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Mapping the Research Landscape of Wastewater Treatment Wetlands: A Bibliometric Analysis and Comprehensive Review

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폐수 처리 위한 습지의 연구 환경 매핑: 서지학적 분석 및 종합 검토

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Abstract

Constructed wetlands (CWs) are effective technologies for urban wastewater management, utilizing natural physico-chemical and biological processes to remove pollutants. This study employed a bibliometric analysis approach to investigate the progress and future research trends in the field of CWs. A comprehensive review of 100 most-recently published and open-access articles was performed to analyze the performance of CWs in treating wastewater. Spain, China, Italy, and the United States were among the most productive countries in terms of the number of published papers. The most frequently used keywords in publications include water quality (n=19), phytoremediation (n=13), stormwater (n=11), and phosphorus (n=11), suggesting that the efficiency of CWs in improving water quality and removal of nutrients were widely investigated. Among the different types of CWs reviewed, hybrid CWs exhibited the highest removal efficiencies for BOD (88.67%) and TSS (95.67%), whereas VSSF, and HSSF systems also showed high TSS removal efficiencies (83.25%, and 78.83% respectively). VSSF wetland displayed the highest COD removal efficiency (71.82%). Generally, physical processes (e.g., sedimentation, filtration, adsorption) and biological mechanisms (i.e., biodegradation) contributed to the high removal efficiency of TSS, BOD, and COD in CW systems. The hybrid CW system demonstrated highest TN removal efficiency (60.78%) by integrating multiple treatment processes, including aerobic and anaerobic conditions, various vegetation types, and different media configurations, which enhanced microbial activity and allowed for comprehensive nitrogen compound removal. The FWS system showed the highest TP removal efficiency (54.50%) due to combined process of settling sediment-bound phosphorus and plant uptake. *Phragmites, Cyperus, Iris*, and *Typha* were commonly used in CWs due to their superior phytoremediation capabilities. The study emphasized the potential of CWs as sustainable alternatives for wastewater management, particularly in urban areas.

Key words : Bibliometrics, constructed wetlands, wastewater treatment

요 약

인공습지(CW)는 도시 폐수처리를 위한 효과적인 기술로, 물리-화학적 및 생물학적 자연처리과정을 통해 오염 물질이 제거된다. 본 연구는 서지학적 분석 방법을 통하여 인공습지의 현재까지의 연구 진행 상황과 향후 연구 동향을 조사하였다. 인공습지를 통한 폐수 처리 성능 평가 분석을 위하여 최근 출판된 논문(오픈 액세스 학술지 포함) 100편을 기반으로 종합적 분석 및 검토를 수행하였다. 분석 결과, 스페인, 중국, 이탈리아, 미국이 논문 출판수가 두드러지는 것으로 나타났다. 논문에서 가장 많이 사용된 핵심용어는 수질(n=19), 식물 정화(n=13), 강우유출수(n=11), 인

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(n=11) 순으로 나타났으며, 수질개선과 영양염류 제거에 대한 인공습지의 효율성 관련 연구가 폭넓게 연구되고 있는 것으로 분석되었다. 검토된 다양한 유형의 인공습지 중 Hybrid 형태의 인공습지가 TSS(95.67%) 및BOD(88.67%)으로 오염물질 저감효율이 가장 높은 것으로 나타났으며, VSSF, HSSF는 TSS 제거(83.25% 및 78.83%)에 가장 효과적인 것으로 조사되었다. VSSF 습지는 가장 높은 COD 제거 효율(71.82%)을 보였다. 일반적으로 인공습지에서 물리적 처리(예: 침전, 여과, 흡착)와 생물학적 메커니즘(예: 생분해)은 TSS, BOD, COD 제거 효율에 영향을 미치기 때문이다. Hybrid 형태의 인공습지는 호기성 및 혐기성 조건, 다양한 식생 유형, 다양한 매체 구성 등의 다양한 인자와 여러 처리 과정을 통해 미생물 활성도 증가 및 질소 처리를 통해 TN(60.78%)의 높은 저감효과를 보였다. FWS 형태의 인공습지는 퇴적물에 결합된 인을 침전 및 식물의 흡수를 통해 높은TP 제거효율(54.50%)로 나타났습니다. 일반적으로 인공습지에는 식물 정화 능력이 뛰어난 *Phragmites, Cyperus, Iris* 및 *Typha* 이 적용되고 있다. 본 연구는 향후 도시 지역에서 발생되는 폐수 처리를 위한 지속 가능한 대안으로 제시 가능할 것으로 사료된다.

핵심용어 : 계량서지학 분석, 인공습지, 하수처리

1. Introduction

Urbanization has caused an exponential increase in wastewater generation, resulting in a significant challenge for sewage management in several countries worldwide. Conventional wastewater treatment methods are often constrained by high construction, operation, and maintenance costs. Moreover, conventional wastewater treatment facilities may exhibit low efficiency since wastewater from urban areas contains a complex mixture of organic and inorganic substances that pose serious human health hazards and environmental concerns if not managed properly (García-Herrero, et al., 2022). To mitigate these challenges, different organization set a goal to improve water quality through the elimination of hazardous substances in wastewater, halving the proportion of untreated wastewater, and increasing water recycling and safe reuse practices by 2030 (UN-Habitat, 2021). In line with the guidelines of Sustainable Development Goal (SDG) 6.3.1, the percentage of wastewater from various sources, such as households, services, and industrial activities, should undergo safe treatment in compliance with the national or local standards prior to being released into the environment.

Addressing issues regarding wastewater management requires cost-effective and sustainable treatment solutions capable of handling the growing volume and complexity of wastewater in urban areas. Constructed wetlands (CWs) gained increasing attention in recent years due to their perceived effectiveness in treating wastewater (Rai et al., 2013; Zhang et al., 2022). CW is a type of a nature-based technology typically utilized to improve the performance of wastewater treatment systems (Vymazal, 2022). Similar to natural wetlands, these engineered systems, mainly comprised of vegetation, soils, substrates, and microorganisms, utilize physico-chemical and biological processes to effectively remove pollutants in wastewater and improve overall quality of receiving water bodies (Gorgoglione and Torretta, 2018; Resende et al., 2019). CWs have demonstrated considerable efficiency in removing diverse contaminants, such as nitrogen, phosphorus, heavy metals, and organic pollutants, thus establishing them as a feasible alternative for treating various type of wastewater (Wu et al., 2015). The treatment efficiency of CWs in removing pollutants from wastewater can be influenced by various factors such as the type and concentration of pollutants, facility design and components, and other environmental factors pertinent to the treatment process. In the case of domestic or urban wastewater, the type and concentration of pollutants can vary widely, but common pollutants include organic matter, nitrogen, and phosphorus. The efficient elimination of these pollutants in CWs is highly dependent on the system's design and components. For instance, a CW intended for nitrogen removal would usually contain a vegetation zone that enhances denitrification, whereas a CW intended for phosphorus removal would include a media zone that encourages chemical precipitation (Hassan et al., 2021).

In recent years, there has been a considerable increase in the number of scientific publications regarding the wastewater treatment performance of CWs. However, the factors that hinder their ability to consistently achieve high levels of water quality improvement remain a considerable knowledge gap (Wu et al., 2015). Moreover, although numerous studies have already investigated the functions, design, potential benefits, and influencing factors on the performance of CWs for treating urban wastewater, no comprehensive analyses of these publications based on a systematic compilation of bibliographic information have been conducted to date. Therefore, this study was conducted to address the aforementioned knowledge gaps through a comprehensive review of the published scientific literature related to constructed wetlands designed for wastewater treatment. A bibliometric analysis was also performed to assess the current state of knowledge, global trends and identify gaps in understanding the effectiveness of CWs for wastewater treatment.

2. Materials and Methods

2.1 Bibliometric Analysis

Categorizing journals into research areas is a fundamental practice for bibliometric analyses (Wang and Waltman, 2016). The process of identifying the disciplinary scope of journals enables researchers to locate relevant literature, track research trends, and evaluate the impact of scholarly publications. Among the various multidisciplinary citation databases available, Scopus is widely regarded as one of the most important and comprehensive resources. Scopus offers a vast collection of bibliographic records from diverse fields of study, including the natural sciences, social sciences, humanities, engineering, and medicine (Harzing and Alakangas, 2016; Zhu and Liu, 2020). Its broad coverage and advanced search functionalities make it a valuable tool for conducting bibliometric research and analysis. In this study, the articles analyzed were taken from Scopus database, which offers superior coverage of scientific literature and provides access to critical, multi-disciplinary research works conducted and published from various countries (Pranckutė, 2021).

The terms ("constructed wetland*" AND "wastewater*" OR "waste water*" OR "artificial wetland*" OR "engineered wetland*" OR "treatment wetland*" OR "sewage" AND "urban") were used to retrieve relevant publications related to constructed wetlands treating wastewater from urban areas, published from 1970 to 2022. In order to ensure the accuracy and reliability of the analysis, standardization of terms was implemented to eliminate duplicate entries or erroneous items in thedatabase. The bibliographic data exported from Scopus provided extensive information such as author names, publication titles, sources, abstracts, author-assigned keywords, affiliations, cited references, and number of citations. The first recorded publication on Scopus regarding constructed wetlands was documented in 1989. As of 2022, a total of 653 scientific publications related to wastewater treatment wetlands were published and registered in the database. The analysis was limited to documents retrieved from the period of 2012 to 2022 in order to ensure that the reviewed articles are relevant and up-to-date. The initial search yielded 457 documents and among these, 317 were classified as articles, 41 as conference papers, 32 as review papers, 27 as book chapters, 13 documents were classified as conference papers, erratum, and short survey. The list was further refined based on exclusion criteria that included document type (articles) and language (English), resulting in 317 documents used for analysis.

2.2 Science Mapping

Science mapping tools were utilized to visually represent and analyze the relationships and connections of the retrieved bibliographic information, allowing for a more comprehensive understanding of how methods have been used and developed over time. Specifically, the contingency matrices were generated using the Cortext platform (cortext.net), whereas the network map was created using the VOSViewer software. VOSviewer is a software tool for constructing and visualizing bibliometric networks, which can be used to create visualizations of co-authorships, keyword co-occurrences, and co-citations among others, to analyze relationships and interrelationships among different variables. Cortext Manager, on the other hand, is an online platform that provides tools for textual analysis, text mining, and science mapping, allowing users to generate diagrams that effectively show the frequency, correlation, and evolution of terms used in different scientific publications (Reyes et al., 2023). The use of these tools enabled the identification of relationships and patterns within the data, leading to a more thorough understanding of the research landscape and facilitating the identification of knowledge gaps and potential areas for further research. The input parameters used in the software were summarized in Table 1.

Table 1. Data and input parameters used in the science mapping software

Software	Parameter	Inputs/ Methods of Analysis
VOSviewer (Network Map)	Bibliographic database file Type of analysis Unit of analysis Counting method Minimum number of co-occurrence	Scopus CSV file Co-occurrence Author keywords Full counting (terms have the same weight) 5
CorText (Contingency matrix)	Bibliographic database file Field values Contingency analysis measure Number of nodes	Scopus RIS file Author keywords – Country Author keywords – Year of publication Chi2 Score 10 (Default software value)

2.3 Comprehensive Review

A comprehensive review is a rigorous research method that involves a systematic and critical evaluation of the available literature related to a particular topic or research question. This method involves collecting, analyzing, and synthesizing data from various sources to provide a comprehensive and unbiased summary of existing knowledge in a particular field. In the present study, a comprehensive review was performed to identify and synthesize important information provided in the relevant scientific publications focused on the performance of constructed wetlands in wastewater treatment in urban areas. Initially, a total of 317 research articles were identified from the Scopus database. Subsequently, 100 most-recently published and open-access articles were selected for review. This allowed for the selection of the most relevant and up-to-date information available in the field. Studies that utilized computer models or simulations were excluded from the review in order to reflect the results of applied scenarios.

The studies considered in this review were conducted at different scales, including field scale, pilot scale, laboratory scale, and mesocosm studies. The inclusion of different types of studies in the analysis allowed for a comprehensive evaluation of the performance of constructed wetlands in wastewater treatment, taking into account various factors that can affect their efficiency. The collected data included important information related to the performance of constructed wetlands in wastewater treatment, such as the source of the wastewater, and the types and components of the constructed wetlands used for wastewater treatment (i.e., filter media and plant types). Moreover, the influent and effluent pollutant concentrations and the removal efficiency of CWs were also noted to assess their effectiveness in treating urban wastewater and determine the factors that potentially affected the pollutant removal performance of these nature-based systems.

3. Results and Discussion

3.1 Bibliometric Analysis and Science Mapping

3.1.1. Tracking Publication and Citation Trends

The number of articles published by various countries or organizations provided valuable insights into the contributions and impact of different research entities in a given field. These papers come from a total of 19 countries contributing to the field with varying number of articles and citations received. The main contributing countries were Spain, with a total of 44 published articles and, followed by China with 41 articles and 700 citations. Although the United States (US) and Italy contributed an equal number of articles (40), publications from the US received 36% lower number of citations as compared to the number of citations of papers from Italy. Remarkably, the top 10 countries, in terms of the number of published articles and citations, included both developed and developing nations, demonstrating a diverse range of contributors in this field. The contributions of the remaining countries, which have fewer than 10 publications each, collectively amounted to a total number of 59 articles, but have fewer citations (868) than the top 10 countries combined. This suggested that publications from the top contributing countries are also considered influential in this field of research.

The trend of annual publication related to urban wastewater treatment wetlands was illustrated in Figure 1. The number of published documents increased gradually from 13 in 2012 to 43 in 2022. Although there was a slight decrease in the number of published documents from 2017 to 2019, the upward trend in annual publication resumed from 2020 to 2022, indicating a growing interest in this area of research. Additionally, the increasing number of citations demonstrated the impact and relevance of the published documents. The initial number of citations in the year 2012 was relatively low with only 3 citations, whereas the maximum number of citations, amounting to 328, was observed in 2022. Generally, the cumulative number of citations and the annual publication of documents demonstrated a consistent upward trend, emphasizing the growing recognition and interest of the scientific community in the research related to urban wastewater management using constructed wetlands.

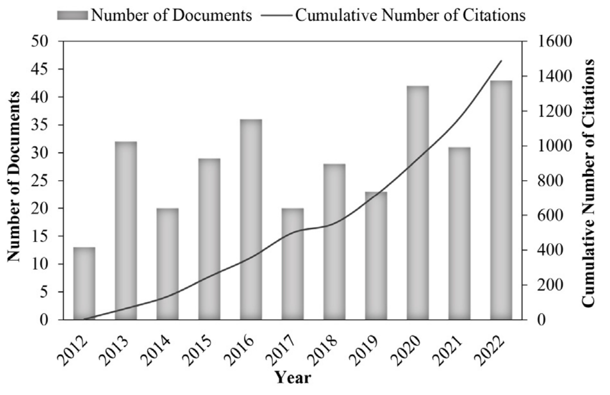
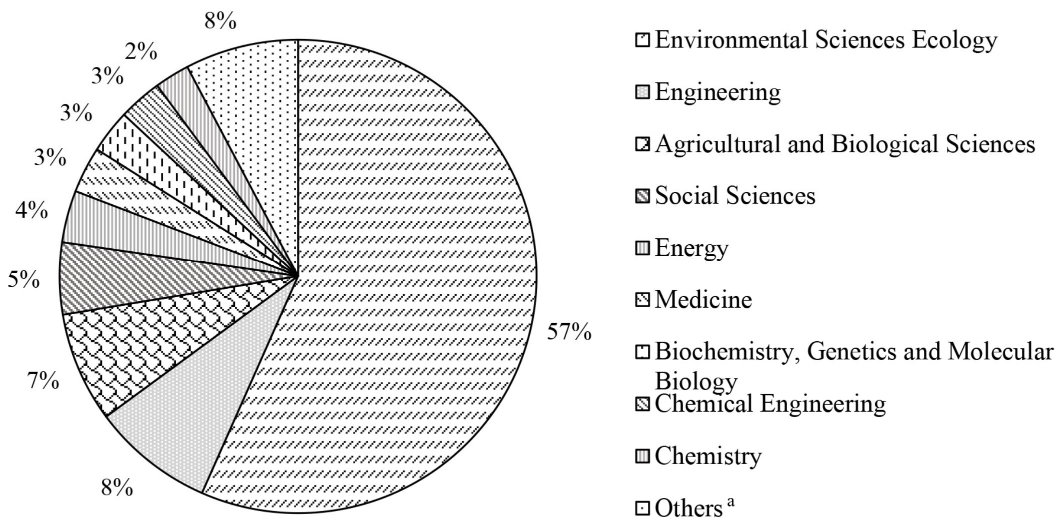


Fig. 1. Trend in annual publication of documents and cumulative citations.



[a] *Subject areas with less than 10 documents.*

Fig 2. Subject areas contributing to research on constructed wetlands for wastewater treatment

3.1.2 Network Analysis of Collaborative Research

Network analysis has emerged as an essential tool for understanding the collaborative research landscape in various fields. One way to explore collaborative research is to analyze the frequency and co-occurrence of keywords used by researchers. This can help identify trends and patterns of research interests and collaborations among researchers. A contingency matrix exhibited in Figure 3 highlighted the annual trends of keywords used by researchers and co-occurrence of keywords from the top publishing states. Red cells indicate a significant association between two fields, denoting a high degree of co-occurrence. On the other hand, blue cells indicate a weak association between two fields, implying a low degree of co-occurrence while white cells suggest neutrality, indicating no meaningful relationship between the two fields (Breucker et al., 2016). The analysis of keyword patterns revealed that "constructed wetlands" was the most prominent keyword used in scientific publications during the early years of research (2013). However, from 2017 to 2022, there was a noticeable shift in the dominant keywords towards wastewater treatment and nutrient removal in wastewater, which became the primary focus of scientific literature related to constructed wetlands. The most dominant keywords during this period were "wastewater," "wastewater treatment," "water quality," and "phosphorus," indicating a growing interest in improving water quality and removing nutrients in wastewater. Generally, the changes in the pattern of keyword usage provided insights into the current state of research in a specific subject area.

The contingency matrix, depicted in Figure 3b, illustrated the relationship and extent of co-occurrence among significant keywords utilized by researchers from the top publishing states. The chi2 score is a statistical measure that indicated the strength of the relationship between keywords. It is calculated based on the difference between the observed number of co-occurrences of the keywords and the expected number of co-occurrences (Reyes et al., 2023). A higher chi2 score indicates a stronger association between the keywords, while a lower score indicates a weaker association (Breucker et al., 2016). This statistical measure is useful for identifying meaningful relationships between keywords and revealing the research interests of different countries. The term "water quality" displayed a strong association with the United States, indicating a high degree of co-occurrence between these two entities. This suggested that researchers from the United States have a particular interest in exploring general water quality issues in their research endeavors. Researchers from China exhibited a focus on nutrient-related issues, as the terms "phosphorus" and "nitrogen" were predominantly used in publications from China. Furthermore, the keyword analysis revealed that "wetland" was the most used keyword in Australia, while "wastewater treatment" was the most prominently used keyword in Brazil, Spain, India, and the Netherlands. This implied that researchers from these countries have a particular interest in wetland-related research and wastewater treatment, respectively. These observations highlighted the importance of considering the variations in keyword usage among researchers from different countries and their potential implications on the research landscape.

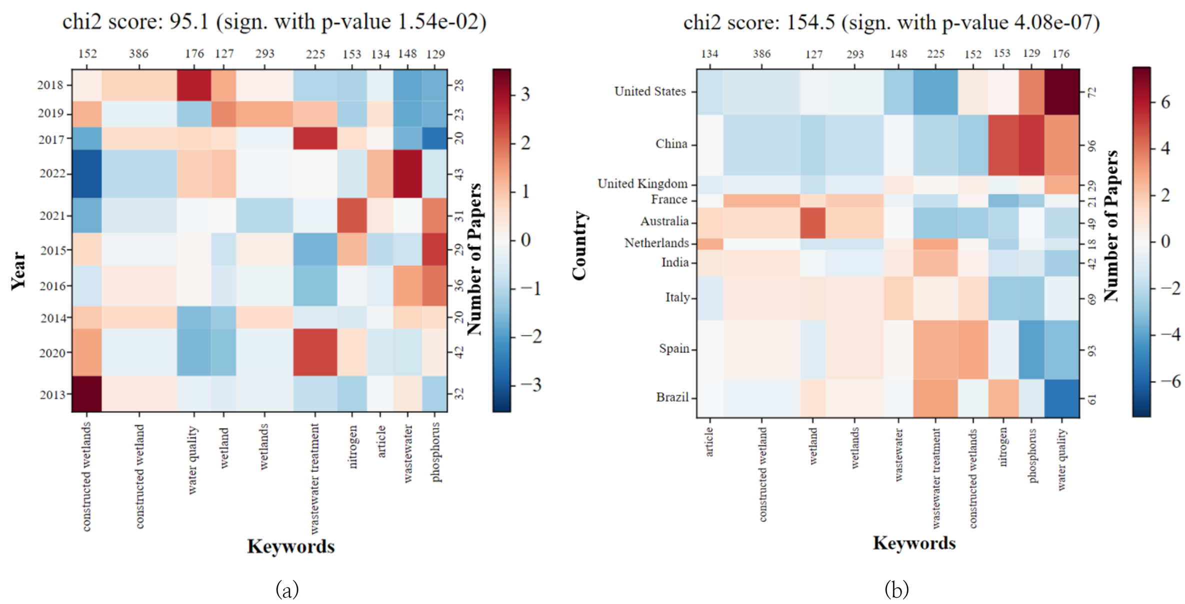


Fig. 3. Contingency matrix showing the relationship of (a) keywords and year of publication; and (b) keywords and country.

3.1.3 Analysis of Keyword Co-Occurrences

To gain further insights into the research areas and trends in wastewater treatment wetlands, a keyword analysis was conducted on the collected data (317 published articles) using VOSviewer software. The co-occurrence network map of keywords was illustrated in Figure 4 which utilized visual elements to convey important information about keyword relationships. The size of the circles represented the frequency or occurrence of a keyword, with larger circles denoting higher frequency. The font color of the keywords was used to represent the different clusters or thematic groups within the network aiding in the identification of related concepts. These visual cues enhance interpretation, providing a deeper understanding of the research landscape and interconnections between keywords.

A total of 1076 unique keywords were identified from the 317 retrieved documents. However, only 33 of these keywords had a frequency of at least five times. After excluding the terms used in the initial query, water quality (n=19), phytoremediation (n=13), stormwater (n=11), phosphorus (n=11), and urban runoff (n=10) were found to be the terms with the highest frequency. These findings indicated that majority of studies on CWs for wastewater treatment are focused on the improvement of water quality, particularly in nutrient removal (i.e., phosphorus and nitrogen). Moreover, the high frequency of phytoremediation reflected the growing interest in using plant-based technologies to remove pollutants in wastewater, as a cost-effective and sustainable alternative to traditional treatment methods, in terms of both operations and maintenance. Phytoremediation systems generally require less energy and resources to operate and maintain compared to conventional treatment methods (Schnabel et al., 2022), making them an attractive option for environmentally conscious wastewater treatment. The presence of the keywords "stormwater" and "urban runoff" in the co-occurrence network map of keywords suggested that studies on CWs for wastewater treatment are increasingly addressing the issue of stormwater management in addition to the improvement of water quality, due to urbanization leading to more impervious surfaces and higher volumes of stormwater runoff containing pollutants. This also emphasized the interconnectedness of different research areas and highlighted the importance of a multidisciplinary approach to wastewater treatment.

Seven clusters were identified, revealing the main research interests and themes in research about treatment wetlands. The red cluster, which is centered around CWs and included keywords such as treatment wetlands, wastewater treatment, urban wastewater, water reuse, and *Typha* latifolia (a type of plant commonly used in CWs), indicated a substantial research interest in using CWs for wastewater treatment in urban areas. The presence of these keywords implied that most of the researchers were studying the effectiveness of CWs in treating urban wastewater, as well as exploring the potential for water reuse. The blue cluster in the keyword co-occurrence analysis, with wastewater as the centered keyword indicated the investigation of various methods to address the challenges associated with wastewater treatment, including heavy metal and pollutant removal. The use of phytoremediation, which employs plants to remove contaminants from soil and water, was also emphasized. The presence of irrigation in the cluster indicated that researchers were considering the potential of using treated wastewater for agricultural purposes, which can contribute to resource reuse and freshwater conservation. The cluster related to water quality, which contained keywords such as stormwater, pollution, and sediment, implied that researchers were exploring ways to address issues such as stormwater runoff and pollution in order to improve water quality. This is particularly relevant in the cluster group involving water treatment and nutrient removal, indicating researchers' interest in removing nutrients from wastewater to prevent eutrophication. Eutrophication, caused by an excess of nutrients in water, leads to the excessive growth of algae and other aquatic plants, which can in turn cause further water quality issues. It can be observed in the nature-based solutions cluster that researchers were exploring the potential of green infrastructure (GI), including the use of CWs, as a nature-based solution for managing stormwater in urban areas. By incorporating GI into urban planning and development, cities can reduce the amount of stormwater runoff that enters the municipal sewer system and reduce the load on wastewater treatment plants. The cluster group of denitrification and wetlands emphasized the use of wetlands to remove nitrogen from wastewater through the process of denitrification. Lastly, the cluster group of macrophytes, constructed floating wetlands, and urban runoff explored the use of nature-based solutions for managing stormwater runoff in urban areas. This can help reduce the amount of pollutants that enter waterways, improve water quality, and protect aquatic ecosystems. Generally, the cluster analysis identified common research themes and highlighted potential areas for further investigation.

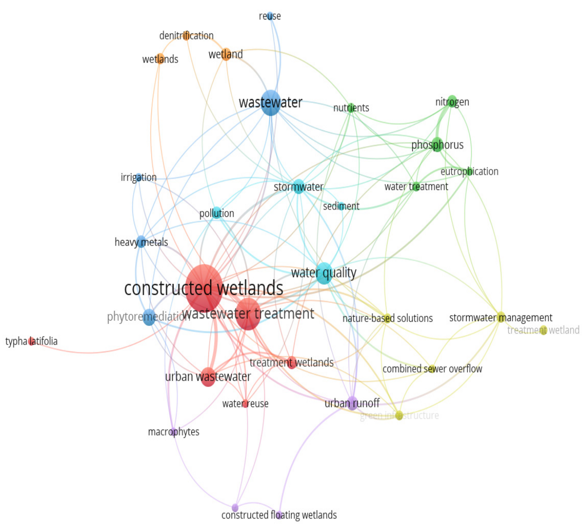


Fig. 4. Keyword-co-occurrence-visualization map used in scientific articles

3.2 Comprehensive Review

3.2.1. Influent pollutant concentrations and removal efficiency of various types of CWs

CWs were found to be frequently employed in both municipal and urban wastewater treatment plants. These CWs were fed with pre-treated urban wastewater from the sewage treatment system that had undergone primary and secondary treatments. These studies have focused on the behavior and capacity of different types of CWs in terms of removing pollutants present in wastewater. In particular, several researchers have investigated the removal efficiencies of CWs for specific pollutants, such as nutrients, organic matter, and pathogens. Horizontal subsurface flow (HSSF), vertical subsurface flow (VSSF), hybrid CWs, and free water surface (FWS) are the most used types of CWs for wastewater treatment. The present study conducted a comprehensive analysis of the influent and effluent concentrations as well as treatment efficiencies, of the five most commonly reported water quality parameters: biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP). The findings were presented in Figures 5 and 6, respectively.

The efficiency of CWs systems in removing BOD from wastewater varied depending on the type of wetland and the organic load of the influent. The influent concentrations of BOD ranged from 181.49 to 506 mg/L, whereas effluent concentrations ranged from 57.32 to 127.08 mg/L. The highest influent concentration was observed in a conventional wastewater treatment plant (WWTP) in Spain, which utilized a hybrid type of wetland to treat urban wastewater. The highest average removal efficiency for BOD, at 88.67%, was observed in a hybrid facility, whereas one study recorded a 98% removal efficiency for treating greywater using VSSF facility. Lakho et al. (2022) and Kotsia et al (2020) successfully achieved high removal efficiency rates using VSSF type of wetland for treating greywater due to lower loading rates and a good level of biodegradability of the organic substances. The effective removal of BOD in hybrid CWs was attributed to a combination of physical and biological processes. The VSSF component facilitated sedimentation, where gravitational forces allowed heavier particles and suspended solids to settle, and adsorption, where contaminants adhered to the media or vegetation surface, reducing their concentration in the wastewater. Both the VSSF and HSSF components promoted microbial activity, with microorganisms such as bacteria and fungi thriving in the wetland environment and actively participating in the degradation of organic matter. Additionally, the HSSF component enhanced plant uptake and microbial degradation of organic matter (Fernandez et al., 2020).

The average influent and effluent concentrations of COD in the reviewed studies were 1039 mg/L and 113.82 mg/L, respectively, indicating a considerable reduction in concentration after treatment. The performance of the different types of CWs, in terms of COD removal, demonstrated that the HSSF, hybrid, and FWS wetlands exhibited almost similar efficiencies, with removal rates of 59.12%, 62.81%, and 59.33%, respectively. Conversely, the VSSF type of wetland displayed the highest COD removal efficiency, with a rate of 71.82%. The high treatment performance can be attributed to the presence of a well-developed microbial community in the media bed, where the synergistic effect of substrates, plants, and microorganisms contributes to the treatment process (Sun et al., 2022).

Hybrid CWs were found to be the most common type of CWs utilized in the reviewed articles. These CWs were typically applied for treating wastewater from sewage plants, domestic sewage, and industrial parks in urban areas. It can be observed from Figure 6 that hybrid systems had the highest removal efficiency for TSS (95.67%) followed by VSSF (83.25%) and HSSF (78.83%). Hybrid systems, by integrating various treatment processes such as physical and biological mechanisms, offered improved performance than any single process alone. The combined features of VSSF and HSSF components provided multiple pathways for particle settling and entrapment, leading to high removal efficiencies. For instance, a hybrid system may incorporate coagulation, sedimentation, filtration, activated sludge or bioreactors, among others. Mohamed et al. (2022) incorporated such processes and found that coagulation-sedimentation process can eliminate all TSS upfront, thereby preventing clogging and removing TSS and other pollutants from wastewater. It is also important to note that although the HSSF system had a lower efficiency in removing TSS compared to the hybrid and VSSF systems, it still had a relatively high TSS removal efficiency of 78.83%. This indicated that HSSF CWs can still be effective in removing TSS, particularly in cases where space limitations or other factors make it difficult to use a hybrid system.

The average influent concentrations of TN and TP, ranging from 15.93 to 110.16 mg/L and 6.50 to 10 mg/L, respectively, whereas the effluent concentrations ranged from 12.42 to 23.41 mg/L and 6.10 to 8.50 mg/L, respectively. Among the different CW types analyzed, the VSSF CW investigated by Morandi et al (2022) received the highest TN influent concentration, amounting to 468 mg/L, from greywater and blackwater. It was noted that high TN concentrations and may be indicative of partial urine contamination in the water used for bathing. On the other hand, studies conducted by Dierberg et al. (2005) and Herrera-Melián et al. (2020) found that TP retention efficiency decreased at high hydraulic loading rates due to lower hydraulic retention time that favored preferential flow and affected the phosphorus diffusion and sorption processes. It is widely accepted that the main dissolved reactive phosphorus removal mechanism in CWs is the adsorption/precipitation on the substrate, as plant uptake and microbial activity are less important (Babatunde et al., 2009).

The TN and TP removal efficiencies of various CW types displayed distinct trends, as exhibited in Figure 6. The hybrid CW system exhibited the highest efficiency for both TN and TP, with values of 60.78% and 57.97%, respectively. The removal of nitrogen from wastewater is typically achieved through sequential processes of nitrification and denitrification, which can be challenging to accomplish in passive single-stage CW systems. This challenge arises due to their limited ability to provide simultaneous aerobic and anaerobic conditions (Ávila et al., 2017). Consequently, hybrid CW systems that combine different types of wetlands have emerged as a common strategy to improve TN removal. These systems exhibited high removal efficiency by integrating diverse treatment mechanisms and processes, including the provision of aerobic and anaerobic conditions, the utilization of various vegetation types, and the implementation of different media configurations (Vymazal, 2013). Particularly, the incorporation of both VSSF and HSSF wetlands in hybrid CWs provided the necessary environmental conditions for effective TN removal. VSSF components facilitated oxygen transport, promoting the conversion of ammonia nitrogen to nitrate through nitrification. On the other hand, HSSF wetlands enhanced denitrification when sufficient carbon is available, further contributing to TN removal. Moreover, a study by Vymazal (2013) indicated higher average nitrogen removal rates in hybrid systems compared to single-stage CW systems, particularly when FWS wetland was included in the hybrid configuration.

The HSSF system exhibited lower TN and TP removal efficiencies of 41.17% and 43.15%, respectively, whereas the VSSF system showed TN and TP removal efficiencies of 37.33% and 47.13%, respectively. The FWS system had a lower TN removal efficiency of 33% but had the high

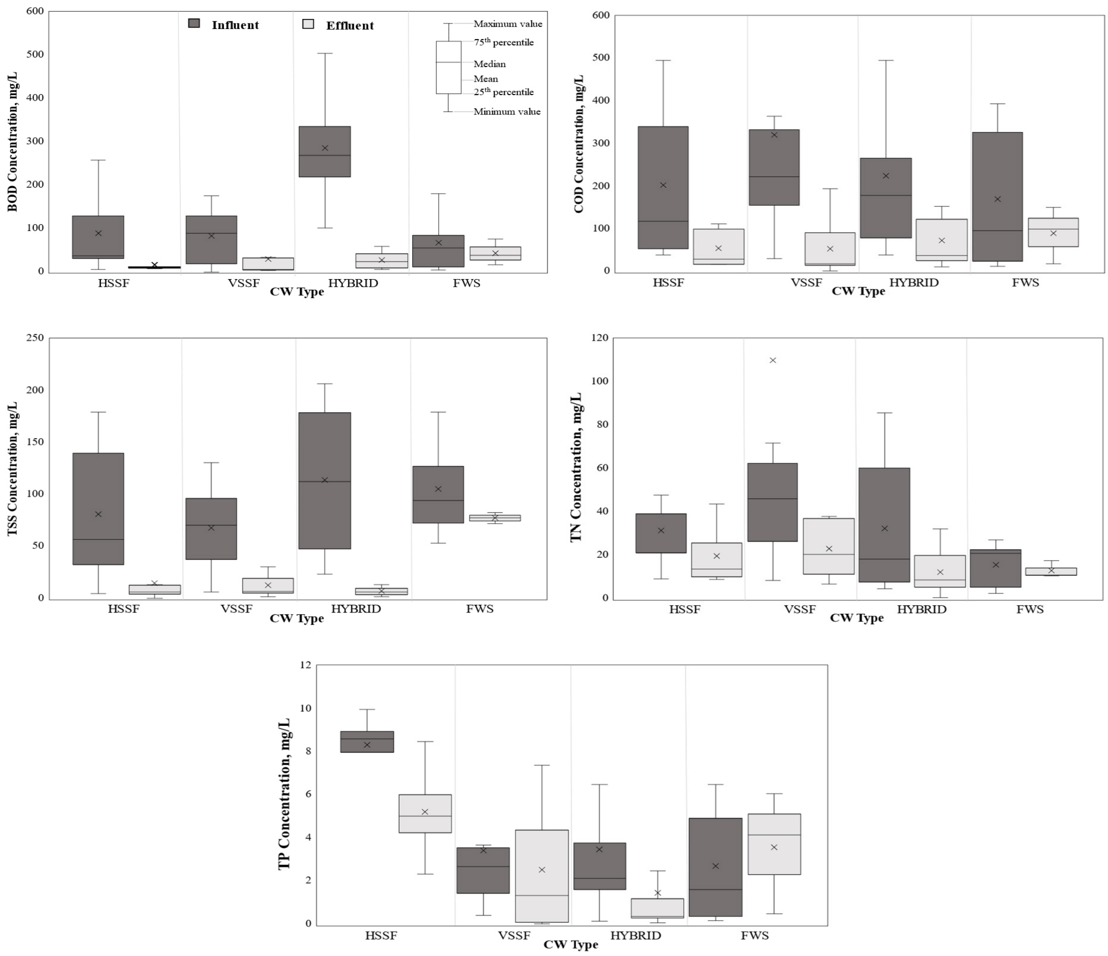


Fig. 5. Influent and effluent pollutant concentrations in different types of CWs

TP removal efficiency of 54.50%. The high TP removal efficiency can be attributed to the combined processes of settling sediment-bound phosphorus and plant uptake. Gravitational forces in FWS systems facilitate the settling of suspended particles and sediment-bound phosphorus, leading to a reduction in their water concentration. Additionally, the presence of aquatic plants enhances phosphorus removal through plant uptake as they assimilate phosphorus from the water column for their growth and development (Acero-Oliete et al., 2022). These findings were consistent with the observation of Hernández (2018) that phosphate removal efficiencies are higher in FWS systems compared to SSF systems.

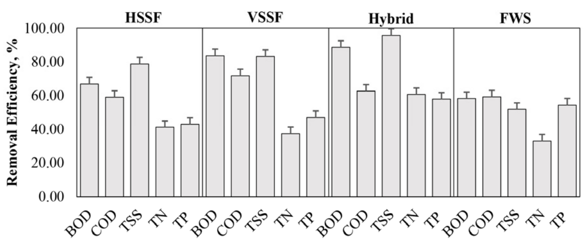


Fig. 6. Efficiency of different types of constructed wetlands in treating various pollutants

3.2.2. Influence of facility size on the effectiveness of pollutant removal

Figure 7 exhibited the range of facility sizes in square meters that were examined in a comprehensive review of the published articles, along with their corresponding treatment efficiencies for various pollutants. Among the pollutants, TSS and BOD exhibited high removal efficiencies ranging from 65.6% to 99% and 60.9% to 96%, respectively, across the entire range of facility sizes. This can be attributed to the physical and biological processes involved in the treatment, including sedimentation, filtration, and microbial degradation of organic matter (Vymazal and Kröpfelová, 2015). The data indicated that there is a no clear relationship between facility size and COD removal efficiency. While some smaller facilities (e.g., size 1m2 and 1.5m2) showed relatively high COD removal efficiency, larger facilities (e.g., size 60m2 and 100m2) did not necessarily exhibit higher COD removal efficiency. Meanwhile, TN and TP showed varied removal efficiencies across the different facility sizes. For TN, the removal efficiency ranged from 8% to 72%, while for TP, it ranged from

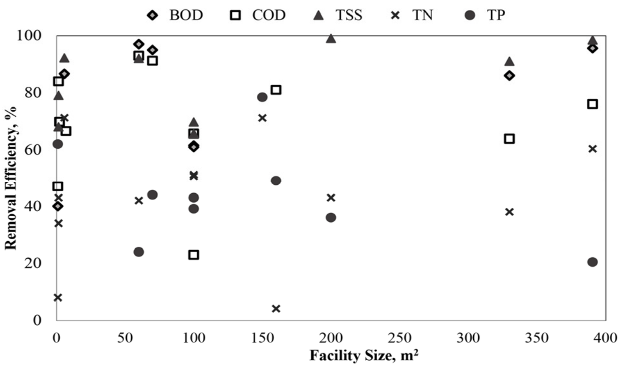


Fig. 7. CWs facility sizes and pollutant removal efficiency

24% to 79%. Notably, the highest removal efficiency for TN was observed in a 6 square meter facility, while the highest removal efficiency for TP was observed in a 150 square meter facility.

The coefficient of determination (R2) measured the proportion of the variation in the dependent variable (removal efficiency) that can be explained by the independent variable (facility size). In this case, the R2 indicated weak relationships between facility size and treatment efficiency for all pollutants, with the highest R2 observed for BOD (0.5203). TSS and COD also showed a relatively low R2 of 0.3783 and 0.1439, respectively, and the R2 values for TN and TP were even lower at 0.0655 and 0.0061, respectively. The results from reviewed articles indicated that CWs can effectively treat a range of pollutants regardless of facility size, but the relationship between facility size and treatment efficiency based on pollutant concentrations is weak. There are several factors that can influence the removal efficiency of CWs for wastewater treatment, and these factors are not related to the size of the facility. These factors include flow rate, pollutant loads, area, and hydraulic retention time (HRT). High flow rates can lead to a decrease in retention time and lower removal efficiency. Likewise, high pollutant concentrations can exceed the treatment capacity of the CW. A larger area and longer HRT can promote microbial activity and pollutant removal, but an excessively long HRT can lead to anaerobic conditions and a decrease in removal efficiency (Kadlec and Wallace, 2009).

3.2.3. Plants commonly used in CWs for wastewater treatment

Vegetation is a crucial element in wastewater treatment wetlands. Plants provide a substrate for microorganisms, which are essential in removing pollutants from the wastewater and promoting microbial activity by supplying oxygen (Brix, 2003). There are many different plant species that can be used in CWs, each with its own unique set of characteristics and benefits. As exhibited in Figure 7, the commonly used plants in constructed wetlands for wastewater treatments are *Phragmites* (27%), *Cyperus* (12%), *Iris* (9%) and *Typha* (7%).

Phragmites, or common reed, is a widely used plant species in constructed wetlands for wastewater treatment due to its ability to tolerate harsh environmental conditions and absorb organic pollutants through its roots (Hechmi et al., 2014; Saleem et al., 2019). The plant's oxygen transportation ability supports the survival of microbial communities and aids in the functioning of biofilm (Syranidou et al., 2016). While it is often planted in treatment wetlands to increase pollutant remediation, *Phragmites* is also considered invasive and phytotoxic due to the production of allelochemicals that can harm other plants (Udin and Robinson, 2017). *Cyperus* in wastewater treatment wetlands, has high treatment efficiency due to its root structures that provide more microbial fixation sites, sufficient residence time, particle entrapment, and surface area for contaminant adsorption. It also absorbs and assimilates pollutants in plant tissues and supplies oxygen for organic matter and inorganic substance oxidation in the rhizosphere, making it a potential plant for domestic wastewater treatment (Perbangkhem & Polprasert, 2010).

Iris species are effective in removing heavy metals, such as lead, zinc, and copper, due to their high metal uptake capacity. This ability is attributed to the presence of metal-binding compounds in their roots. *Typha* is a ubiquitous wetland plant that can colonize wetlands over great distances due to its wind-dispersed seeds and rapid growth rate. Its ability for clonal propagation can result in dense stands that can impact the ecology of the wetland. Despite its negative effects, *Typha* can also provide beneficial services such as bioremediation in constructed wetlands and serving as biofuel feedstocks to offset carbon dioxide emissions (Bansal et al., 2019).

In addition, other common plant species used in constructed wetlands for wastewater treatment include *Miscanthus* (5%), *Arundo* (5%), *Canna* (5%), and *Acorus* (5%). The remaining 25% of the plant species used in CWs are comprised of various other plants. *Miscanthus* is known for its high biomass production and ability to absorb nutrients (Chou, 2009), while *Arundo* can tolerate a range of water depths and is resistant to pests and diseases (Al-Snafi, 2015). *Canna* is highly effective at removing organic matter from wastewater (River et al., 2016), and *Acorus* can tolerate

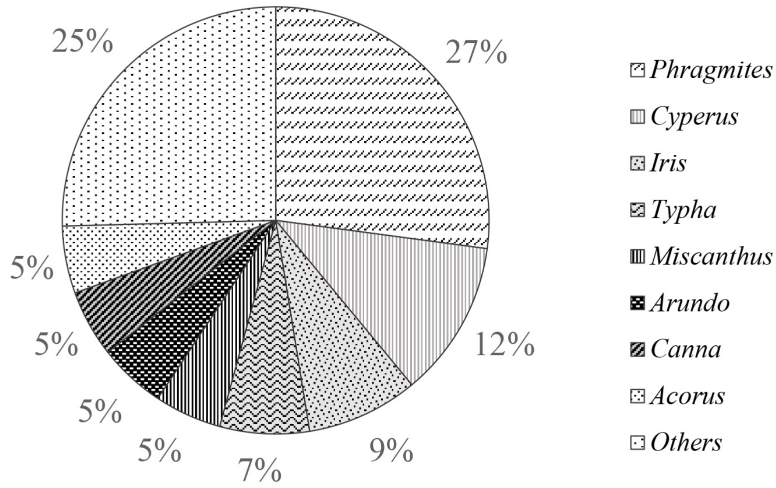


Fig. 8. Plants commonly used in CWs for wastewater treatment

low temperatures and has been shown to remove heavy metals from wastewater (Meena et., 2010). The selection of plant species for CWs depends on several factors, including the local climate, water quality, and intended use of the treated wastewater.

Among the commonly used plants, *Phragmites* and *Cyperus* are known for their high nutrient uptake capacity due to their extensive root system, which provides a large surface area for nutrient absorption and microbial fixation (García-Ávila, et al., 2019). Hence, allowing them to effectively remove pollutants from the wastewater. On the other hand, *Iris* and *Typha* have higher survivability rates due to their tolerance to waterlogging and low oxygen conditions, making them suitable for use in wetlands with varying water levels. Their ability to grow in oxygen-deprived and waterlogged soil allows them to thrive in wetland environments and continue to perform effectively in wastewater treatment systems despite unfavorable conditions (Brix, 1997). These findings can be supported by the study of Ibrahim et. al (2017) which showed that *Phragmites* exhibited the highest nitrogen uptake through roots, while *Typha* had a higher survival rate (56%) than *Phragmites* (44%) over growth seasons.

4. Conclusion

CWs have emerged as an effective and sustainable solution for treating urban wastewater. The bibliographic analysis revealed a growing interest in CWs as nature-based technologies for various types of wastewater treatment. Spain (44 articles), China (41 articles), Italy (40 articles), and the United States (40 articles) were among the most productive countries with a high number of publications and recognized for their influential contributions. Hybrid CWs, frequently employed for treating urban wastewater, showed high removal efficiency for pollutants such as BOD (88.67%), COD (62.81%), TSS (95.67%), TN (60.78%), and TP (57.97%). The performance of CWs in pollutant removal was attributed to physical and biological processes, including sedimentation, adsorption, microbial activity, and plant uptake. Hybrid systems integrating different wetland types demonstrated improved performance compared to single-stage systems. TN removal efficiency was particularly high in hybrid systems due to their ability to provide aerobic and anaerobic conditions. FWS wetlands were effective in TP removal through process involving the settlement of sediment-bound phosphorus and plant uptake. *Phragmites, Cyperus*, *Iris,* and *Typha* are typically employed in CWs due to their superior phytoremediation capabilities. Generally, CWs were found to have positive contributions for improving wastewater treatment processes, particularly in urban areas where there is a growing need for efficient and environmentally friendly solutions.

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