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Mapping Scientific Progress in Struvite Technology Applications for Wastewater Treatment

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Struvite precipitation has attracted increasing attention as a promising approach for nutrient management in wastewater treatment. This study presents a comprehensive bibliometric and thematic analysis of global research on struvite precipitation, aiming to elucidate its development trends, intellectual structure, and emerging directions. The article evaluates 1,717 studies on struvite technology as a nutrient recovery method, from 1999 to 2024 extracted from Scopus®, through a structured bibliometric analysis using the Biblioshiny tool. The results identify a major turning point around 2013, marking a shift from foundational laboratory-scale studies to rapid expansion characterised by increased research output, pilot-scale applications, and integration with advanced treatment technologies. China is found to be the top country in the number of citations and total publications, which hosted the first two leading institutions. Additionally, keyword analysis illustrates strong connections between "struvite" and terms like "phosphorus recovery" and "wastewater", emphasising struvite precipitation as a still-promising method for recovering phosphorus from emerging P-rich wastewaters. Furthermore, two major research gaps are highlighted; the role of struvite technology in climate change remediation, as well as the economic feasibility of struvite fertiliser harvested from waste streams.

Keywords: Struvite; bibliometric analysis; phosphate recovery; wastewater treatment; fertiliser

I. INTRODUCTION

The recovery of nitrogen (N) and phosphorus (P) from wastewater is of significant interest to many researchers, because of the positive economic and environmental impacts. The food and fertiliser industry (Mushiri *et al.*, 2016) is a major consumer of N and P elements (Krongsamsri *et al.*, 2025). As global concern about the depletion of natural P rocks increases, researchers have tended to find other approaches to narrow the gap between P demand and consumption. Several types of wastewater are considered sinks of P, such as digested dairy manure (Tao *et al.*, 2016), food processing wastewater (Thant Zin & Kim, 2019) and fertiliser industry wastewater (Matynia *et al.*, 2013). Nitrogen is recovered from wastewater via three main technologies: (i) ammonia stripping; (ii) membrane concentration, and (iii) struvite crystallisation, while P is recovered mainly by microorganisms and struvite crystallisation. Compared to other nutrient recovery approaches, struvite (magnesium ammonium phosphate, $MgNH_4PO_4.6H_2O$) crystallisation provides selective removal of N and/or P from wastewater and recovers nutrients in the

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form of an environmentally friendly fertiliser. Struvite is a crystalline compound formed by the combination of magnesium (Mg), ammonium-nitrogen (NH_4-N) and P. Early studies on struvite formation date back several decades and were primarily concerned with its unintended formation as a nuisance in wastewater infrastructure, where it caused pipe blockages and maintenance challenges (Ohlinger *et al.*, 1998). Consequently, initial research efforts focused on understanding the chemical conditions governing precipitation, including pH, supersaturation, and ion interactions. Over time, the perception of struvite shifted from being an operational problem to a valuable resource. By the early 2000s, research began to explore controlled precipitation processes for phosphorus recovery, supported by advances in reactor design and process optimisation. (Battistoni *et al.*, 2002; Doyle & Parsons, 2002; Munch & Barr, 2001; Nelson *et al.*, 2003). This transition marked a critical phase in the intellectual development of the field, where fundamental chemical studies evolved into applied engineering solutions. More recently, the growing emphasis on sustainability and circular economy principles has further positioned struvite as a viable slow-release fertiliser, contributing to resource recovery and reuse strategies (Kataki *et al.*, 2016; Ye *et al.*, 2017).

Using struvite in agriculture contributes to reducing eutrophication (Sena *et al.*, 2021), a problem that arises from the excessive discharge of N and P compounds into aquatic ecosystems (Shah *et al.*, 2022). In the literature, several publications have reviewed the application of struvite as a chemical treatment approach for N and P in wastewater. The basic theory and fundamentals of struvite formation and recovery were reviewed by Doyle & Parsons (2002). Le Corre *et al.* (2009) discussed the principles of P recovery from wastewater by struvite crystallisation technology. Some review papers have presented the factors affecting struvite recovery in wastewater, either for the purpose of removing N or P, as well as (Darwish *et al.*, 2016; Kumar & Pal, 2015; Liu *et al.*, 2013), while crystallisation and decomposition mechanisms were reviewed by others (Tansel *et al.*, 2018). Struvite production process design (Krishnamoorthy *et al.*, 2021), technical challenges (Li *et al.*, 2019a), as well as economic and commercialisation matters (Li *et al.*, 2019a; Yetilmezsoy *et al.*, 2017) were thoroughly examined. Struvite crystallisation enhancement technologies, such as ultrasound and electrochemical technologies, were evaluated by Guan *et al.* (2023). In the same context, Kataki *et al.* (2016) and Siciliano *et al.* (2020) analysed the aspects of utilising alternative Mg and P sources to enhance the feasibility of struvite recovery.

A number of publications have presented a systematic review of struvite recovery from specific sources, such as human urine (Kabdaşlı & Tünay, 2018), liquid anaerobic digestate (Lorick *et al.*, 2020; Tao *et al.*, 2016) and agro-food wastes (Campos *et al.*, 2019). Moreover, the applications and sustainability of struvite fertiliser in the agronomic field were reviewed by several researchers (Ahmad & Gupta, 2021; Hertzberger *et al.*, 2020; Nagy *et al.*, 2019; Rahman *et al.*, 2014; Sena & Hicks, 2018; Vasa & Pothanamkandathil Chacko, 2021), whereas the economic aspects of struvite recovery from wastewater were thoroughly discussed (Chandrasekaran *et al.*, 2024). However, most of these reviews lack a comprehensive analysis of research impacts, trends, and needs, which is essential for properly guiding future investigations in the field of struvite technology.

In this context, bibliometric analysis provides a powerful tool to quantitatively and systematically evaluate the intellectual landscape of a research domain (Hire *et al.*, 2022; Zare *et al.*, 2017). It identifies research strengths and weaknesses, leading countries, key authors, and top journals (Al Qudah *et al.*, 2024; Dabous *et al.*, 2024). Additionally, it supports document citation mapping, co-author network visualisation (Chen & Laokhongthavorn, 2024), cluster analysis, keyword co-occurrence, collaboration patterns, and theme evolution (Liu *et al.*, 2022). Generally, bibliometric analysis summarises research trends over the past decade and provides insights for future studies (Guleria & Chakma, 2022). With regard to struvite technology in the environmental field, only a few bibliometric studies have been published. Nageshwari & Balasubramanian (2022) conducted a bibliometric analysis on struvite studies for fertilising applications, and highlighted the role of advanced technologies like microbial fuel cells and electrochemical precipitation for future progress. Other researchers have published bibliometric studies on P recycling, in the form of struvite, from specific types of wastewater such as livestock manure (Ran *et al.*, 2023) and human urine (Li & Li, 2024), emphasising the main aspects related to struvite recovery and application. However, to the best of our knowledge, there has been no previous bibliometric study that has analysed the research trend of struvite technology as a wastewater treatment method, either for P or N removal and recovery. Given that struvite crystallisation has been increasingly adopted for treating diverse wastewater types across laboratory, pilot, and full-scale operations, a comprehensive mapping of research trends, knowledge gaps, and collaborative networks is urgently needed. Such an analysis is essential for understanding how the field has evolved, where current limitations lie, and how research directions can be strategically aligned. Ultimately, this study provides evidence-based insights that will guide future innovation toward more advanced, efficient, and sustainable struvite recovery processes within the broader context of circular wastewater management. Therefore, this study aims to provide an in-depth understanding of the research trend related to struvite technology application in the wastewater treatment field. Thus, it (1) tracks the development of struvite technology in wastewater treatment in the last 25 years, (2) highlights the most impactful studies and journals in the field of struvite research, (3) identifies the leading researchers, their institutions, and their countries contributing to struvite technology, (4) discovers the key topics in struvite research and how they've evolved over time, (5) examines the collaborative efforts between different countries and researchers in the field of struvite technology, and (6) groups similar research topics and analyses the factors driving these connections within the struvite research community.

II. METHODOLOGY

The methodology begins with the collection of publications from the Scopus® database on struvite technology in wastewater treatment. The Scopus® database is selected due to its comprehensive coverage, high-quality metadata, and suitability for bibliometric analysis. Following this, the inclusion and exclusion criteria applied to gather relevant literature on the focus area are outlined. A comprehensive explanation of the procedure is provided in the following subsections. After assembling the necessary literature, a basic performance analysis of the publication database is performed. Subsequently, science mapping techniques are employed, including the analysis of three-field plots and the network visualisation of co-citations and co-authorships. Finally, concluding remarks are made, suggesting future research directions based on the bibliometric analysis results.

Table 1. Procedures followed for collecting data from the Scopus® database

Step no.	Search steps	Query on Scopus®
1	Search keywords	TITLE-ABS-KEY(struvite OR "magnesium ammonium phosphate" OR "Ammonium Magnesium Phosphate") AND TITLE-ABS-KEY(wastewater OR sewage OR effluent OR "waste stream" OR "polluted water" OR sewerage) AND NOT TITLE-ABS-KEY(review OR "recent advance*" OR "state-of-the-art")
2	Years	AND PUBYEAR > 1998 AND PUBYEAR < 2025
3	Document type	AND (LIMIT-TO (DOCTYPE,"cp") OR LIMIT-TO (DOCTYPE,"ar"))
4	Document language	AND (LIMIT-TO (LANGUAGE,"English"))

A. Data Collection Strategy

This study employs a comprehensive research design to explore literature on applications of struvite crystallisation in wastewater treatment (Table 1). Initially, only papers published in English are included, while those in other languages are excluded. The second step limits the selection to papers published between 1999 and 2024, as the study aims to analyse the research trend over the past 25 years. Only journal and conference articles are selected for the bibliometric analysis, excluding review articles, which tend to summarise the strengths and weaknesses of existing mathematical models. Book chapters are also excluded because they often provide generalised content and lack the specific focus needed for this study. Furthermore, only studies related to environmental engineering and science field were included, whereas all other studies from irrelevant fields, such as medicine, were manually excluded. The dataset is limited to titles, abstracts, and author keywords, which is consistent with standard bibliometric practices. Accordingly, a total of 1,717 papers is included, with a primary objective of exploring past, present, and future trends in struvite crystallisation technology in wastewater treatment.

B. Analysis Tool

The Biblioshiny R-toolbox is mainly used to examine yearly trends in top journals that focus on struvite research in wastewater treatment, key authors, leading countries, and the most productive institutions (Aria & Cuccurullo, 2017). The identification of top authors, countries, institutions, and highly cited papers is based on total citations, number of publications, and average yearly citations per article. The development of the targeted research trend is assessed using tree-plot analysis, three-phase field diagrams, and the temporal trends of author keywords. Thematic maps and cluster visualisations are generated to highlight research hotspots within the scope of the study, while collaboration patterns between countries and co-author networks are also mapped using Biblioshiny.

RESULTS AND DISCUSSIONS

A. Analysis of Publication Trends

1. Temporal distribution of related publications

Figure 1 shows the overall trend of annual publications in the field of wastewater treatment using struvite technology. Generally, the evolution of studies throughout the past 25 years shows an S-shaped curve, with an initial moderate growth, followed by a rapid acceleration, and then a period of stability. More precisely, the publication trend can be divided into four phases. In Phase 1 (1999-2004), the growth rate of annual publications was quite slow, as indicated by the trend line. The same applies for Phase 2 (2005-2012), with a slightly higher rate than Phase 1. It is believed that most of the studies in Phase 1 focused mainly on the characterisation of struvite, theoretical establishments of influential factors and some other studies on agricultural applications, while studies in Phase 2 showed more interest in investigating struvite technology for different types of wastewater, including the use of alternative sources of Mg and P required for struvite precipitation, as well as a deeper understanding of influencing factor interactions. Phase 3 (2013-2019) witnessed a sharp increase in yearly publications, with a wide range of topics and applications being explored, which extended to pilot-scale studies, integration with other technologies and novel advanced discoveries such as the co-precipitation mechanisms of heavy metals. Finally, it can be observed that the research trend became steady in Phase 4 (2020-2024), probably because of the establishment of several aspects related to struvite application in the wastewater field. Overall, the research trend is anticipated to remain stable for a period of time, though it may experience a decline thereafter.

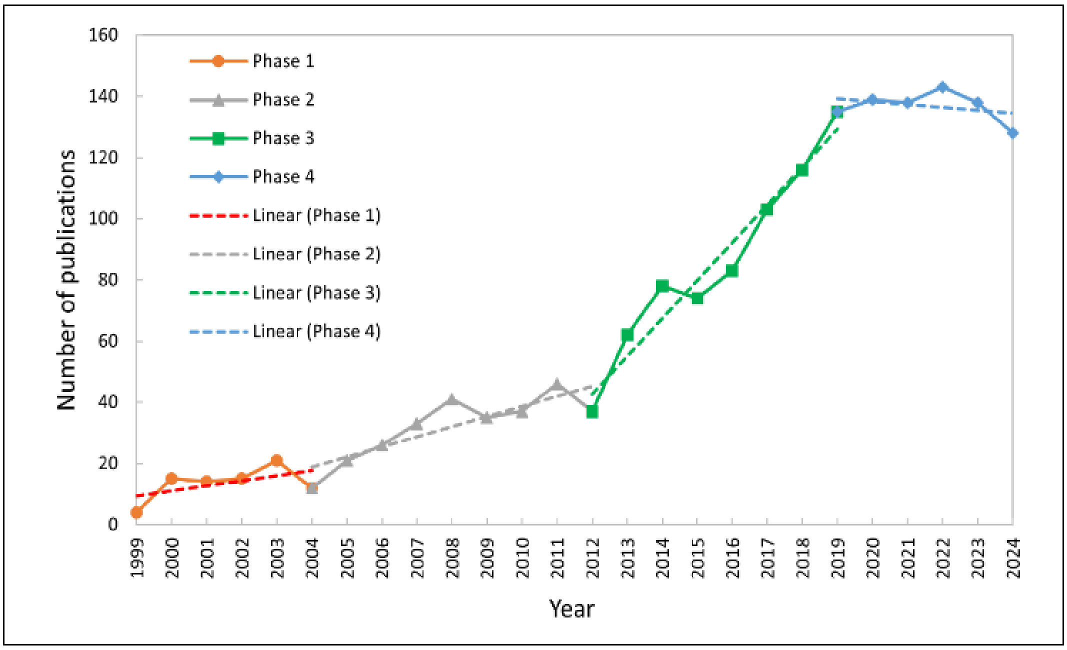

Figure 1. Statistics of yearly publication based on Scopus database (1999-2024).

Table 2. List of top 10 published articles in the field of struvite technology for wastewater treatment

First author	TC	Rank based on TC	Publication year	ACY	Rank based on ACY	Reference
Munch E.V.	441	1	2001	18.38	5	(Munch & Barr, 2001)
Jaffer Y.	420	2	2002	18.27	6	(Jaffer *et al.*, 2002)
Nelson N.O.	415	3	2003	18.87	4	(Nelson *et al.*, 2003)
Wilsenach J.A.	398	4	2007	22.12	3	(Wilsenach *et al.*, 2007)
Li R.	394	5	2017	49.25	1	(Li *et al.*, 2017)
Stratful I.	389	6	2001	16.21	9	(Stratful *et al.*, 2001)
Udert K.M.	378	7	2003	17.19	8	(Udert *et al.*, 2003)
Le Corre K.S.	355	8	2005	17.75	7	(Le Corre *et al.*, 2005)
Huang H.	353	9	2017	44.13	2	(Huang *et al.*, 2017)
Maurer M.	319	10	2003	14.5	10	(Maurer *et al.*, 2003)

The top ten most influential articles are listed in Table 2. The primary ranking criterion was the total number of citations (TC), supplemented by the average citations per year (ACY) as a secondary measure. It is observed that all of the top 10 articles have received more than 300 citations. The paper by Munch & Barr (2001) ranked first in TC (441) and fifth in ACY (18.38), while the article by Li *et al.* (2017) ranked fifth in TC (394) but held the top position in ACY (49.25). The second- and third-ranked articles garnered 420 and 415 of TC, as well as 18.27 and 18.87 ACY values, respectively, which is very close to the first-ranked article. Additionally, it is interesting to see that the first three articles are published in Phase 1 of the research trend. The top cited article titled "Controlled struvite crystallisation for removing phosphorus from anaerobic digester sidestreams", from *Water Research* investigated the recovery of struvite from sludge anaerobic digester filtrate in a pilot-scale reactor. This study was the first to use magnesium hydroxide (MgO) slurry as both an alkali and Mg source for struvite recovery from waste streams (Munch & Barr, 2001). Additionally, it provides more in-depth knowledge and details beyond what is available from full-scale operations in Japan and Korea (Morse *et al.*, 1998). The second-highest ranked article based on TC (and the seventh based on ACY), authored by Jaffer *et al.* (2002), explored the potential for recovering struvite from the sewage treatment plants' pipelines that are often obstructed by struvite crystals. The authors estimated that 42 to 100 tonnes of struvite could be recovered annually, generating a revenue of £8,400 to £20,000 per year. It is worth mentioning that this study was one of the first to emphasise the economic benefits of struvite recovery from wastewater. The research article by Nelson *et al.* (2003), ranked third in terms of TC (415), was among the earliest to examine struvite recovery from swine wastewater, investigating the effects of pH adjustment and Mg:P ratio on struvite crystallisation, while also determining the rate constant of pH influence in anaerobic swine lagoon liquid. Struvite recovery from urine has gained significant attention from different highly cited studies; the fourth-, seventh- and tenth-ranked articles, based on TC, focused on struvite production from urine separation systems. The main goal of the fourth-ranked article by Wilsenach *et al.* (2007), also the fourth based on ACY, was to discover potential effects of potassium on struvite precipitation in source-separated urine. The scope of the seventh (Udert *et al.*, 2003) and tenth (Etter *et al.*, 2011) ranked articles revolved around the dynamics of urea hydrolysis and struvite precipitation, and the exploration of the practical potential and feasibility of reusing struvite as fertiliser in Nepal, respectively. Moreover, the latter three studies highlighted the coprecipitation of hydroxyapatite, presenting the side effect of calcium in urine on the purity of struvite (Etter *et al.*, 2011; Udert *et al.*, 2003; Wilsenach *et al.*, 2007). The fifth-ranked paper according to TC is by Stratful *et al.* (2001). This paper was published in 2001, and it is considered a cornerstone for optimising struvite precipitation conditions, mainly in terms of pH, reaction time and NH_4 concentration, and underscored the resulted crystal yield and size. The study by Li *et al.* (2017), ranked sixth in terms of TC, found that struvite crystallisation plays a key role in treating swine wastewater by aiding in the removal of phosphate, ammonium, and organic substances. It should be highlighted that the article of Li *et al.* (2017) was published in 2017 and held the top rank based on ACY (49.25). The study by Le Corre *et al.* (2005), which ranked eighth, assessed the influence of Ca^{2+} ions on the nucleation and growth of struvite crystals and examined the subsequent impact on the quality of the recovered product. The pilot-scale study ranked ninth and led by Huang *et al.* (2017) found that fluoride significantly inhibited struvite crystallisation in semiconductor wastewater, especially at lower pH levels, whereas the optimal pH was found to be 9.5. Lastly, the study by Maurer *et al.* (2003) compared the energy efficiency of recycling nutrients from urine to traditional methods. It found that recovering nutrients, especially through struvite, is a much more energy-friendly approach than conventional wastewater treatment and fertiliser production.

Collectively, the top 10 most influential articles show that research has consistently advanced around core themes of process optimisation, economic viability, and practical implementation, despite the diversity of wastewater types studied. These works demonstrate how early foundational studies set the direction for the field, while more recent publications continue to elevate its relevance through higher citation intensity and broader applications. This progression indicates that future impactful research will move toward integrated modelling, multi-nutrient recovery, and improved product quality to enhance the scalability and sustainability of struvite-based technologies.

2. Distribution of articles based on journals

Table 3 presents the top ten journals ranked by the number of articles (NoA) in the field, with their total counts of citations (ToC), along with their corresponding h-index values. It is indicated that *Water Research* achieved the highest ToC for the papers within the analysed scope, and ranked second in the NoA. Interestingly, it is noticed that 5 out of the 10 highest-cited articles, listed in Table 2, were published in *Water Research*, indicating its vital role in the investigations of struvite recovery from wastewater. *Bioresource Technology* is ranked the 2nd in terms of ToC. Although it published only 60 articles in struvite recovery topic, the journal contributed with cornerstone articles in essential subtopics, such as Lind *et al.* (2000), who were the first to explore struvite recovery from source-separated urine, Nelson *et al.* (2003) who measured the rate constant for struvite formation in swine lagoon effluent, and Türker & Çelen (2007) who established the methodology of multi-step precipitation of struvite by recycling Mg and P from the precipitant. *Water Science and Technology*, the 3rd ranked journal according to ToC (3,479), has the highest NoA (119) and the highest h-index (27). In comparison, *Chemosphere*, ranked fourth, has a similar ToC (3,272) but a significantly lower NoA (55), nearly half that of *Water Science and Technology*. The *Journal of Cleaner Production* shared the 5th position with ToC of 2,802, which was close to the 6th journal, *Chemical Engineering Journal*, with 2,580 citations. This is followed by *Environmental Technology United Kingdon*, *Science of the Total Environment*, *Journal of Environmental Management* and *Desalination and Water Treatment*, with lower ToCs and NoAs.

Bradford's Law is a widely recognised model for identifying core journals and analysing the dispersion of bibliographic information across various publications. It classifies journals into core, middle, and scattered groups based on their contribution to a field's literature (Lei *et al.*, 2019; Tsay & Li, 2017). The results obtained from Bradford's Law analysis show that 9 journals (i.e. all the top 10 journals except *Desalination and Water Treatment*) fall in the core journals' zone, among the list of 403 journals that published studies related to struvite technology in wastewater treatment. Table A1 (Supplementary Material) presents the top 10 journals based on Bradford's Law, while a total of 403 journals are classified into three zones. It is noteworthy that the top 10 journals account for 36.28% (623 out of 1,717) of the total articles published in the analysed research field from 1999 to 2024 (Table A1).

Table 3. Leading journals on struvite technology in wastewater treatment.

Title of Journal	ToC	Rank based on TC	NoA	Rank based on NoA	h-index
Water Research	8,808	1	92	2	21
Bioresource Technology	4,263	2	60	3	20
Water Science and Technology	3,479	3	119	1	27
Chemosphere	3,272	4	55	5	17
Journal of Cleaner Production	2,802	5	60	3a	13
Chemical Engineering Journal	2,580	6	49	8	8
Environmental Technology United Kingdom	1,413	7	47	9	8
Science of the Total Environment	1,370	8	51	7	18
Journal of Environmental Management	1,319	9	53	6	12
Desalination and Water Treatment	456	10	37	10	5

3. Productive authors

The results gathered from Biblioshiny present several statistics related to researchers' productivity. The leading authors in struvite technology for wastewater treatment are ranked based on ToC and NoA (Table A2). Based on the Scopus® database from 1999 to 2024, it is observed that Haiming H. ranked first in the field of struvite technology for wastewater treatment. Haiming H., a Professor of Environmental Engineering at the School of Environment and Civil Engineering, Dongguan University of Technology, China, has received a total of 1,910 citations despite beginning his publications only in 2010. He has published 32 articles and holds an h-index of 19, a g-index of 32, and an m-index of 1.188, ranking the highest in all these metrics among researchers in the field. The second-ranked author, Mavinic D.S. (based on NoA), from the Department of Civil Engineering, University of British Columbia, has received a total of 1,240 citations for his 27 articles, and has an h-index of 16. It is noteworthy that no collaborative works between Huang H. and Mavinic D.S. have been identified since 2010, the publication starts year of Huang H. However, two studies were found in which Huang H. appears to have been affiliated with the same institution as Mavinic D.S. (Huang *et al.*, 2006; Mavinic *et al.*, 2007), likely during Huang's postgraduate study period before beginning his career in China. It is noted that the top 5 authors (in terms of ToC) received more than 1,000 total citations (Table A2). Moreover, 4 out of the top 10 authors work in China, indicating the significant role of China in the field of struvite technology. Overall, all top authors have published at least 12 papers, achieved more than 450 total citations, and have a minimum h-index of 11 and a minimum m-index of 0.423.

4. Leading institutions

According to the Scopus® database, there are 160 affiliations involved in the research of struvite technology on wastewater treatment. Figure S2 shows that Tongji University ranked first in the number of articles (139), followed by the Institute of Urban Environment (93) and Hefei University of Technology in third place with 73 articles. It is observed that all top institutions in Figure S2 published at least 52 articles in the field of study. Generally, 7 out of 10 affiliations are from China, while the other 3 are from the United States, Canada and the Netherlands, depicting the significant role of China institutes in the development of struvite technology for wastewater treatment and reuse (Figure 2 (a) and (b)). In the field of struvite applications in wastewater treatment, China emerges as the most dominant country, accumulating a total of 12,836 citations, ranking first based on total citations (TC). The U.S. comes in second place with 5,460 citations, while the United Kingdom ranks third with 2,978 citations. Notably, all the top 10 countries have received at least 1,670 citations, reflecting a significant contribution to the research field. However, when considering the Average Article Citations (AAC), European countries take the lead, with Switzerland achieving the highest AAC of 119.30, followed by the United Kingdom (72.60) and the Netherlands (70.50). Despite China's dominance in total citations, it ranks eighth in AAC (30.40), suggesting that while China has produced a large volume of impactful research, individual articles may have lower citation rates compared to those from other leading countries. Similarly, the U.S., despite ranking second in TC, ranks ninth in AAC (30.30), further highlighting the disparity between research quantity and per-article impact.

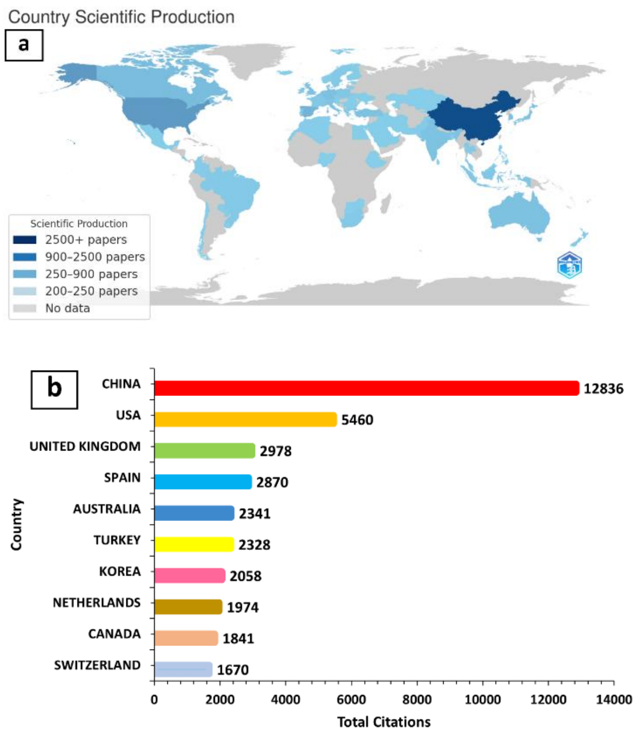

Figure 2. Country-based article production map (a) and total citations (b).

B. Co-occurrence and Content Analysis

It is observed that the "struvite" dominates the list of author keywords, followed by "phosphorus recovery", "phosphorus", "nutrient recovery" and "struvite crystallisation". All of the top 10 author keywords (see Figure A3) are strongly connected to the "struvite" node (shown in red, Figure 3) at different levels. On the other hand, some nodes such as "circular economy", "fertiliser" and "resource recovery" show less connectivity, likely because they are associated with an emerging trend regarding the role of struvite recovery in agriculture and the economy.

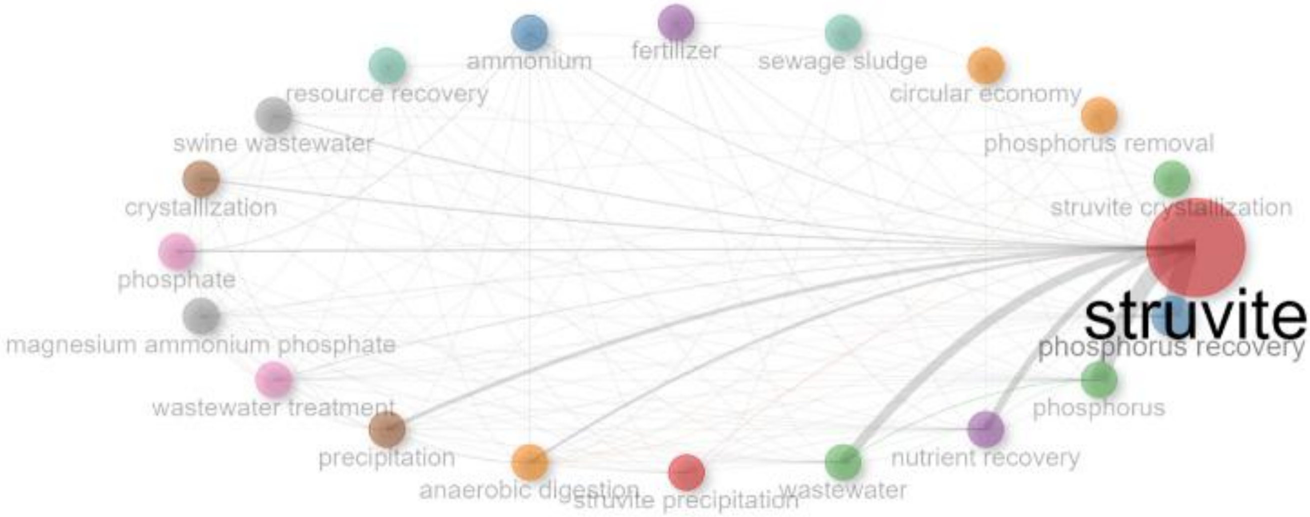

Figure 3. Co-occurrence network of top 20 most influential author's keywords based on Scopus® database (1999 – 2024).

In order to spot the core themes of the keywords, the keywords tree diagram is constructed using the "Author's keywords" search criteria, with 25 boxes (Figure 4). The keywords "struvite" and "phosphorus" appeared in the top 2 positions according to their frequency, as shown in Figure 4. Words such as "wastewater treatment", "nitrogen" and "ammonia" are observed in the top 10 frequent words, depicting their significance in struvite research on wastewater treatment, as several studies in this field have focused on nitrogen recovery from waste streams in the form of struvite (Darwish *et al.*, 2016).

The cumulative occurrences of the top 10 authors' keywords in struvite technology over time are presented in Figure A4 in the Appendix section. It is observed that the keyword "struvite", followed by "phosphorus recovery" and "phosphorus", remained in the top three positions based on the yearly changes of cumulative rates in the period from 1999 to 2024. The keyword "struvite" exhibits a sharp upward trend, surpassing all other keywords in growth. Meanwhile, "phosphorus recovery," "phosphorus," "nutrient recovery," and "wastewater" began to show noticeable growth starting in 2013. These keywords are closely related to the recovery of phosphorus from waste streams and its conversion into a valuable product (i.e. struvite fertiliser). The rest of the keywords depict mild growth over the past two decades, as they are connected to secondary research areas related to the improvement of technical aspects and the economic viability of struvite recovery from wastewater, mostly in pilot and large-scale applications, and thus have potential for growth in the future.

The keyword evolution shows a clear Technology Readiness Level (TRL) progression in struvite research. The TRL is a scale (1 to 10) used to assess the maturity of a technology from early research to full-scale deployment (Maqdasi *et al.*, 2025, Townes, 2026). Early terms like precipitation and pH optimisation reflect low TRLs (2–4), focused on fundamental lab-scale studies. Later keywords such as life cycle assessment, economic analysis, and resource recovery indicate higher TRLs (6–9), emphasising system integration and real-world feasibility. Overall, this shift demonstrates the field's transition from basic research to practical, sustainability-driven implementation aligned with industrial and circular economy applications.

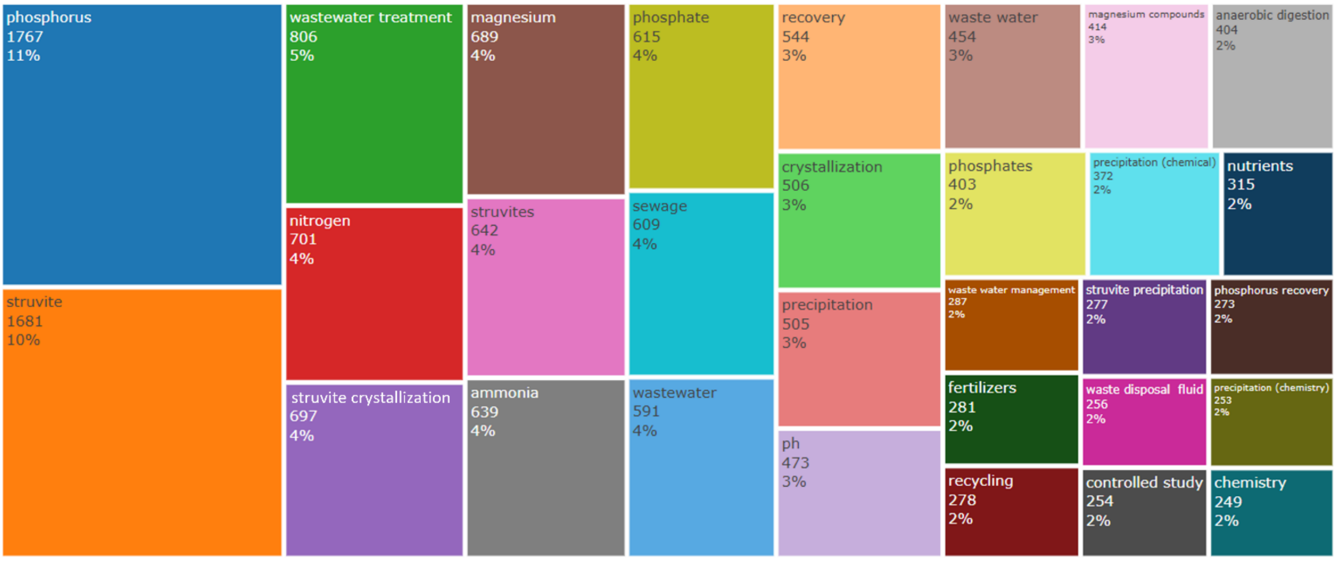

Figure 4. Tree plot of the top 25 authors' keywords.

1. Three field plots on struvite technology in wastewater

Three-field plots, commonly referred to as Sankey diagrams, are used to illustrate the relationships between various attributes within a research database. These diagrams effectively represent weighted features, allowing the visualisation of different systems and their interactions (Guleria & Chakma, 2022). Notably, the sum of incoming flows at each node equals the sum of outgoing flows, thereby maintaining equilibrium within the system. In this study, a three-field plot was generated using the Biblioshiny package in R to visually represent the relationships among journals, prominent authors, countries, affiliations, author keywords, and other search field attributes. The driving components are shown as rectangular blocks in various colours, with the number of connections between different elements of the plot being directly proportional to the height of each rectangle. The Sankey diagram presented in Figure 5 illustrates the associations between leading authors (left), countries (middle), and institutions (right). It shows that authors such as Liu Y., Wang Y., Li J., Liu X. and Li Y. demonstrated the strongest associations with top-ranked countries and affiliations. Furthermore, the connections between the top 15 journals, leading countries, and affiliations indicate that China and the USA are the most influential countries, exhibiting the strongest associations with the other two components (Figure A4). It is also noticed that most frequently, papers on struvite technology in wastewater are published in *Water Research*, *Water Science and Technology*, and *Bioresource Technology*, while authors are associated with Tongji University, Institute of Urban Environment and Central South University. Figure A5 presents the connection between the top 10 most productive authors, the 5 leading countries, and the 5 most relevant journals publishing research on struvite recovery from wastewater. The analysis shows that the top 10 most productive authors primarily published their articles in journals, following a priority order from highest to lowest, with *Bioresource Technology* and *Water Research* having the highest ranking among sources.

It is worth mentioning that the prominence of China, the US, and European countries reflects differing national priorities and regulatory drivers. China leads in this field probably due to strong government policies on wastewater treatment, resource recovery, and circular economy, resulting in high research output (Hu *et al.*, 2026). European countries achieve higher citation impact, likely driven by strict environmental regulations that promote high-quality, application-focused research (Collivignarelli *et al.*, 2026). The US contributes significantly through innovation-driven funding and interdisciplinary programs, though with relatively lower citation intensity (Miller *et al.*, 2025).

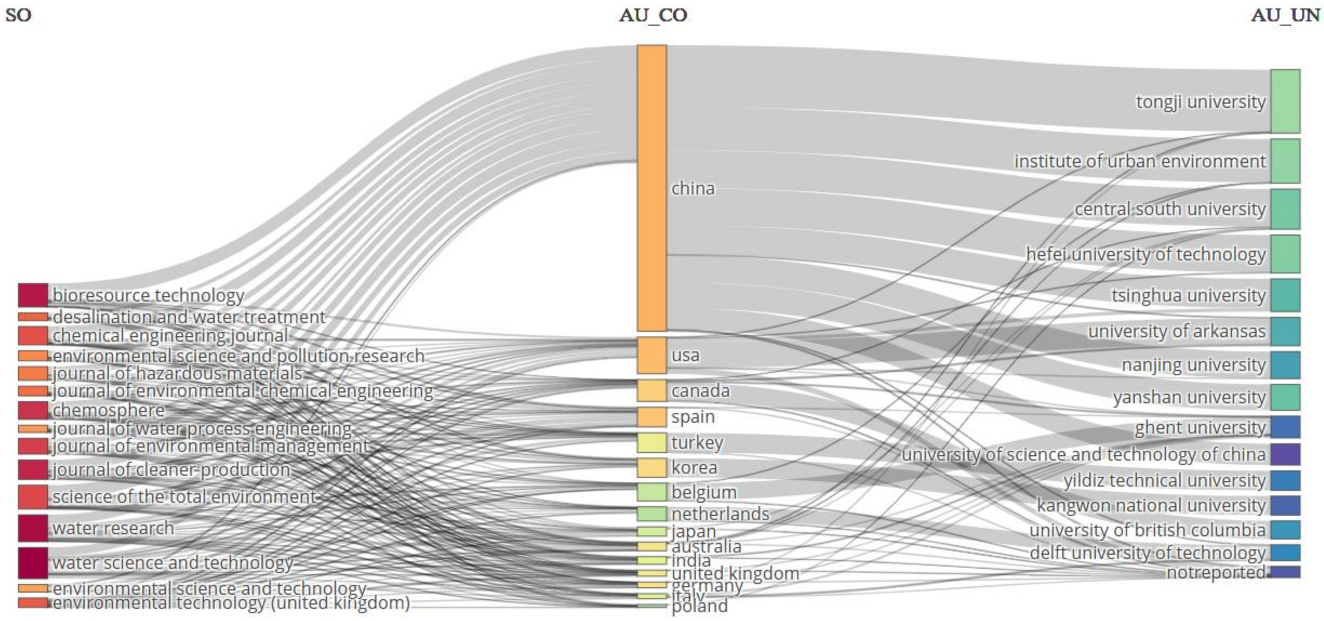

Figure 5. Three-field plot of authors (left), countries (middle) and leading affiliations (right).

2. Co-author network analysis

Figure 6 illustrates the co-citation network of prominent authors in the field of struvite recovery from wastewater. The bubble size represents the number of publications by each author, while the thickness of the connecting lines indicates the strength of their co-citation links. The network was constructed using the "Authors" search field, with the Fruchterman and Reingold layout, the Leiden clustering algorithm, 50 nodes, and a repulsion force of 0.10. Based on the Scopus® database, a total of four distinct clusters were identified (Figure 6). Each cluster demonstrates strong interconnections among its leading authors, while cross-connections between clusters are also evident. It can be observed that the leading authors in each cluster tend to dominate specific research topics, even though other contributions in different minor related fields are also present. Researchers in Cluster 1, such as Huang H., Liu J. and Zhang P., have focused on the alternatives of Mg sources and their role in the feasibility of struvite recovery (Huang *et al.*, 2015; Huang *et al.*, 2014; Huang *et al.*, 2011a). In addition, Cluster 1 authors have investigated struvite recovery from unique wastewater types, including rare-earth wastewater (Huang *et al.*, 2011b), saponification wastewater (Huang *et al.*, 2010a), and coking wastewater (Huang *et al.*, 2010b). Cluster 2, represented by researchers such as Chen S. and Ye Z-L, has primarily concentrated on swine wastewater treatment, the combined effects of heavy metals, and the subsequent applications of recovered struvite (Lou *et al.*, 2018; Shen *et al.*, 2016; Ye *et al.*, 2016; Ye *et al.*, 2011). In Cluster 3, key authors including Liu Y., Wang J. and Zhang Y. have focused on nutrient recovery from wastewater, with particular attention to the potential of recovered struvite-based compounds for immobilising heavy metals (e.g. Cu, Pb, Cd, Zn) in soils and aqueous solutions (Li *et al.*, 2019b, Wang *et al.*, 2016). Cluster 4 comprises only 3 prominent authors. Fattah KP and Mavinic DS conducted joint research on optimising the struvite crystallisation process for struvite recovery from wastewater. Their work includes determining Mg addition requirements, optimising precipitation conditions, and exploring cost-reduction strategies. Notably, they examined carbon dioxide stripping as a method to reduce caustic dosage and improve operational efficiency (Fattah *et al.*, 2010; Fattah *et al.*, 2012; Fattah *et al.*, 2022).

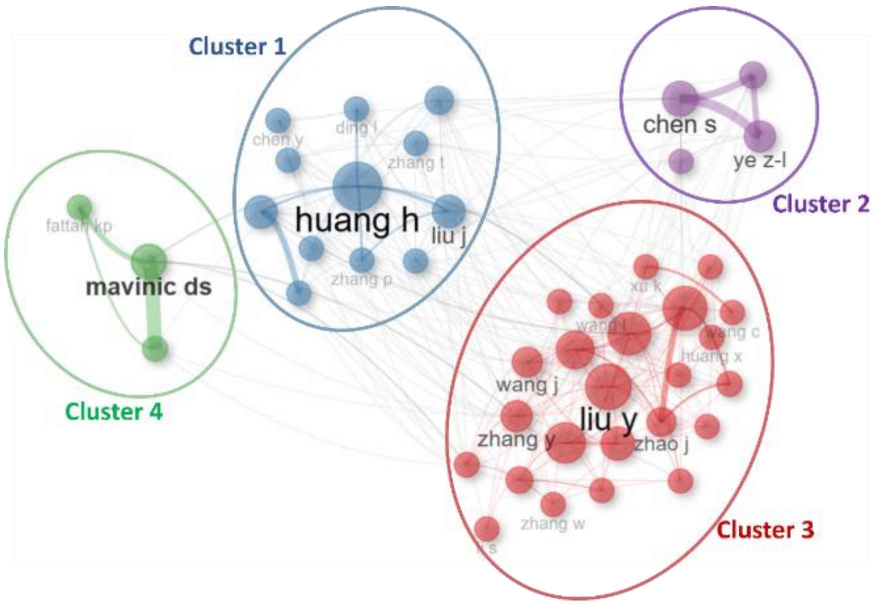

Figure 6. Three-field plot of authors (left), countries (middle) and leading affiliations (right).

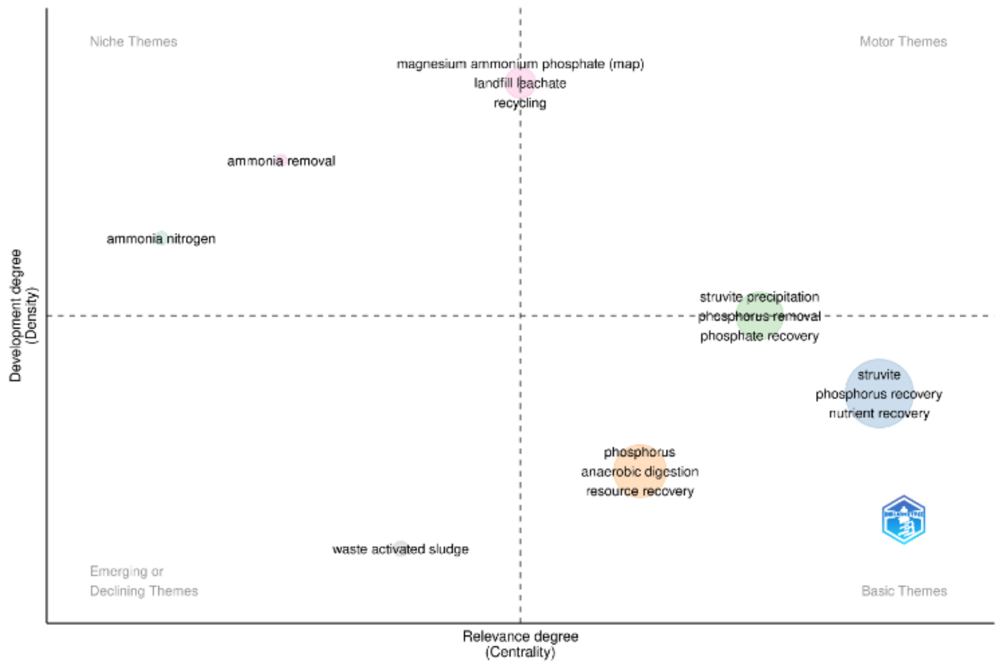

Figure 7. Thematic map of research trends in struvite technology applications in wastewater treatment.

Figure 7 provides a thematic analysis of research trends in struvite recovery and wastewater treatment. It is divided into four categories of themes, based on the degree of development (density) and the degree of relevance (centrality):

Motor themes, niche themes, basic themes and emerging or declining themes. This classification helps to understand which research areas are well-developed, which are foundational, and which may be gaining or losing significance in the field.

The top-right quadrant (motor themes) reflects the most influential and well-developed research topics, which include struvite precipitation, phosphorus removal and phosphate recovery. These are driving forces in this field, as they are linked to almost all studies within the field. The position of the green bubble on the edge between the motor themes area and the basic themes area (bottom-right) suggests that some aspects of struvite precipitation are well established, such as influencing factors and process design parameters, which have been extensively studied across several kinds of waste streams. This is connected to the basic themes (blue bubble; struvite, phosphorus recovery and nutrient recovery) which refer to keywords of comprehensively studied topics. Nevertheless, researchers can still focus on these areas to align their studies with the most impactful topics, such as struvite precipitation and phosphorus recovery from new types of wastewater and emerging influential factors. These topics are likely to receive continued funding and policy support due to their significant role in wastewater treatment and sustainable phosphorus management.

The niche themes quadrant (top-left) contains topics that are well-researched but have limited influence on the broader field. Here, ammonia removal and ammonia nitrogen are highlighted. This corresponds to the fact that the recovery of ammonia nitrogen in low P concentration conditions is economically challenging (Darwish *et al.*, 2016). Furthermore, all pilot and large-scale studies have been applied to wastewaters rich in phosphates, to ensure higher feasibility and durability (Chandrasekaran *et al.*, 2024). Some topics appear on the borderline between motor themes and niche themes (i.e. magnesium ammonium phosphate, landfill leachate and recycling). This aligns with the research trends observed for these topics, especially "landfill leachate", which is limited to a certain type of wastewater (but well-recognised as a hazardous stream with high loads of ammonia (Agbenyeku *et al.*, 2016), and "recycling", which is restricted to recycling struvite as an alternative source of Mg and P for further struvite recovery.

Finally, the emerging or declining themes quadrant (bottom-left) contains topics that are either gaining interest or becoming outdated. The term "waste activated sludge" suggests that research in this area is losing momentum. A quick review of the studies involving "waste activated sludge" and "struvite" among the 1,717 studies in the Scopus® database reveals that the number of published studies peaked in 2016 and declined afterwards. However, this topic may attract funding if it is recognised as a potential future direction in climate change remediation, because handling and disposing of waste-activated sludge generates 40% of the overall greenhouse gas emissions associated with wastewater treatment (Otieno *et al.*, 2023).

The "alternative magnesium sources" cluster reflects a clear shift from laboratory-scale cost reduction to engineering-driven feasibility. Early studies focused on low-cost reagents (Etter *et al.*, 2011; Ye *et al.*, 2011), whereas more advanced work demonstrated practical implementation, such as the use of MgO slurry as both an alkali and Mg source in pilot-scale systems, and the application of bittern and recycled Mg streams to enhance process efficiency (Aguilar-Pozo *et al.*, 2025). This progression shows that Mg source selection is no longer a minor optimisation parameter, but a critical determinant of scalability, process stability, and circular-economy integration, particularly when accounting for impurity effects (e.g., Ca^{2+}) and product quality.

A more granular inspection of the thematic structure reveals emerging subfields that may not be immediately apparent in the global network visualisation. For instance, clusters associated with nutrient recovery and fertiliser application indicate a growing interest in advanced concepts such as bio-struvite and smart fertilisers, where struvite is integrated with biological or controlled-release systems to enhance agronomic performance. Similarly, clusters linked to resource recovery and recycling suggest a shift toward hybrid and circular process designs, combining struvite crystallisation with other treatment technologies.

These subthemes, although embedded within broader clusters, represent important directions for future research, particularly in bridging the gap between material recovery and value-added applications. Their increasing presence reflects a transition from conventional precipitation studies toward more innovative, application-driven approaches in sustainable wastewater management.

III. CONCLUSION

The present study outlined the status of struvite technology application as a wastewater treatment method, through a bibliometric review of a 1,717 research studies extracted from Scopus® database, conducted between 1999 and 2024. The analysis and visualisation were performed using Biblioshiny. The main findings are as follows:

- *Water Research*, *Bioresource Technology* and *Water Science and Technology* are the top 3 journals publishing studies on struvite technology as a wastewater treatment method, and they have received the highest number of citations in the past 25 years.

- China is a leading country in the field of struvite technology, either in terms of affiliations (7 out of top 10), key authors (4 out of top 10), or number of citations. However, AAC records show Switzerland as the leading country. A significant link between the most influential authors' keywords, i.e. "struvite" and "phosphorus recovery", "wastewater", and "precipitation" was revealed from the co-occurrence network of authors' keywords. It illustrates the significant role of struvite technology in phosphorus recovery from wastewater.
- The co-citation network of key authors generated four clusters. Authors in Cluster 1 focused on exploring alternative Mg sources and recovering struvite from unique wastewater types. Cluster 2 researchers primarily studied swine wastewater treatment, heavy metal interactions, and struvite applications. Cluster 3 authors investigated nutrient recovery and heavy metal immobilisation using struvite-based compounds. Cluster 4 authors concentrated on optimising struvite crystallisation for phosphorus recovery and cost-reduction strategies.
- Thematic mapping of authors' keywords suggests that struvite precipitation can still be applied as a potential P recovery approach from new P-rich wastewaters.

Research on struvite technology as a wastewater treatment method is quite established in terms of influencing factors and process design parameters. However, applying struvite technology within climate change remediation approaches, in addition to the cost-benefit analysis of wastewater-derived struvite fertiliser, needs to be further explored.

This study was limited to the Scopus® database from 1999 to 2024, potentially overlooking valuable studies from other sources published before this period. In addition, this study focused on struvite technology from the perspective of wastewater treatment, possibly excluding some research on struvite material as a fertiliser. This encourages future bibliometric reviews on the applications of wastewater-sourced struvite in agriculture, in order to gain a better understanding of the research trend in this vital field. Additionally, analysing the economic feasibility of struvite precipitation in wastewater (via a critical review) is crucial for determining its cost-effectiveness, scalability, and potential for widespread implementation in wastewater treatment facilities.

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