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Emerging Trends and Knowledge Structure of Advanced Oxidation Processes for Chemical Industry Wastewater Treatment: A Bibliometric Mapping Study

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ABSTRACT

Advanced Oxidation Processes (AOPs) are increasingly applied to chemical industry wastewater because they generate reactive radical species capable of degrading refractory and toxic organic pollutants that conventional biological treatment cannot fully remove. However, the development, knowledge structure, and emerging directions of this specific research field remain insufficiently mapped. This study aims to analyze the scientific landscape, research evolution, and thematic trends of AOP-based treatment for chemical industry wastewater through bibliometric mapping, and to identify the specific knowledge gaps that distinguish this sectoral focus from prior, more broadly scoped bibliometric reviews. An initial pool of 2,017 records was retrieved from the Web of Science database using keyword combinations related to wastewater, chemical industries, and AOPs, then screened and refined to 1,000 documents for analysis. Bibliometrix, VOSviewer, CiteSpace, and OriginLab were used to examine publication trends, collaboration networks, keyword co-occurrence, citation and co-citation patterns, thematic evolution, and conceptual structures. The findings show a marked increase in publications since 2017, with China as the leading contributor in publication output and international collaboration. Dominant themes include pollutant degradation, photocatalysis, ozonation, electrochemical oxidation, and radical-based mechanisms, while emerging topics involve persulfate activation, carbon-based materials, nanocatalysts, and emerging contaminants such as pharmaceuticals and personal care products. The field remains grounded in radical chemistry while shifting toward integrated, hybrid wastewater treatment systems. This study provides a structured, sector-specific overview of research gaps and future directions to support the sustainable, economically feasible implementation of AOPs in chemical industry wastewater treatment.

Keywords: Advanced Oxidation Processes; Bibliometric Analysis; Chemical Industry Wastewater; Pollutant Degradation

1. Introduction

Conventional wastewater treatment processes still face limitations in completely eliminating pathogens, particularly bacteria, viruses, and protozoa, which pose potential health risks. Advanced Oxidation Processes (AOPs) have proven effective in reducing pathogen levels through the formation of highly reactive hydroxyl radicals. However, the ability of AOPs to prevent the regrowth of pathogenic microorganisms after treatment remains incompletely understood. Research comprehensively assessing the effectiveness of various AOPs, such as ozonation, photocatalysis, and hybrid AOPs, in achieving water quality standards for agricultural irrigation is still very limited. Furthermore, the use of metal catalysts such as TiO₂, Fe, Mn, and Ag in AOPs has the potential to pose a risk of bioaccumulation in soil, plants, and ultimately the human food chain, but this aspect has not been studied in depth (Oluoch et al., 2024).

Industrial wastewater generally contains refractory organic compounds that are difficult, if not impossible, to biodegrade through conventional treatment processes. Advanced Oxidation Processes (AOPs) technology has been recognized as an effective method for degrading these compounds through the formation of highly reactive hydroxyl radicals. However, the application of AOPs on an industrial scale still faces various challenges, including high energy requirements, complex operating systems, and the lack of clear sustainability standards for long-term implementation. Furthermore, the lack of pilot-scale field research testing the performance of AOPs on real wastewater creates a gap between laboratory results and practical industrial applications. Another obstacle is the limited availability of inexpensive, efficient, and environmentally friendly catalysts, which are crucial for the sustainability of this technology. Furthermore, evaluation of the economic, environmental, and policy aspects related to the application of AOPs is still very limited, requiring multidisciplinary studies to ensure the effective and sustainable implementation of this technology (Silva, 2025).

Wastewater now contains many emerging pollutants, such as pharmaceuticals, cosmetic ingredients, pesticides, and hormones, which are difficult to decompose using conventional systems like activated sludge. The presence of these compounds poses new challenges in wastewater treatment due to their persistent nature and potential toxicity to the environment. Although Advanced Oxidation Processes (AOPs) have demonstrated high performance in degrading various pollutants, most studies have been conducted on synthetic solutions rather than on real wastewater, so their effectiveness in the field remains uncertain. The oxidation products formed during AOP processes are sometimes more toxic than the original compounds, but this aspect has rarely been the focus of research. Other challenges include high operational costs and operational complexity, which make AOPs economically inefficient for widespread application. Therefore, a combination of AOPs and biological processes needs to be developed to achieve more optimal, efficient, and sustainable treatment results (Satyam & Patra, 2025). Previous bibliometric studies have shown that research on wastewater treatment using advanced oxidation processes has increased globally, reflecting the growing relevance of AOPs in environmental pollution control and water treatment technologies (Garrido-Cardenas et al., 2020). Based on these developments, a focused bibliometric mapping study is needed to examine the knowledge structure, collaboration patterns, and emerging trends of AOP-based treatment in chemical industry wastewater.

Table 1. Research Gap Analysis in AOP-Based Industrial Wastewater Treatment.

Data Sources	Year Range	Software Used	Type of Industry	Type of Environmental Issues	Reference
Scopus	2010-2024	VOSviewer (bibliometric mapping)	Car wash industry	Car wash wastewater pollution (COD, heavy metals, surfactants)	Alazaiza et al. (2024)
Web of Science	2019-2020	Bibliometrix (R), ScientoPy, Excel, MS-Access, VOSviewer	General wastewater research, multiple sectors	Wastewater environmental issues (sewage, effluent, virus removal, contamination)	Bador, et al. (2020)
Web of Science	2001-2021	VOSviewer 1.6.17 (cooperation & keyword networks)	Chemical, industrial, environmental engineering sectors	Organic pollutants: pesticides, PAHs, phenols, dyes, pharmaceuticals, endocrine disruptors	Dos Santos, et al. (2022)

Data Sources	Year Range	Software Used	Type of Industry	Type of Environmental Issues	Reference
Scopus	2015-2025	VOSviewer 1.6.20 (co-authorship, keyword clusters)	Wastewater treatment, industrial & municipal AOP systems	Wastewater pollutants: oil, hydrocarbons, TKN, chemical contaminants; AOP degradation issues	Ata (2025)
Web of Science	2000-2023	VOSviewer (co-occurrence, co-authorship, clustering).	Wastewater treatment industry (municipal & industrial)	Wastewater contamination (organic, inorganic, pathogens)	Urbina-Suarez et al. (2024)
Scopus & Orbit Express (patents)	1991–2022	ITELLIXIR ORBIT for data visualization	Focuses on AOPs for various waste types	Pollutant degradation issues: organic, emerging contaminants, heavy metals, hazardous by-products	Montenegro-Apraez & Machuca-Martínez (2025)
Web of Science	1990-2019	VOSviewer, CiteSpace, HistCite, Excel	Textile industry, pharmaceutical industry, landfill leachate, phenol wastewater	Pollution issues: textile dyes, toxic pollutants, phenolic compounds, landfill leachate, recalcitrant pollutants	Raji & Mirbagheri (2021)
Web of Science	1991–2021	Microsoft Excel 2016 (bibliometric data processing)	Textile industry (dyeing, finishing, printing)	Water contamination: dyes, pigments, organic load, toxic chemicals, decolorization issues	Islam et al. (2024)
Web of Science (WoS)	2000–2023	VOSviewer and Bibliometrix R-package for bibliometric mapping.	The eyewear industry	Plastic pollution, eyewear industry waste, sustainability materials (bio-based, biodegradable), circular economy in eyewear	Kemeç & Altınay (2023)
Web of Science (WoS)	2020-2024	CiteSpace (v6.3.R1) and VOSviewer (v1.6.18)	Wastewater-producing industries	Wastewater pollution, organic pollutants (pharmaceuticals, dyes, pesticides), micropollutants, water quality & environmental standards	Brdarić et al. (2024)

As summarized in Table 1, the closest related work is Dos Santos et al. (2022), who examined electrochemical degradation of organic pollutants across chemical, industrial, and environmental engineering sectors more broadly, using Web of Science data from 2001–2021 and VOSviewer only. Other bibliometric studies listed in Table 1 have instead concentrated on specific non-chemical sectors, such as the car wash industry (Alazaiza et al., 2024), the textile industry (Raji & Mirbagheri, 2021; Islam et al., 2024), or the eyewear industry (Kemeç & Altınay, 2023), or on wastewater treatment in general without a defined industrial focus (Bador et al., 2020; Ata, 2025; Urbina-Suarez et al., 2024; Montenegro-Apraez & Machuca-Martínez, 2025; Brdarić et al., 2024). None of these studies specifically delineates chemical industry wastewater as the unit of analysis, nor do they combine Bibliometrix, VOSviewer, CiteSpace, and OriginLab within a single mapping framework. The present study addresses this gap by narrowing the bibliometric scope specifically to AOP-based treatment of chemical industry wastewater and by integrating descriptive, network, thematic, conceptual-structure, and citation-based analyses to produce a more sector-specific and methodologically comprehensive knowledge map than the studies listed in Table 1.

It should be noted that the specific technical and health-related concerns raised above—including pathogen regrowth after AOP treatment, the bioaccumulation risk of metal-based catalysts (TiO₂, Fe, Mn, Ag) in the soil–plant–food chain, and compliance with irrigation water-quality standards—cannot be answered directly

through bibliometric mapping, which does not generate new experimental or toxicological data. These concerns are presented here to illustrate the practical stakes that motivate continued research on AOPs, and are examined indirectly in this study by tracking how frequently, and how recently, related sub-topics appear in the analyzed literature. Based on this scope, the present study aims to: (1) map the annual publication trend and the country-, institution-, and author-level collaboration structure of AOP-based chemical industry wastewater research; (2) identify the dominant and emerging keyword clusters and thematic structure of the field through co-occurrence, thematic-map, and conceptual-structure analyses; and (3) examine the citation and co-citation structure to identify the most influential documents and intellectual foundations shaping this research area. The technical and health-related concerns raised above are revisited in the Conclusion as priority directions for future experimental and field-based research.

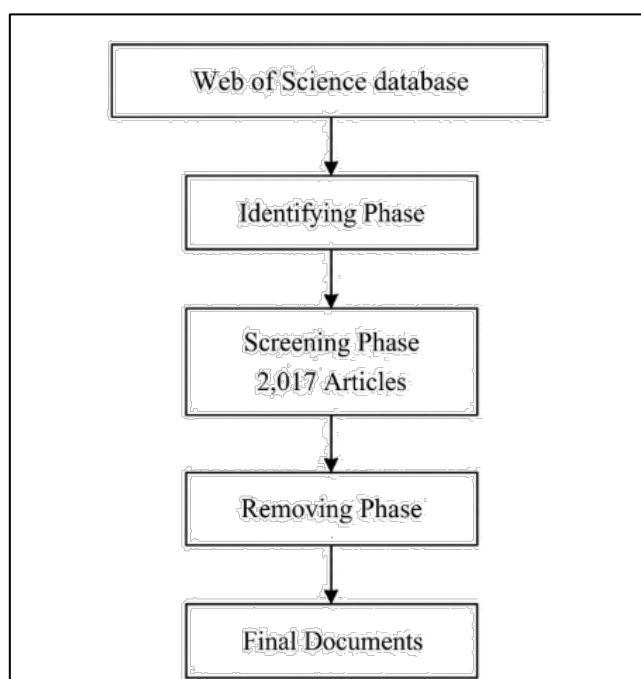


Figure 1. Bibliometric analysis workflow

2. Methods

Bibliometric analysis was employed in this study to systematically examine the development, knowledge structure, and emerging research trends in AOP-based treatment of chemical industry wastewater. This approach enables the quantitative mapping of publication patterns, collaboration networks, thematic evolution, and conceptual relationships within a specific research field (Fitria et al., 2023; Prayogo et al., 2025; Prayogo et al., 2026a; Prayogo et al., 2026b; Brahmana et al., 2026). As illustrated in Figure 1, the data collection process began with the retrieval of scientific publications from the Web of Science database. The identification stage was conducted using a Boolean search strategy combining terms related to wastewater, chemical industries, and advanced oxidation processes, including “wastewater,” “chemical industry,” “industrial wastewater,” “pharmaceutical industry,” “Advanced Oxidation Processes,” “AOPs,” “hydroxyl radicals,” “reactive oxygen species,” “UV/H₂O₂,” “ozonation,” and “Fenton reaction.” The literature search was conducted on 19 October 2025. As shown in Figure 2, eligible documents were limited to articles, review articles, and conference proceedings papers published in English and Indonesian. The identification stage retrieved 2,017 initial records from the Web of Science database. Title, abstract, and keyword screening narrowed this pool to 1,793 records, and a subsequent full-record and data-extraction screening—applied to confirm topical relevance to AOP-based chemical industry wastewater treatment and to remove duplicate, incomplete, or out-of-scope records—yielded a final dataset of 1,000 documents. These final documents were subsequently used for bibliometric mapping to identify research trends, scientific collaboration patterns, thematic clusters, and knowledge structures related to the application of AOPs in chemical industry wastewater treatment.

Figure 1 illustrates the bibliometric workflow used in this study. The process began with data retrieval from the Web of Science database, selected for its broad literature coverage and indexing quality. During the identification phase, articles matching the initial search terms were collected. These records were then screened based on publication year, topic relevance, metadata completeness, and suitability to the theme of Advanced Oxidation Processes (AOPs) in chemical industry wastewater treatment. The selected articles were further processed through bibliographic data extraction, data cleaning, keyword normalization, and metadata clustering. The final documents that met all criteria were then used for bibliometric analysis, ensuring that only relevant publications with strong analytical value were included in the mapping process.

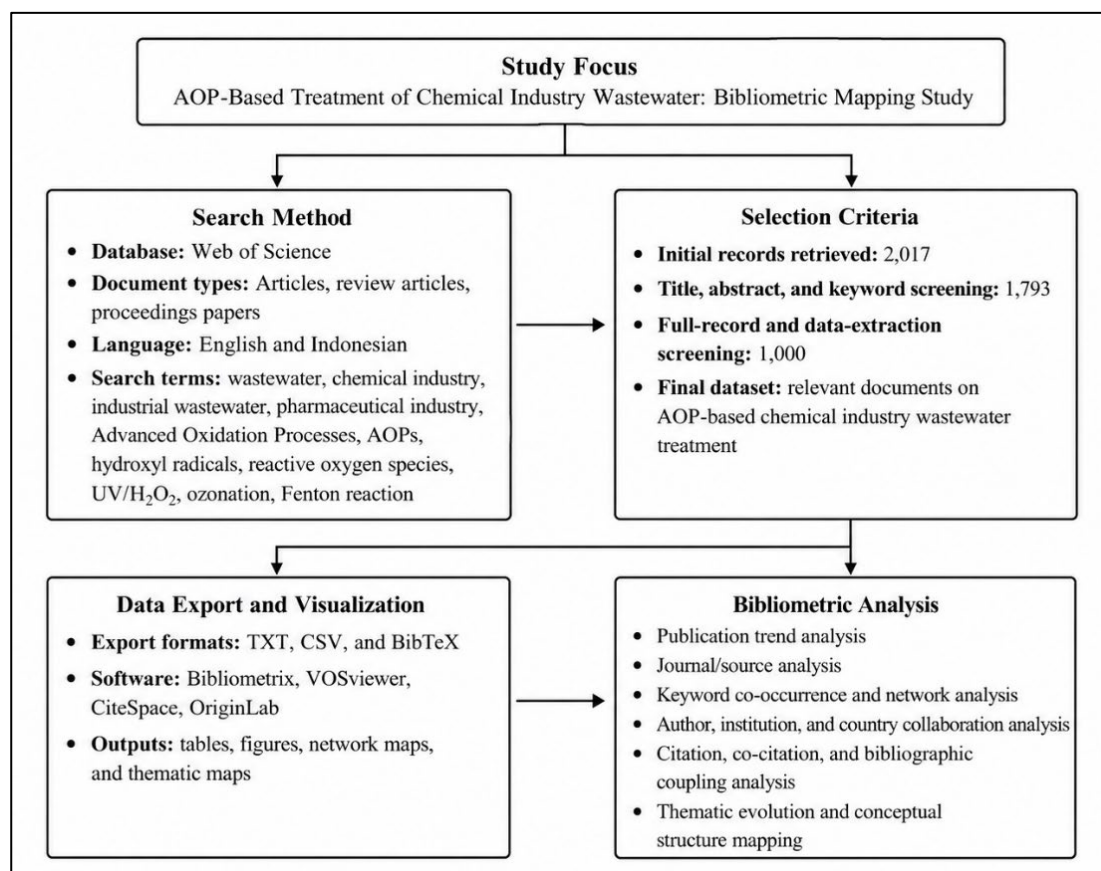


Figure 2. Bibliometric analysis workflow, bibliometric analysis framework, and data processing workflow

Figure 2 presents the methodological framework of the bibliometric analysis conducted in this study. The workflow begins with the search method, which defines the Web of Science database as the data source, the selected document types, the language criteria, and the keyword strategy used for data retrieval. The selection criteria describe the initial number of records retrieved from Web of Science, followed by filtering based on titles, abstracts, and keywords to ensure the relevance and quality of the documents included in the analysis. The keyword section outlines the Boolean search combinations used to capture studies related to chemical industry wastewater and Advanced Oxidation Processes (AOPs). After the screening process, the selected data were exported in compatible formats, such as .txt and .csv, for further processing and visualization. The bibliometric analysis stage included the examination of publication trends, journal distribution, keyword networks, author and institutional collaboration, citation structures, thematic evolution, and bibliographic coupling or co-citation patterns. Overall, this framework illustrates the sequential process from data retrieval and screening to visualization and interpretation of the bibliometric results.

Bibliometrix was used to support descriptive bibliometric analysis, thematic mapping, and conceptual structure analysis (Aria & Cuccurullo, 2017). VOSviewer (version 1.6.21) was applied to visualize co-authorship networks, keyword co-occurrence, citation maps, and co-citation relationships (Van Eck & Waltman, 2010). CiteSpace (version 6.3.R1) was used to identify keyword clusters, timeline visualization, and the intellectual structure of the research field, configured with a 1-year time-slicing interval and a g-index selection ($k = 25$, $LRF = 2.5$, $L/N = 10$, $LBY = 5$, $e = 1.0$) (Chen, 2006).

3. Result and Discussion

This section presents a bibliometric analysis of scientific publications obtained from the Web of Science (WoS) database. Data were analyzed using Bibliometrix for descriptive analysis and thematic mapping, OriginLab for statistical visualization, VOSviewer for bibliometric network mapping including Co-Authorship (authors, organizations, countries), Co-Occurrence (all keywords), Citations (documents), and Co-Citation (cited references), and CiteSpace for citation analysis and the intellectual structure of the research.

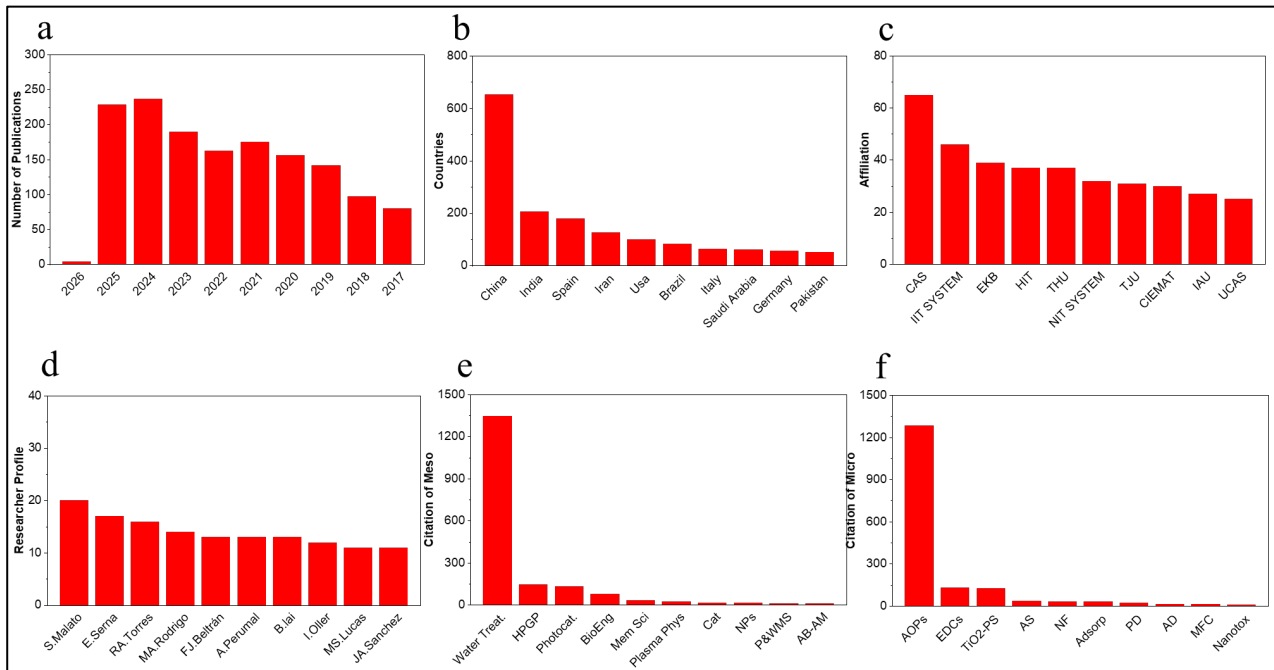


Figure 3. Descriptive Analysis of Publications (a) number of Publications; (b) countries; (c) affiliation; (d) research profile; (e) citations of meso; (f) citations of micro

Figure 3 presents the descriptive bibliometric profile of publications related to Advanced Oxidation Processes (AOPs) in wastewater treatment. Figure 3a shows the annual publication trend from 2017 to 2026, indicating a substantial increase since 2017 and consistently high publication output during 2021–2025, with the highest levels observed in 2024–2025 (approximately 238 and 228 publications, respectively, based on the OriginLab chart). This trend reflects sustained scholarly interest in AOP-based wastewater treatment as an effective approach for removing refractory, toxic, and persistent pollutants. The low number of records in 2026 should be interpreted cautiously because publications from the ongoing year may not have been fully indexed at the time of data retrieval.

Figure 3b shows the distribution of publications by country. China is the most productive country, with approximately 655 records involving Chinese-affiliated authors and far exceeding other countries, followed by India (approximately 205), Spain (approximately 180), Iran, the United States, Brazil, Italy, Saudi Arabia, Germany, and Pakistan (figures approximated from the OriginLab chart; author affiliations may include more than one country per document). This distribution suggests that AOP research is strongly concentrated in countries with active research communities in environmental engineering, chemical engineering, and wastewater treatment. The contribution of both developed and developing countries also indicates that AOP-based wastewater treatment has become a global research topic, particularly in regions facing challenges related to industrialization, water pollution, and the need for advanced treatment systems.

Figure 3c illustrates the leading institutional affiliations contributing to this field. The Chinese Academy of Sciences (CAS) appears as the most productive affiliation (approximately 65 publications), followed by the IIT System, EKB, HIT, THU, NIT System, TJU, CIEMAT, IAU, and UCAS. The strong contribution of CAS and several Asian research institutions is consistent with the country-level distribution shown in Figure 3b. This pattern indicates that the development of AOP research is supported by major research institutions and

university systems with established expertise in environmental chemistry, catalysis, materials science, and wastewater treatment technologies.

Figure 3d presents the most productive authors in the dataset. S. Malato ranks as the leading author (approximately 20 publications), followed by E. Serna, R. A. Torres, M. A. Rodrigo, E. Brillas, A. Perumalsamy, B. Lai, I. Oller, M. S. Lucas, and J. A. Sánchez. The presence of these authors reflects the contribution of established research groups that have consistently advanced AOP-related studies. Their productivity also indicates that the field is supported by a strong knowledge base, particularly in areas such as photocatalysis, electrochemical oxidation, solar-driven oxidation processes, and radical-based pollutant degradation.

Figure 3e presents the meso-level citation profile. “Water Treatment” appears as the most dominant cited category, followed by topics or sources related to HPGP, photocatalysis, bioengineering, membrane science, plasma physics, catalysis, nanostructured systems, and wastewater management. This finding confirms that AOP research is closely linked to broader water treatment studies while also intersecting with materials science, catalysis, membrane processes, and plasma-based treatment technologies. The dominance of water treatment reinforces the central application of AOPs in pollutant removal and wastewater treatment performance improvement.

Figure 3f shows the micro-level citation profile, with AOPs as the dominant topic, followed by endocrine-disrupting compounds, TiO₂-based persulfate systems, activated sludge, nanofiltration, adsorption, photocatalytic degradation, anaerobic digestion, microbial fuel cells, and nanotoxicity. These topics indicate that AOP research has expanded toward hybrid treatment systems, advanced materials, emerging contaminants, and environmental risk assessment. Overall, Figure 3 shows that AOP-based wastewater treatment has developed into a multidisciplinary field integrating environmental engineering, chemical oxidation, catalysis, membrane technology, and emerging contaminant management.

Figure 4 presents the author co-authorship network in AOPs research, generated using VOSviewer. The network visualization on the left illustrates the collaboration structure among authors, where each node represents an author and the links indicate co-authorship relationships. Larger nodes indicate authors with greater weight in the network, while thicker or denser links represent stronger collaborative relationships. The map shows that the co-authorship structure is organized into several clusters, suggesting the presence of distinct but interconnected research communities within the field of AOP-based wastewater treatment.

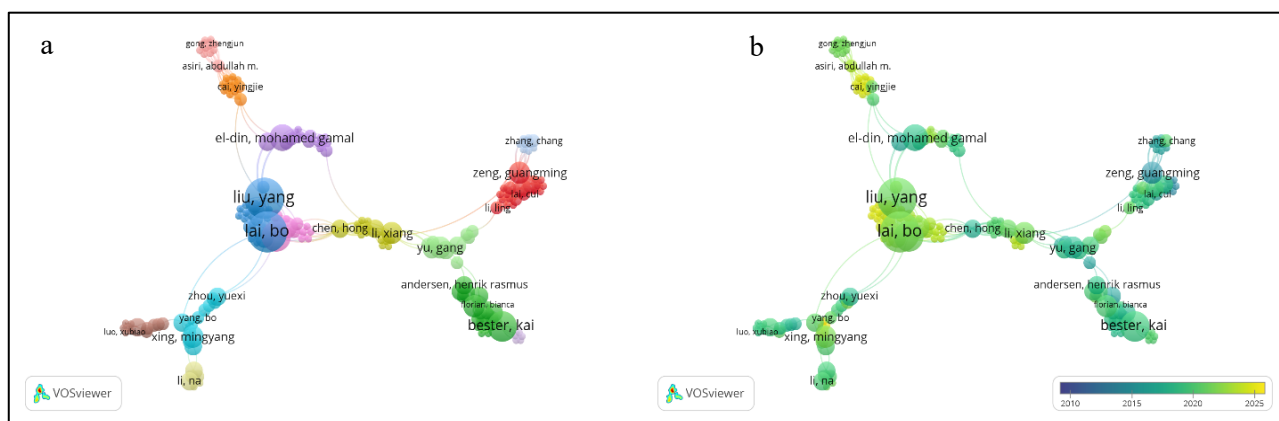


Figure 4. Author co-authorship network in Advanced Oxidation Processes (AOPs) research generated using VOSviewer: (a) network visualization showing author collaboration clusters based on co-authorship links; (b) overlay visualization showing the temporal distribution of author contributions

Several authors, including Liu Yang, Lai Bo, El-Din Mohamed Gamal, Zeng Guangming, and Zhang Chang, appear as prominent nodes in the network. Their position and node size indicate that these authors play important roles in shaping collaboration patterns and connecting different research groups. The presence of multiple clusters suggests that AOP research has been developed by several active author communities rather

The overlay visualization on the right provides temporal information on author activity. The color gradient, ranging from darker colors for earlier publication periods to brighter colors for more recent periods, shows the evolution of author contributions over time. Some established authors appear to remain influential across the network, while several more recent authors are represented by brighter nodes, indicating the emergence of newer contributors in AOP research. This pattern suggests that the field is not only supported by long-standing research groups but also continues to attract new researchers.

Figure 1 displays two network visualizations (a and b) illustrating the evolution of research trends in the field of "chinese acad sci".

Visualization (a) is a CiteSpace network, and visualization (b) is a VOSviewer network. Both visualizations show clusters of institutions and their interconnections. The color scale at the bottom right of visualization (b) indicates the year from 2010 to 2025.

Figure 5 presents the organization-based co-authorship network in AOPs research generated using VOSviewer. In this map, each node represents an institution, while the node size indicates its relative contribution or weight in the collaboration network. The links between nodes represent institutional co-authorship relationships, and the clustering pattern reflects groups of institutions that collaborate more closely with one another.

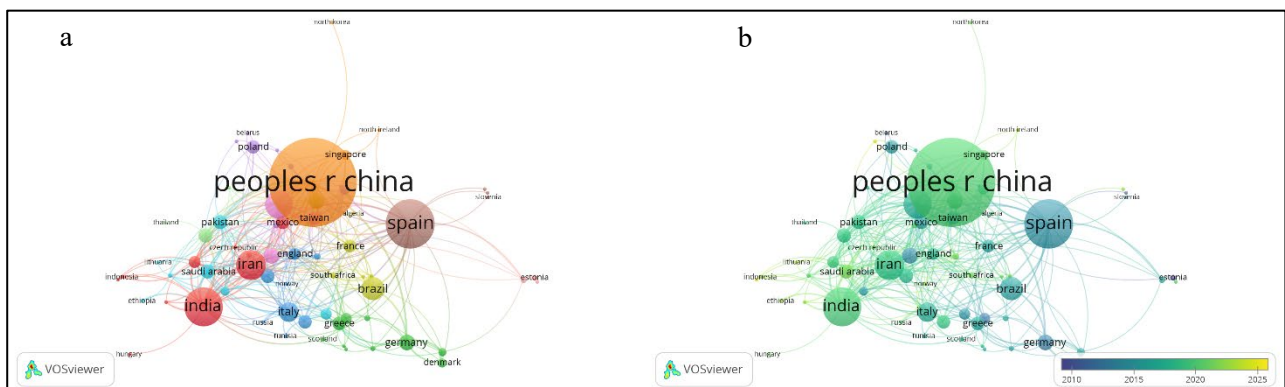


Figure 6. Country-based co-authorship network in Advanced Oxidation Processes (AOPs) research generated using VOSviewer: (a) network visualization showing collaboration clusters among countries and (b) overlay visualization showing the temporal distribution of country-level collaboration

The network visualization shows that AOP research is supported by several major institutional clusters rather than by a single dominant collaboration group. Institutions such as the Chinese Academy of Sciences, Hunan University, the University of Castilla-La Mancha, Universidad de Extremadura, Islamic Azad University, and the University of São Paulo appear as prominent nodes, indicating their important roles in institutional collaboration. The presence of links among institutions from different regions also suggests that AOP research has developed through cross-institutional and international collaboration.

The overlay visualization provides additional information on the temporal development of institutional contributions. Institutions shown in darker colors represent earlier contributions, whereas brighter colors indicate more recent activity. This pattern suggests that some institutions have maintained their role over time, while others have become more visible in recent years. In summary, the organization-based co-authorship network indicates that AOP research has evolved through a broad and interconnected institutional structure, with established and emerging institutions contributing to the expansion of this multidisciplinary research field.

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The overlay visualization on the right illustrates the temporal development of country-level collaboration. The color gradient from blue to yellow represents the transition from earlier to more recent publication periods. Countries shown in green to yellowish tones indicate continuing or more recent collaborative activity. This pattern suggests that international collaboration in AOP research has remained active in recent years, reflecting the growing need for multidisciplinary and cross-border approaches to address complex wastewater treatment and environmental pollution challenges.

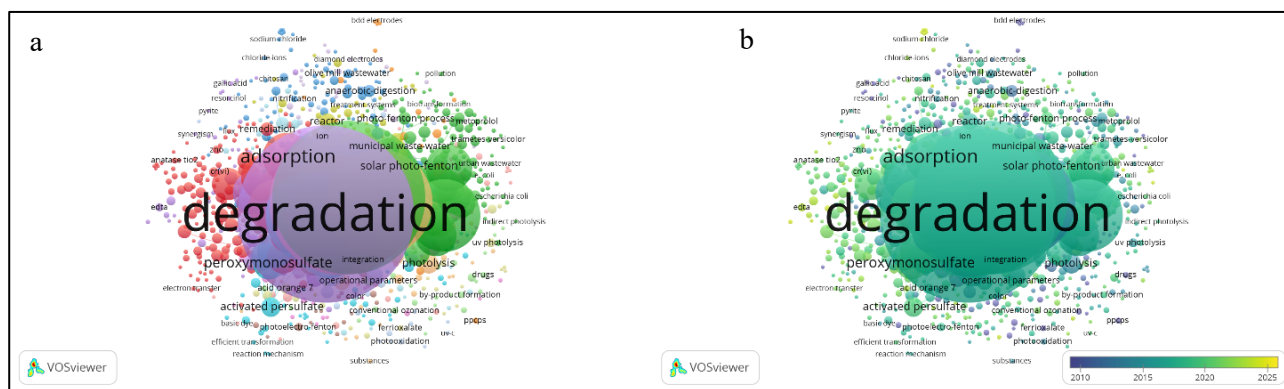


Figure 7. Keyword co-occurrence map in Advanced Oxidation Processes (AOPs) research generated using VOSviewer: (a) network visualization showing relationships among frequently co-occurring keywords and (b) overlay visualization showing the temporal development of research keywords

Figure 7 presents the keyword co-occurrence map generated using VOSviewer. The network visualization shows that “degradation” is the most dominant keyword, as indicated by its largest node size and central position in the map. This finding suggests that pollutant degradation is the core focus of AOP-related research in the analyzed dataset. The close association of “degradation” with keywords such as adsorption, peroxymonosulfate, activated persulfate, photocatalysis, photo-Fenton, wastewater, and reactor indicates that AOP research is strongly oriented toward pollutant removal through oxidation-based, photocatalytic, and material-assisted treatment processes.

The network map also reveals several overlapping thematic clusters. Keywords related to adsorption and material-based treatment suggest the important role of adsorbents and functional materials in improving pollutant removal. Meanwhile, terms such as peroxymonosulfate, activated persulfate, photo-Fenton, and photocatalysis reflect the prominence of radical-based oxidation mechanisms in AOP studies. The presence of application-related terms, including wastewater, municipal wastewater, organic pollutants, and pollution, further confirms that most studies are directed toward environmental treatment applications, particularly water and wastewater remediation.

The overlay visualization illustrates the temporal development of research topics. Earlier topics are represented by darker colors, while more recent topics are shown in green to yellow tones. The distribution indicates that research attention has expanded from general degradation and adsorption studies toward more specific AOP configurations, including persulfate activation, photo-Fenton processes, photocatalysis, and reactor-related optimization. In summary, Figure 7 demonstrates that AOP research is centered on pollutant degradation while increasingly integrating advanced oxidants, functional materials, and process optimization for wastewater treatment applications.

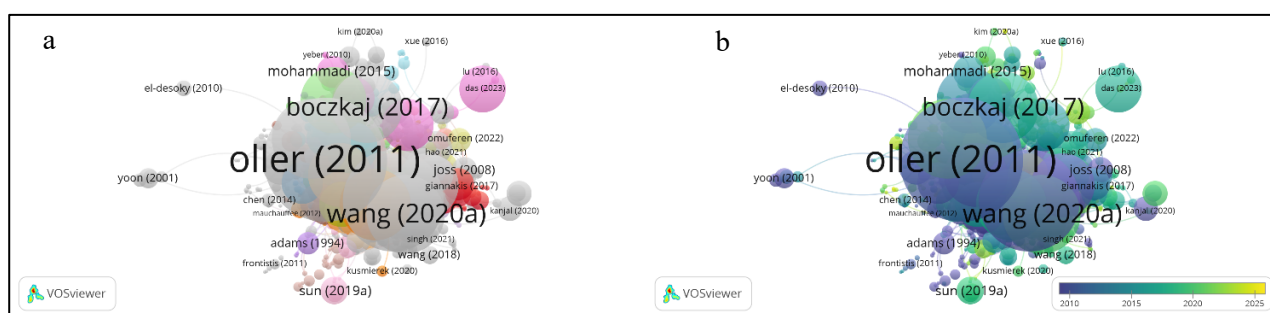


Figure 8. Document citation network in Advanced Oxidation Processes (AOPs) research generated using VOSviewer, showing citation relationships among the most influential cited documents in the dataset

Figure 8 presents the document-based citation map of AOPs research generated using VOSviewer. In this visualization, each node represents a cited document, while the node size indicates its relative citation weight within the dataset. Larger and more centrally positioned nodes reflect documents that have stronger influence and closer citation relationships with other publications in the field.

The map shows that Oller et al. (2011) is the most prominent document, as indicated by its large node size and central position. This suggests that the publication serves as an important citation anchor in AOP-related research, particularly because it connects advanced oxidation processes with biological treatment approaches for wastewater decontamination. Other highly visible documents, including Boczkaj and Fernandes (2017), also appear as influential references with strong connections to surrounding publications. Their positions indicate that these documents contribute significantly to the development and continuation of research themes in the field.

The network visualization shows several interconnected citation clusters, suggesting that the knowledge structure of AOP research is formed by groups of related documents rather than by isolated publications. Earlier cited documents remain connected to the broader network, indicating their continuing relevance as part of the intellectual background of the field. Meanwhile, more recent documents are linked to established references, showing that current studies continue to build upon earlier research foundations while extending the field toward new applications and research directions.

The overlay visualization shows the temporal distribution of cited documents, with darker colors representing earlier publications and green to yellow tones indicating more recent works. The presence of both older and newer influential documents suggests that AOP research has developed through the interaction between foundational studies and recent advances. Taken together, Figure 8 illustrates a structured citation network in which several key documents contribute to the development of AOP-based wastewater treatment research.

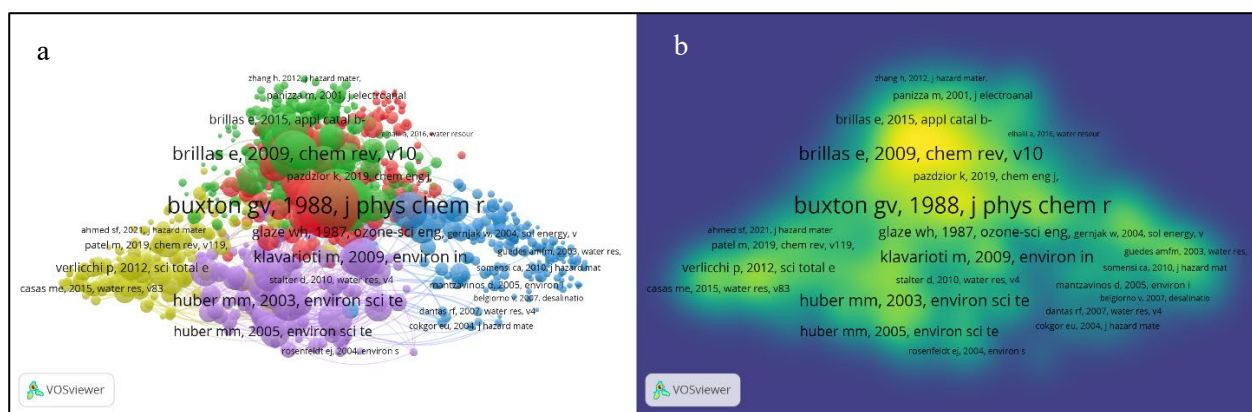


Figure 9. Co-citation map of cited references in Advanced Oxidation Processes (AOPs) research generated using VOSviewer: (a) network visualization showing co-citation relationships among cited references and (b) density visualization showing the concentration of highly co-cited references

Figure 9 presents the co-citation map of cited references in AOPs research generated using VOSviewer. The network visualization shows that the intellectual structure of this field is shaped by several highly co-cited references, as indicated by the presence of large and centrally positioned nodes. These dominant nodes suggest that a limited number of cited works have played an important role in connecting different research streams within AOP-related studies.

The clustering pattern in the network visualization indicates that the cited references are organized into several related groups. These clusters reflect the development of knowledge around key themes in AOP research, including radical-based oxidation mechanisms, pollutant degradation, electrochemical oxidation, ozonation, and environmental treatment applications. The close connections among clusters suggest that the field is built through the integration of fundamental chemical concepts and applied wastewater treatment studies.

The density visualization on the right further highlights the concentration of co-citations around several central references. Brighter areas indicate higher co-citation intensity, showing that certain cited references are repeatedly used together and function as important intellectual anchors in the field. In summary, Figure 9 demonstrates that AOP research has a well-established knowledge base, strongly supported by earlier foundational studies and progressively expanded through applications in pollutant degradation and wastewater treatment technologies.

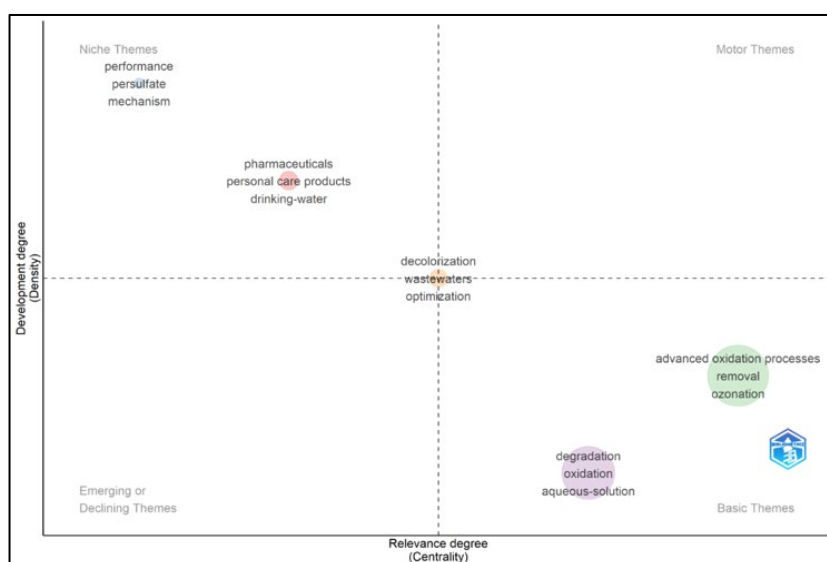


Figure 10. Thematic map of Advanced Oxidation Processes (AOPs) research generated using Bibliometrix, showing the distribution of themes based on centrality and density

Figure 10 presents the thematic map of AOPs research generated using Bibliometrix. The map classifies research themes into four quadrants based on centrality, which reflects the relevance of a theme to the overall research field, and density, which reflects the degree of internal development of the theme. In this map, the Motor Themes quadrant is relatively empty, indicating that no theme simultaneously shows high centrality and high density. This suggests that the field has not yet consolidated around a highly developed and central research theme.

The Basic Themes quadrant contains clusters such as “advanced oxidation processes–removal–ozonation” and “degradation–oxidation–aqueous solution.” These themes have high relevance but relatively lower internal development, indicating that they form the core foundation of AOP research. Their position shows that pollutant degradation, oxidation processes, removal efficiency, and ozonation are central topics that support the broader development of the field.

The Niche Themes quadrant includes “performance–persulfate–mechanism” and “pharmaceuticals–personal care products–drinking water.” These themes show relatively high development but lower centrality, suggesting that they have been studied in specific research communities but are not yet fully integrated into the main structure of AOP research. Meanwhile, the cluster consisting of “decolorization–wastewaters–optimization” is positioned close to the center of the map, indicating its potential role as a bridging theme between basic and more specialized research directions.

The Emerging or Declining Themes quadrant is relatively empty, suggesting that no major theme in the dataset clearly falls into this category. Taken together, the thematic map indicates that AOP research is primarily structured around basic themes related to pollutant degradation and oxidation, while more specific topics such as persulfate mechanisms, pharmaceutical contaminants, and drinking-water applications remain more specialized and have potential for further integration into the mainstream research agenda.

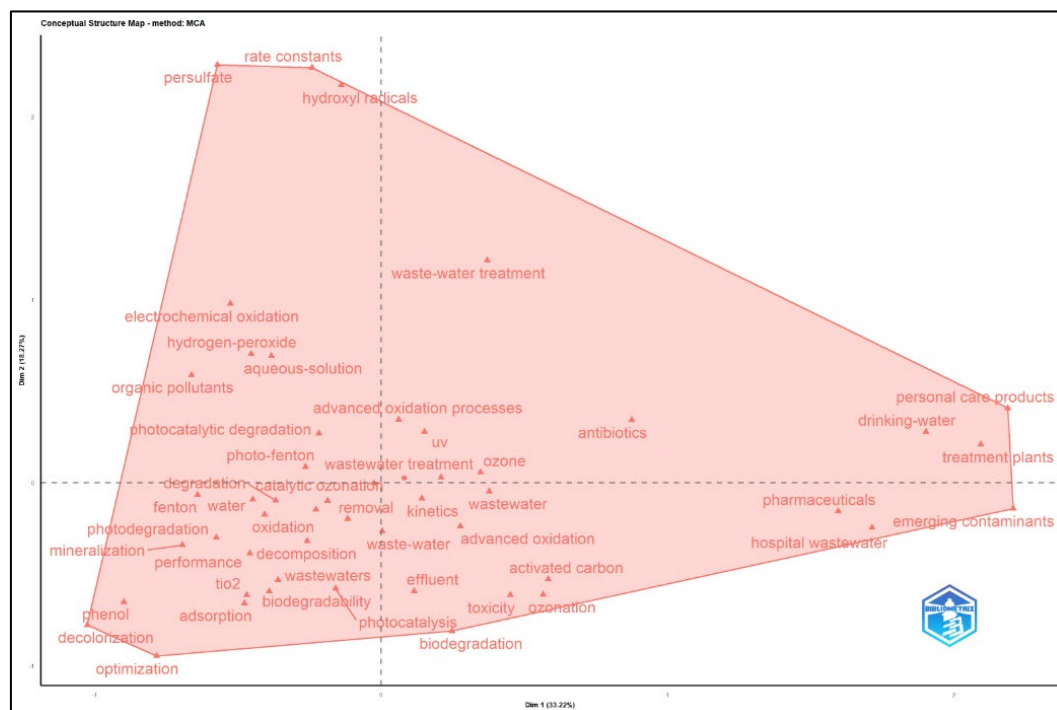


Figure 11. Conceptual structure map of Advanced Oxidation Processes (AOPs) research generated using Multiple Correspondence Analysis (MCA) in Bibliometrix

Figure 11 presents the conceptual structure map of AOP-related research generated using Multiple Correspondence Analysis (MCA) in Bibliometrix. The map illustrates the conceptual proximity among keywords, where terms located closer to each other indicate stronger thematic association. Overall, the

distribution of keywords shows that the research field is organized around a broad and interconnected conceptual structure, integrating mechanistic studies, process development, and environmental applications.

Keywords positioned near the central area, such as “advanced oxidation processes,” “wastewater treatment,” “aqueous solution,” “organic pollutants,” and “degradation,” represent core concepts that connect different research directions. These terms indicate that the field is primarily structured around pollutant degradation and wastewater treatment using oxidation-based processes. On the left side of the map, keywords such as “hydroxyl radicals,” “rate constants,” “persulfate,” “hydrogen peroxide,” “photocatalytic degradation,” “photo-Fenton,” and “Fenton” are closely associated with reaction mechanisms, kinetics, and reactive species formation. This pattern reflects the importance of fundamental chemical processes in explaining the performance of AOP systems.

In contrast, the right side of the map contains application-oriented keywords, including “pharmaceuticals,” “antibiotics,” “personal care products,” “emerging contaminants,” “drinking water,” “hospital wastewater,” and “treatment plants.” Their relatively distinct position suggests that contaminant-specific and application-based studies form a specialized conceptual area within the broader AOP research landscape. Meanwhile, keywords located toward the lower part of the map, such as “adsorption,” “activated carbon,” “toxicity,” “biodegradability,” “effluent,” and “optimization,” indicate the integration of AOPs with supporting treatment methods and post-treatment evaluation. In summary, Figure 11 shows that AOP research is conceptually structured around three main dimensions: fundamental oxidation mechanisms, wastewater treatment applications, and performance or impact evaluation

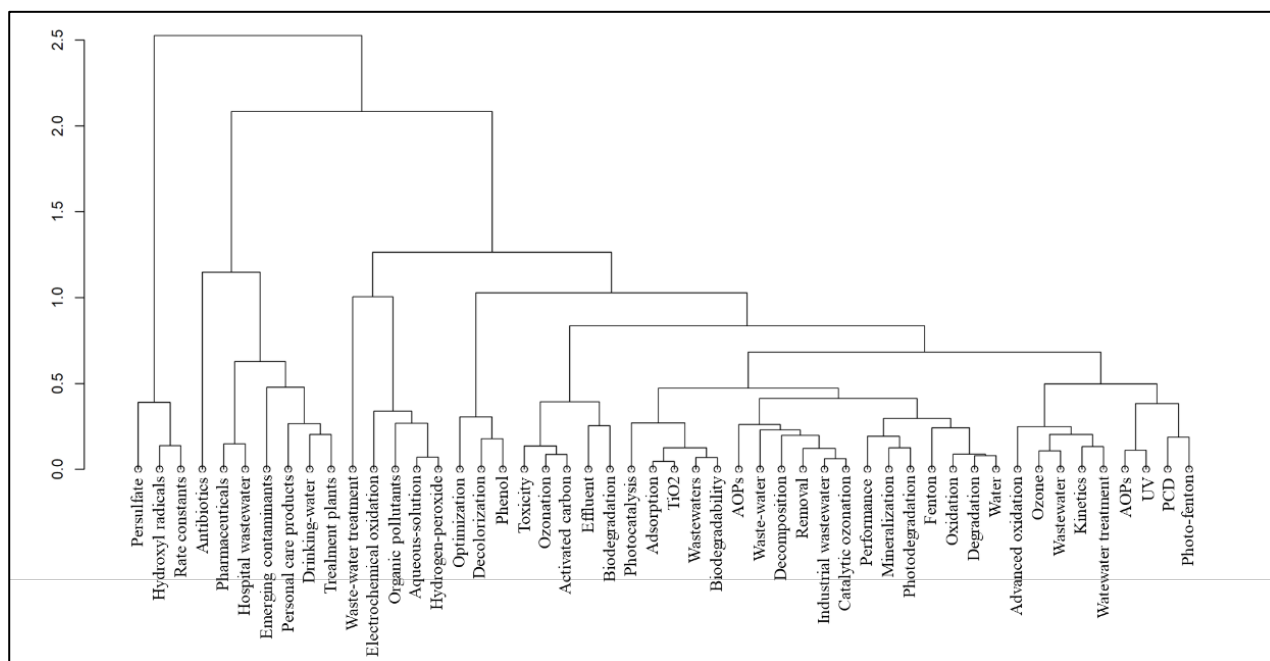


Figure 12. Dendrogram of hierarchical cluster analysis showing the grouping of research keywords based on their conceptual similarity and co-occurrence relationships in AOP-related wastewater treatment research

Figure 12 presents the dendrogram generated from hierarchical cluster analysis of research keywords. The dendrogram groups keywords based on their conceptual similarity and co-occurrence relationships, where shorter linkage distances indicate stronger thematic proximity. Taken together, the clustering pattern shows that AOP-related research is organized into several interconnected thematic groups, reflecting the integration of fundamental mechanisms, pollutant types, treatment technologies, and performance evaluation.

One major cluster consists of keywords such as “persulfate,” “hydroxyl radicals,” and “rate constants,” representing mechanistic and kinetic aspects of oxidation processes. This cluster indicates that understanding radical formation, reactivity, and reaction kinetics remains an important foundation in AOP research. Another

cluster includes contaminant- and application-related terms, such as “pharmaceuticals,” “antibiotics,” “personal care products,” “hospital wastewater,” “emerging contaminants,” and “drinking water.” The close grouping of these keywords suggests that studies on AOPs are increasingly associated with specific pollutant classes and real water or wastewater matrices.

Other clusters are related to treatment processes and supporting technologies, including “advanced oxidation,” “ozonation,” “photo-Fenton,” “UV,” “photocatalysis,” “activated carbon,” and “adsorption.” These groupings indicate that AOP research combines oxidation-based treatment with complementary physicochemical processes to improve pollutant removal. Keywords such as “optimization,” “performance,” “toxicity,” “biodegradability,” and “effluent” further show that the field also considers process efficiency and post-treatment impacts. Collectively, Figure 12 confirms that AOP research is thematically structured around three main dimensions: oxidation mechanisms, contaminant-specific applications, and treatment performance evaluation.

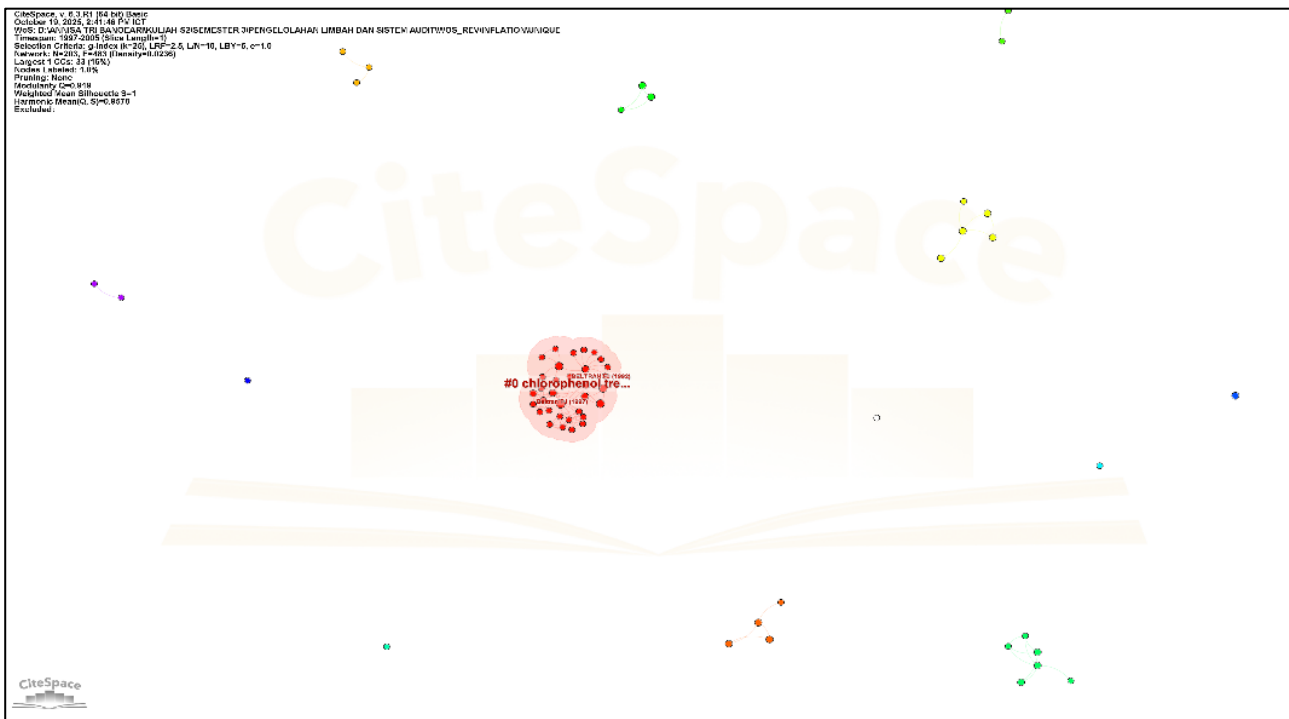


Figure 13. CiteSpace visualization of keyword clusters in Advanced Oxidation Processes (AOPs) research

Figure 13 presents the CiteSpace visualization of keyword clusters in AOP-related research. The map shows that the most prominent cluster is located at the center and is labelled as the chlorophenol-related cluster. The high concentration of nodes within this cluster indicates that chlorophenol has been an important topic in the analyzed literature, particularly as a representative pollutant in studies of wastewater treatment, degradation mechanisms, and advanced oxidation processes. The central position of this cluster suggests that chlorophenol-related studies are strongly connected to the broader knowledge structure of the field.

Several smaller clusters are distributed around the main cluster with relatively weaker connections. This pattern indicates that, although the research field covers diverse topics, many subthemes remain more fragmented and less strongly connected to the central research focus. The presence of these smaller clusters also suggests that AOP research has developed through both core topics and supporting subtopics, reflecting variation in pollutant types, treatment mechanisms, and application contexts.

The network statistics shown in the CiteSpace output indicate a high modularity value ($Q = 0.919$) and a high mean silhouette score ($S = 1.0$), suggesting that the cluster structure is well defined and internally consistent. In summary, Figure 13 confirms that chlorophenol-related research occupies a central position in the knowledge structure of AOP studies, while other topics develop as supporting or more specialized research

directions. This finding also indicates that chlorophenol has frequently been used as a model compound for evaluating the performance of advanced oxidation and wastewater treatment technologies.

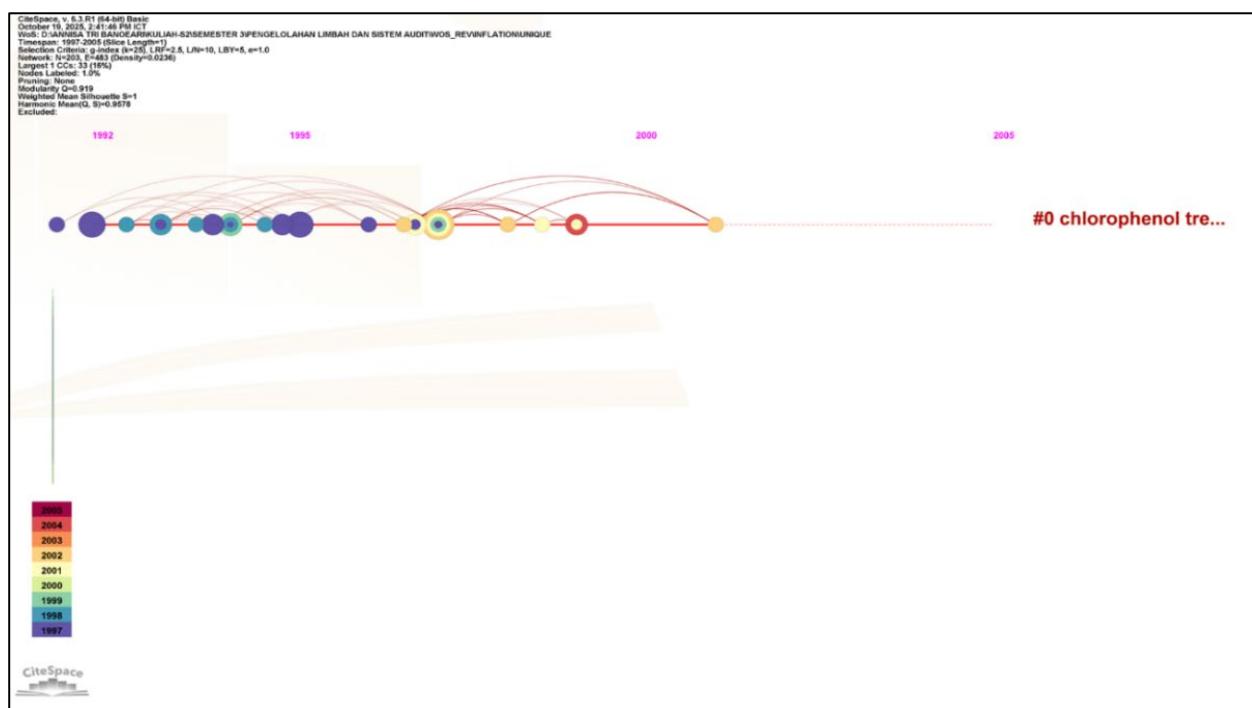


Figure 14. CiteSpace timeline visualization of the chlorophenol-related cluster, showing the temporal distribution and citation links of research items within the cluster

Figure 14 presents the CiteSpace timeline visualization of the main chlorophenol-related cluster. The visualization shows the temporal distribution and citation links of documents within this cluster, with nodes representing cited references or related research items and links indicating intellectual connections among them. The timeline indicates that chlorophenol-related studies began to appear in the early 1990s and became more visible from the late 1990s to the early 2000s. The concentration of nodes and links during this period suggests that chlorophenol was an important research focus in the development of wastewater treatment and pollutant degradation studies.

The prominence of the chlorophenol cluster reflects the relevance of this compound as a representative organic pollutant in environmental research. Chlorophenol has commonly been used as a model contaminant because of its toxicity, persistence, and relevance to industrial wastewater. The connected nodes in the timeline indicate that studies on chlorophenol were linked to broader research themes, including degradation mechanisms, oxidation processes, adsorption, biodegradation, and treatment performance.

The reduced number of visible nodes after the early 2000s should be interpreted cautiously. It may indicate a decline in the dominance of chlorophenol as a central topic, but it may also reflect a shift toward broader groups of emerging contaminants or other model pollutants in AOP research. Taken together, Figure 14 shows that chlorophenol has played an important historical role in the knowledge development of AOP-based wastewater treatment, particularly as a model compound for evaluating pollutant degradation and treatment efficiency.

4. Conclusion

This bibliometric mapping study provides a systematic overview of the development, collaboration patterns, knowledge structure, and thematic evolution of Advanced Oxidation Processes (AOPs) in chemical industry wastewater treatment. The findings show that research on AOP-based wastewater treatment has grown substantially since 2017, with publication output remaining high in recent years. This trend confirms the increasing scientific attention given to AOPs as promising technologies for degrading refractory, toxic, and persistent pollutants in wastewater. The country, institution, and author collaboration maps further indicate

that this field has developed through broad international and cross-institutional networks, with China, the Chinese Academy of Sciences, and several prominent research groups playing central roles in publication output and collaborative connectivity.

The keyword co-occurrence, citation, co-citation, thematic, and conceptual structure analyses demonstrate that AOP research is strongly centered on pollutant degradation, oxidation processes, ozonation, photocatalysis, persulfate activation, and radical-based reaction mechanisms. The dominance of “degradation” as the central keyword confirms that pollutant removal remains the core orientation of this research field. At the same time, the conceptual structure map and dendrogram show that AOP studies are organized into three major dimensions: fundamental oxidation mechanisms, contaminant-specific applications, and performance or impact evaluation. These findings indicate that the field integrates basic radical chemistry with applied wastewater treatment technologies.

The thematic map shows that basic themes such as degradation, oxidation, removal, and ozonation remain central, while more specialized topics, including persulfate mechanisms, pharmaceutical contaminants, personal care products, and drinking-water applications, have not yet been fully integrated into the mainstream research structure. CiteSpace analysis further reveals the historical importance of chlorophenol-related studies, particularly as model compounds for evaluating degradation mechanisms and treatment performance. Overall, this study confirms that AOP-based wastewater treatment has evolved into a multidisciplinary research field that connects environmental chemistry, chemical engineering, catalysis, materials science, and wastewater treatment applications.

5. Future Research

Future research should address the technical, environmental, and practical challenges of AOP implementation beyond bibliometric trends. More studies are needed using real chemical industry wastewater matrices, as many existing studies still rely on synthetic solutions or model contaminants. Pilot-scale and full-scale investigations should also be strengthened to evaluate operational stability, treatment efficiency, energy demand, and process feasibility under realistic industrial conditions.

In addition, future studies should examine transformation products, toxicity reduction, catalyst leaching, nanomaterial safety, and post-treatment impacts to ensure that pollutant degradation does not create secondary environmental risks. In particular, dedicated experimental and field-based studies are needed to evaluate pathogen regrowth after AOP treatment, the bioaccumulation of metal-based catalysts (e.g., TiO₂, Fe, Mn, Ag) in soil–plant systems, and compliance with irrigation water-quality standards, as these concerns motivated the present bibliometric mapping but remain outside its analytical scope.

Further research should also explore hybrid and integrated treatment systems, such as AOPs combined with adsorption, biological treatment, membrane processes, activated carbon, or persulfate-based oxidation, to improve overall treatment efficiency and sustainability. In addition, techno-economic analysis, life-cycle assessment, and sustainability evaluation should be incorporated more consistently to support industrial decision-making and policy development. Finally, emerging contaminants, including pharmaceuticals, personal care products, microplastics, endocrine-disrupting compounds, and complex industrial micropollutants, should be prioritized as future research targets. These directions are essential to strengthen the transition of AOPs from laboratory-scale innovation toward reliable, economically feasible, and environmentally sustainable wastewater treatment technologies.

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7. Conflict of Interest

The authors declare no conflict of interest.

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