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Bibliometric Analysis of Nitrogen Removal in Constructed Wetlands: Current Trends and Future Research Directions

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Abstract: Nitrogen pollution in water environments has reached critical levels globally, primarily stemming from agricultural runoff, industrial discharges, and untreated sewage. The excessive presence of nitrogen compounds poses a significant threat to water quality, leading to adverse impacts on ecosystems and human health. Reaching a breakthrough in the technology of constructed wetlands (CWs) for mitigating nitrogen pollution is hindered by existing knowledge gaps regarding the mechanisms involved in the removal process. Reaching this understanding, we offer a comprehensive summary of current advancements and theories in this research field. Initially, bibliometric techniques were employed to identify yearly patterns in publications and areas of research focus. Subsequently, the chosen documents underwent statistical analysis using VOSviewer_1.6.20 to determine countries' annual productivity, significant publication years, influential authors, keyword clustering analysis, and more. Finally, a comprehensive overview is provided on the elimination of nitrogen through CWs, encompassing insights into microbial communities and structure types. This analysis aims to uncover potential strategies for optimizing the rate of nitrogen removal. Furthermore, this study elucidates the current research trend concerning the nitrogen removal performance of CWs and identifies challenges and future research directions in this field.

Keywords: constructed wetlands; nitrogen removal; bibliometrics; VOSviewer; current trend

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1. Introduction

Nitrogen stands as a linchpin element in aquatic ecosystems, driving essential ecological processes that shape the dynamics of these environments. The cycling of nitrogen, encompassing ammonium, nitrate, and nitrite, influences primary production, nutrient availability, and trophic interactions [1]. Ascertaining the significance of nitrogen in aquatic ecosystems is fundamental for advancing our comprehension of the intricate interplay of biogeochemical cycles.

However, the problem of nitrogen pollution in aquatic ecosystems is worsening due to human activities, primarily stemming from agricultural, urban, and industrial sources [2,3]. Agricultural runoff, laden with excess nitrogen from fertilizers and animal waste, represents a major contributor. Urban stormwater runoff, carrying dissolved inorganic nitrogen from impervious surfaces and atmospheric deposition, also significantly impacts water quality [4]. Industrial discharges containing nitrogen-based compounds further exacerbate the issue, introducing elevated nitrogen concentrations into aquatic environments. The ecological impacts of nitrogen pollution in water bodies are multifaceted and profound. Excessive nitrogen inputs often result in eutrophication and disrupt the nitrogen-fixing capabilities of certain symbiotic organisms, affecting nutrient cycling and overall ecosystem productivity [5]. Furthermore, nitrogen pollution can disrupt nitrogen cycling carried out by microbes. Nitrification and denitrification, crucial processes in nitrogen transformation, may experience imbalances, affecting the availability of nitrogen in the ecosystem [6,7]. This disturbance in nitrogen cycling has cascading effects on nutrient dynamics and can ultimately influence the overall productivity of aquatic ecosystems. Recovering and recycling nitrogen is encouraged in this context due to concerns about the stability of aquatic ecosystems [8].

There exist numerous effective technologies for the elimination of nitrogen. However, many of these options are associated with elevated expenses and energy requirements, intricate operational procedures, and excessive maintenance needs. Examples include activated sludge [9], photobioreactors [10], and membrane bioreactors [11]. Consequently, constructed wetlands (CWs) incorporating sorption filter media offer a comprehensive and cost-effective treatment solution by effectively removing various contaminants through precipitation, microbial activity, and plant absorption processes. CWs represent a proactive and innovative approach to ecological conservation and water management. In the realm of wastewater treatment, CWs play a crucial role in purifying contaminated water [12]. The intricate network of plants and microorganisms within these systems acts as a natural filter, breaking down pollutants and enhancing water quality [13]. This sustainable approach to water treatment not only helps mitigate pollution but also contributes to the preservation of aquatic ecosystems.

Currently, the primary method utilized in CWs for nitrogen removal is the process of phytoremediation. Wetland plants, particularly emergent and submerged species, play a crucial role in absorbing and assimilating nitrogen compounds, such as nitrate and ammonium, through their roots [14]. This biological uptake, facilitated by the specific metabolic activities of wetland vegetation, significantly contributes to reducing nitrogen levels in water. Additionally, the substrate composition of CWs, often designed with materials such as gravel, sand, and organic matter, fosters conditions conducive to denitrification [15]. Denitrifying bacteria found within the sediments of wetlands transform nitrate into nitrogen gas, thereby effectively eliminating nitrogen from the aquatic ecosystem [6,16]. The efficiency of nitrogen removal in CWs is influenced by several factors, including the hydraulic residence time (HRT), plant species selection, and overall design considerations [17]. Optimizing these parameters enhances the performance of CWs in reducing nitrogen concentrations in treated water. Therefore, there is a need for long-term monitoring to assess the sustained efficiency of CWs and the optimization of design parameters for varying environmental conditions. Continued research and technological advancements are crucial to refining the performance of CWs and ensuring their role as effective tools in the ongoing efforts to combat nitrogen pollution in water bodies. Thus, the current situation and research frontiers in nitrogen removal technology for constructed wetlands need to be examined, considering advancements in theoretical knowledge and new domains.

Bibliometrics is employed for analyzing the research status and development trend of a specific field of study and can be utilized to recognize and establish connections between crucial elements within a certain subject [18,19]. For example, Colares et al. conducted a bibliometric analysis to investigate the key factors influencing the performance and feasibility of floating treatment wetlands (FTWs) in terms of design and operational conditions. Through bibliometric mapping, the authors observed correlations between HRT, water depth, and phosphorus removal efficiency in these systems [20]. In summary, bibliometrics serves as a valuable tool for understanding the dynamics of nitrogen removal research in CWs. Its applications contribute to the identification of trends, assessment of research impact, recognition of key contributors, and the overall advancement of knowledge in this specialized environmental domain [21].

Considering the aforementioned circumstances, a textual corpus was established by conducting a search via the Web of Science. It cannot be denied that there is currently insufficient discussion regarding controlled operational parameters for nitrogen removal using CWs, both in laboratory and field studies. Additionally, there is a dearth of comprehensive mechanistic studies pertaining to the elimination process. The primary aim of this study is to identify key knowledge gaps that need filling, based on the current understanding of conclusions regarding the effectiveness of CWs in nitrogen management. This study aims to (1) summarize bibliometric data on nitrogen removal in CWs including publication title, author information, affiliations, and field of study; (2) analyze research keywords within the text corpus to predict trends for better domain support; (3) monitor research progress on nitrogen removal by CWs; and (4) evaluate the potential nitrogen removal capacity of CWs and identify challenges and future research directions in the nitrogen removal of CWs.

2. Materials and Methods

2.1. Bibliometric Data Sources

In order to assess the current status of research, a bibliometric analysis was conducted using data from the Web of Science platform. A total of 4557 scholarly articles on the subject of "constructed wetlands" and "nitrogen" were retrieved for examination. The search results included various details about each document such as author(s), title, source (journal title), language, document type, author keywords, addresses, cited reference count, times cited, publisher information, page count, ISSN, and subject category. Complete records were downloaded for further investigation. Contributions from different countries and institutions were estimated based on the location affiliation of at least one author mentioned in each published paper [22]. The analysis focused on the examination of articles published in the period between 2008 and 2024 that revolve around the topics of "constructed wetlands" and "nitrogen". Various factors were taken into consideration, including document type, language of publication, characteristics of publication output (such as authors involved, the average number of authors per article, cited references count, average number of references per article, and page count), patterns of publications (percentage distribution of articles across different categories, impact factor, and subject category classification for journals and their respective positions within those categories), as well as research interests related to wetlands determined through author keyword analysis and analyses based on title words and Key Words Plus.

2.2. Bibliometric Methodology

Bibliometric mapping was conducted using VOSviewer_1.6.20 software, following the methodology of De Souza et al. and considering all research records and document types throughout the entire period [23]. The 2008–2023 period was investigated because the most advanced research on nitrogen removal using CWs was performed during this period. Hence, the complete period was regarded as a reflection of the progress in research within this field from its inception to the current era. The maps generated in this study were network visualizations, with labels and circles representing items based on their importance. Lines indicate links between items, and the distance reflects the strength of their connection [24]. Previous studies have also demonstrated the high efficiency of VOSviewer in bibliometric analysis [19]. Bibliometric mapping data were used for literature research to better understand the highlighted topics and their connections and investigate recent scientific advances related to the study subject.

3. Results and Discussion

3.1. Research Area Analysis

By utilizing the search keywords "constructed wetlands" and "nitrogen", we acquired data from various sources on the Web of Science platform, including articles, reviews, and more. The research direction is primarily divided into ten distinct fields, as can be observed from Figure 1. These categories are environmental sciences (70.4%), environmental engineering (33.3%), water resources (22.1%), ecology (16.5%), chemical engineering (8.9%), biotechnology applied microbiology (8.4%), agricultural engineering (6.4%), energy fuels (6.1%), green sustainable science technology (3.8%), and marine freshwater biology (2.6%). It is demonstrated that the use of CW for nitrogen removal is an important water treatment and environmental protection technology. This could be because the nitrogen removal capacity of CWs directly contributes to water treatment objectives. By mitigating nitrogen pollution, these wetlands enhance the quality of water bodies, reducing the risk of eutrophication and maintaining ecological balance [25]. The natural processes within the wetland act as a biological filter, promoting the purification of water. Additionally, the synergy between CWs, nitrogen removal, water treatment, and environmental protection technology collectively contributes to enhanced environmental sustainability [26]. Therefore, CWs, as a sustainable environmental protection technology, play a crucial role in removing nitrogen from water.

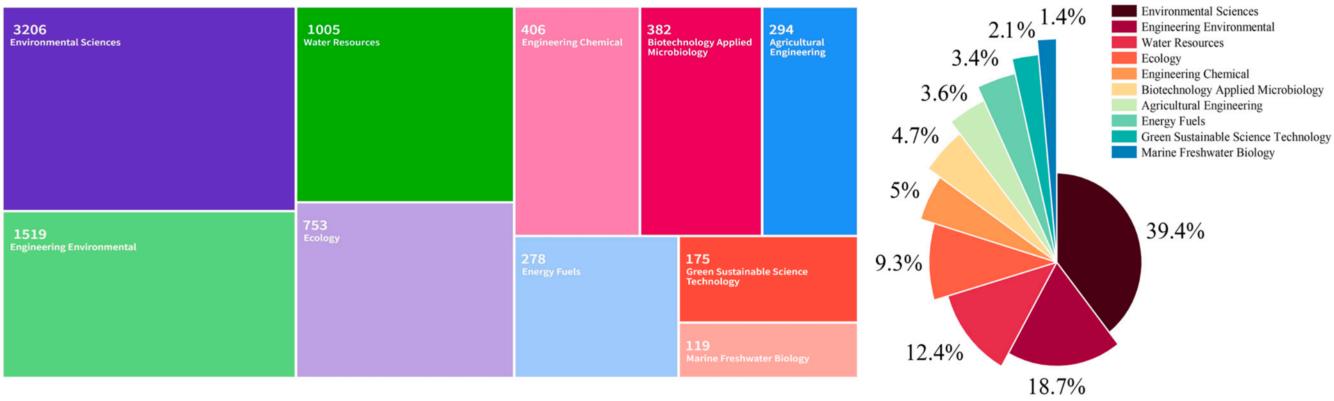

Figure 1. The publications related to the search terms "constructed wetlands" and "nitrogen", obtained from the Web of Science, are categorized.

3.2. Publication Years and Authors Analysis

The keywords "constructed wetlands" and "nitrogen" were used to search for long-term publications. The nitrogen removal capacity of CWs was rarely studied before 2009, with subsequent fluctuations observed from 2009 to 2014 (Figure 2a). The number of articles published per year exhibited a marked increase in 2014–2021. The number of articles published per year increased from 99 in 2008 to 492 in 2021, spanning the period from 2008 to 2021, and the difference in cumulative trends was evident between 2008 and 2015 and between 2015 and 2021. Therefore, the curve fitting shows a high growth rate for articles published annually from 2014 to 2021. However, there is a downward trend in the number of articles published annually from 2021 to 2023. This can be attributed to the gradual maturation of conventional CW nitrogen removal technology and the absence of novel enhanced techniques and methodologies, resulting in stagnation in the advancement of this field. Additionally, the publication rate of relevant articles has witnessed a decline in the last two years as an outcome. Since the 1990s, global scientific exchange has facilitated the widespread adoption of CW technology as a globally preferred approach for addressing diverse wastewater-related issues [27]. Therefore, the nitrogen removal technology of CWs has attracted increasing attention and exploration from scientists, further promoting the growth in the number of related articles published each year.

A total of 11,217 authors were identified from the analysis of 4557 articles. As shown in Figure 2b, the author with the highest publication volume has published a total of 125 articles (2.7%) on nitrogen removal using CWs. The number of articles published by authors ranked second, third, and fourth is, respectively, 66 (1.5%), 65 (1.4%), and 61 (1.3%). The remaining authors ranked in the top fifteen have an average publication volume of around 50 articles. The researchers were likely experts in various academic areas beyond CWs, thanks to the interconnectedness of physical, chemical, and biological processes in complex research [13]. This necessitated a diverse and multidisciplinary knowledge base, requiring collaboration among researchers from different disciplines. Furthermore, the diverse interests of researchers may lead to a decentralization of their publications, potentially resulting in a lower number of articles on CW research [28]. This could help explain the variation in the number of publications among different researchers. We predict that an increased publication rate, as discussed above, will lead to more researchers being involved in studies on CWs. The analysis may be biased for authors who consistently use the same name or different names in their published works [29]. The increasing number of articles on CWs suggests a promising future with more papers and researchers.

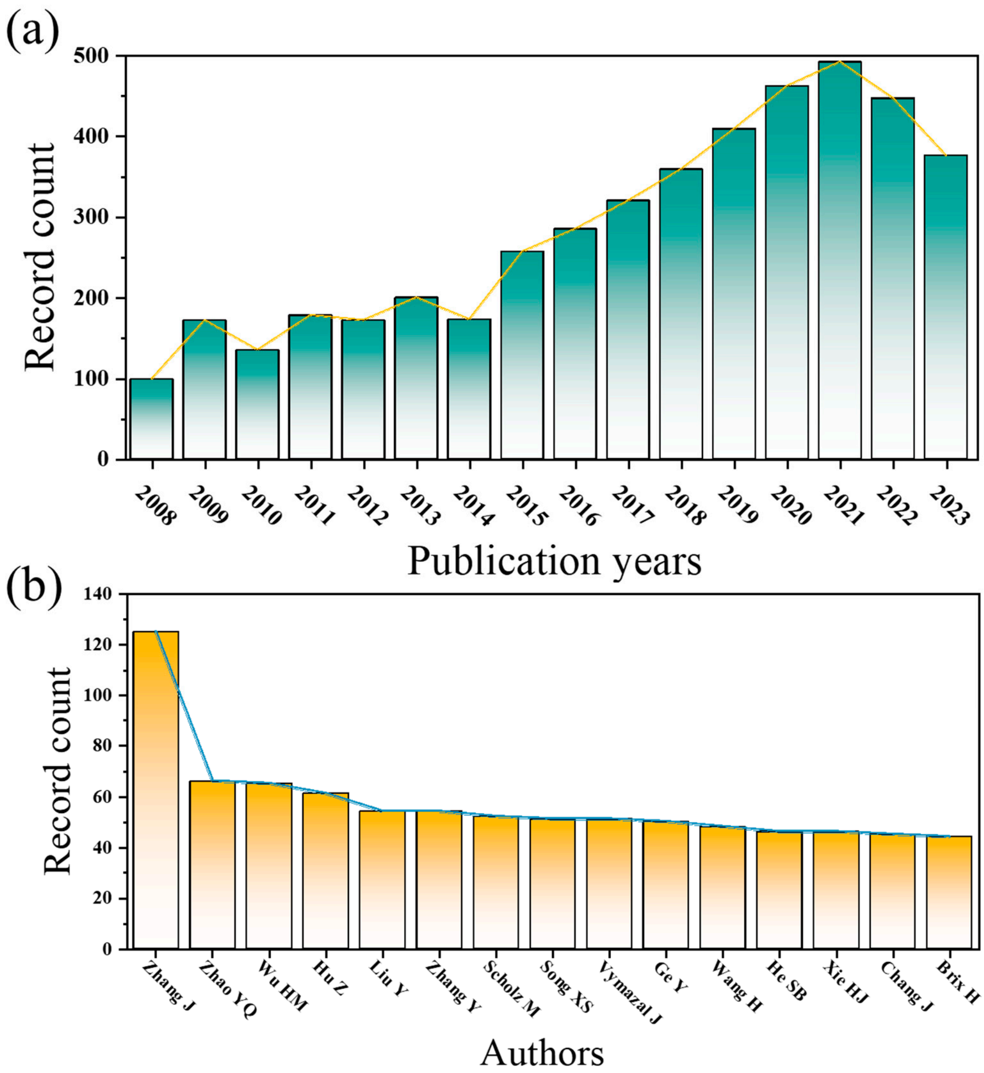

Figure 2. The years (**a**) and authors (**b**) of publications on the topic of "constructed wetlands" and "nitrogen", obtained from the Web of Science, were analyzed.

3.3. Publication Regions and Languages Analysis

The 4557 articles primarily originate from 10 different countries (Figure 3a), with 2125 being independent publications from a single country (53.4%). Over the past 16 years, the nitrogen removal capacity of CWs has been extensively researched by more than one-third of the world's countries. Notably, China, America, India, and Spain emerged as the dominant regions in terms of generating publications on CWs for nitrogen removal. Among these regions, it is noteworthy that developing countries exhibited the highest total number of relevant publications. One potential explanation is that CWs offer a cost-effective method for wastewater treatment and are particularly favored by developing nations [30]. The publication trend results for the ten most productive countries, namely China, USA, India, Spain, Australia, Canada, England, Brazil, Italy, and Denmark, revealed the predominant contribution of China in nitrogen removal capacity research conducted on CWs since 2008. The overall increase in the total number of articles published in these countries from 2014 to 2021 can be attributed to the rapid global development of nitrogen removal research in CWs. Meanwhile, slight fluctuations observed in the total article count in each country are likely due to publication delays resulting from the extensive processes involved in correlational research [31]. The rapid urbanization, industrialization, and accelerated economic development in China position it as a promising leader in the field of research papers on CWs in the coming years [32,33]. These factors have resulted in significant environmental challenges, rendering traditional energy-intensive sanitation systems inadequate and ineffective in meeting the country's demands. Consequently, there has been a promotion of wetland-related research.

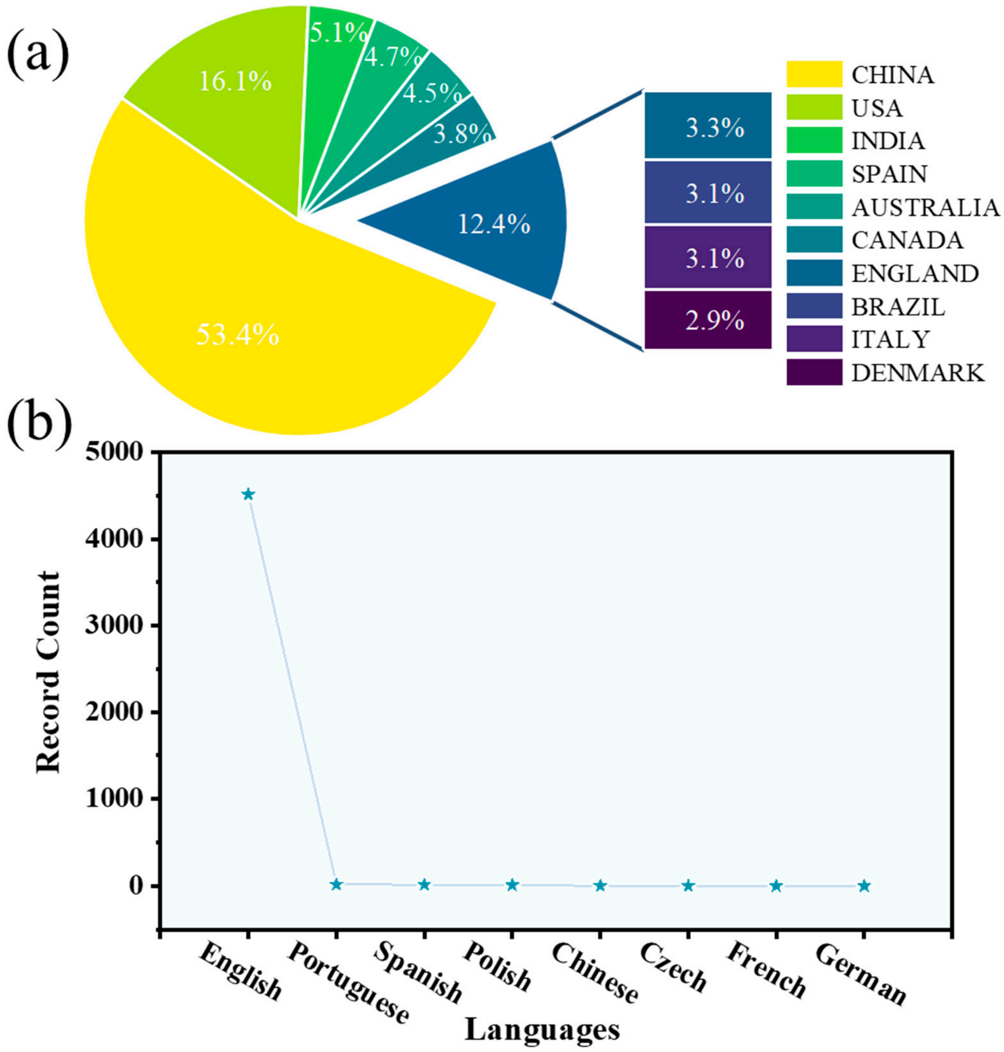

Figure 3. The regions (**a**) and languages (**b**) of publications pertaining to the search terms "constructed wetlands" and "nitrogen", as derived from data obtained through Web of Science.

The articles were published in eight languages (Figure 3b), with English being the predominant language for articles on nitrogen removal capacity in constructed wetlands, accounting for 99% of all publications. This can be attributed to the fact that SCI is an American-based database, and most ISI-listed journals are published in English [29]. The English language is also extensively utilized in international conferences and communications and continues to maintain its dominance across various academic disciplines [34]. However, during the period from 2008 to 2023, a total of 43 non-English articles pertaining to the nitrogen removal capacity of CWs were identified in the Web of Science database. These articles encompassed various languages, including Portuguese (16; 0.35%), Spanish (14; 0.31%), Polish (8; 0.17%), Chinese (2; 0.04%), Czech (1; 0.02%), French (1; 0.02%) and German (1; 0.02%).

3.4. Publication Keywords and Main Items Analysis

The analysis of keyword records involved 4557 articles from the Web of Science database. The utilization of bibliometric analysis through keywords, as demonstrated by Garfield [35], has proven successful in identifying future directions for scientific research. In recent years, the application of keyword-based bibliometric analysis has emerged as an effective approach to analyzing research trends and advancements [29]. It should be noted that highly important items may overlap in the bibliometric map. To improve clarity, we selected only the most relevant terms (with 60% or more relevance) using VOSviewer and generated a new visualization, as shown in Figure 4.

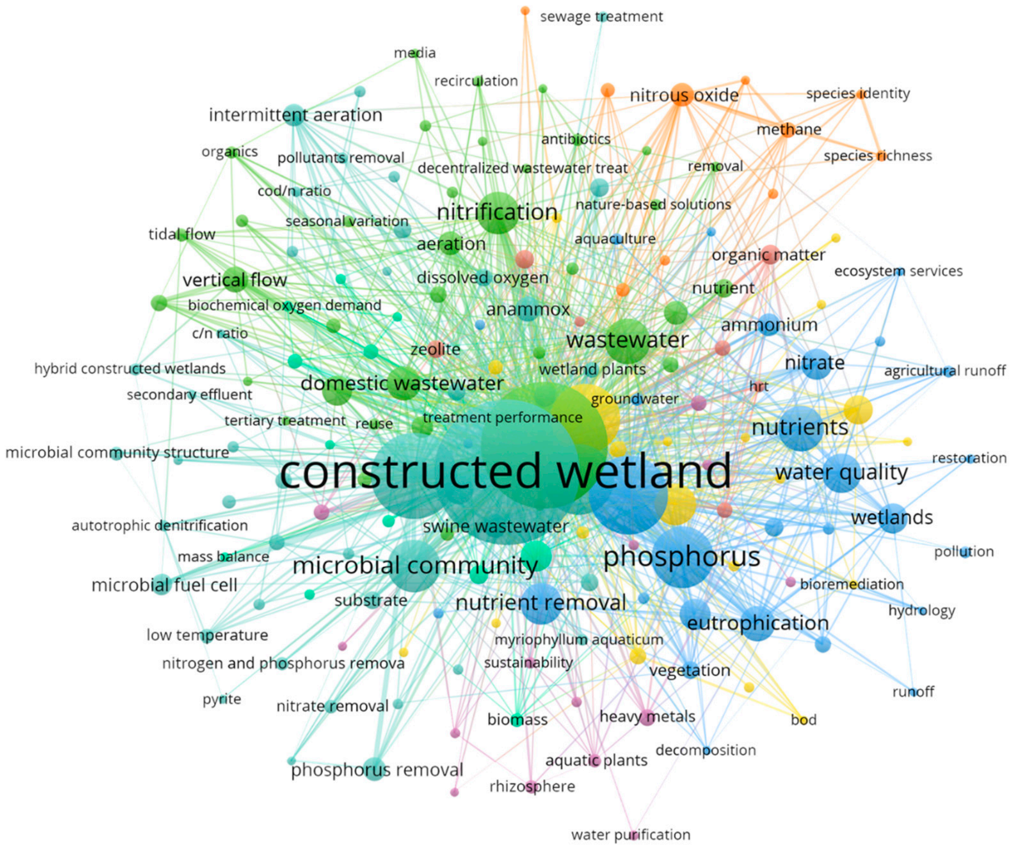

Figure 4. A bibliometric network map was generated in VOSviewer using the search terms "constructed wetlands" and "nitrogen", based on data obtained from the Web of Science.

The accuracy of the results was enhanced by selecting keywords that have a frequency of occurrence exceeding 15 times. Findings revealed that out of the total 8841 keywords, only 2.1% were utilized more than 15 times. The prevalence of low-frequency usage (less than 15 times) may be attributed to research discontinuity or a diverse research focus. Furthermore, the presence of various synonymous terms, spelling variations, and abbreviations might deviate from standardized or widely accepted conventions among researchers [36]. The keywords "constructed wetland", "wastewater" and "nutrient removal" had higher frequencies of use compared to others, denoted as 819, 433, and 130, respectively. This is because CWs play a crucial role in wastewater treatment, particularly in the context of nutrient removal. Wastewater, which contains various pollutants, including nutrients like nitrogen and phosphorus, can have detrimental effects on the environment if discharged untreated [37]. CWs act as natural filtration systems where aquatic plants and microorganisms help break down and absorb contaminants from the wastewater. Moreover, the intricate relationship between CWs, wastewater, and nutrient removal is facilitated by a range of biochemical and physical processes such as benthic bioturbation, substrate adsorption, and microbiological deterioration that collectively contribute to the effective purification of wastewater [38]. The wetland ecosystem harbors a diverse array of plants that serve as a conducive habitat for microorganisms actively engaged in the decomposition of organic matter. Moreover, the wetland substrate effectively facilitates nutrient removal through processes such as adsorption, precipitation, and microbial transformations [39]. This integrated approach results in the effective reduction in nutrient concentrations in the wastewater, making it environmentally safer before discharge. Therefore, the high frequency of usage is attributed to the correlation between these keywords.

The nitrogen removal mechanism in CWs was further investigated, elucidating the pivotal role of microorganism-mediated nitrification and denitrification in the chemoautotrophic process (Figure 5). The keyword nitrification was used 139 times in nitrogen removal in CWs. CWs are efficient in removing nitrogen through a process that involves both nitrification and denitrification. Nitrification is the conversion of ammonia (NH_4^-) to nitrate (NO_3^-), while denitrification is the reduction of nitrate to nitrogen gas (N_2), completing the nitrogen removal cycle [40]. Nitrification is the aerobic process where ammonia (NH_3) is oxidized to nitrite (NO_2^-) and then further to NO_3^-. This process is typically executed by two distinct groups of bacteria, namely ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB) [41]. Denitrification is the anaerobic process where NO_3^- is reduced to N_2 or other gaseous nitrogen compounds. This process is carried out by denitrifying bacteria. The relationship between CWs and these nitrogen transformations lies in the controlled conditions provided by the wetland environment. CWs create a suitable habitat for both aerobic and anaerobic microorganisms, allowing for a sequential occurrence of nitrification and denitrification processes [42]. The subsurface flow constructed wetland facilitates the percolation of wastewater through the wetland matrix, thereby supplying oxygen to support surface-level nitrification [43]. As water moves deeper into the wetland, anaerobic conditions prevail, promoting denitrification. The intricate network of plant roots further enhances nitrogen removal by providing surfaces for microbial attachment and facilitating the transport of oxygen into the wetland matrix.

Therefore, in CWs designed for nitrogen removal, managers often optimize conditions to encourage both processes. This may involve controlling the water flow, maintaining suitable oxygen levels, and providing organic carbon sources to stimulate denitrification [44]. Balancing these factors within CWs of diverse structures ensures efficient removal of nitrogen from wastewater while minimizing the release of nitrogen compounds that could have negative environmental impacts. However, the structure of CWs varies due to the different design methods employed, resulting in significant disparities in achieved efficiency when balancing these factors. This integrated approach plays a crucial role in mitigating nitrogen pollution in wastewater and promoting a more sustainable water treatment process.

3.5. Current Research Hotspot Analysis

Based on a timeline of 4557 existing studies, we analyzed the latest research trends in nitrogen removal in CWs (Figure 6). Recently, the primary research focus has been directed toward microbial-enhanced nitrogen removal technology in CWs. The keyword was extensively discussed 276 times between 2020 and 2023.

Firstly, microorganisms such as *Nitrocellulose*, *Bacillu*, *Pseudomonas*, *Micrococcus*, and others play a crucial role in the biotransformation of nutrients within CWs. They facilitate processes like decomposition and enzymatic breakdown to convert complex nutrients such as dissolved organic matter into simpler forms [45]. This microbial activity not only helps in nutrient cycling but also promotes water quality by reducing the accumulation of nutrients. Secondly, microorganisms are crucial for nitrogen cycling in CWs (Figure 7). These microbes actively participate in nitrification, where ammonia is converted into nitrite and nitrate, and denitrification, where nitrate is transformed back into nitrogen gas [6]. This nitrogen removal process is vital for preventing water contamination and maintaining a balanced nitrogen cycle within the CWs. Additionally, microorganisms contribute to the breakdown of organic matter present in the CWs. The decomposition of organic material releases nitrogen in various forms, and microorganisms assist in converting these nitrogen compounds into more stable forms or facilitating their removal from the system [46]. In addition, microorganisms support the establishment of a diverse and stable ecosystem within CWs. They form symbiotic relationships with plants, promoting nutrient uptake and enhancing plant growth [47]. This synergy between microorganisms and vegetation contributes to the overall resilience and sustainability of the wetland ecosystem.

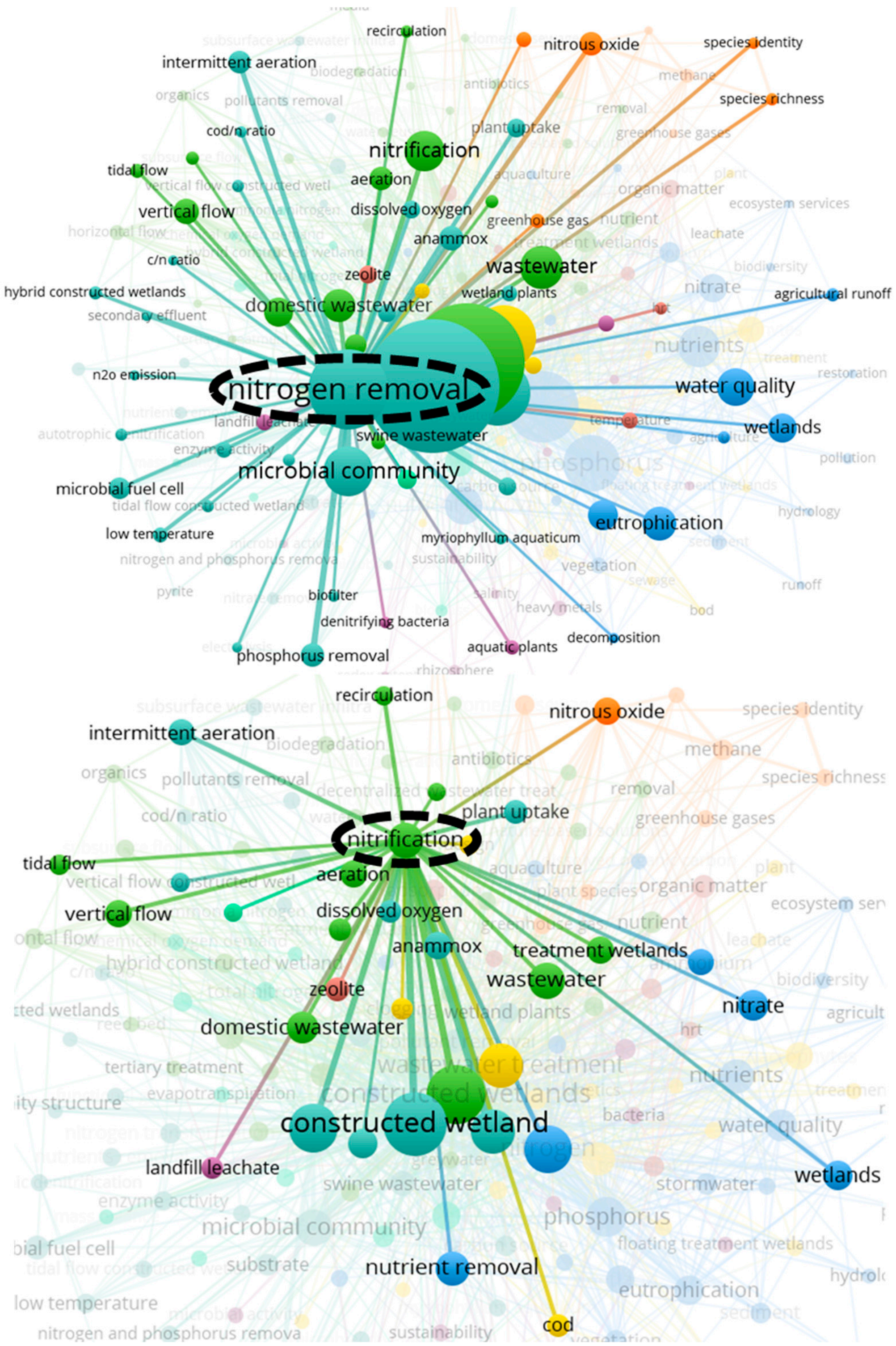

Figure 5. Highlighted terms associated with nitrogen removal were selected based on data obtained from the Web of Science.

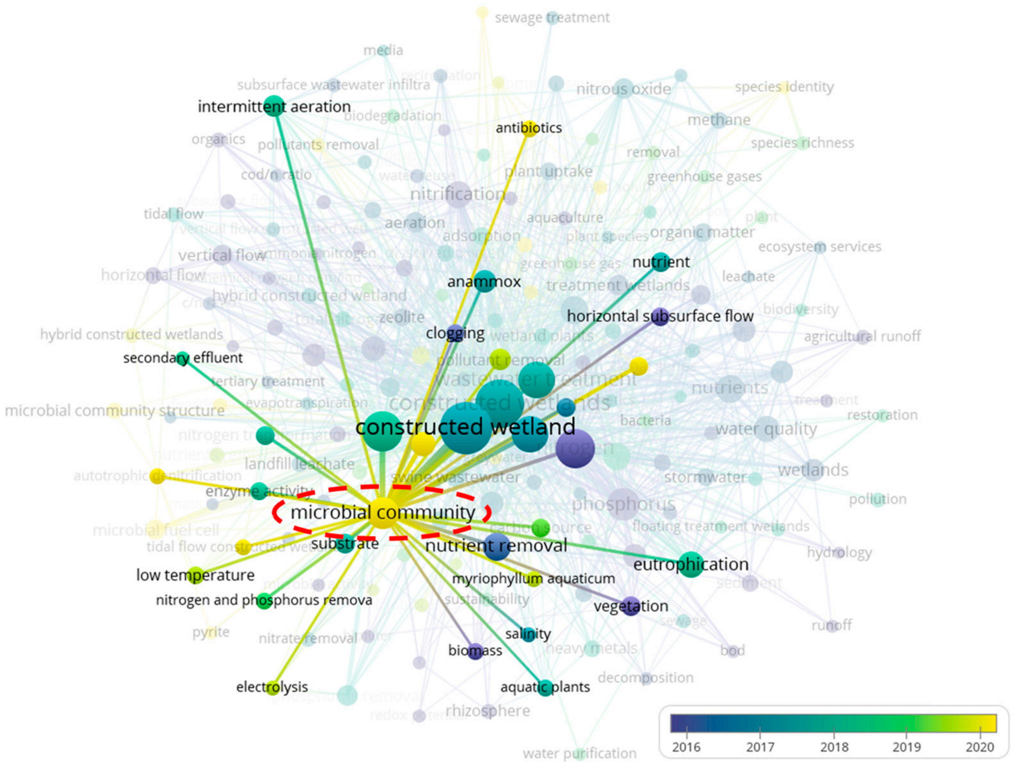

Figure 6. The highlighted terms related to "constructed wetlands" and "nitrogen" were selected based on timeline analysis using data from the Web of Science.

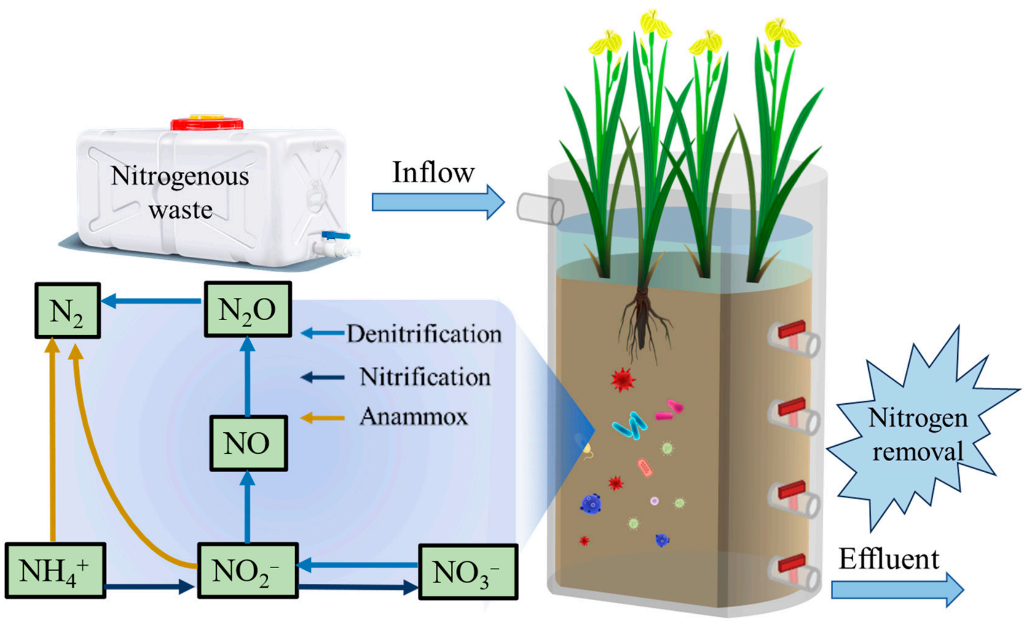

Figure 7. Conceptual model for the mechanisms of microbial nitrogen removal in CWs.

This provides evidence that the significance of microorganisms in CWs lies in their ability to mediate the transformation of nitrogen compounds, playing a pivotal role in the overall nitrogen removal process. Through nitrification and denitrification, these microorganisms significantly contribute to the overall effectiveness and ecological balance of these engineered ecosystems.

4. Knowledge Gaps and Future Studies

Limited studies have provided comprehensive insights into the genetic mechanisms underlying microbial nitrogen removal in CWs, while a significant gap still exists in linking theoretical frameworks to practical applications. Therefore, further investigations should focus on elucidating the migration and fate of nitrogen within CWs, with particular emphasis on understanding the biological effects involved, in order to unravel the intricate response mechanisms at play. Furthermore, researchers should remain vigilant regarding the residual nitrogen by-products that may persist on plant surfaces or be absorbed by plants for prolonged periods due to varying water flow impacts. The disruption of roots and leaves, decomposition of plants, or disturbances caused by aquatic animals could reintroduce these nitrogen compounds and their by-products into the CWs environment, which is critical for ensuring the sustainability of CWs. Based on this review, future research on nitrogen removal in CWs should prioritize the following areas:

(1). Efficient nitrogen removal materials should be further explored to continuously optimize the substrate composition in CWs, taking into account both economic viability and environmental sustainability.
(2). Researchers should investigate the use of genetic and ecological interventions for enhancing microbial populations' ability to perform nitrogen conversion processes, such as nitrification, denitrification, ammonification, and anaerobic ammonia oxidation, at higher rates and with greater efficiency.
(3). The advancement of bioscience control technologies in CWs, encompassing aquatic organisms, plants, biofilms, and microbial techniques, still encounters a substantial knowledge gap. Future research is anticipated to prioritize the investigation of the interplay between living organisms and nitrogen capture.
(4). The integration of advanced sensors and real-time monitoring systems is essential for advancing microbial engineering in CWs. It enables continuous surveillance of microbial activity, environmental conditions, and nitrogen levels, facilitating the precise control and optimization of nitrogen removal performance. Smart data-driven systems can revolutionize this field by improving adaptability to changing nitrogen loading conditions.

The complex nitrogen removal process in CWs should be comprehensively analyzed through model development and software fitting when sufficient data are available. It will be necessary for future research to establish emission limit standards and toxicological limit standards for nitrogen, aiming to provide better guidance for environmental management practices.

5. Conclusions

We conducted a comprehensive review encompassing 4557 publications sourced from the Web of Science database, elucidating the removal of nitrogen using CWs. This study encompasses pertinent countries and organizations, publication years, authors, and sources, as well as clustering and co-occurrence analysis of keywords. Furthermore, we examined the parameters and mechanisms influencing nitrogen removal in CWs. Overall, our survey provides an extensive knowledge base for potential collaborators or researchers in this field. Additionally, our research underscores the urgent need to enhance legislative and policy frameworks to mitigate nitrogen pollution at its source by addressing future threats. Extensive in-depth research is imperative to focus on developing controlled conditions for CWs that are cleaner and offer potential methods for efficient nitrogen removal.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: 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 raw data supporting the conclusions of this article will be made available by the authors on request.

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