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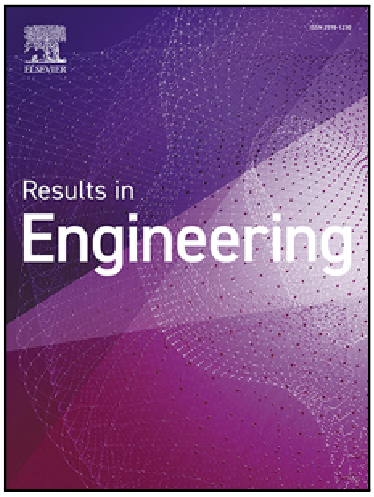

Tetracycline Adsorption Research (2015–2025): A Bibliometric Analysis of Trends, Challenges, and Future Directions

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PII: S2590-1230(25)02454-5
DOI: https://doi.org/10.1016/j.rineng.2025.106383
Reference: RINENG 106383

To appear in: *Results in Engineering*

Received date: 17 June 2025
Revised date: 14 July 2025
Accepted date: 19 July 2025

Please cite this article as: Ramesh Vinayagam , Thivaharan Varadavenkatesan , Raja Selvaraj , Tetracycline Adsorption Research (2015–2025): A Bibliometric Analysis of Trends, Challenges, and Future Directions, *Results in Engineering* (2025), doi: https://doi.org/10.1016/j.rineng.2025.106383

Highlights

- Tetracycline adsorption research shows rapid growth in the past decade (2014-2025)
- VOSviewer and Bibliometrix visualized the Bibliometric data (567 articles)
- China, USA, India are top contributors
- Metal organic frameworks and magnetic biochar are trending adsorbents
- DFT, AI/ML and continuous studies are major research gaps

Tetracycline Adsorption Research (2015–2025): A Bibliometric Analysis of Trends, Challenges, and Future Directions

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Abstract

Tetracycline is a commonly used antibiotic that has emerged as a significant environmental contaminant due to its widespread use and persistence in aquatic ecosystems. Its presence in water bodies poses ecological risks and contributes to the growing concern over antibiotic resistance. Among the various treatment technologies, adsorption has gained prominence as a cost-effective and efficient approach for removing tetracycline from contaminated water. This bibliometric review analyzes 567 articles published between 2015 and 2025 retrieved from the Web of Science Core Collection to uncover the scientific trends, influential contributors, research hotspots, and emerging gaps in the field of tetracycline adsorption. Using VOSviewer and Bibliometrix, the study presents a comprehensive visual mapping of publication growth trends, leading countries, institutions, authors, and journals. China, the USA, and India dominate the research output, with significant institutional contributions from Hunan University and Anhui Agricultural University. "Desalination and Water Treatment" and "Bioresource Technology" are identified as prominent journals, with the latter having 2236 citations. Keyword co-occurrence and thematic evolution analyses highlight trending materials like magnetic biochar and metal-organic frameworks. Additionally, it highlighted underexplored areas, including computational modeling, Artificial Intelligence/Machine Learning integration, and continuous adsorption. The findings offer a holistic understanding of the current research landscape and provide strategic directions for advancing future studies in tetracycline adsorption for environmental sustainability.

Keywords: Tetracycline; Adsorption; Bibliometric Analysis; VOSviewer; Bibliometrix

1. Introduction

Tetracycline (TC), is a widely used broad-spectrum antibiotic, known for its potent antimicrobial activity, high oral bioavailability, and low toxicity, making it extensively employed in medicine, livestock farming, agriculture, and aquaculture [1]. Despite its benefits, TC's excessive use has resulted in serious environmental contamination [2]. Because of incomplete metabolism in humans and animals, significant amounts of TC are excreted as metabolites or in unaltered form, accumulating in aquatic systems [3]. TC has been detected in a broad spectrum of environments, from medical and municipal waste to groundwater and surface water [4]. This persistent presence in water bodies poses severe ecological and health risks. TC contamination disrupts microbial communities, damages ecosystems, and fosters antibiotic resistance by promoting antibiotic-resistant genes [5]. TC’s presence in water sources has been linked to inhibited growth and impaired photosynthesis in microalgae [6], as well as liver damage in aquatic species like zebrafish [7]. Long-term usage of TC-contaminated water may lead to gastrointestinal discomforts, liver issues, and impaired bone growth in humans [8]. Additionally, the accumulation of TC residues along the food chain poses further risks to public health. Inefficient wastewater treatment systems have exacerbated the problem, increasing antibiotic concentrations in aquatic environments, including drinking water. As a result, developing effective TC removal strategies is crucial.

Adsorption is the most efficient method to remove a variety of contaminants such as heavy metals [9,10], dye [11], and emerging contaminants [12] because of its ease, low cost, and high effectiveness. Compared to alternate methods such as biodegradation [13], advanced oxidation processes (AOPs) including Fenton reactions and photocatalysis [14] [15], membrane filtration [16], and coagulation [17], adsorption outperforms removing TC without generating toxic byproducts or requiring excessive energy input [18].

Biodegradation, though eco-friendly, often suffers from slow processes and incomplete removal of TC, leading to the generation of lethal intermediates [19]. AOPs are highly effective but are expensive require high energy [20], and possess challenges related to catalyst recovery and secondary pollution [21]. Membrane filtration, though efficient in removing TC, faces drawbacks such as membrane fouling, high maintenance costs, and the necessity of frequent replacements, making long-term operation costly. Coagulation, though easy to use, struggles with incomplete removal, excessive sludge generation, and additional disposal concerns. In contrast, adsorption provides an economical, scalable, and highly efficient solution for TC removal, capable of achieving high adsorption capacities with low operational complexity [22]. The availability of diverse adsorbent materials, comprising of activated carbon, biochar, clay minerals, and novel nanomaterials, further enhances its applicability. Moreover, adsorbents can often be regenerated and recycled, decreasing whole treatment costs and environmental impact [23].

In recent years, several review articles have explored TC adsorption and other emerging contaminants **(Table 1),** largely focusing on reviewing specific research findings. However, there remains a lack of thorough analysis of TC adsorption characteristics and its research development.

To the best of our knowledge, this is the first bibliometric review exclusively focused on TC adsorption, integrating advanced visualization and performance analysis tools to map the evolution and structure of this research field. This proposed bibliometric review aims to address this gap by scientifically analyzing the research trends and knowledge dissemination. Although existing reviews **(Table 1)** tend to concentrate on specific adsorbent materials such as activated carbon, biochar few have integrated into the evolving landscape of TC adsorption using quantitative methods. By mapping citation networks, tracking keyword trends, and assessing author collaborations, this review aims to identify emerging research directions, highlight influential studies, and pinpoint critical knowledge gaps. Such insights will be instrumental in guiding future research endeavors and supporting policymakers and environmental engineers in devising effective strategies to combat TC contamination in water systems. Recently, bibliometric analysis has been applied to review diverse technologies involving cellulose-based pollutant removal [24], cesium adsorption [25], cyclodextrin-based adsorbents for pollutant removal [26], treatment of uranium-containing wastewater [27], as well as the removal of PFAS [28] and fluoride [29]. However, no bibliometric study to date has systematically examined the body of literature related specifically to TC adsorption. Hence, conducting a bibliometric review on TC adsorption is crucial for accurately capturing the developmental trends and research hotspots in this field.

The present review employs a bibliometric approach to systematically examine the literature on TC adsorption, using the data extracted from the Web of Science Core Collection (WOSCC). By analyzing key aspects such as keywords, authors, and institutions, this study highlights significant advancements in TC adsorption. The key highlights are as follows:

1. Identification of Key Contributors: The bibliometric analysis identified influential countries, leading research institutions, prominent journals, and key authors driving TC adsorption research.
2. Research Trends: Through keyword analysis, the review outlines current research progress and emerging trends in TC adsorption.
3. Future Directions and Challenges: Based on bibliometric insights and existing literature, potential research challenges and future directions are proposed to guide further exploration in this field.

2. Collection of data

The flow diagram depicting the bibliometric analysis is shown in **Fig. 1**, and the dataset was retrieved from WOSCC databases. The search strategy included keywords such as TS = "Tetracycline adsorption" OR "Tetracycline removal" OR "adsorption of Tetracycline" OR "removal of Tetracycline" OR "Tetracycline desorption" OR "desorption of Tetracycline." The search period spanned from 2015 to 2025, with data collected on March 8, 2025. The search was limited to document types "article" and "review," initially yielding 1,523 records. Including photocatalytic and degradation studies would significantly broaden the scope and introduce methodological heterogeneity, thereby limiting the depth of bibliometric insight specific to adsorption. Hence, the search was further filtered using NOT photocataly* OR degrad*, narrowing the dataset to 567 articles. The retrieved records were exported in multiple formats for subsequent analysis. The analysis was limited to publications from 2015 to 2025 to reflect the most recent developments in TC adsorption.

The bibliometric analysis was performed with VOSviewer (version 1.6.20) and Bibliometrix software within R Studio (R version 4.4.3). VOSviewer is an open-source software tool designed to create and visualize bibliometric maps [30]. It is known for its robust graphical capabilities, enabling better representation of complex bibliometric data. Bibliometrix is a powerful bibliometric tool built on the R programming language. It offers an efficient and thorough way to analyze and visualize scientific data. Evaluating several bibliometric parameters like the number of publications, citations, and reference articles, facilitates in-depth scientific analysis [31]. These tools enabled comprehensive network visualization, keyword mapping, and trend analysis, providing the progress and research focus areas. Though VOSviewer and Bibliometrix are powerful tools for bibliometric analysis, they have certain limitations, such as algorithmic differences in clustering and sensitivity to data preprocessing. To address this, both tools were used complementarily, allowing for cross-validation of results. Manual standardization of author names, keywords, and institutions was also performed to enhance the accuracy and interpretability of the data.

3. Result and Discussions

3.1 Data Visualization

Biblioshiny, a web-based interface of Bibliometrix, was used to generate data for visualization [32]. **Fig. 2** presents a concise summary of essential information extracted from the WOSCC database, highlighting key insights into research trends on TC adsorption over the timespan 2015–2025. A total of 567 documents were published across 186 sources, reflecting an annual growth rate of 9.76%, indicating consistent interest in TC adsorption. The research community is extensive, involving 2234 authors, with only 7 single-authored documents, highlighting a strong culture of collaboration. Each document, on average, has 6.64 co-authors, with 21.34% involving international co-authorship, suggesting significant global collaboration. The dataset contains 1353 unique keywords, demonstrating a broad spectrum of research themes. With 19,525 references, the field is well-supported by extensive literature. The average document age of 3.64 years implies that recent developments are actively contributing to the knowledge base. Additionally, an impressive 34.05 average citations per document indicate that these publications are impactful and frequently referenced in related adsorption studies.

3.2 Publication Growth Trend Analysis

Analysis of 567 documents reveals that research on TC adsorption started gaining momentum in 2015, as shown in **Fig. 3**. It reveals a significant upward trend in both publications and citations from 2015 to 2025, indicating growing interest and impact in this area of research. Annual publication counts increased steadily, reaching a peak of 111 articles in 2024. Citation counts also rose markedly, totaling 4,854 in the same year. About 53.4 articles were published annually during this period, reflecting sustained research growth. The average number of citations per year was around 1,855.4, indicating increasing academic recognition and influence in the TC adsorption research.

The data on TC adsorption bibliometric review reveals three distinct stages of growth and impact. In the emergence stage (2015-2017), the research field was still emerging, with relatively low numbers of publications and citations. The growth stage (2018-2020) saw a significant increase in both metrics, indicating growing interest and recognition. The peak stage (2021-2024) represents the peak of TC adsorption research, with a high volume of publications and substantial citations, reflecting the field's importance and influence. The dip in 2025 data is likely due to the year still being ongoing. As the year progresses, these numbers are expected to increase, aligning with the overall upward trend observed in previous years. Overall, the trends highlight the progressive development and increasing impact of TC adsorption research over the past decade.

3.3 Web of Science categories and SDG classifications

Fig. 4a highlights the highly interdisciplinary nature of research in this domain, spanning diverse fields such as Engineering (29.5%), Chemistry (28.7%), Environmental Sciences & Ecology (23.8%), Materials Science (9.4%), and Water Resources (8.6%). This distribution emphasizes the multifaceted nature of TC adsorption research, which integrates material development, chemical processes, environmental impact assessment, and water treatment strategies. As illustrated in **Fig. 4b**, the research on TC adsorption is predominantly allied with the United Nations Sustainable Development Goal (SDG) 6: Clean Water and Sanitation, accounting for 85.9% of the focus. This strong emphasis underscores the critical role of TC adsorption research in ensuring access to clean and safe water by addressing the removal of antibiotic contaminants. Additionally, there is a notable secondary focus on SDG 3: Good Health and Well-being (10.9%), highlighting the importance of reducing antibiotic pollution in water sources to protect human health and mitigate the risk of antimicrobial resistance. Smaller percentages are directed towards SDG 12: Responsible Consumption and Production (1.4%) and SDG 2: Zero Hunger and SDG 11: Sustainable Cities and Communities (0.9% each), indicating some consideration of sustainable resource management and the broader implications of water quality on agriculture and urban environments.

3.4 Sankey diagram

Sankey diagram, commonly known as the three-field plot offers a valuable perspective on the research landscape of TC adsorption, illustrating the interconnectedness of leading research institutions, dominant research themes, and prominent publication journals [33]. **Fig. 5** offers a detailed outline of the research topics across various institutions and their preferred publication journals, revealing key trends and patterns. Hunan University, Anhui Agricultural University, and Northwest A&F University demonstrate strong involvement, as seen from the many connections coming from their nodes. The strong presence of Chinese institutions in TC adsorption research potentially reflects a concentrated effort and robust collaboration networks within the country. The core research themes center around tetracycline, adsorption processes, and the application of biochar. The prevalence of "biochar" highlights its popularity as an adsorbent material for TC removal. Further investigation focuses on the mechanisms and kinetics governing the adsorption, signifying efforts to optimize the process. Given the established focus on biochar-based adsorbents, opportunities may exist for exploring alternative materials and innovative approaches. This could involve investigating metal oxides, nanocomposites, or hybrid systems to enhance adsorption capacities or address specific environmental conditions. "Bioresource Technology" and "Desalination and Water Treatment" appear as significant publishing journals which suggests that these journals have published a noteworthy amount of research on TC adsorption. "Journal of Environmental Chemical Engineering," "Chemical Engineering Journal," and "Science of the Total Environment" also stand out, highlighting the field's focus on viable wastewater treatment solutions.

3.5 International collaborations

This section examines international collaboration patterns with co-authorship data using VOSviewer software, as illustrated in **Fig. 6**. The circle size represents the number of publications produced by each country, whereas the lines connecting circles signify international cooperation, with thicker lines representing strong collaborations, providing understandings of the dynamics of global research partnerships [34].

Analysis of the VOSviewer image (**Fig.6**) and co-authorship data (**Table 2**) reveals a network dominated by China ("Peoples r China"), boasting 348 publications, 13376 citations, and a total link strength of 58, signifying its central and prolific role in the TC adsorption. The United

States also holds a prominent position, with 35 publications, 1263 citations, and a total link strength of 39, showing strong collaborative links, suggesting a high degree of international cooperation. India emerges as another key player, with 39 publications, 1065 citations, and a total link strength of 36, forming a distinct cluster with connections to countries like Iraq, South Korea (14 publications, 706 citations, link strength 26), and Taiwan (6 publications, 174 citations, link strength 12), highlighting its regional collaborations. Several other nations, including Iran (52 publications, 1156 citations, link strength 17), and Vietnam (16 publications), contribute to the network's interconnectedness, while countries such as Mexico (6 publications), Algeria (6 publications), and Scotland (5 publications) appear more isolated, indicating limited co-authorship activity in this specific research domain.

The overwhelming contribution from Chinese institutions has significantly shaped the direction and volume of TC adsorption research. This dominance influences both the research agenda and thematic focus – often prioritizing specific adsorbents or materials popular in Chinese research settings. While this strong output strengthens the global evidence base, it also raises concerns about geographical skewness, where findings may not fully reflect regional priorities, water treatment challenges, or environmental conditions in less-represented areas. To improve the generalizability of findings and promote equitable scientific development, increased international collaboration and regional diversification are essential. Countries with emerging research capacities can benefit from shared infrastructure, joint funding programs, and thematic partnerships that reflect local environmental realities.

3.6 Journals and Citation Analysis

The top 10 journals for TC adsorption (**Table 3**) highlight a diverse range of publications that focus on environmental science, chemical engineering, and materials science. While

“Desalination and Water Treatment” has the highest number of publications (31), it has a relatively low impact factor (IF) of 1.0, indicating that publication volume does not necessarily equate to research influence. However, “Bioresource Technology” – with 20 articles and 2,236 citations – has a strong IF of 9.0, underscoring its high influence and collaborative network strength (link strength 195). Journals such as “Chemical Engineering Journal” (IF 13.2), “Science of the Total Environment” (IF 8.0), and “Journal of Environmental Chemical Engineering” (IF 7.2) exhibit both high citation rates and strong total link strengths, suggesting their role as platforms for impactful, multi-authored studies. The inclusion of journals like “Journal of Molecular Liquids” and “Separation and Purification Technology” reflects the growing interest in material science aspects of adsorption. The collective coverage of these journals spans water purification, chemical processes, and environmental remediation, often employing adsorption models like Langmuir and Freundlich isotherms to analyze pollutant removal mechanisms. This variety underscores the interdisciplinary approach necessary for advancing innovative adsorption technologies and applications.

Analysis of the top 10 cited articles on TC adsorption reveals a landscape dominated by biochar-based materials and a strong emphasis on environmental remediation. It can be seen from **Table 4** that three articles were published in the "Bioresource Technology” journal which significantly leads in total citations (1194), primarily driven by articles focused on biochar-based materials. The significant number of citations garnered by articles in this journal underscores their prominent role in advancing research. The most-cited article, "Modification of biochar derived from sawdust and its application in removal of tetracycline and copper from aqueous solution: Adsorption mechanism and modelling" (594 citations, “Bioresource Technology”) [35], highlights the effectiveness of modified biochar in removing multiple pollutants. Several other top articles also focus on biochar derived from various sources like sewage sludge (491 citations, "Chemical Engineering Journal") [36] and cow manure (322 citations, "Bioresource Technology") [37], indicating its potential for sustainable and cost-effective TC removal. Modification techniques, such as alkali-acid treatment and magnetization, are frequently explored to enhance biochar's adsorption capacity. Beyond biochar, other materials like activated carbons from tyre pyrolysis char (270 citations, "Chemosphere") [38] and nanocomposites containing graphene oxide (254 citations, "Carbohydrate Polymers") [39] are also investigated. Review article (240 citations, "Desalination and Water treatment") [40] provide comprehensive overviews, while studies employing adsorption modeling and DFT simulations (226 citations, "Journal of Hazardous Materials") [41] deepen the understanding of adsorption mechanisms. Lastly, innovative approaches like using metal-organic frameworks (MOFs) doped with nanoparticles (213 citations, "Science of the Total Environment") [42] demonstrate the breadth of research in this field. Overall, these highly cited articles collectively contribute to the development of effective and sustainable methods to remove tetracycline from water, with a strong focus on biochar and modified carbon-based materials.

3.7 Keyword analysis - Research Trends, themes and gaps

Keyword co-occurrence network visualization offers a powerful tool for illustrating the intricate relationships between keywords. By mapping these connections, researchers can directly observe how keywords correlate, making it easier to pinpoint the most relevant or extensively studied areas within a field. The spatial arrangement of keywords reveals their semantic similarity: those positioned in proximity form cohesive clusters, while those farther apart diverge into distinct thematic groups. This visual representation not only highlights key research areas but also provides insights into emerging trends and potential gaps [34].

To investigate the relationships among author keywords, a co-occurrence technique was used. To ensure statistical significance, only keywords with at least eight occurrences were included. This methodology facilitated the finding of essential themes and relationships within the dataset, offering valuable insights about the research interests and significance of the authors. Ultimately, these methods enabled a thorough and systematic examination of the keywords, providing a comprehensive understanding [43].

The visual representation of keyword networks is a multifaceted tool that offers an understanding of keyword relationships. Key elements include node size, which reflects the frequency of occurrence of each keyword, and links between nodes, which signify co-occurrence where keywords emerge together. The thickness of these links is proportionate to the co-occurrence frequency, visually representing how often keywords are paired. Additionally, different colors are used to distinguish thematic clusters, allowing for the identification of topics based on the keywords and their interconnected relationships [44].

There are five clusters seen in **Fig. 7** with various colors like red, green, blue, yellow, and purple. Each cluster represents a unique aspect of research in the field of TC removal. These themes not only illustrate the diversity of research approaches but also highlight potential areas for further study and development. 'Tetracycline' and 'adsorption' are the most prominent keywords, belonging to Cluster 2 (**Table 5**). They have high occurrences (264 and 247, respectively) and strong total link strengths (322 and 352), indicating they are frequently discussed together and are central to the research.

The red cluster focuses on traditional and established methods for wastewater treatment, with a strong emphasis on adsorption involving materials like activated carbon and montmorillonite. Keywords like 'tetracycline adsorption,' 'regeneration,' and both 'wastewater treatment' and 'water treatment' indicate a comprehensive approach to purifying water from tetracycline and other antibiotics, ensuring these technologies are effective and can be regenerated for long-term use.

Cluster 2 (green) highlights the use of novel materials and composites in adsorption, such as chitosan, graphene oxide, and various nanocomposites. These materials are linked to the removal of tetracyclines from wastewater, suggesting a focus on enhancing the effectiveness and specificity of adsorption with advanced, engineered adsorbents.

Cluster 3 (Blue) centers on the mechanisms behind adsorption and the exploration of cutting-edge materials such as biochar, magnetic biochar, and metal-organic frameworks. These materials are associated with the removal of tetracycline antibiotics and reflect a trend toward developing new adsorbent technologies that offer high efficiency and targeted adsorption capacities.

Cluster 4 (yellow) delves into the fundamental science underpinning adsorption processes, including kinetics, thermodynamics, and isotherm studies. This cluster appears to focus not only on the process of antibiotic removal, including ciprofloxacin but also on understanding the conditions that optimize such processes.

The single theme focus of Cluster 5 (Purple) on 'mechanism' suggests a deep dive into the theoretical and practical aspects of how adsorption and other related processes function at a molecular or atomic level. This could involve detailed studies on the interactions between pollutants and adsorbents, aiming to refine and optimize the effectiveness of treatment methods.

3.7.1 Trend topics

Fig. 8 displays the progress of trending topics, yielding valued insights into the most recent research areas on TC adsorption. A significant and persistent focus is evident in the high frequency (Frequency 279, year 2022) activity surrounding the term "tetracycline," and similarly, "adsorption" (Frequency 265, 2022) underscores the core interest in this specific pollutant's removal via adsorptive processes. Delving deeper, the exploration extends to specific forms of the antibiotic, as indicated by the trending topic of "tetracycline hydrochloride" (Frequency 11, 2024), suggesting investigations into how different derivatives behave during adsorption. This core theme is further enriched by a strong emphasis on advanced materials and their application in TC adsorption, particularly in the context of wastewater treatment (Frequency 12, 2024). Recent years have witnessed a surge in research centered on "metal-organic frameworks (MOFs)" (Frequency 8, 2024), "nanocomposites" (Frequency 9, 2023), and "magnetic biochar" (Frequency 7, 2023), highlighting the pursuit of enhanced adsorption capacities, selectivity, and ease of separation. The term "biochar" (Frequency 55, 2022) and "activated carbon" (Frequency 24, 2020) maintain their relevance as established adsorbents, the emergence of modified forms like magnetic biochar signals a drive towards improving material properties and recovery methods. Concurrently, investigations into the fundamental aspects of TC adsorption, such as "mechanism" (Frequency 26, 2021) and "kinetics" (Frequency 20, 2021), remain valuable for optimizing adsorption processes and gaining deeper insights into the interactions at play. Notably, there appears to be a relative decline in the prominence of "graphene" (Frequency 5, 2017) and "graphene oxide" (Frequency 8, 2020) compared to the newer materials, suggesting a shift in focus toward alternative solutions.

Refining a broad TC adsorption search (567 results) with 'activated carbon' narrows results to 145, reflecting its well-established nature within the field. Trend analysis confirms this, showing activated carbon's earlier positioning in the timeline compared to emerging materials. Though research persists, as evidenced by the 145 results, it is likely focused on specific applications and incremental improvements rather than novel discoveries.

In conclusion, the analysis of trend topics in TC adsorption research indicates a growing interest in advanced materials, particularly MOFs, magnetic biochar, and nanocomposites. These materials represent the emerging frontier in TC adsorption, driven by the need for enhanced performance, selectivity, and practical applicability in wastewater treatment. Even as established adsorbents like biochar and activated carbon continue to play a role, the recent surge in research on MOFs, magnetic biochar, and nanocomposites underscores their potential to overcome limitations of traditional materials and achieve more efficient and sustainable TC removal from contaminated water sources.

The initial keyword searches for TC adsorption yielded a broad range of results (567), however, refining the search to specifically include 'metal-organic framework' (MOF) narrowed the results to 73. This reduction, although significant, is justified by the emerging trend of MOFs as promising adsorbents for TC removal. The trend topics analysis indicates that MOFs are a recent area of focus.

Table 6 summarizes ten recently published studies on MOF adsorbents for TC removal revealing a diverse landscape of materials with varying characteristics and performance. The specific surface area (SSA) ranges significantly, from a relatively low 10.78 m^2/g for graphene quantum dot/MIL88A(Fe) [45] to a high of 2858.7 m^2/g for UiO−67-HAc-NH_2−3 [46], indicating the importance of MOF structure on the overall performance. Similarly, the maximum adsorption capacity (Q_m) varies widely, with MRCU102 showing 1215.46 mg/g adsorption [47] and others showing 213.8 mg/g [48], depending on the MOF structure and composition. The presence of both single components such as MOFs (e.g., [Cu(Fum)(MIM)$_2$(H_2O)$_2$] (MRCU102) [47], Al-UiO-66-NH_2 [49], NH_2-MIL-101(Fe)) [50] and composite materials (e.g., Fe_3O_4@PCN-333 (Fe) [51], HKUST-1/cellulose/chitosan composite aerogel [52]) highlights different strategies for enhancing TC adsorption. Overall, the data underscores the tunability of MOFs for TC adsorption, suggesting that strategic design and modification of MOF materials can lead to high-performance adsorbents for addressing tetracycline contamination.

3.7.2 Research Gaps and Future Research Directions

Despite progress in TC adsorption, several research gaps hinder real-world application (**Fig. 9**). Trend analysis highlights MOFs, magnetic biochar, and nanocomposites as emerging, and the VOSviewer network emphasizes the interconnectedness of key terms.

Although the VOSviewer network emphasizes the association of "regeneration" with adsorption, there is a noticeable lack of emphasis on sustainable and cost-effective regeneration strategies for newer, advanced materials. From an economic standpoint, the feasibility of large-scale application of MOFs and nanocomposites depends heavily on low-cost synthesis routes, regeneration efficiency, and minimal performance loss over multiple cycles. Studies must prioritize low-energy regeneration using green solvents and assess cost-benefit tradeoffs under field conditions.

The keyword 'wastewater treatment' is a prominent term in both the trend analysis and network, however, there's a limited understanding of the influence of complex wastewater matrices on the performance of these adsorbents. The network shows connections to 'chitosan,' indicating some exploration of natural polymers, but a more comprehensive assessment is needed to understand how mixtures of organic matter, salts, and other pollutants in real wastewater affect adsorption kinetics, capacity, and selectivity. Lab-scale studies often rely on simplified conditions, limiting translational relevance. Hence, more pilot-scale and long-term field trials are essential to determine operational robustness, fouling resistance, and scalability.

Though kinetic and mechanistic studies are prevalent, a deeper investigation is needed to connect these processes with surface chemistry and structural properties for material optimization. For example, the term DFT is absent in both analyses. Furthermore, a refined search reveals limited use of DFT studies (only 17 articles out of 567 initial results) in the literature. Very recently, Jin *et al.,* 2025 reported the efficacy of CTAB-geopolymer adsorbents for the rapid adsorption of TC [53]. DFT modeling elucidated that the adsorption behavior and underlying mechanisms are modulated by dynamic pH variations, stemming from the inherent alkaline release characteristic of the geopolymer matrix.

The absence of another term "statistical physics model" highlights a critical research gap in TC adsorption studies. Classical models, like Langmuir and Freundlich, fail to provide a comprehensive mechanistic understanding of adsorption due to their limited fundamental basis [54]. Even though various modeling approaches have been explored, statistical physics models provide deeper insights into adsorption mechanisms by considering molecular interactions, energy distributions, and surface heterogeneities [55] [56]. Their omission suggests a lack of focus on advanced theoretical modeling, which could enhance the predictive accuracy and mechanistic understanding of adsorption processes. Future research should integrate statistical physics models to bridge this gap, offering a more comprehensive and fundamental approach to adsorption studies.

Similarly, both visualizations omit the term 'packed/fixed bed columns', highlighting another research gap. A more targeted search yielded only 20 studies on continuous systems using packed/fixed bed columns **(Table 7)**, which accurately reflect industrial performance. This scarcity, compared to the initial 567 articles, underscores a significant gap in translational research studies. This lack of translational research hinders the development of full-scale treatment plants. Future efforts should focus on dynamic adsorption behavior, breakthrough modeling, and regeneration in fixed beds, especially under varying flow and loading rates. A review of very recent literature reveals some relevant work but remains limited. For example, “Chemical Engineering Journal” published a study on synergistic enhancement of N, S co-modified biochar [4], while “Environmental Science and Pollution Research” has several articles comparing different versions of the Yoon-Nelson model [57] and sugar molasses as a sustainable precursor [58]. Other latest articles include “Desalination and Water Treatment” which focuses on Artificial Neural Network modeling for tetracycline adsorption [59], “Environmental Technology” which studied the removal of tetracycline by natural and iron-modified orange peel [60], and “Journal of Environmental Management” discusses the one-step synthesis of iron and nitrogen co-doped porous biochar [61]. Despite these recent contributions, more investigations into continuous, scalable systems are needed to bridge the gap between lab-scale adsorption research and real-world wastewater treatment applications.

Also, emerging approaches, such as Artificial Intelligence/Machine Learning, are conspicuously absent. Addressing these gaps – the development of novel adsorbents such as MOFs, nanocomposites, real-world validation, advanced modeling, sustainable regeneration, continuous operation, and innovative process integration – is essential to translate lab findings into practical solutions for TC contamination.

In addition to technical aspects, regulatory considerations are vital. Future research should align with global water quality standards and address material safety, toxicity of adsorbents or their degradation byproducts, and environmental disposal guidelines. Developing standardized protocols for performance evaluation and lifecycle assessment will help translate lab findings into policy-compliant and scalable technologies.

4. Conclusions

This bibliometric review has uncovered the structural evolution, collaborative dynamics, and emerging frontiers in tetracycline adsorption research over the past decade. By analyzing 567 articles, we identified not only geographic and institutional leadership but also thematic shifts toward advanced adsorbents and interdisciplinary approaches. Importantly, this study reveals that while conventional materials like activated carbon continue to be explored, the research frontier is moving toward functional materials such as magnetic composites and metal-organic frameworks. Despite this progress, several underdeveloped areas – particularly the limited use of computational tools (e.g., DFT), AI/ML-driven predictive modeling, and continuous-flow adsorption systems– remain bottlenecks to real-world applications. These findings highlight the need for a shift from material discovery to system-level integration and performance optimization. Researchers are encouraged to explore hybrid technologies, pilot-scale studies, and AI-assisted material screening to close the lab-to-field gap. Furthermore, enhanced international collaboration and standardization in experimental reporting could accelerate innovation and comparability across studies. By presenting a structured overview of global research trends, this work serves as a roadmap to strategically address the growing challenge of tetracycline pollution in water systems. Future studies that bridge experimental research with digital tools and sustainable design principles are crucial to realizing scalable, cost-effective solutions for antibiotic-contaminated environments.

Declaration of generative AI and AI-assisted tools in writing

The authors utilized ChatGPT for grammar checking and sentence refinement for the preparation of this article. Following the usage of the tool, the contents were carefully reviewed and modified. They assume complete accountability for the final contents of this manuscript.

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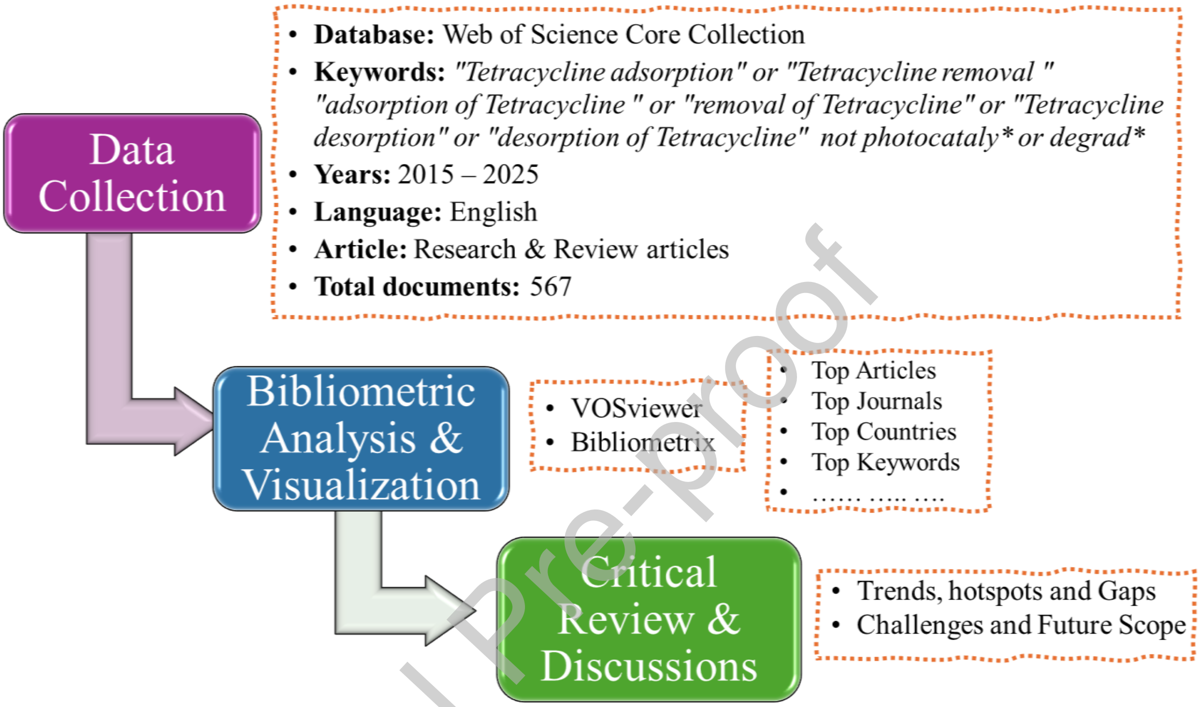

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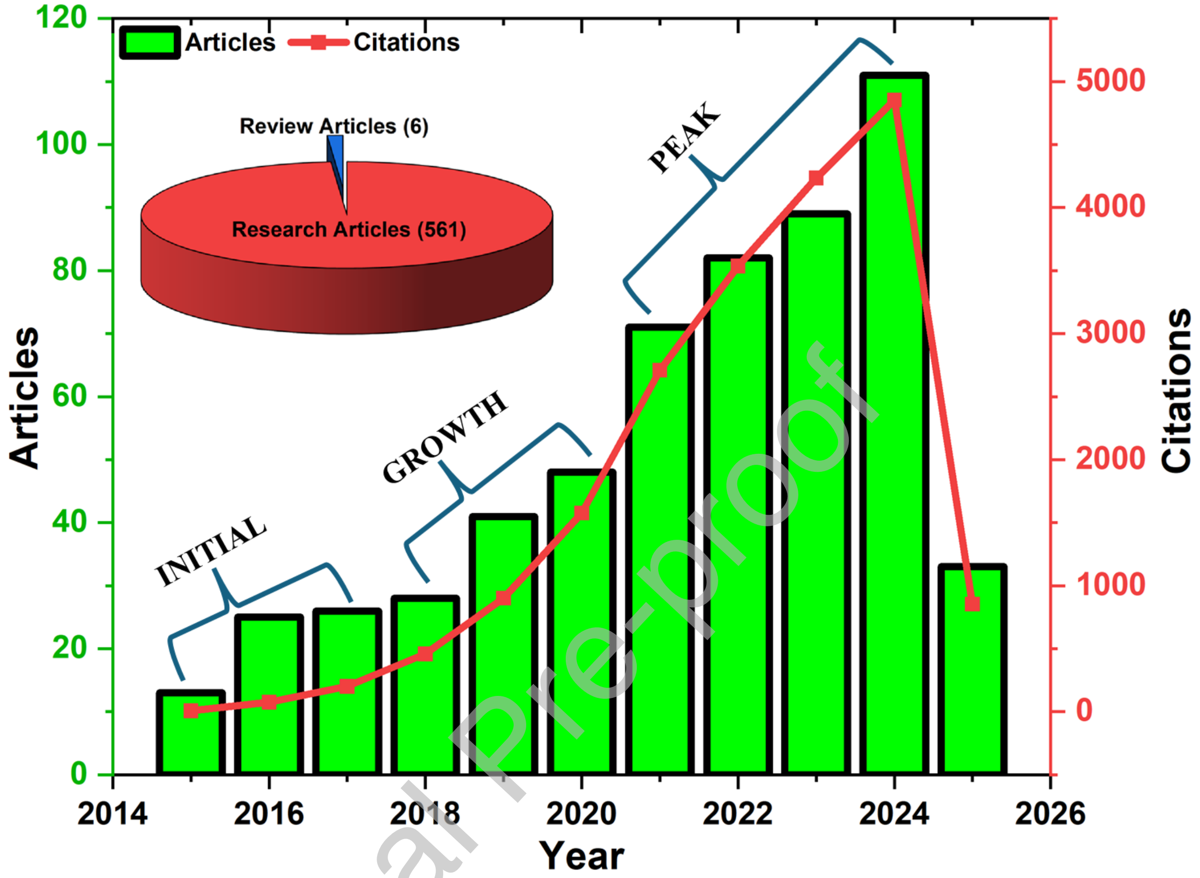

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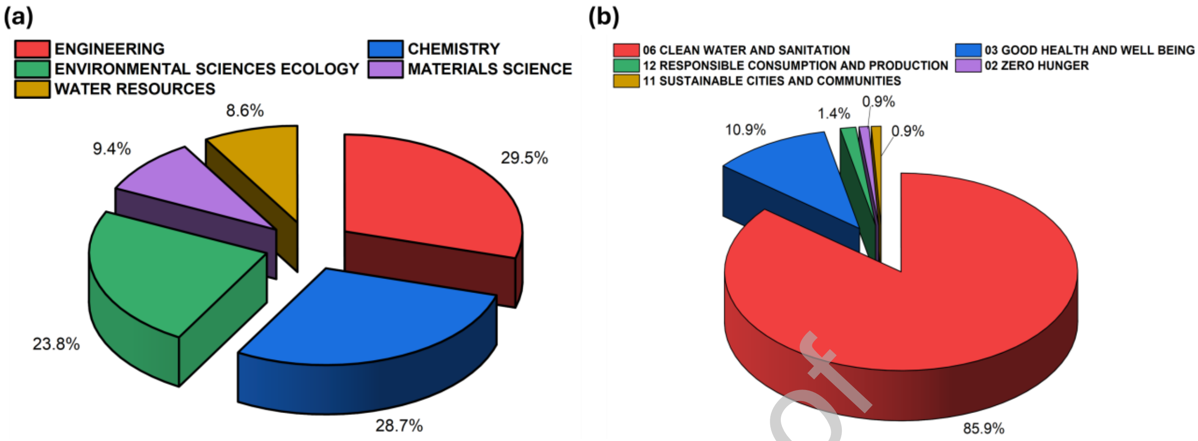

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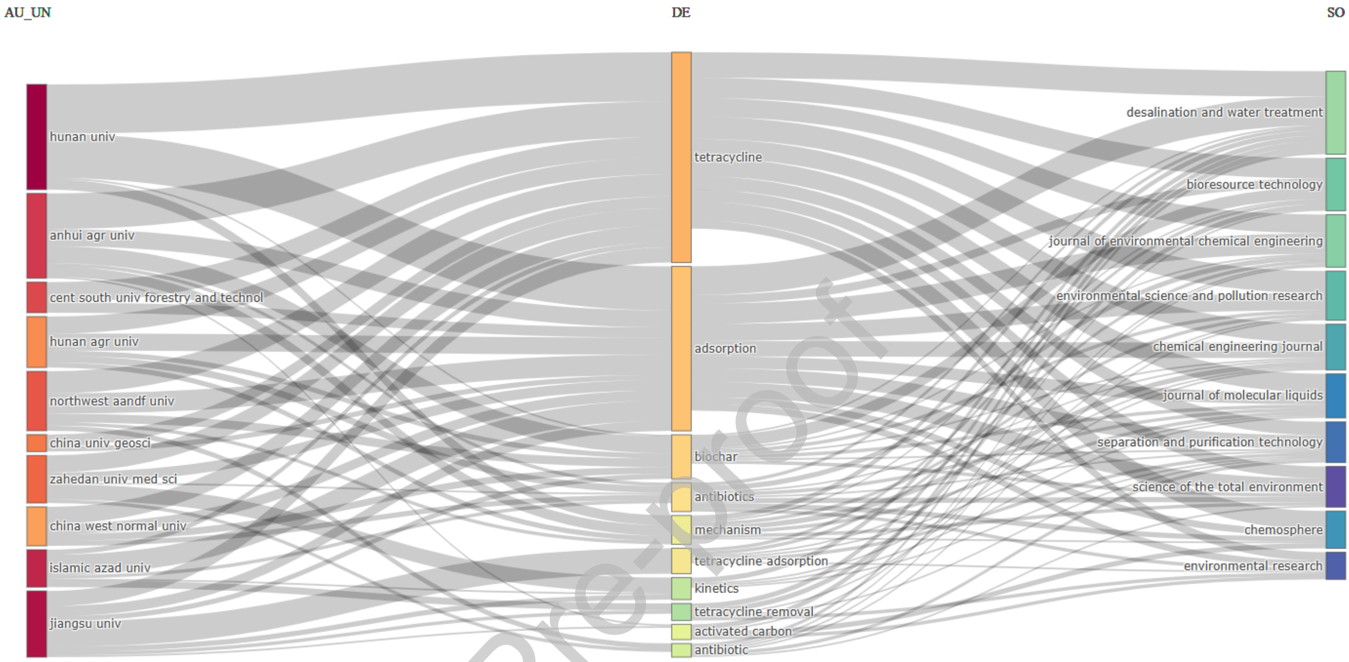

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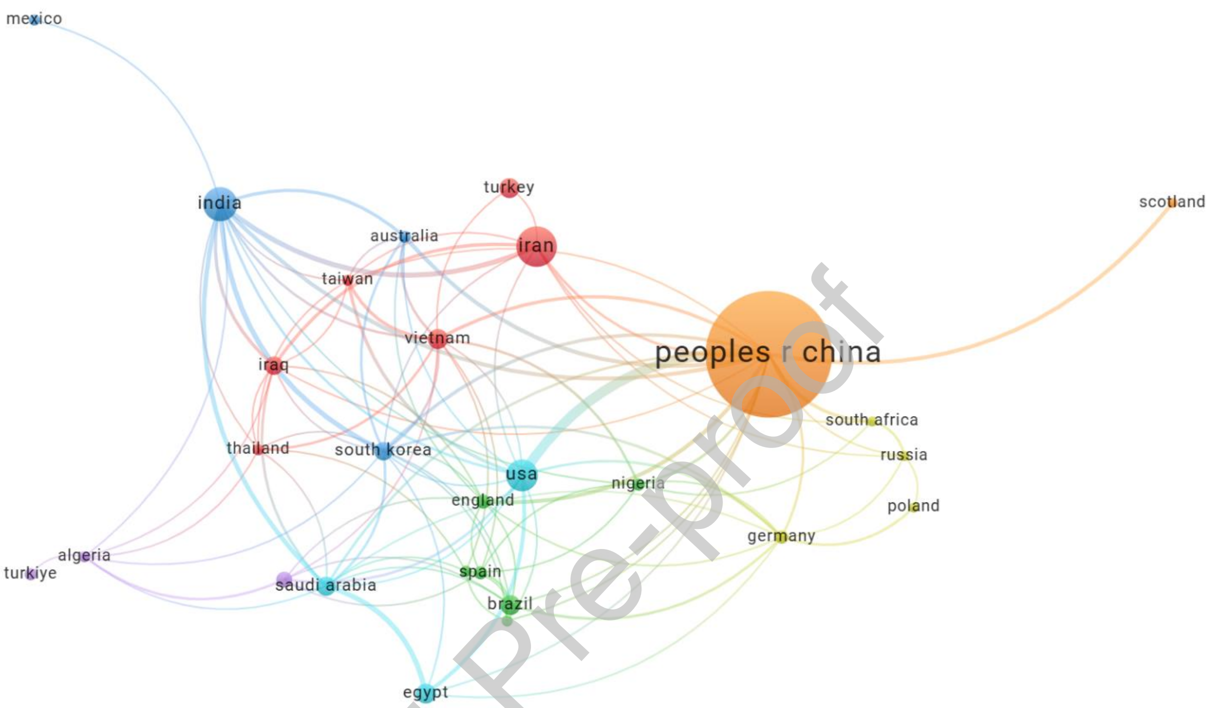

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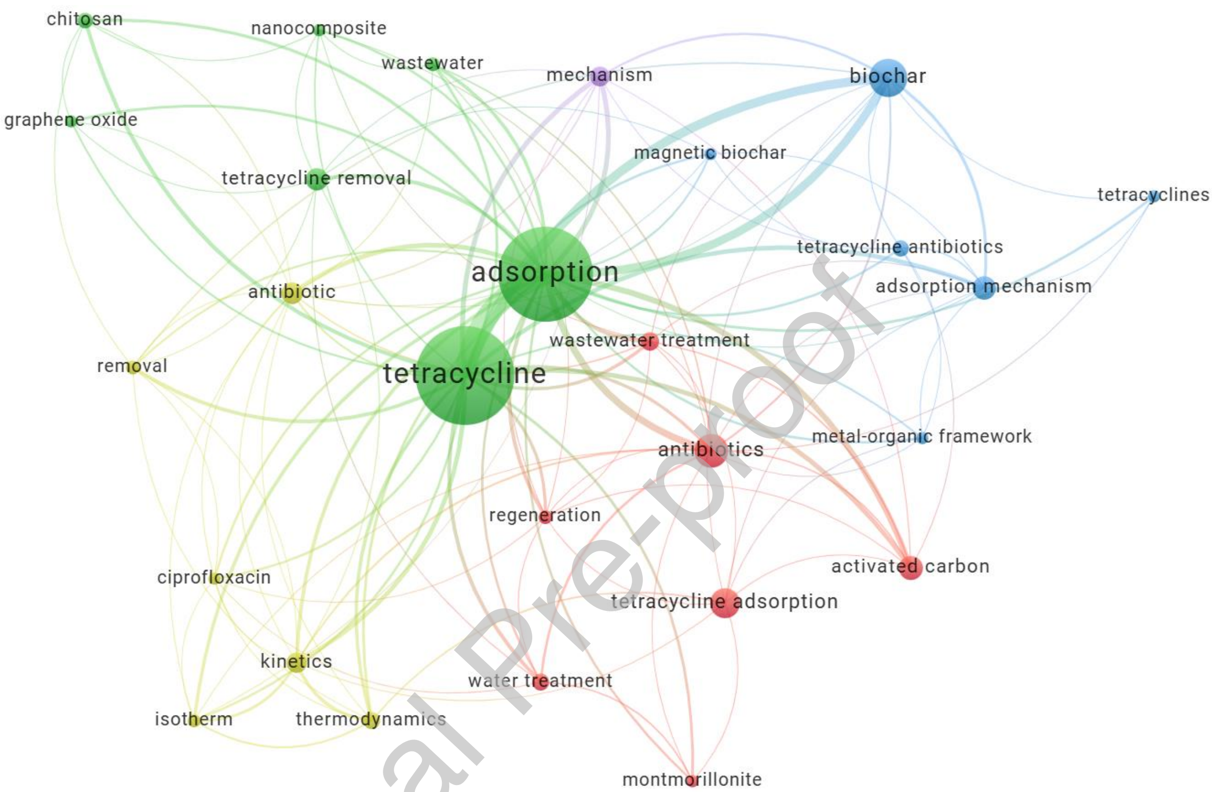

Figure 7. Keyword co-occurrence network for TC adsorption (Data analyzed using VOSviewer)

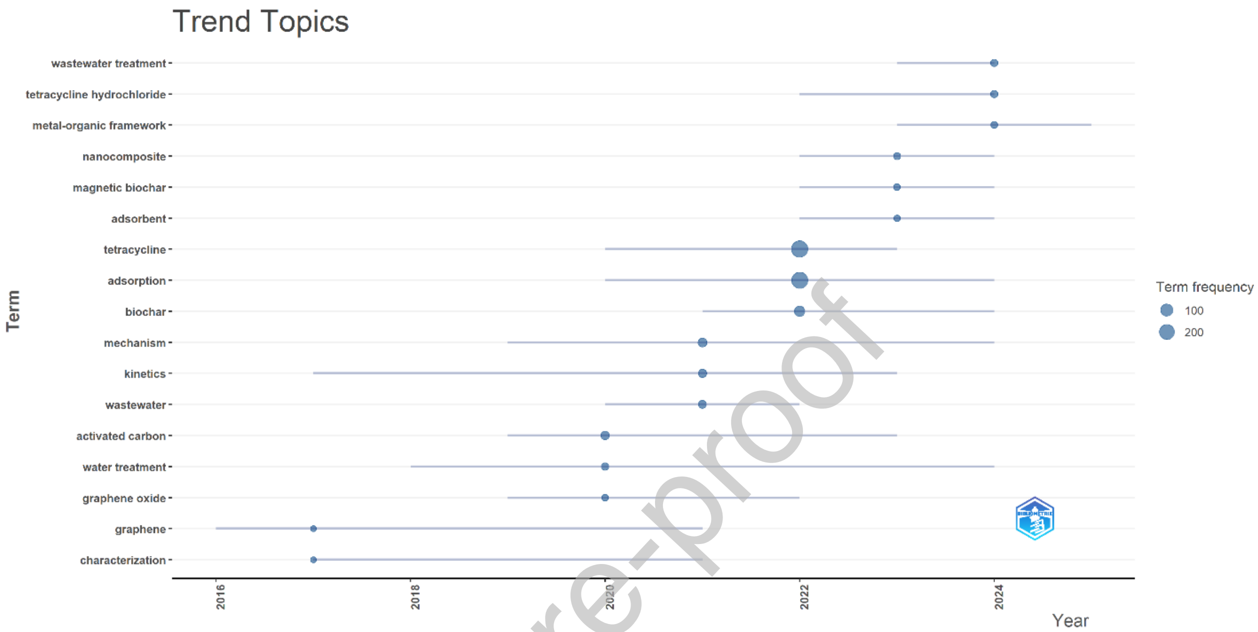

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Table 1: Recent review articles related to recent TC adsorption

No.	Article Title	Objective	Ref.
1	Zeolites and their composites as novel remediation agent for antibiotics: A review	Reviewed the versatility of zeolites and their composites in antibiotic remediation, showcasing recent advancements in adsorption and photocatalytic degradation	[62]
2	Removal of tetracycline from water by adsorption with biochar: A review	Reviewed biochar raw materials and preparation methods along with factors influencing TC adsorption, adsorption mechanisms, regeneration methods, and real wastewater applications.	[12]
3	Density functional theory for selecting modifiers for enhanced adsorption of tetracycline in water by biochar	Reviewed the atomic and energy-level interactions in tetracycline adsorption by modified biochar, critically analyzing modification techniques and adsorption mechanisms using DFT calculations.	[63]
4	Application of graphene-based materials for removal of tetracyclines using adsorption and photocatalytic-degradation: A review	Reviewed comprehensively the graphene-based materials for tetracycline removal, focusing on adsorption and photocatalytic mechanisms.	[64]
5	Antibiotics Removal from Aqueous Solution and Pharmaceutical Wastewater by Adsorption Process: A Review	Reviewed antibiotics, their classification, toxicity, and treatment methods, with a focus on adsorption mechanisms and adsorbent performance.	[65]
6	The use of activated carbon for the removal of pharmaceuticals from aqueous solutions: a review	Reviewed the removal of pharmaceuticals from water using activated carbon from various precursors.	[66]
7	Treatment technologies for emerging contaminants in water: A review	Examined the state-of-the-art technologies to remove emerging contaminants from water, highlighting trends in adsorption, membrane processes, biological treatment, and advanced oxidation.	[67]
8	A review on removal of pharmaceuticals from water by adsorption	Explored pharmaceutical removal using conventional and advanced treatments, with a focus on adsorptive removal from water sources.	[40]

9	A comparative review of the adsorption and photocatalytic degradation of tetracycline in aquatic environment by g-C_3N_4-based materials	Outlined recent advances in g-C_3N_4@Ms for tetracycline adsorption and photocatalytic degradation in aqueous solutions.	[68]
10	MOFs-based adsorbents for the removal of tetracycline from water and food samples	Discussed MOF-based adsorption of tetracycline from food and water, highlighting mechanisms and key influencing factors in adsorption and degradation.	[69]

Table 2: Top 10 countries related to recent TC adsorption

Number	country	Number of documents	Citations	Total link strength
1	China	348	13376	58
2	Iran	52	1156	17
3	India	39	1065	36
4	USA	35	1263	39
5	Brazil	16	364	11
6	Egypt	16	660	13
7	Turkey	16	443	2
8	Vietnam	16	601	21
9	Saudi Arabia	15	326	24
10	Iraq	14	239	14

Table 3: Top 10 journals related to recent TC adsorption

Number	Journal name	Number of documents	Number of citations	Total link strength	Journal impact factor
1	Desalination and water treatment	31	542	55	1.0
2	Journal of environmental chemical engineering	25	768	142	7.2
3	Bioresource technology	20	2236	195	9.0
4	Environmental science and pollution research	20	366	71	NA
5	Chemical engineering journal	17	1476	98	13.2
6	Chemosphere	17	957	86	NA
7	Journal of molecular liquids	16	917	107	5.2
8	Separation and purification technology	15	276	81	9.0
9	Environmental research	13	287	60	7.7
10	Science of the total environment	13	1152	101	8.0

Table 4: Top 10 cited articles related to recent TC adsorption

Number	Article Title	Source Title	Citations	Ref.
1	Modification of biochar derived from sawdust and its application in removal of tetracycline and copper from aqueous solution: Adsorption mechanism and modelling	Bioresource Technology	594	[35]
2	Sustainable efficient adsorbent: Alkali-acid modified magnetic biochar derived from sewage sludge for aqueous organic contaminant removal	Chemical Engineering Journal	491	[36]
3	Carbon-based materials as adsorbent for antibiotics removal: Mechanisms and influencing factors	Journal of Environmental Management	325	[70]
4	Characteristics of tetracycline adsorption by cow manure biochar prepared at different pyrolysis temperatures	Bioresource Technology	322	[37]
5	Effects of modification and magnetization of rice straw derived biochar on adsorption of tetracycline from water	Bioresource Technology	278	[71]
6	Tetracycline adsorption onto activated carbons produced by KOH activation of tyre pyrolysis char	Chemosphere	270	[38]
7	Effect of Cu(II) ions on the enhancement of tetracycline adsorption by Fe_3O_4@SiO_2-Chitosan/graphene oxide nanocomposite	Carbohydrate Polymers	254	[39]
8	A review on removal of pharmaceuticals from water by adsorption	Desalination and Water treatment	240	[40]

9	Adsorption modeling, thermodynamics, and DFT simulation of tetracycline onto mesoporous and high-surface-area NaOH-activated macroalgae carbon	Journal of Hazardous Materials	226	[41]
10	Cu and Co nanoparticles co-doped MIL-101 as a novel adsorbent for efficient removal of tetracycline from aqueous solutions	Science of the Total Environment	213	[42]

Table 5: Keywords analysis for recent TC adsorption

Cluster	**Keyword**	**Occurrences**	**Total link strength**
2	Tetracycline	264	322
2	Adsorption	247	352
3	Biochar	54	88
1	Antibiotics	44	51
1	Tetracycline adsorption	36	10
1	Activated carbon	25	37
3	Adsorption mechanism	24	26
2	Tetracycline removal	22	16
4	Antibiotic	21	29

4	Kinetics	19	39

Main keywords and related research			
Cluster	**Color**	**Primary Keywords**	**Focus area of research**
1	Red	Activated carbon, Tetracycline adsorption, Regeneration, wastewater treatment	Comprehensive Water Treatment Solutions
2	Green	Tetracycline, Adsorption, Chitosan, Graphene oxide, Nanocomposite	Innovative Adsorbent
3	Blue	Biochar, Magnetic biochar, Metal organic framework	Cutting-edge Material Technologies
4	Yellow	Antibiotic, Isotherm, Kinetics, Removal	Fundamental Adsorption Science
5	Purple	Mechanism	Mechanistic Insights

Table 6: MOF Adsorbents for recent TC adsorption

No.	MOF Adsorbent	Highlights	Reference
1	$[Cu(Fum)(MIM)_2(H_2O)_2]$ (MRCU102) MOF	SSA: -- Q_m: 1215.46 mg/g	[47]
2	UiO−67-HAc-NH_2−3	SSA: 2858.7 m^2/g Q_m: 605 mg/g	[46]
3	Fe_3O_4@PCN-333 (Fe)	SSA: 465.3 m^2/g Q_m: 303.3 mg/g	[51]
4	HKUST-1/cellulose/chitosan composite aerogel	SSA: 694.514 m^2/g Q_m: 285.7 mg/g	[52]
5	NH_2-MIL-101(Fe)	SSA: 403.55 m^2/g Q_m: 244 mg/g	[50]
6	Cu modified ZIF-8 pellets	SSA: 1372 m^2/g Q_m: 213.8 mg/g	[48]
7	Al-UiO-66-NH2	SSA: 392.42 m^2/g Q_m: 520 mg/g	[49]
8	Graphene quantum dot/MIL88A(Fe)	SSA: 10.78 m^2/g Q_m: 672 mg/g	[45]
9	Fe_3O_4@Zr-MOF	SSA: 868 m^2/g	[72]

		Q_m: 942.12 mg/g	
10	Eu-based metal–organic framework	SSA: 123.865 m^2/g Q_m: 397.65 mg/g	[73]

Table 7: Fixed bed studies for recent TC adsorption

No.	Article Title	Source Title	Ref.
1	Synergistic enhancement of N, S co-modified biochar for removal of tetracycline hydrochloride from aqueous solution: Tunable micro-mesoporosity and chemisorption sites	Chemical Engineering Journal	[4]
2	Comparing different versions of the Yoon-Nelson model in describing organic micropollutant adsorption within fixed bed adsorbers	Environmental Science and Pollution Research	[57]
3	Artificial Neural Network [ANN] modeling for tetracycline adsorption on rice husk using continuous system	Desalination and Water Treatment	[59]
4	Removal of tetracycline by natural and iron-modified orange peel from aqueous solutions: processes in batch, column, and mechanism	Environmental Technology	[60]
5	One-step synthesis of iron and nitrogen co-doped porous biochar for efficient removal of tetracycline from water: Adsorption performance and fixed-bed column	Journal of Environmental Management	[61]
6	ZIF-67 grows in chitosan-rGO hydrogel beads for efficient adsorption of tetracycline and norfloxacin	Separation and Purification Technology	[74]

7	Batch and continuous fixed-bed adsorption of antibiotics from aqueous solution using stearic acid-activated carbon composite	Energy Ecology and Environment	[75]
8	Natural phenol-inspired porous polymers for efficient removal of tetracycline: Experimental and engineering analysis	Chemosphere	[76]
9	Sugar molasses as a sustainable precursor for the synthesis of graphene sand composite adsorbent for tetracycline and methylene blue removal	Environmental Science and Pollution Research	[58]
10	Removal of tetracycline using modified wheat straw from solution in batch and column modes	Journal of Molecular Liquids	[77]

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: