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Trends and hotspots in tetracycline removal research over the last 20 years: A bibliometric analysis

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Abstract

Tetracyclines are a novel pollutant that has become a significant environmental contaminant due to their widespread use and poor biodegradability, leading to their accumulation in ecosystems and posing potential hazards. Concerns over the ecological risks and antibiotic resistance associated with these antibiotics have prompted research into removal technologies. In recent years, various techniques have emerged, with both single and combined technologies demonstrating excellent performance in removing tetracyclines from different environments. This study uses the CiteSpace bibliometric software, in conjunction with literature data obtained from the Web of Science (WoS) database, to conduct a visual analysis of publication volume, author groups, publishing institutions, clustering of high-frequency keywords, and co-citation patterns in research into the removal of tetracyclines. The results demonstrated an overall upward trend in the number of publications from 2004 to 2024. China leads in publication volume, with the Chinese Academy of Sciences dominating the top 10 institutions in the WoS rankings. Keyword co-occurrence network analysis and literature co-citation analysis revealed an evolution of removal technologies from single materials to composite materials, from simple adsorption to functionalized degradation, from non-biological removal to biodegradation, and from single technologies to integrated composite systems. Looking ahead, as materials science, microbiology, environmental chemistry, and other disciplines continue to converge, tetracycline removal technologies are poised to advance toward precision, intelligence, and scalability. This evolution will provide stronger support for addressing tetracycline pollution worldwide.

Keywords: Tetracyclines, CiteSpace, Bibliometrics, Visualization, Research hotspots

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1. Introduction

Tetracyclines are derived from various species of the genus *Streptomyces*, with a total of 20 compounds introduced to the market as antibiotics.[1,2] These constitute a widely used class of broad-spectrum antibiotics that exhibit highly effective bactericidal activity. Tetracyclines are widely recognized for their potent antibacterial activity, high oral bioavailability, and low toxicity, leading to their extensive use in various fields, including medicine, animal husbandry, agriculture, and aquaculture.[3] However, the overuse of tetracycline has resulted in significant environmental pollution due to substantial antibiotic release into the environment.[4] It has been evident that tetracyclines are subject to incomplete metabolism in humans and animals, resulting in the excretion of substantial amounts as metabolites or other forms.[5] This phenomenon has led to the accumulation of these antibiotics in various aquatic systems through continuous exposure and inadequate disposal practices.[6,7]

The presence of tetracyclines in water bodies has significant ecological and health implications. The disruption of aquatic ecosystems by tetracycline pollution affects microbial communities and the survival of aquatic plants and animals. It has also been demonstrated that tetracyclines promote antibiotic resistance by facilitating the generation of antibiotic resistance genes.[7] Tetracyclines in aquatic environments exert ecotoxicity on aquatic organisms and accumulate within biological tissues. Studies have reported the presence of oxytetracycline and tetracycline in the liver, bile, and muscle tissues of wild fish samples from Lake Taihu.[8]

The toxicological effects of tetracyclines on algae have been well documented. In a seminal study, Shang *et al.*[9] reported that exposure to tetracyclines at certain concentrations resulted in significant inhibition of *Chlorella* growth, accompanied by a substantial increase in reactive oxygen species levels and superoxide dismutase and catalase activities. Furthermore, tetracyclines have been demonstrated to exhibit ecotoxicity toward higher aquatic plants. Consequently, they may bioaccumulate within food chains, posing a threat to entire ecosystems and human health.

Moreover, the long-term consumption of water contaminated with tetracyclines has been shown to directly cause human gastrointestinal discomfort, liver issues, and impaired bone growth.[10] In addition to the toxicity of parent tetracyclines, recent studies have increasingly focused on the biotoxicity of their oxidation products and metabolites. During advanced oxidation processes (e.g., photocatalysis and chemical oxidation), tetracyclines are often not fully mineralized, generating transformation intermediates that may retain or even exhibit enhanced toxicity. For example, a recent study demonstrated that certain oxidation by-products of tetracycline exhibit greater inhibition of aquatic microorganisms than the parent compound.[11] These toxic metabolites can induce oxidative stress and disrupt photosynthetic systems in algae. As novel pollutants, tetracyclines persist in ecosystems due to their potential hazards, resistance to degradation, tendency to accumulate, and incomplete removal by conventional wastewater treatment units.

Beyond toxicity and resistance, the ability of tetracyclines to form stable complexes with metal ions represents another critical aspect that influences their environmental fate and treatability.[12] As demonstrated by Kabanov *et al.*,[12] such complexation, particularly with Fe(II), can produce highly soluble and stable species that resist conventional coagulation removal. Consequently, the development of effective remediation technologies is imperative to remove tetracyclines from wastewater. This renders the elimination of tetracyclines a prominent research focus in environmental science.

In recent decades, a plethora of technologies have been developed for the detection and elimination of tetracyclines from the environment.[7,13] The elimination of tetracyclines can be categorized into abiotic and biotic removal, depending on the involvement of biological processes. Abiotic elimination methods include adsorption,[14] chemically catalyzed oxidation,[15] photocatalytic oxidation,[16] and electrochemical approaches.[17] Meanwhile, biotic elimination methods include biodegradation.[18,19]

Adsorption methods are widely utilized in the pretreatment or advanced purification stages of wastewater containing low concentrations of tetracycline, owing to their operational simplicity and relatively low cost. It is an effective method for removing oxytetracycline and tetracycline from water, and is commonly used in small wastewater treatment plants and emergency treatment scenarios. A variety of adsorbents have been developed for this purpose, with commonly used materials including montmorillonite,[20] silica,[21] carbon nanotubes,[22] graphene,[23] activated carbon,[24] biomaterials,[19,25] and novel materials such as metal–organic frameworks (MOFs).[26]

Advanced oxidation processes, including chemical-catalytic and photocatalytic oxidation, are suitable for degrading tetracyclines at medium-to-high concentrations in industrial wastewater, including pharmaceutical and livestock effluents. These processes achieve rapid antibiotic mineralization through reactive radicals such as ·OH and $SO_4{\cdot}^-$.[15] For example, magnetic biochar-activated persulfate-based chemical catalytic oxidation achieved up to 93% tetracycline removal at ambient temperatures within short durations.[27] Meanwhile, TiO_2-based photocatalysts, driven by UV or visible light, are suitable for in situ remediation of surface and groundwater.[28] The oxidation mechanism of electrochemical methods primarily involves ·OH radicals generated by electrochemical oxidation attacking the double bonds, phenolic groups, and amine groups of tetracyclines.[7,29] Due to characteristics such as strong reaction control and the absence of secondary pollution, direct degradation of pollutants or the generation of strong oxidizing intermediates via anodic oxidation can achieve degradation rates of up to 99%, demonstrating significant potential for industrial wastewater treatment.[30]

The process of biological degradation is contingent upon the presence of microbial strains (e.g., bacteria and fungi) that facilitate the metabolic transformation of tetracyclines into innocuous by-products by ring-opening or cleavage of linked functional groups. This method is suitable for treating wastewater containing low-concentration, readily biodegradable tetracyclines, such as aquaculture effluents and advanced treatment units in municipal sewage treatment plants.[31] Recent studies have demonstrated the efficacy of techniques that utilize mixed microbial communities,[32] activated sludge,[33] membrane bioreactors,[34] and enzymatic methods[35] in achieving effective biodegradation. The field has witnessed substantial advancements in recent years, with the development of genetically engineered bacteria and immobilized microbial technologies further enhancing degradation efficiency and environmental adaptability.

However, these approaches are limited in their tolerance to toxic substances and require integration with other technologies. In practical applications, single technologies are often constrained by cost, efficiency, or applicability, making combined processes the mainstream approach. For example, integrating adsorption (for pretreatment enrichment) with photocatalytic oxidation (for advanced degradation) is a strategy that addresses catalyst poisoning by high concentrations of tetracyclines. The combination of electrochemical oxidation with biological degradation—where the former reduces pollutant concentration, and the latter mineralizes residual organic matter—is an approach that achieves compliant discharge. It can be concluded that abiotic methods excel at rapid removal of high-concentration tetracycline scenarios, while biotic methods offer greater advantages in terms of ecological friendliness and sustainability.

In recent years, there has been a proliferation of literature examining the occurrence, manifestations, risk assessment, removal, and challenges associated with tetracyclines.[2,7,31] These studies have primarily focused on reviewing specific research findings. However, there remains a paucity of comprehensive collation and analysis of recent advances in tetracycline research, removal technologies, and their efficacy.

Bibliometrics employs statistical methods to quantitatively analyze scientific papers, describing the current state and emerging trends within a field while identifying future research hotspots and directions.[36] This study employed CiteSpace (6.2.R2), a bibliometric analysis software developed by Professor Chao-Mei Chen at Drexel University, United States (US), to analyze research progress in the field of tetracycline removal published domestically and internationally over the past two decades.[37] The analysis encompassed publishing countries, publication volume, institutions, keyword trends, author collaboration networks, and citation networks. Visual representation of knowledge, termed "knowledge maps," is a methodical approach to understanding the current state of research, identifying areas of high interest, and delineating future development directions. This approach is expected to provide a framework for guiding future studies and addressing the critical issue of tetracycline pollution in water systems.

2. Methods

2.1. Data sources

The Web of Science (WoS) Core Collection database was used as the data source for literature retrieval. The retrieval formula used was: "Title"= "tetracycl* OR oxytetracycl* OR chlortetracycl*" AND "Topic" = "removal OR degradation OR adsorption OR AOPs" AND "Topic"= "water OR wastewater OR aquatic environment." The search period spanned from 2004 to 2024, with a time slice of one year, yielding 4,991 records prior to screening.

All retrieved records were exported in plain text format with the content set to "abstract, full record (including cited references)" and imported into CiteSpace version 6.2.R3 for bibliometric analysis. To ensure transparency and reproducibility, the screening process was conducted as follows: Titles and abstracts were independently reviewed by two authors. Only peer-reviewed articles and review articles were included, whereas conference proceedings, editorials, and book chapters were excluded. Discrepancies between reviewers were resolved through discussion. A total of 4989 articles were included in this study. Prior to analysis, synonym normalization was performed to avoid fragmentation of semantically equivalent terms. Variant spellings and morphological forms (e.g., "tetracycline", "tetracyclines", and "oxytetracycline") were consolidated under the root term "tetracycl*" to ensure consistent treatment of related concepts.

2.2. Analysis methods

The node types selected for the analysis were author, institution, country, and keywords. The collaborative network comprised authors, institutions, countries, and keywords, enabling analysis of the basic status and research trends. The visualized network co-occurrence diagram used circles from the inside to the outside to indicate the time span of the research from the past to the present, with size serving as a proxy for importance and connecting lines signifying relevance and collaboration. The quality of the clusters was evaluated using the "S value" and "Q value" metrics (Q value > 0.3, reliable clustering; S value > 0.5, reasonable clustering; S value ≥ 0.7, complete reliability). In this study, all S values were greater than 0.85, and all Q values were greater than 0.7, indicating that the analysis results were reasonable and reliable.

3. Results and discussion

3.1. Publishing trends

A comprehensive analysis of the temporal and quantitative characteristics of publications on tetracycline removal offers insight into the field's development rate, its evolutionary trends, and the level of emphasis it has garnered. Figure 1 illustrates the number of articles published over time. As depicted in the figure, publications have been documented since 2008. No publications were found from 2004 to 2007. The number of published articles exhibited minimal interannual variation, yet the overall trend was upward, indicating that researchers have increasingly prioritized this area.

The publication trajectory over the past two decades can be divided into three phases. The initial phase, spanning from 2008 to 2013, is characterized by the initiation of research, during which the number of articles published increased from 14 to 63 by 2013. This phase is characterized by a relatively small number of articles but a gradual and steady annual increase, indicating that the field began to garner attention. The subsequent phase, from 2014 to 2017, is marked by steady development, during which the research results steadily increased, reaching 144 articles by 2017. The final phase, from 2018 to 2024, is characterized by a rapid escalation in research activity, resulting in a substantial increase in the number of published articles, reaching 1,054 in 2024, thus establishing the field as a prominent research hotspot.

3.2. Cooperation network analysis

3.2.1. Core authors

High-frequency co-cited authors have typically innovated theories and methods within the research domain, thereby making substantial contributions to its advancement. Figure 2 and Table 1 present statistics on collaboration mapping, publication counts, and co-citation frequency among domestic and foreign scholars. An analysis of Figure 2 revealed decentralized collaboration among authors, with a significant proportion tending to collaborate within stable groups, thereby forming multiple collaborative clusters, each typically comprising two or more core authors. Among these authors, the top three by number of publications were Guangming Zeng (31), Jun Wang (28), and Feng Guo (27). Notably, the majority of authors under consideration were Chinese scholars, indicating their greater international activity in this research field. The author's co-citation frequency is presented in Table 1. Hou Wang, Yan Wang, and Yi Zhang ranked in the top three, each with a frequency exceeding 650, reflecting their exceptional activity and influence.

Wang *et al.*[38] synthesized an In_2S_3@MIL-125(Ti) core-shell photocatalytic adsorbent with a large specific surface area and mesoporous structure using the solvothermal method. This absorbent exhibited good adsorption performance and photocatalytic activity for tetracycline. Wang *et al.*[39,40] researched environmental catalysis and water pollution control, and synthesized a series of new materials that, combined with photocatalysis, can effectively remove antibiotics from water. They consecutively reported the use of an internal loop-lift reactor and an ultrasound-enhanced rectangular air-lift reactor to enhance the oxidative degradation of tetracycline in water, demonstrating that tetracycline elimination could be substantially enhanced by both reactor types. The early initiation of research by multiple scholars on contamination control, employing diverse combined chemical and engineering techniques for tetracycline removal, has facilitated subsequent research and may contribute to their high citation frequency.[41-43]

3.2.2. Institutions

To explore the major institutional forces in tetracycline removal research, Citespace was used to visualize and analyze issuing institutions (Figure 3). In the resulting visual graph, each node represents an institution, with node size indicating publication volume. Nodes with purple outer circles are defined as high centrality nodes (centrality > 0.1) that serve as inter-node association ties. The mapping comprised 246 nodes and 230 connections, with a network density of 0.0076, indicating a sparse network. The maximum connectivity branch accounted for 65% of the nodes, suggesting a larger core cluster in the network. Table 2 presents the rankings of the top 10 research institutions and countries by publication volume. In the ranking of issuing institutions, the Chinese Academy of Sciences, Hunan University, and Jiangsu University ranked first, second, and third, respectively, with more than 100 articles each; the Chinese Academy of Sciences had 276 articles.

Moreover, the institutions participating in the study are predominantly in China. With respect to institutional collaboration, the Chinese Academy of Sciences, as the primary research institution, has established cooperative relationships with the majority of these institutions. The Chinese Academy of Sciences has been a pioneering institution in this field, supported by prominent authors,

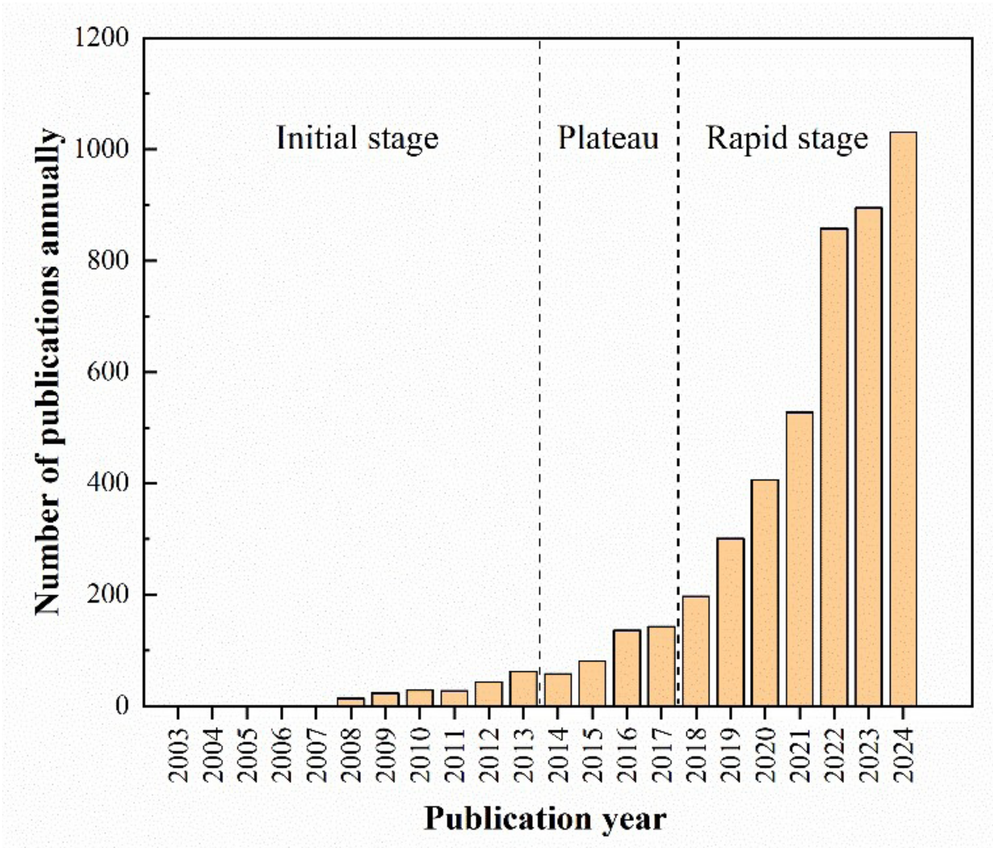

Figure 1. The annual number of publications in tetracycline removal research

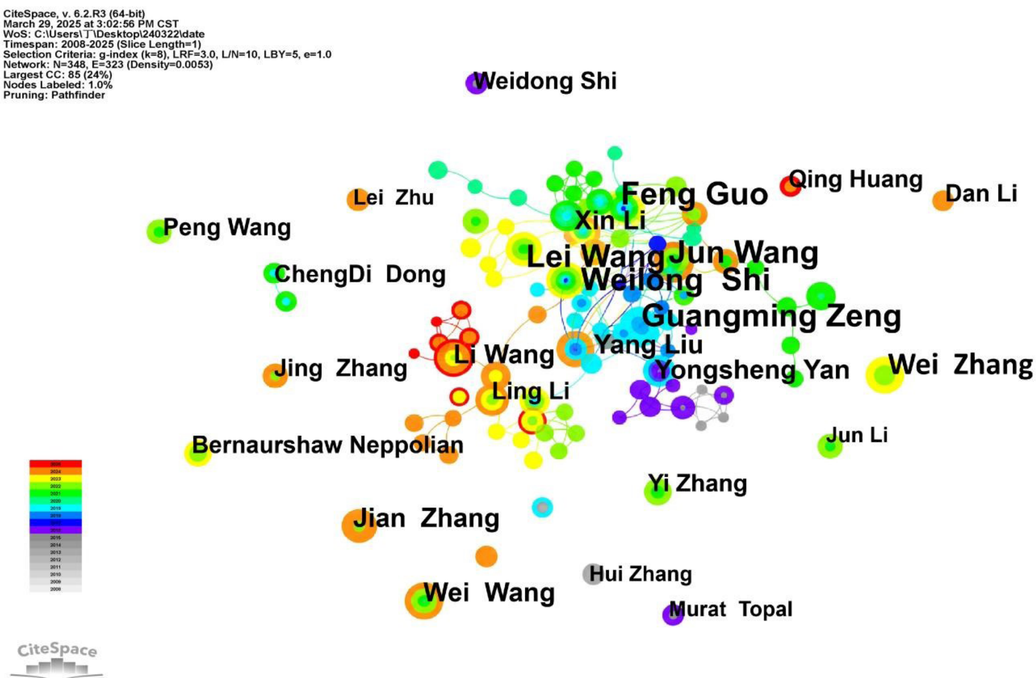

Figure 2. Collaborative network of authors on tetracycline removal research

Table 1. Top 10 authors by publication volume and citation frequency

Number	Top 10 by publications		Top 10 by citation frequency		
	Author	Publications	Author	Frequency	Centrality
1	Guangming Zeng	31	Hou Wang	696	0.03
2	Jun Wang	28	Yan Wang	654	0.04
3	Feng Guo	27	Yi Zhang	652	0.02
4	Wei Wang	27	Yuan Gao	507	-
5	Li Wang	27	Yang Liu	485	0.02
6	Jian Zhang	26	Rimeh Daghrir	468	0.02
7	Yang Liu	25	JianLong Wang	458	-
8	Wei Zhang	24	Jun Wang	457	0.01
9	Weilong Shi	24	Jun Li	457	-
10	Xin Li	22	Yi Yang	452	0.01

including Guibin Jiang, Jiuhui Qu, and Yongguan Zhu, who form its research backbone. The Harbin Institute of Technology, Tongji University, and the University of Chinese Academy of Sciences, in collaboration with Jilin University, Hunan University, and Jiangsu University, constitute the primary force in tetracycline removal research.

China's diverse ecological environments and complex environmental issues have led to a strong national emphasis on environmental protection and restoration. The Ecological Environment Research Center of the Chinese Academy of Sciences has been working closely with the environmental faculties of Hunan University, Wuhan University, the University of Chinese Academy of Sciences, Tongji University, and other universities.[7,27,44] These collaborations involved numerous units and achieved significant progress in high-level research and technologies, jointly promoting ecological environmental protection and restoration.[7]

3.2.3. Country

Analysis of publication volume by country facilitates understanding of academic support and recognition for the field, thereby benefiting its development.[45] Figure 4 illustrates publications and collaborations on tetracycline removal research in different countries. The top 10 countries by the number of publications were China, India, Iran, the US, South Korea, Saudi Arabia, Turkey, Spain, Australia, and Brazil, in that order. With regard to the ranking of countries (Table 2), China had the largest volume of 3,733 articles, while the other countries ranged from 65 to 271. In terms of mediational centrality, Spain scored 0.76, indicating a key role and greater impact. While China had the largest volume of articles, the value of its mediational centrality was relatively small, suggesting that China's influence is insufficient in this area.

3.3. Mapping and analysis of keywords

The majority of scholarly research is predicated on prior findings, meaning that keywords within a discipline neither emerge nor vanish arbitrarily. Instead, they evolve through continuous research advancement, exhibiting inherent continuity and extension.[46] Keywords serve as essential components for expressing thematic concepts, reflecting an article's research content and core subject matter. Keyword co-occurrence analysis maps keyword co-occurrence patterns within cited literature, where two keywords appearing in the same document constitute one instance of co-occurrence.[2,37] This analysis primarily relies on keyword co-occurrence frequency matrices. Keyword co-occurrence networks reveal current research hotspots within a field and historical trends in prominent studies.[47]

A comprehensive analysis and synthesis of keywords from the extant literature on tetracycline removal research

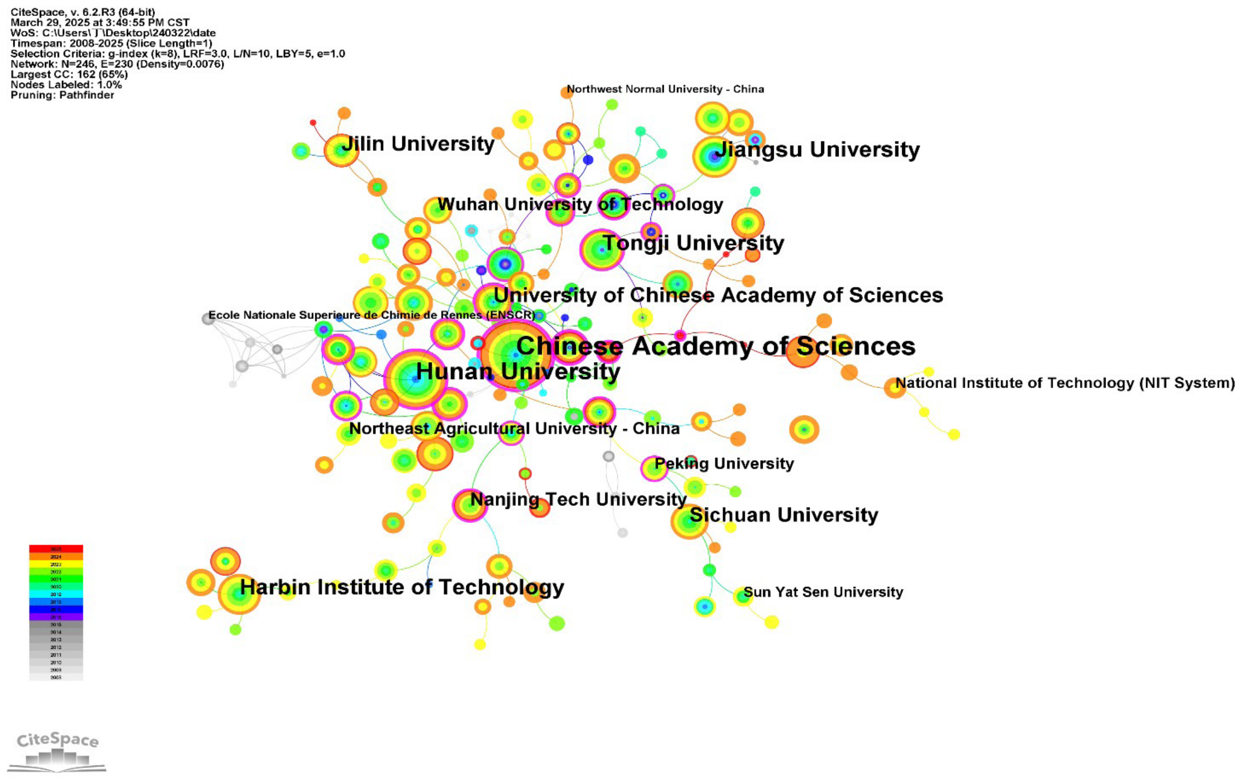

Figure 3. Collaborative network of institutions in tetracycline removal research

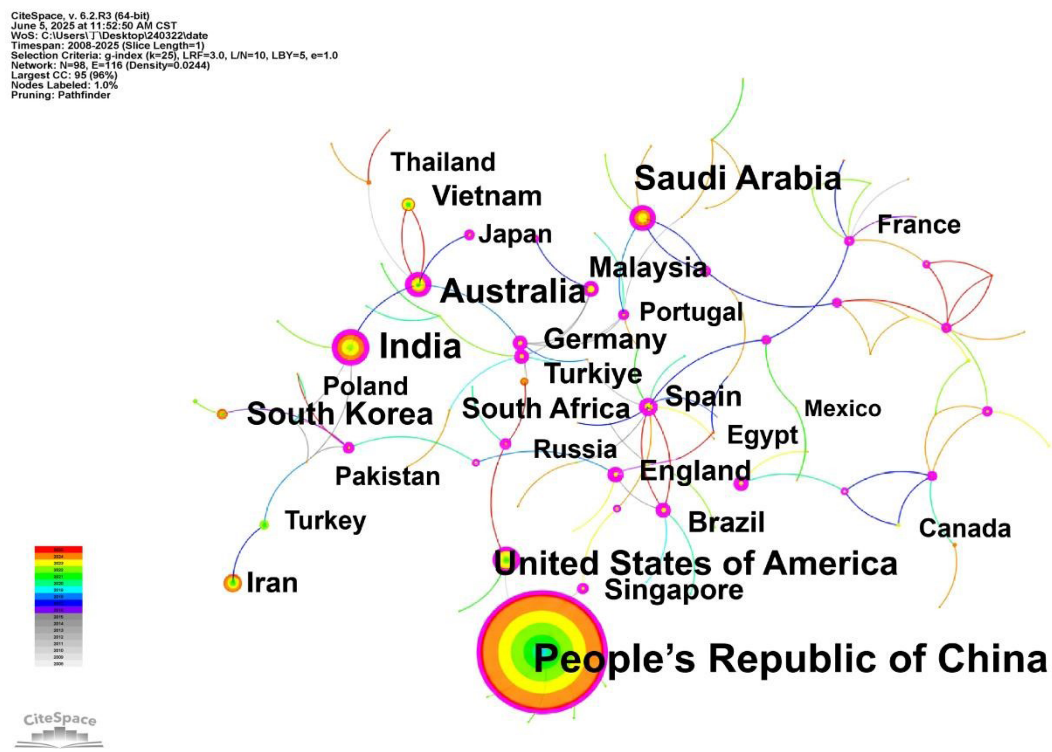

Figure 4. Collaborative network of countries in tetracycline removal research
Abbreviation: USA: United States of America.

Table 2. Top 10 institutions and countries in the publications of tetracycline removal research

Number	Top 10 Institutions			Top 10 Countries		
	Institution	Publications	Centrality	Country	Publications	Centrality
1	Chinese Academy of Sciences	276	0.48	China	3,733	0.17
2	Hunan University	142	0.21	India	271	0.31
3	Jiangsu University	100	0.04	Iran	262	0
4	Harbin Institute of Technology	88	0.04	United States	244	0.12
5	Tongji University	84	0.12	South Korea	155	0.04
6	University of Chinese Academy of Sciences	69	0.26	Saudi Arabia	129	0.36
7	Jilin University	68	0.03	Turkey	91	0.04
8	Ministry of Agriculture & Rural Affairs	60	0.06	Spain	87	0.76
9	Sichuan University	59	0.06	Australia	83	0.46
10	Jiangsu University of Science & Technology	58	0	Brazil	65	0.34

was conducted to identify key issues, developmental trajectories, and foundational knowledge within this field. The generated keyword co-occurrence map is shown in Figure 5, comprising 187 nodes and 203 connections with a network density of 0.0117. Larger nodes indicate higher occurrence frequency, font size represents betweenness centrality, and larger fonts denote higher centrality. Figure 5 shows that nodes associated with tetracycline removal research included "removal," "antibiotics," "water," "degradation," "performance," "wastewater," "adsorption," "oxidation," "aqueous solution," and "nanoparticles." Among these, the most frequently occurring keywords were "removal" and "antibiotics," indicating the primary research directions in tetracycline removal studies and essentially summarizing the core content of this field. "Water" and "degradation" indicate that most researchers focus on removing tetracycline pollutants from aquatic environments.[2,7] Simultaneously, "degradation" represented the primary method for removing pollutants from aquatic environments. Additionally, nodes with larger sizes included "wastewater," "adsorption," "oxidation," and "nanoparticles." As key methods and technical approaches for removing pollutants from water bodies, "adsorption," "oxidation," and "nanoparticles" were also frequently reported in tetracycline removal studies.[48,49]

As illustrated in the keyword cluster map (Figure 6), studies on tetracycline removal were categorized into 10 groups: adsorption, photocatalytic degradation, microbial community, singlet oxygen, hydrogen evolution, peroxymonosulfate activation, performance, degradation pathways, carbon nitride, and water. Subsequent analysis categorized these 10 research groups into 2 types. The first type represents traditional methods, primarily adsorption, including terms such as "adsorption," "performance," "carbon nitride," and "water." It focuses on conventional adsorption techniques, investigating the removal capacity, performance, and mechanisms of tetracyclines on various adsorbent materials. The second type represents removal methods centered on degradation, including terms such as "photocatalytic degradation," "singlet oxygen," "hydrogen evolution," "peroxymonosulfate activation," and "water."

The high-frequency keywords associated with tetracycline removal over the past three years were examined (Table 3). The relevant research in 2022 was predominantly focused on the study and application of photocatalytic materials for the environmental remediation of tetracyclines, as evidenced by the emergence of keywords such as "s-scheme heterojunction" and "environmental remediation."[50] In 2023, the research focus shifted to magnetic biochar-based materials and catalytic oxidation for the degradation of tetracyclines, as evidenced by the keywords "PMS [peroxymonosulfate] activation" and "magnetic biochar."[51-53] In 2024, the research emphasis shifted toward the application of composite structural materials in tetracycline removal, primarily reflected in the emergence of keywords such as "shell" and "oxides."[54]

The strongest keyword citation salience analysis (Figure 7) demonstrated that research on tetracycline removal entered the scientific spotlight in 2008. During the early phase (2004–2019), studies primarily focused on topics such as "wastewater," "wastewater treatment," "soil," "antibiotics," "oxytetracycline," "manure," "antibiotic resistance," "activated sludge," "sorption," "liquid chromatography," and "solid phase extraction." This indicates that during this period, efforts primarily centered on removing antibiotics such as tetracyclines from wastewater treatment and soil environments using adsorption and activated sludge processes, emphasizing chemical methods for antibiotic removal.[55-59] In recent years (2019–2025), keywords such as "microbial community," "efficient removal," "degradation products," and "wastewater treatment" indicate a growing emphasis on tetracycline removal efficiency, mechanisms, and green approaches. Consequently, as research advances, the future of tetracycline removal will continue to prioritize green, environmentally friendly, and highly efficient methods.[18,60-62]

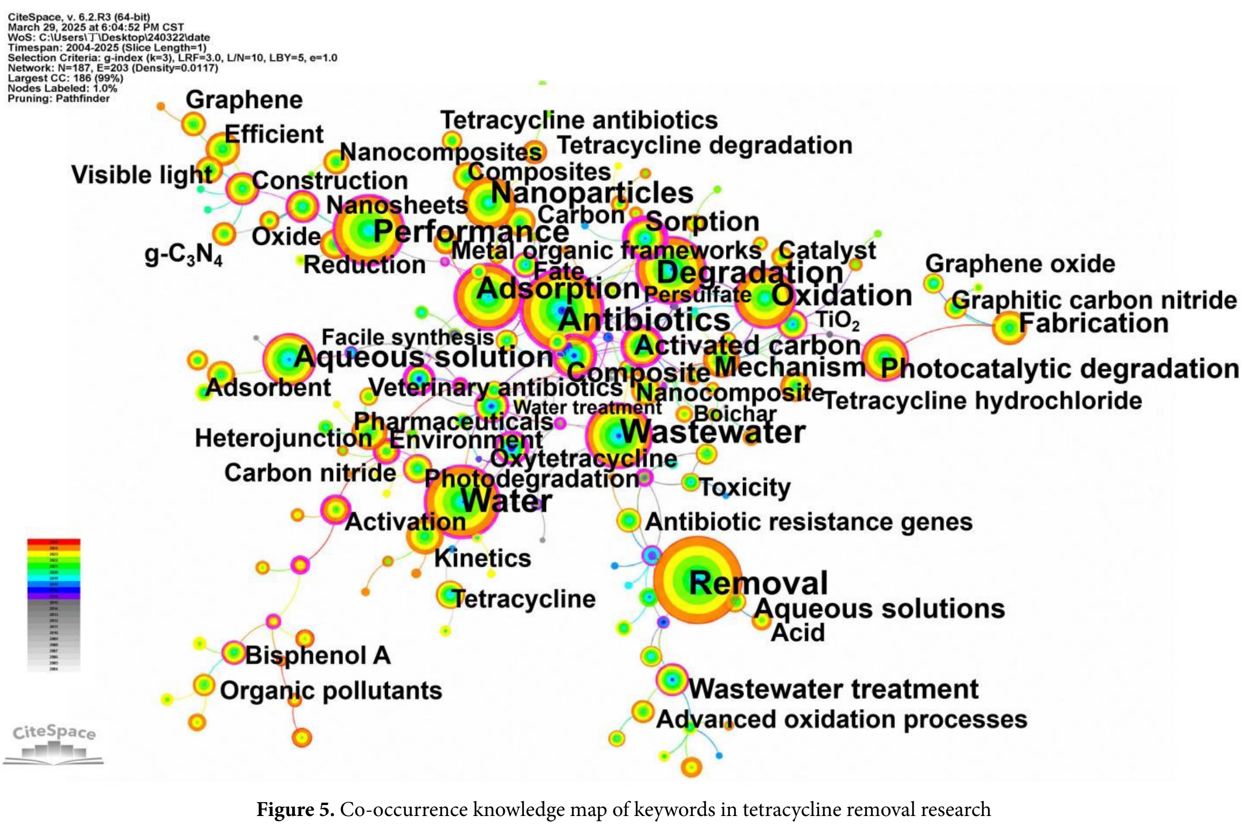

Figure 5. Co-occurrence knowledge map of keywords in tetracycline removal research

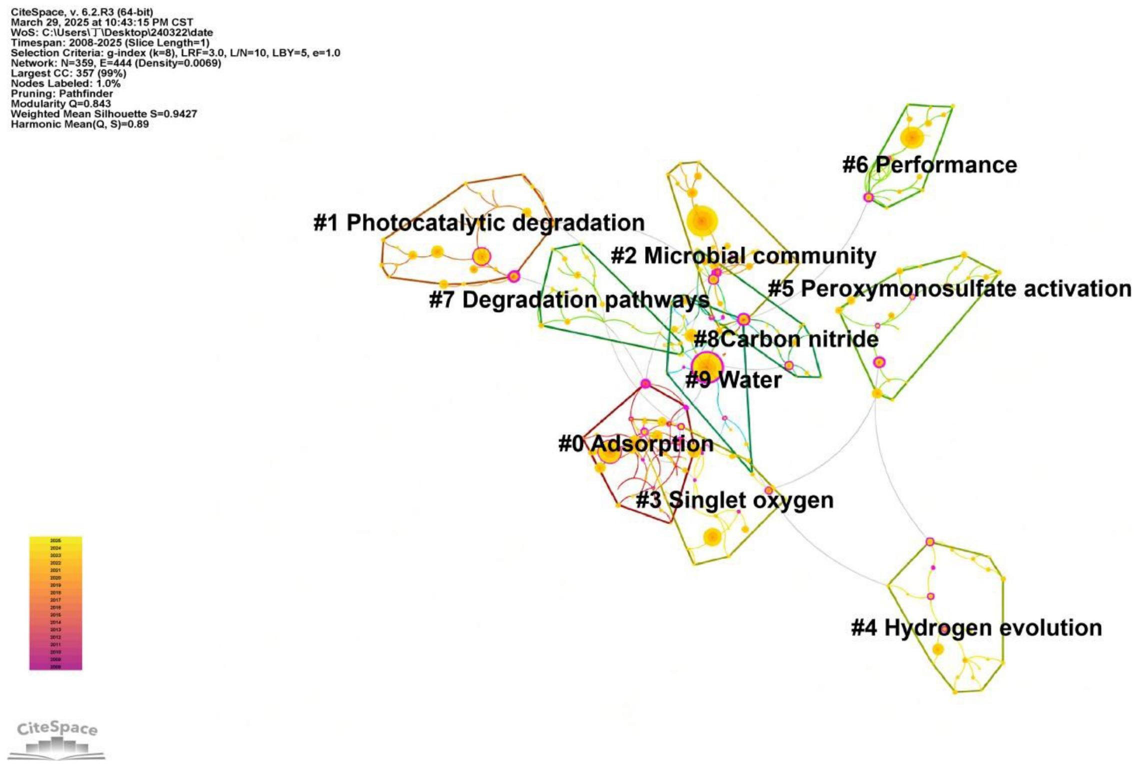

Figure 6. Cluster map of keywords in tetracycline removal research

Table 3. High-frequency keywords in tetracycline removal research in 2022–2024

Year	Keyword (centrality/count)
2024	Water pollution (0/11), oxides (0/10), shell (0/8), PMS (0/7), s-scheme heterojunction (0/7),
2023	PMS activation (0/18), magnetic biochar (0/12), pathway (0/12), sodium alginate (0/10), tetracycline antibiotic (0/9)
2022	S-scheme heterojunction (0/41), reactive oxygen species (0/30), environmental remediation (0.01/23), energy (0/22), H_2O_2 (0/20)

Abbreviation: PMS: Peroxymonosulfate.

The timeline diagram is chiefly used to depict the relationships between clusters and the historical span of literature within each cluster.[37] Research on tetracycline removal was divided into 10 clusters based on keywords. Each keyword in the keyword timeline diagram was positioned according to its cluster affiliation and publication date, thus forming a timeline view. Keywords within the same cluster were arranged chronologically along a horizontal line, with keywords from each cluster strung along a single timeline to showcase the historical achievements of that cluster.[63] Figure 8 presents the origin, development, and temporal scope of the research topics.

The existing body of research on tetracycline removal can be categorized into two types based on temporal segmentation and duration. The first type involves shorter-duration research that has recently emerged as a hot topic, encompassing three themes (#4, #5, and #7) and key research keywords such as "hydrogen evolution," "peroxymonosulfate activation," and "degradation pathways." These studies primarily focus on the use of photocatalysts to simultaneously drive water splitting for hydrogen production and organic pollutant oxidation under illumination, thereby achieving energy conversion and pollution control.[64-66] For example, an α-NiS/g-C_3N_4

nanocomposite suitable for photocatalytic hydrogen evolution and tetracycline degradation was reported by Qi *et al.*[66] Peroxymonosulfate activation efficiently degrades antibiotics in water by generating highly oxidizing sulfate radicals ($SO_4^{\cdot -}$) and hydroxyl radicals (·OH), representing a current research focus in environmental remediation.[67,68] For example, the degradation performance, intermediates, toxicity, and mechanisms of zero-valent iron-activated peroxymonosulfate for tetracycline were significantly enhanced, as reported by Cao *et al.*[67] Similarly, the integration of biochar with oxidative degradation was proposed as a viable biochar synthesis strategy for tetracycline removal.[69] Photocatalytic oxidation, chemical catalytic oxidation, and the integration of multiple techniques will remain key research focuses for eliminating tetracyclines.

The second category comprises topics with longer research durations that remain active research hotspots. These include seven themes: #0, #1, #2, #3, #6, #8, and #9. Key research keywords are "adsorption," "photocatalytic degradation," "microbial community," "singlet oxygen," "performance," "carbon nitride," and "water." The primary focus of these studies is the utilization of adsorption, photocatalytic oxidation, microbial techniques, and other methods to remove tetracyclines from water bodies, evaluate their performance, and investigate removal mechanisms. For example, Chang *et al.*[70] studied tetracycline adsorption on illite, a non-swelling layered clay mineral. Acosta *et al.*[71] reported the adsorption process of tetracycline on potassium hydroxide-activated tire pyrolysis activated carbon. Wang *et al.*[29] demonstrated the simultaneous efficient adsorption and photocatalytic degradation of tetracycline using iron-based MOFs. Peng *et al.*[72] investigated the performance, kinetics, and microbial community dynamics of tetracycline hydrochloride degradation via microbial electrochemistry,

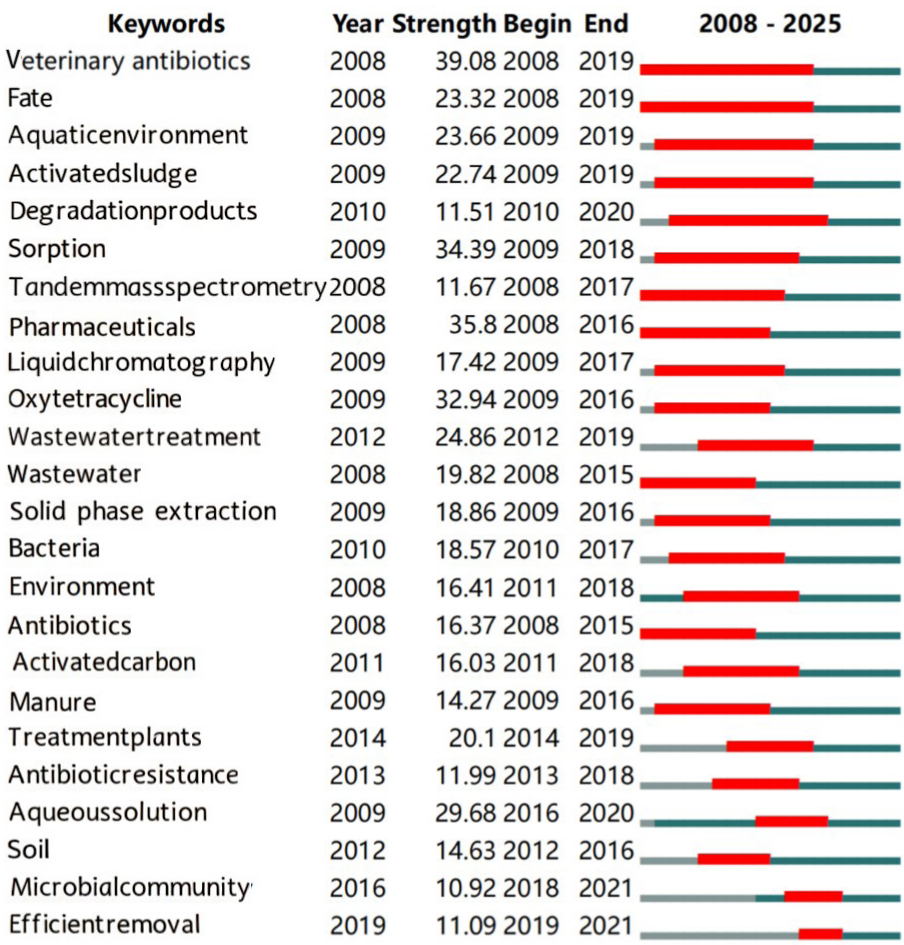

Figure 7. Top 24 keywords with the strongest citation bursts on tetracycline removal research

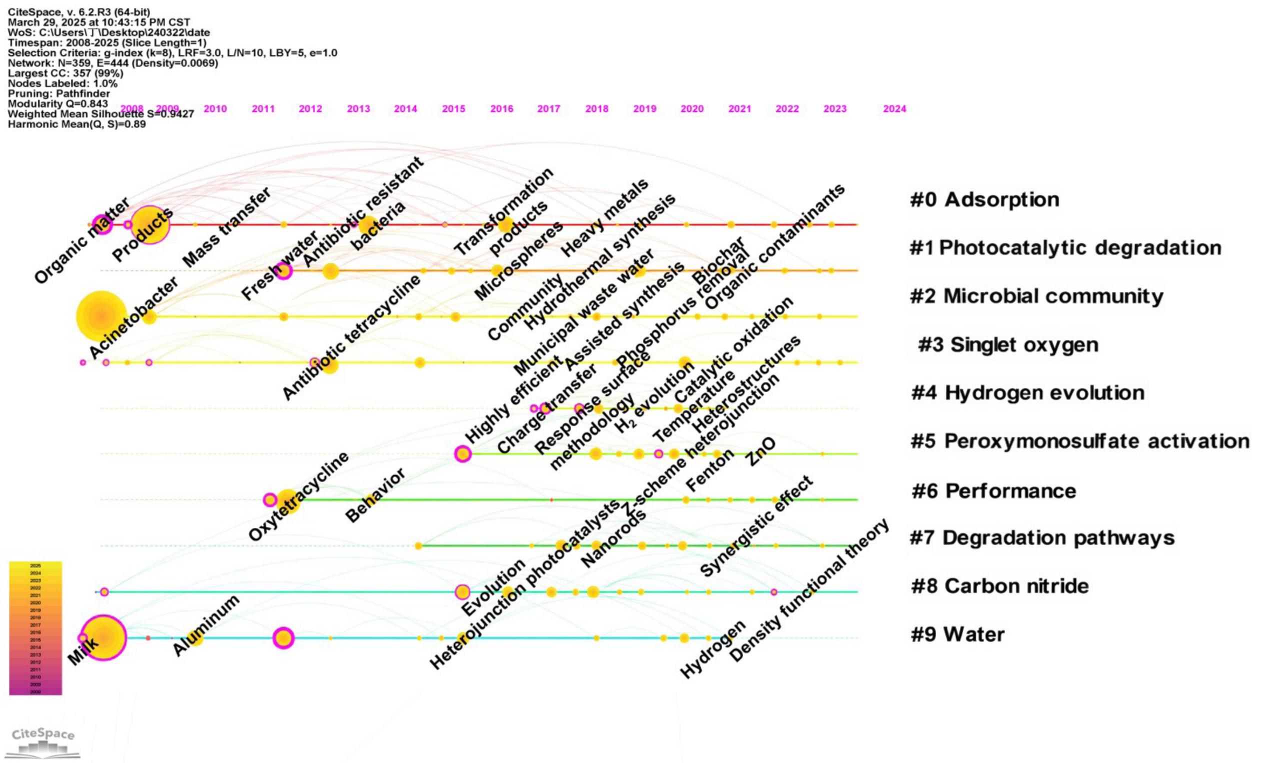

Figure 8. Timeline map of keywords on tetracycline removal research

exploring a novel anaerobic degradation pathway for tetracycline. With advancements in materials science, omics technologies, and catalytic oxidation techniques, the removal of tetracyclines will evolve toward simpler and more efficient methods.

The Citespace Time Zone View is a tool for displaying knowledge evolution across temporal spans.[37] The keyword time-zone map is a valuable resource that enables the observation of evolving trends and mutual influences in research on tetracycline removal. In the map, nodes representing keywords are positioned within their corresponding time zones based on the time of their first occurrence. The map illustrates the frequency of a keyword's appearance within a given zone. A low number of keywords and nodes within a time zone indicates a period of low research activity in that zone. Furthermore, connections between nodes across different time zones reveal the inheritance relationships among studies conducted at different times.[63]

As illustrated in Figure 9, the evolution of keywords in the field of tetracycline removal was characterized by a persistent focus on adsorption and catalytic oxidation as key research directions. Over time, there was an increasing emphasis on developing research toward greater specificity, selectivity, and efficiency. With respect to the evolution of research directions, the focus of studies on tetracyclines shifted sequentially from adsorption processes to adsorption kinetics, and from adsorbent properties to adsorbent selection (e.g., activated carbon, nanoparticles, graphene oxide, and nanocomposites). In the context of catalytic oxidation technology, research progressed sequentially through removal capacity, degradation capability, degradation mechanisms, oxidation performance, photocatalytic degradation capacity, photocatalyst types, heterojunctions, MOFs, peroxymonosulfate, activation, oxygen vacancies, quantum dots, and advanced oxidation processes.

Research on tetracycline removal is predominantly concentrated on two primary areas: adsorption and catalytic oxidation. In the early stages, the focus was on characterizing various adsorbents, investigating their adsorption properties, and assessing the impact of adsorption processes on tetracycline removal.[56,58,73] As research progressed, there was a gradual integration of catalytic oxidation with adsorption, using various catalytic oxidation methods, such as advanced oxidation and photocatalysis, to remove tetracycline contamination.[48,67,74] This was accompanied by a thorough examination of their degradation mechanisms and capabilities. Additionally, the use of microorganisms to remove tetracycline contamination and the combination of adsorption with catalytic oxidation through a synergistic treatment approach have emerged as prominent areas of research interest.[19,75,76]

3.4. Mapping and analysis of references

The analysis of the top 10 most highly cited references, co-cited references, and co-cited reference clustering results is presented in Table 4, Figures 10 and 11, respectively. Among the most highly cited references, Xu *et al.*[7] received the most citations (269), followed by Wang *et al.*[17] (140), Wu *et al.*[74] (139), Wang *et al.*[29] (130), and Li *et al.*[77] (127). These studies systematically investigated tetracycline removal through electrochemical catalytic oxidation, photocatalytic oxidation, adsorption, adsorption combined with photocatalysis, and chemical catalytic oxidation. Their results indicate that while individual technologies achieve some removal, advanced composite processes achieve superior tetracycline degradation compared to any single method. As of the data collection period, the top 10 most-cited articles each exceeded 100 citations, underscoring their significant contributions to advancing research on tetracycline removal.

Table 4. Top 10 most cited references of tetracycline removal research

Number	Count	Year	Cited references
1	269	2021	Xu *et al.*[7]
2	140	2018	Wang *et al.*[17]
3	139	2020	Wu *et al.*[74]
4	130	2018	Wang *et al.*[29]
5	127	2019	Li *et al.*[77]
6	125	2019	Cao *et al.*[67]
7	124	2018	Jang *et al.*[58]
8	116	2021	Scaria *et al.*[78]
9	114	2019	Zhang *et al.*[79]
10	113	2018	Xie *et al.*[80]

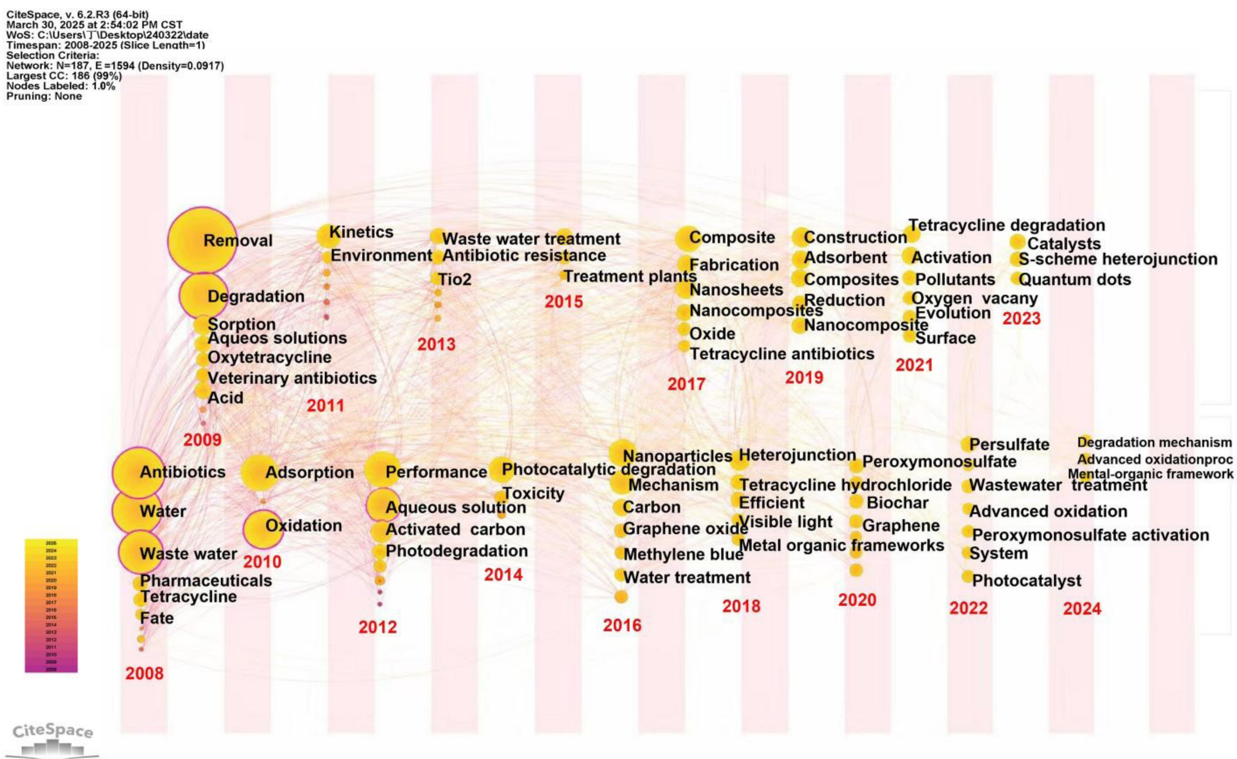

Figure 9. Time-zone map of keywords on tetracycline removal research

As demonstrated in Figure 10, which illustrates the co-citation network of cited references, the most significant publication is "Occurrence, fate, and risk assessment of typical tetracyclines in the aquatic environment: A review" by Xu *et al.*,[7] published *in Science of the Total Environment* in 2021. Despite its recent publication, this paper is the most frequently cited and has the highest citation burst intensity. The paper reviews the presence of tetracyclines in aquatic environments, treatment technologies, and their aquatic toxicity, conducting an ecological risk assessment of these antibiotics. It highlights that conventional methods cannot completely remove tetracyclines from wastewater, proposing anaerobic–aerobic combination processes and advanced oxidation processes as alternative methods to improve tetracycline degradation and mineralization.[7] Two other highly cited papers ranked among the top three in influence are "Evaluating tetracycline degradation pathway and intermediate toxicity during the electrochemical oxidation over a Ti/Ti_4O_7 anode" by Wang *et al.*[17] and "Visible light photocatalytic degradation of tetracycline over TiO_2" by Wu *et al.*[74] These two papers examined tetracycline removal efficacy and toxicity assessment from electrochemical catalytic oxidation and photocatalytic degradation perspectives, demonstrating that these methods are viable single-technology approaches for eliminating tetracyclines.

The application of the "pruning slice network" method to the clustering analysis of co-cited literature is illustrated in Figure 11. This analysis revealed 12 major co-citation clusters: #0 oxytetracycline, #1 adsorption, #2 peroxymonosulfate, #3 tetracycline degradation, #4 sorption, #5 MOF, #6 photocatalysis, #7 biochar, #8 biodegradation, #9 photoelectrocatalytic oxidation, #10 ion chromatography–electrospray ionization–mass spectrometry (IC-ESI-MS), and #11 inhibition. The color-coding system in Figure 11 indicates the temporal proximity of the respective studies, with red signifying early research and yellow denoting more recent investigations. The analysis of the clustering information and the timeline slice revealed three distinct research phases.

Prior to 2010, the research focused on the detection and identification of tetracyclines. The primary research themes were analytical determination, detection, ecotoxicity, and adsorption behavior of tetracyclines. These four themes are hereafter referred to by their respective numerical designations: #0 oxytetracycline, #4 sorption, #10 IC-ESI-MS, and #11 inhibition. During this period, Kulshrestha *et al.*[85] investigated interactions between oxytetracycline and clay adsorbents using natural montmorillonite, sodium-based montmorillonite, and clay adsorbents. Kim and Carlson[73] established an analytical

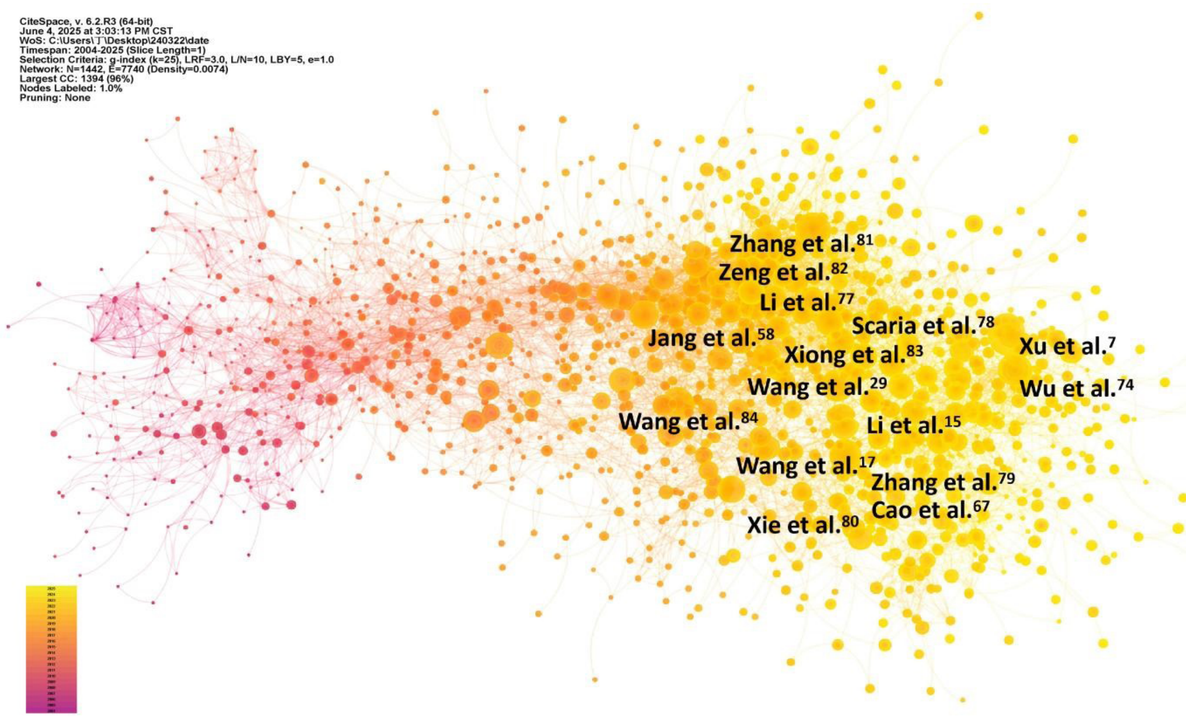

Figure 10. Co-citation reference network of tetracycline removal research

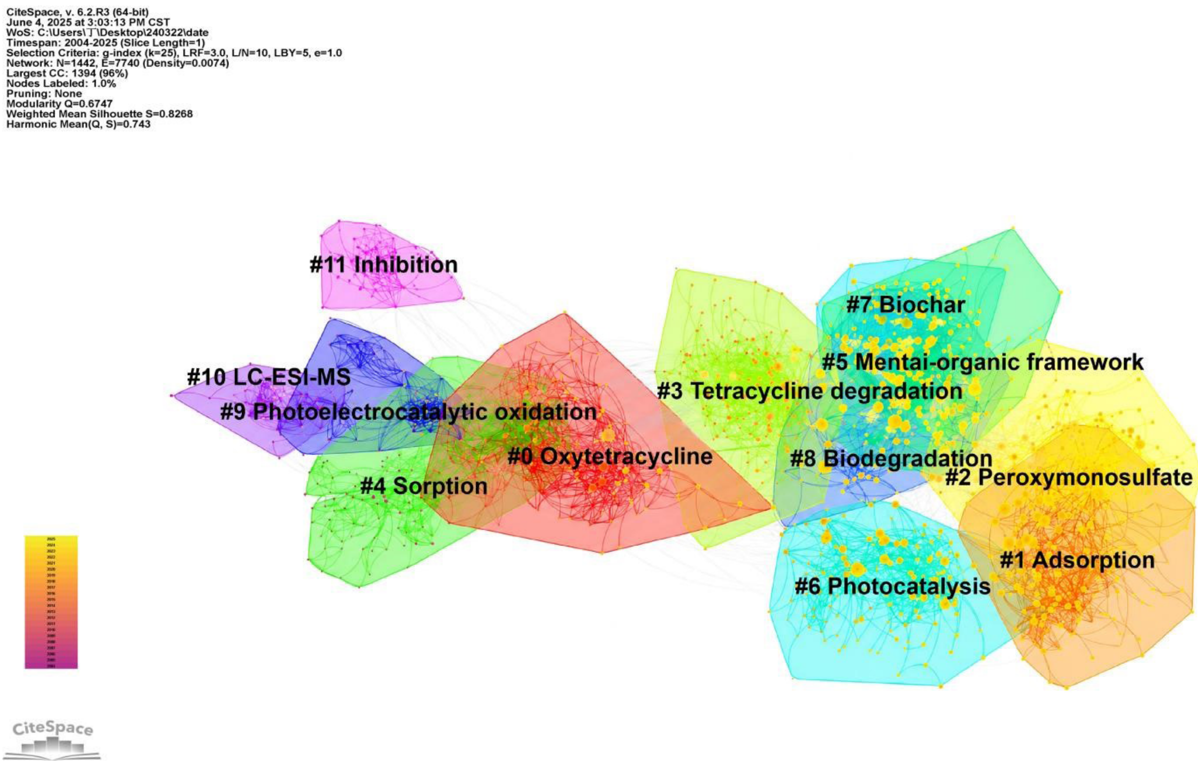

Figure 11. Co-citation reference clustering of tetracycline removal research

method for determining four different veterinary antibiotics in river water and sediments, employing high-performance liquid chromatography-tandem mass spectrometry for sample separation and quantification. Concurrently, Fernández *et al.*[86] assessed the ecotoxicity of doxycycline in aged spiked pig manure using a multispecies soil system comprising plants, earthworms, and soil microorganisms.

The second phase (2010–2018) focused on the removal and degradation of tetracyclines. Common single-technology approaches were primarily employed for tetracycline removal, with keywords #1 adsorption, #3 tetracycline degradation, and #7 biochar. During this period, several conventional pollutant removal techniques emerged. Li and Zhang[87] reported the biodegradation and adsorption of antibiotics in activated sludge systems, investigating the adsorption efficacy of activated sludge for 11 antibiotics across 6 classes. Liu *et al.*[56] utilized biomass char—a by-product of fast pyrolysis—as an adsorbent, studying its adsorption capacity for tetracycline and characterizing its performance. Oturan *et al.*[88] published a study employing electrocatalytic degradation via electrochemical advanced oxidation processes to remove tetracycline from aqueous media. In addition, Liu *et al.*[89] documented the removal of tetracycline, sulfonamide, and quinolone antibiotics through industrial-scale composting and anaerobic digestion processes. This phase witnessed the emergence of diverse novel technologies, enabling researchers to achieve tetracycline removal while laying the foundations for subsequent technological advancements.

The third phase, commencing after 2018, concentrated on the mechanisms of tetracycline removal, degradation pathways, and the development of composite technologies. This phase encompassed five key themes: #2 peroxymonosulfate, #5 MOF, #6 photocatalysis, #8 biodegradation, and #9 photoelectrocatalytic oxidation. During this period, significant advancements were made in adsorbent materials, photodegradation materials, and degradation technologies. Wu *et al.*[74] and Cao *et al.*[67] reported the visible-light photocatalytic degradation of tetracycline on TiO_2 and the performance, intermediates, toxicity, and mechanism of zero-valent iron-activated peroxymonosulfate degradation of tetracycline, respectively, systematically elucidating the degradation mechanisms. Wang *et al.*[50] reported enhanced photocatalytic degradation efficiency of tetracycline via a $g\text{-}C_3N_4/FeWO_4$ Z-scheme heterojunction assisted by peroxymonosulfate, elucidating the underlying mechanism. In addition, Fang *et al.*[54] reported on mechanism exploration in tetracycline degradation by Ni–Fe layered double hydroxide-biochar/peroxymonosulfate system. Shen *et al.*[75] demonstrated effective tetracycline removal through the combined use of MOF materials and laccase. With the rapid advancement of materials science and technology, numerous novel materials have been applied to the removal and degradation of tetracyclines.[7] The rapid development of photocatalytic technology has also led to the emergence of various composite techniques for removing tetracyclines.

3.5. Limitations

Several limitations should be acknowledged. First, this study relied exclusively on the WoS Core Collection, which may have introduced selection bias toward English-language and journal-indexed publications and excluded relevant studies indexed in Scopus, PubMed, and regional databases. As database coverage differs substantially, the observed bibliometric rankings, collaboration networks, and research hotspots may change with broader data sources. Thus, the findings should be interpreted within the scope of the WoS-indexed literature. Second, the results were influenced by the search strategy, including keyword selection, time span, and inclusion criteria, which may have led to the omission of relevant studies or inclusion of marginally relevant records. Third, citation-based metrics may favor older publications, thereby underestimating the impact of more recent studies. Finally, bibliometric visualization reflects mainly quantitative relationships and cannot fully assess the methodological rigor or scientific value of individual publications.

4. Conclusion

This study presents a comprehensive bibliometric mapping of tetracycline removal research and provides a valuable reference for future work in this field. Over the past two decades, research activity has increased steadily, indicating that this field remains in a phase of continued expansion. China, India, Iran, and the US have been the major contributors, with Chinese universities and research institutes playing a leading role.

Technological development has evolved from single materials to composites, from simple adsorption to functionalized degradation, from abiotic removal to biodegradation, and from standalone methods to integrated treatment systems. As materials science, microbiology, and environmental chemistry continue to intersect, research emphasis has shifted from material discovery toward system-level integration and performance optimization. Emerging hotspots, including hybrid technologies, pilot-scale studies, and artificial intelligence-assisted material screening, are expected to facilitate the transition from laboratory-scale research to real-world applications.

Future studies should integrate multiple databases to improve coverage and reduce database-related bias. The use of broader and more standardized search strategies may further enhance the sensitivity and reproducibility of bibliometric analyses. Moreover, combining quantitative mapping with qualitative content analysis could provide a more in-depth understanding of emerging themes. Periodic updates of bibliometric analyses may also help track changes in research hotspots, collaboration networks, and field priorities over time.

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Conflict of interest

The authors declare they have no competing interests.

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Writing – review & editing: Aiguo Luo

Availability of data

Not applicable.

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