to large amounts of it.

The long-term persistence of phenol in the environment increases its impact and potential to contaminate drinking water sources [69]. Since phenol risks human health when found in surface or groundwater, adequate treatment is required [70]. Exposure to phenol can cause respiratory problems, liver and kidney damage, eye and skin irritation, and other side effects [71].

Thus, measures and processes are needed to control and treat effluents in the industrial production chain [72]. For example, phenol removal systems can be installed to remove the substance before it is discharged into the environment, and alternative manufacturing techniques can be developed to reduce the amount of waste that is produced that may contain phenol. From a regulatory perspective, environmental regulations must be designed to ensure that phenol concentrations are within a safe range for public health and the environment.

4.2 Conventional phenol treatment methods

Table 5 summarizes the pros and cons of the phenol treatment method. This analysis is essential for selecting the most appropriate method for each situation, considering several factors, such as efficiency, availability, speed of action, ease of use and environmental impact. By understanding the pros and cons of each approach, professionals involved in chemical waste management can make more informed and effective decisions to ensure treatment effectiveness and protection of the environment. Phenols can have a significant environmental impact due to their high toxicity and solubility in aquatic environments [73]. Therefore, several treatment strategies have been developed recently, highlighted in Fig. 12, and their environmental and economic aspects have been evaluated.

4.2.1 Electrochemical oxidation

Electrochemical oxidation removes phenol by passing an electrical current through electrodes (made of platinum, graphite, or lead oxide) [74]. As a result, the electrical current plays an oxidizing role, causing the degradation of the organic molecule and releasing it to less dangerous components such as carbon dioxide and water [75]. Advantages include reduced production of unwanted byproducts and the ability to handle a wide range of phenol concentrations [76].

Table 5 Pros and cons of the phenol treatment method

Aspects	Pros	Cons	References
Efficiency	Effective in removing phenols in wastewater	Efficacy may vary depending on initial phenol concentration and treatment conditions	[11–13]
Availability	Phenol is widely available as a reagent They are widely used in the chemical and pharmaceutical industry	Costs associated with purchasing and handling phenol Fluctuations in phenol prices make it less affordable at certain times or regions	[14–16]
Action speed	Fast in degrading phenols Rapid action on the degradation of organic compounds	Additional time may be required for neutralization and proper disposal of generated waste Require time to treat large volumes of water	[17–20]
Ease of use	It can be relatively easy to apply and operate	Requires trained personnel to handle correctly and avoid health risks Requires care due to its toxicity	[21–23]
Environmental impact	It can reduce the organic load in the final effluent	Due to the toxic waste generated, it can be environmentally harmful if not carried out correctly Potential toxicity to aquatic organisms at high concentrations	[24–27]

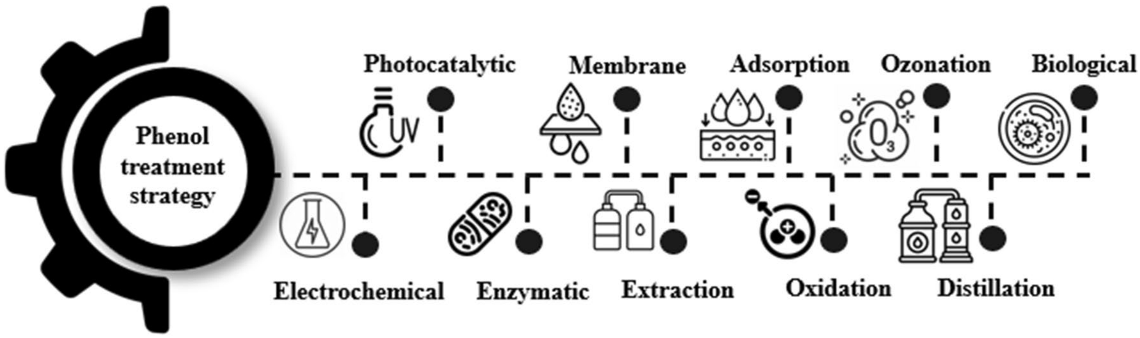


Fig. 12 Schematization of the techniques and processes used to treat residual phenol in water samples

However, to guarantee the effectiveness and economic sustainability of the process, the electrodes must be selected appropriately, and the operating conditions must be analyzed [77]. Electrochemical techniques may present themselves as viable options for treating phenol as they do not require reagent costs and do not lead to the formation of new by-products. However, they do require the assembly of apparatus and electrochemical cells for the process.

4.2.2 Photocatalytic techniques

Photocatalytic techniques use natural or artificial light to degrade phenolic compounds. This process is efficient and environmentally friendly due to the low or zero consumption of chemical reagents [78]. A disadvantage from an economic point of view is that although the performance and cost of photocatalytic cells are favourable, they have a low reuse rate, i.e., the valuable life per cell is significantly reduced [79].

4.2.3 Enzymatic treatment

The use of biocatalysts in the degradation of polluting organic compounds is not new and has been explored by industry for many years [80]. This is because enzymes have high catalytic efficiency, are highly selective catalysts, and can operate in different temperature and pH ranges. The yield of these reactions is also of great interest, as enzymes, combined with immobilization techniques, can perform several reuse cycles without losing their catalytic efficiency [81]. An advantage of using enzymes is their solubility, which forms a homogeneous system in this catalysis, making removing phenolic compounds more efficient. Enzymatic treatment can also be used as one of the steps in other combined processes to optimize the residual phenol treatment route. A disadvantage is the need to isolate the enzymes and the low stability to high temperature and acid conditions [82].

4.2.4 Membrane method

Other very efficient techniques that offer several advantages for removing residual phenol are those that use membrane technologies. They are based on the difference in concentration, pressure, or temperature [83]. The membrane process has been studied for its efficiency and adaptability. This method uses semipermeable membranes that allow selective passage of water and other soluble components while retaining contaminants (e.g., phenol) [84]. The most common processes include “reverse osmosis”, which removes impurities from water by using pressure to force water through a semi-permeable membrane, leaving behind contaminants [85]. "Nanofiltration" uses membranes with nanopores to remove organic molecules and larger particles from water while allowing the passage of water and some minerals [86, 87]. “Ultrafiltration” uses a semipermeable membrane to remove particles, colloids, microorganisms and macromolecules [88]. These treatments can be used alone or in combination if specific criteria for phenol removal are met [89]. Advantages include low use of chemical reagents, high efficiency, and adaptability for operation in various environmental conditions. These methods are very reliable, reproducible and have low operating costs. One of their disadvantages is the encrustation of materials adhering to their surface, which reduces the activity of the membrane [90]. The primary membrane methods are listed in Table 6.

Table 6 Main membrane methods and their advantages and disadvantages for the phenol degradation process in wastewater

Method	Merits	Demerits	References
Reverse osmosis and nanofiltration	Easy to operate, low maintenance cost, and high reaction efficiency	Membrane fouling and the need for diluted samples	[28, 29]
Pervaporation	Highly selective technique for phenol and low energy Consumption	Smaller sample quantities and low separation	[30, 31]
Extractive membrane bioreactor	Possibility of treating high quantities of samples and programming membrane operating conditions	Requirement of space for equipment and need for constant maintenance	[32]
Emulsion liquid membrane	Combined separation processes and high-efficiency	Low reuse rate and reproducibility	[33, 34]
Membrane distillation	Milder pressure and temperature conditions	Low membrane selectivity for phenol and high-cost	[33, 35–37]
RO, NF, and UF	It is highly efficient, low cost, and operates under different concentration, temperature, and pressure conditions	Treatment time and cost with nanomaterials	[38–40]

4.2.5 Extraction method

This technique is based on extracting residual phenol from water samples using eutectic solvents or specific types of surfactants. Extraction systems are set up to handle high volumes of phenol [91]. This technique can also be used as a preliminary step to other combined processes, usually in more concentrated samples, and has a high efficiency in recovering phenols [92]. A disadvantage of the method is the experimental time, which can be pretty long in some cases of high concentrations [93].

4.2.6 Adsorption processes

Using adsorption techniques to remove phenol from the aqueous medium also presents an excellent alternative for removing this residue [94]. When an adsorbent material is added to contaminated water samples, phenolic compounds adsorb to the material's surface. This can then be washed with methanol, producing a phenol mixture [95]. A significant advantage of this technique is its simplicity of operation, resulting in efficient and rapid removal of these products [96]. A disadvantage is that most adsorbents require thermal activation of the material and reactivation after use with chemical reagents [97].

4.2.7 Oxidation

Chemical oxidation efficiently removes Phenol from wastewater, using strong oxidants to degrade organic compounds into smaller or easily removed molecules [98]. The most common oxidants are ferrates, permanganates, peroxides and ozone, and their use varies depending on the pH range, temperature and system specifications [99]. A particularity of this method is phenol degradation, even at low concentrations [100]. This process can be combined with other treatment techniques to improve phenol removal efficiency [101]. The advantages involve the cost and efficiency of the method concerning other processes that require equipment assembly and constant maintenance. A disadvantage is using chemical reagents during the steps, which can lead to more significant waste generation and, consequently, a demand for treating these materials. Thus, concerns about the disposal and treatment of these wastes can make this technique more complex [102].

4.2.8 Ozonation

The ozonation process is based on heterogeneous catalysis using metals as catalysts. The degradation of phenols with ozonation leads to the formation of free radicals with the help of metal catalysts [103]. One of the advantages of the ozonation process is the operating time and catalytic efficiency. Although noble metal catalysts have cost disadvantages, they can be replaced by less expensive transition metals [104].

4.2.9 Distillation method

This method is based on differences in the boiling points of phenolic compounds and their relative volatilities [105]. The advantage of the technique is its efficiency on concentrated samples of phenolic compounds and large volumes of wastewater [106]. Disadvantages include low yield on samples with low phenol concentrations and higher operating costs [107].

4.2.10 Biological treatment

Based on aerobic and anaerobic processes of microorganisms, this technique presents itself as an excellent alternative for treating and degrading phenol in water. Advantages such as low operating costs and versatility in selecting different microorganisms make the technique viable [108]. Another positive aspect is the production of biodegradable materials that do not pose a pollution risk to the soil, making these processes an efficient and environmentally sound choice for treating pollutants [109]. A drawback is that these processes are only effective at low concentrations, as a high concentration of phenols interferes with the degradation activity of microorganisms. Thermal and acidic conditions must also be adapted and controlled for each process [110].

5 Recent technological advances

More effective and sustainable systems for phenol removal from wastewater are being developed. Diverse and improved methods are being developed to address the problems associated with phenol in municipal and industrial wastewater.

Nanotechnology provides new perspectives for wastewater treatment, with nanomaterials based on graphene (Gr) standing out for their excellent magnetic, electrical, optical, mechanical and catalytic properties, having a large surface area and high purity [111–113]. Graphene, a two-dimensional material known for its remarkable mechanical, electrical and thermal properties, has emerged as a promising choice for environmental applications, including the treatment of contaminated water [114]. Carbon nanotubes and nanocomposites exhibit greater surface area and chemical reactivity, making them highly effective at adsorbing and degrading organic and inorganic contaminants, including phenol [115]. Furthermore, a relatively small number of researchers have recently explored using green synthetic nanoparticles in wastewater purification, indicating a promising advancement in the search for more effective and sustainable solutions [116, 117]. This broad, integrated approach enables a deeper understanding of emerging trends and future opportunities in the field of wastewater treatment, helping to guide future research and engineering practices aimed at continually improving water quality and preserving the environment.

On the other hand, recent studies in the application of artificial intelligence (AI) have been contributing to phytobial remediation involving the use of machine learning algorithms and models to analyze and interpret data related to plant growth and the effectiveness of removing contaminants from plant bodies. 'water [118]. Furthermore, AI enables real-time analysis of large volumes of data, allowing for early detection of phenol concentration spikes and rapid adaptation of treatment strategies. The successful adoption of these technologies drives further research and innovation in structural models to overcome the limitations faced in the effective operation within water treatment industries [119]. Although AI models help treat wastewater with phenol, their disadvantages cannot be overlooked. Challenges such as the demand for large volumes of data, poor management of this data, low interpretability of the models, limited reproducibility, and lack of transparency pose significant obstacles to their effective use [120].

Ultrasound technology has attracted attention as a promising approach to improving the efficiency of wastewater treatment [121–123]. In this process, high-frequency ultrasound is applied to contaminated water, generating cavitation bubbles imploring under pressure [124–126]. It breaks these compounds into smaller fragments by generating explosions that create micro-liquid jets and shock waves, facilitating their treatment. [127, 128]. However, its high energy consumption represents a significant disadvantage, resulting in high operating costs [129].

Furthermore, in waters with a high concentration of suspended solids, the effectiveness of the technology may be compromised due to obstruction of cavitation bubbles [130–132]. Despite these limitations, Ultrasound Technology is widely applied in several industries, such as chemical products, to treat effluents contaminated with phenols [133, 134]. A real example of this application is found in chemical factories, where ultrasound fragments organic compounds, allowing them to be removed by subsequent treatment processes such as flocculation, filtration or sedimentation [135, 136].

Activated Carbon Technology is an established option for removing organic contaminants, including phenols, from water [137, 138]. Recent advances in technology have resulted in the development of more effective forms of activated carbon, such as granular activated carbon (CAG) and powdered activated carbon (PAC) [139–141]. These advanced forms have an even greater adsorption capacity and improved phenol removal efficiency, thus contributing to improved water quality in a variety of industrial and environmental applications [142, 143]. Regarding the advantages of Activated Charcoal, its effectiveness in removing flavors and undesirable odors, eliminating contaminants such as heavy metals, toxic gases, and reducing natural organic matter, which limits the formation of by-products, stands out [144–146]. However, Activated Charcoal also has disadvantages. Its large-scale use can be expensive [147, 148]. Activated Carbon's adsorption capacity is limited, meaning it can only trap a limited amount of pollutants before becoming ineffective [149, 150]. Therefore, Activated Carbon Technology plays a crucial role in mitigating climate change by demonstrating its value and effectiveness in real-world applications.

Supercritical water gasification is a new way to treat phenol in wastewater because it subjects the water to supercritical conditions (high pressures and temperatures above the critical point of water) to create a reactive medium [151]. The phenol then combines with water vapour and breaks into less harmful compounds [152]. Supercritical water gasification is still in the research and development stage. Although it offers benefits such as eliminating the need for additional chemical products, reducing costs, and minimizing the environmental impact of treating polluted wastewater, it is still a work in progress [153].

Finally, ozonation is a sophisticated approach to address phenol removal in wastewater due to its ability to oxidize organic molecules. In the ozonation process, ozone (O_3) is introduced into the water to react with phenol, resulting in oxidation and the formation of less hazardous chemical compounds (such as phenic acid and carbon dioxide) [154, 155]. This process has several advantages, including adaptability, speed of reaction, and the absence of harmful by-products [156]. Ozone is an oxidant that can eliminate a wide range of organic contaminants in wastewater. Challenges to overcome include the equipment cost needed to produce and administer ozone [157, 158].

6 Future trends and opportunities

The methods presented in the work show a vital concern with chemical waste treatment that has gained momentum in recent research [159]. The high volume of work highlighting the use and concepts of removing phenol from wastewater confirms this pursuit of developing other innovative and low-cost techniques for handling organic substances [160, 161]. The environmental impacts of generating these materials show the need for this ecological responsibility, which must take even more excellent shape in industry, especially in the petrochemical and pharmaceutical areas [162]. Among the techniques and processes presented in this work, innovations in adsorption techniques and using enzymes or microorganisms stand out. In adsorption, innovations in the materials used and their association with nanotechnology stand out, which, in addition to being innovative and technological, has a high rate of efficiency and reproducibility [163, 164]. The economic factor also increases the spotlight in business sectors on this technique, which leads to a demand for improving its stages. In the case of enzymes, many current works tested have their use with immobilization supports, where different materials are tested to increase their thermal and pH stability, maintain their catalytic activity, and the need for low concentrations of enzymes [165, 166]. From this optimization that the support provides to the biocatalyst, properties such as high selectivity and yield under environmental conditions are added to the use of enzymes for handling residual phenols in water samples [167–169]. As a result, several research groups focus on improving, discovering, and optimising efficient adsorbents and ideal enzymatic solutions, both for processes combined with others and for their single technique.

7 Environmental, regulatory aspects, and financial viability

The primary sources of water pollution are agricultural activities, sewage systems, and commercial, domestic, and industrial waste discharge. The sources generate about two million tons of wastewater daily [170]. One of the most prevalent toxic substances is phenol, a critical component in producing pesticides, dyes, pharmaceuticals, and plastics [171]. Phenol production has reached an annual volume of 8.9 million tons, making it a priority pollutant due to its high toxicity even at minimal concentrations [172]. Exposure to phenol, which can occur through the skin, oesophagus, and respiratory tract, poses potential risks to the central nervous system, liver, and kidneys [173].

Phenol exists in the atmosphere, mainly in the gas phase [174]. The atmospheric half-life of phenol varies from 2.28 to 22.8 h, depending on conditions and reactions with the hydroxyl radical [175]. Highly soluble in water (88,360 mg/L) and most organic solvents, phenol acts as a weak acid (pKa = 9.99), and its toxicity is influenced by environmental pH [176–178]. The slower penetration of the phenolate ion through biological membranes than the neutral molecule explains the inverse relationship between water pH and phenol toxicity—higher water pH correlates with lower toxicity.

The US Environmental Protection Agency (US EPA) study ranked phenol eleventh among one hundred and twenty-six chemical pollutants [179, 180]. Concentrations above 50 ppm are associated with health problems such as neurological damage, kidney dysfunction, and decreased blood haemoglobin levels [181]. Phenolic derivatives, such as 2,4-dichlorophenol, exhibit mutagenic properties and cause liver damage at concentrations as low as 0.002 ppm [182]. Consequently, the US EPA has set the limit for phenol at 0.001 ppm in drinking water and 0.5 ppm in wastewater [183]. Because of its high toxicity, phenol has become a critical quality parameter closely monitored by regulatory agencies, especially concerning industrial effluents [184]. Various methods have been proposed for treating phenol in wastewater, including extraction, adsorption, chemical oxidation, biochemical oxidation, and electrochemical processes. Each technique has significant drawbacks regarding cost, by-product formation, and incomplete removal

[185]. To ensure effectiveness and economic viability, selecting the appropriate effluent extraction and treatment technologies is critical [186, 187].

In 2015, the United Nations Sustainable Development Goal 6 (UN SDG6) highlighted the need to recycle wastewater to ensure water availability for individuals [188, 189]. Notably, the use of treated wastewater in agriculture is a promising application to address the scarcity of water resources, mainly caused by climate change and the increase in water consumption resulting from human activities [190].

However, the challenges, limitations, and opportunities in successful wastewater reuse have been widely discussed by various experts who are trying to achieve sustainable wastewater recycling [191]. In many regions of the world, environmental restrictions, aggravated by recurrent and prolonged droughts due to the effects of climate change, have led communities to explore the potential of treated waters as an alternative to meet their water needs, especially in applications that do not require the strict drinking water quality standards [192–195].

Yet, according to Chojnacka et al., anti-pollution legislation has significantly reduced discharges of harmful materials into coastal waterways over the past 40 years [196]. Accordingly, the popularity of wastewater reuse has increased across the planet, influencing several countries to adopt local legislation to regulate the quality of water for reuse to reduce risks to health and the environment [197]. In summary, regulatory laws for wastewater treatment are being updated and adapting to environmental and economic demands, seeking to mainly benefit the planet and safeguard the future population [198].

8 Sector applications and specific challenges

Phenol and its derivatives do not occur naturally in water. Their presence is invariably associated with human activities, particularly in industries (e.g., pharmaceuticals, mining, petrochemicals, and paper and pulp) [199]. The concentration of phenolic compounds in industrial wastewater typically ranges from 800 to 2000 ppm [200]. Out of the various treatment techniques, biodegradation has emerged as a notable method due to its environmental soundness and cost-effectiveness. Biodegradation is based on the concept that certain microorganisms can utilize phenol as their sole energy source and carbon. Studies indicate that indigenous bacterial species adapted to specific effluents excel in overcoming competition from other organisms, emphasizing the need to identify novel phenol-degrading bacterial species [201]. Two bacterial strains, *Pseudomonas aeruginosa* and *Pseudomonas pseudomallei*, were used to treat wastewater from the pharmaceutical industry. The *P. aeruginosa* strain showed a 26.16 mg L-1 h-1 phenol degradation rate. TP. *pseudomallei* strain showed a rate of 13.85 mg L^{-1} h^{-1}, demonstrating high efficiency in degrading phenol from the specific effluent [202]. One hundred and eight rhizobial strains were isolated from wild legumes in a mining tailings area in Shaanxi Province, China. The strain CCNWTB701, isolated from *Astragalus chrysopteru*, showed remarkable efficiency in degrading phenol, achieving a 99.5% reduction from an initial concentration of 900 ppm within a 62-h interval [203].

Because of the low permissible limit for phenol as a pollutant, developing a sensitive and reliable sensor for monitoring this substance is essential. Colourimetric, chromatographic, or electrochemical methods can be used. In contrast, chromatographic methods have demonstrated the ability to achieve detection rates as low as four ppt when using single-drop microextraction and syringe derivatization [204]. A potential challenge is that much of the research on phenol removal in wastewater remains limited to laboratory conditions.

8.1 Innovations in materials and analytical methods

Innovations in materials and analytical methods for treating wastewater containing phenol have been fundamental in searching for more efficient and sustainable solutions [205]. In addition, materials functionalized with specific groups have excelled in the selectivity and effective removal of phenol in aqueous environments [206].

Continued research has led to promising new materials [207]. Some of these innovative materials include nanomaterials that have stood out. Mal oxide nanoparticles such as graphene, titanium dioxide, and zinc oxide have demonstrated significant efficacy [208–211]. Their adsorptive and photocatalytic properties effectively remove phenol, contributing to water purification [210].

Another promising category is metal–organic frameworks (MOFs), structures characterized by high porosity and surface area [212, 213]. These materials are effective in both the adsorption and degradation of phenolic compounds in wastewater [214]. The unique porosity of these MOFs makes them highly efficient in this treatment, providing an innovative approach to removing this contaminant [215].

Porous silicon carbide is characterized by its porous structure. Also, the remarkable chemical stability of porous silicon carbide contributes to the material's durability during the treatment process [216]. These innovative alternatives, coordination polymers, functional hydrogels, hierarchical porous carbons, and magnetic compounds, offer diverse options to meet specific needs in water treatment systems and provide more environmentally friendly solutions [217, 218]. The constant evolution of these materials reflects the continuous effort to develop new innovative, economical, and sustainable technologies for this research field.

Regarding analytical methods, new technologies have contributed to more accurate and real-time monitoring of phenol concentrations in wastewater [219]. Techniques such as high-performance liquid chromatography (HPLC), UV–Vis spectroscopy, and electrochemical methods have been improved to provide more sensitive and rapid analysis [220]. In addition, integrating advanced analytical methods, such as mass spectrometry and sensor-based techniques, allows for a more comprehensive assessment of phenol characteristics and transformations during treatment [221].

Innovative analytical methods are crucial in the treatment discussed here [222, 223]. Near-infrared spectroscopy (NIR) is a technique that offers rapid and non-destructive analysis [224]. In addition, gas chromatography coupled to mass spectrometry (GC–MS) offers high sensitivity and selectivity, allowing detailed analysis and precise identification of phenol, contributing to a deeper understanding of the components present [225].

In the field of sensors, notable advances include electrochemical sensors that, when specific for phenol, allow real-time monitoring [226]. In addition, environmental mass spectrometry (DART-MS) offers direct analysis of phenol in wastewater, eliminating the need for sample preparation and optimizing time and resources [227].

In addition, nanomaterial-based sensors using gold nanoparticles or carbon nanotubes show increased sensitivity in the detection of phenol [228–231]. Applying biosensory methods, such as enzymes or living organisms, or the selective detection of phenol represents a specific and environmentally friendly approach [232]. Finally, real-time UV–Vis spectroscopy can be used to monitor changes in phenol concentration during treatment, providing immediate insight into the effectiveness of ongoing processes.

These innovations in analytical methods improve the accuracy and sensitivity of phenol detection and facilitate the implementation of new strategies for treating wastewater contaminated with this compound [233]. Overall, the synergy between innovations in adsorbent materials and advances in analytical methods ultimately contributes significantly to environmental protection and public health.

8.2 Global and comparative perspectives between technologies

The choice of the most appropriate method for treating phenol-contaminated wastewater depends on the specific characteristics of the water. Out of the various options available, adsorption with activated carbon is an effective method due to its porous surface, which has an affinity for phenol [234]. Bioremediation, using microorganisms specialized for phenol degradation in aerobic or anaerobic processes, is an efficient approach [235]. Electrocoagulation, which uses electric fields to promote coagulation and phenol removal, is also recognized as an effective technique [236].

The technologies surrounding this issue are promising, and their results have the potential to change the current scenario significantly. In treating water contaminated with phenol, technological innovations have played a crucial role in the search for more effective and sustainable solutions. Various approaches, from traditional methods to state-of-the-art advances, have been explored to address the challenges posed by phenol in aquatic environments, offering several critical perspectives for progress in this field. The finding that the treatment method choice depends on the specific characteristics of the water, phenol concentrations, and environmental requirements highlights the need for a multidisciplinary approach. The diversity of techniques, from adsorption to bioremediation and electrocoagulation, highlights the importance of tailoring strategies to optimize treatment efficiency.

8.3 Practical applications of phenol wastewater treatment technologies

Several practical alternatives have been developed over the years for removing phenols, such as electrochemical oxidation, ozonation, UV/H_2O_2, Fenton reaction, and enzymatic treatment, among other processes [237–240].

In this sense, electrochemical oxidation (EO) uses electrical current or potential difference between two electrodes (anode and cathode), with which hydroxyl radicals or oxidizing species can be generated and used for the oxidation of pollutants [241]. The advancement of technology (EO) is no longer limited to treating simulated wastewater in a laboratory environment. It has currently been applied to the practical treatment of various sewage. However, its large-scale implementation still faces limitations due to high energy consumption [242, 243]. With the limitations of conventional treatment procedures, there is a pressing need to develop innovative and more environmentally acceptable methods for removing contaminants [244].

Still, in this field of alternative technologies, based on biological treatment principles, enzymatic treatments of an enzyme as a biocatalyst transform phenolic compounds, thus promoting their efficient removal from water [245]. Enzymes oxidize pollutants into simpler organic compounds [246]. Furthermore, enzymes are biological catalysts that accelerate biochemical reactions in living organisms and can be extracted from cells to facilitate various processes of great commercial importance [247]. The degradation of pollutants is rapid and selective [248]. Enzymes further increase their potential when immobilized on solid support[249].

As the most prominent example, peroxidases are enzymes widely used in phenol remediation due to heme cofactor or redox-active cysteine/selenocysteine residues in their active sites [250–252]. Several studies have investigated peroxidase and proven its efficiency in removing phenol from contaminated water. Kurnik et al. analyzed the application of peroxidases produced from potato pulp waste byproducts in removing phenol from synthetic and industrial wastewater. The phenol removal efficiency reached 95% with an initial phenol concentration of 94.11 mg/L, where enzymes maintained their activity over a pH range of 4 to 8 and remained stable over a wide temperature range [253].

In another study, peroxidases extracted from an invasive plant *(Prosopis juliflora)* were used for phenol remediation with an initial phenol concentration of approximately 40 mg/L, where crude peroxidases were found capable of degrading phenol in 30 min and with higher efficiencies. to 90% for textile and leather industrial wastewater [254]. This study showed that agricultural residues for different products could be used as an essential source of potent enzymes that are highly efficient in remediating phenolic compounds [255]. In summary, wastewater contains several pollutants that are harmful to life, including phenol in different concentrations [256].

The literature presents several alternatives for removing phenols in wastewater, with advantages and disadvantages. Few are applied on an industrial scale, but some previously presented are promising, as with enzymes. Depending on the concentration of pollutants, the type of treatment method can be selected, considering the cost-effectiveness of the treatment chosen systems. Therefore, it is imperative to analyze the components present in wastewater and understand their levels to use the most efficient treatment for a given sector.

9 Conclusion

The treatment of phenol-containing wastewater has proven to be a fascinating and promising field in modern science and technology. The convergence of unique properties opens up a wide range of applications in different fields, as demonstrated in this study, but also triggers a fascinating synergy between these elements. The bibliometric analysis highlights the growing interest and dynamism surrounding this domain by revealing a notable increase in publications on this topic at an accelerated rate. The publication "The use of zero-valent iron for groundwater remediation and wastewater treatment: A review" was highlighted as the most influential in the field, providing a comprehensive and fundamental overview for investigations. The results of the bibliometric analysis not only point to China as the leader in terms of article production, number of citations, and institutions involved but also highlight the notable collaborations between the prominent authors in this dynamic scenario. The diversity of article publication areas, revealing applications in different contexts and a multidisciplinary approach, highlights the breadth and relevance of treating wastewater containing phenols. Network analysis of the main keywords identified thematic clusters, with "phenol", "degradation", and "removal" being the most salient, signalling crucial areas of research. Given these advances and highlighted areas, future research in this area should prioritize wastewater treatment and feedstock diversification. This focus is essential to address significant challenges such as production costs, stability, and durability of treatment processes.

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Data availability For data availability inquiries, you can contact jcs@unilab.edu.br. All data used for this research will be made available to the journal as upon request.

Declarations

Competing interests The authors declare no competing interests.

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