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THEMATIC ESSAY

Constructed Wetlands for Wastewater Treatment: A Review of Research Development

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Abstract: Constructed wetlands (CWs) mimic natural wetland processes and are designed primarily for wastewater treatment. Their cost-effectiveness and energy efficiency have made them popular globally. In the present study, the online Scopus database was used to identify 4407 documents related to CWs from 1991 to 2020 and bibliometric analysis was conducted. Among these, 209 publications were highly cited (>100 times), constituting 5.1% of all publications. VOSviewer software was used to conduct citation network analyses, which revealed a steady increase in annual publications on the topic over time. The United States, China, and the Czech Republic produced the highest number of highly cited publications. Notably, the journal *Ecological Engineering* received the most citations, followed by *Water Research* and *Water Science and Technology*. The literature analysis explored CW design, the role of macrophytes and microorganisms, organic pollutant and nutrient removal processes, and operation and maintenance. *Typha latifolia* and *Phragmites australis* are commonly used plant species in CWs. Despite their efficacy and cost-efficiency, challenges such as difficulties in procuring land, conducting regular maintenance, and raising public awareness persist. Further research and innovation are crucial for maximizing CW applications in wastewater treatment in the modern era.

Keywords: Constructed Wetlands; Wetlands; Wastewater; Wastewater Treatment; VOSviewer

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1. INTRODUCTION

Natural wetlands are a unique ecosystem characterized by the presence of water, either permanent or seasonal, which supports vegetation adapted to saturated soil conditions. These shallow, slow-moving bodies of water are typically populated with cattails, bulrushes, reeds, or other water-tolerant plants. Wetland ecosystems are characterized by the presence of water on the surface and in the root zone, with soil conditions distinct from those of adjacent uplands. To maintain saturation, wetlands are inundated with surface water or, occasionally, groundwater, for extended periods of time (Polprasert 2004). Wetland systems are classified based on their water sources, including groundwater, river water, and rainfall (Roy *et al.* 2021). Local people utilize these wetlands in various ways, such as for improving fish supply, enhancing agriculture, bathing cattle, washing clothes and utensils, and other purposes (Roy *et al.* 2021).

Wetlands not only help prevent environmental pollution but also serve as water sources. They are often artificially created as man-made systems, typically consisting of long, narrow channels (Polprasert 2004). Constructed wetlands (CWs) are designed to mimic the natural processes of wetlands—such as their vegetation, soil characteristics, and associated microorganisms—to aid in wastewater treatment.

Kathe Seidel conducted pioneering experiments in the 1950s at the Max Planck Institute in Germany to assess the feasibility of using wetland plants for wastewater treatment (Vymazal 2010). The study involved a series of experiments aimed at treating several categories of wastewater, such as livestock and dairy wastewater. Most of the experiments were conducted in horizontal flow (HF) or vertical flow (VF) subsurface CWs. The first surface water CW system (free water) in the Netherlands was built in 1967 (Vymazal 2010). Surface water CW systems (free water) are rare in Europe, but subsurface flow (SSF) became dominant between 1980 and 1990 (Vymazal 2010).

Wastewater is treated in CWs through physical processes (sedimentation and filtration), chemical processes (precipitation and adsorption), and a combination of both biological and chemical activities (microbial degradation and water uptake from the substrate) (Bakhshoodeh *et al.* 2020). CWs are also referred to as man-made, engineered, or artificial wetlands (Vymazal 2014). Many of these systems were specifically designed and operated for wastewater treatment, while others serve multiple purposes. For example, treated effluents can be used for wetland habitat development, restoration, agriculture, and environmental enhancement (Vymazal 2014).

Domestic, municipal, industrial, and agricultural run-off wastewater can all benefit from CW treatment (Saha *et al.* 2024). Likewise, several studies demonstrate that CWs can effectively treat urban storm water, polluted rivers, and reservoirs. CWs can also enhance local populations' economic well-being by increasing agricultural output and fish production, similar to the broader benefits provided by natural wetlands (Roy *et al.* 2021).

The study undertakes a critical analysis of the published research, including review articles from national and international sources. Primary research was done using Google Scholar and the Scopus online database, which also facilitated data collection and citation tracking for bibliometric analysis.

2. DATA SOURCE AND METHODOLOGY

The data for this study was collected from the Scopus online database, ensuring relevance and reliability. The included studies spanned from 1991 to 2000. The analysis employed bibliometric analysis, with assumptions clearly defined to ensure the validity of results.

2.1. Bibliometric Analysis

The data for bibliometric analysis was obtained from Scopus, one of Elsevier's most extensive online databases. While the Web of Science (WOS) database is better suited for citation analysis and evaluation, Scopus was chosen for this study due to its more comprehensive representation of research in this field. The keyword "constructed wetlands" was used to identify publications on CWs in the Scopus database from 1991 to 2020, as of December 15, 2021. The document types covered included articles, review papers, book series, books, chapters, and conference proceedings, resulting in 4,074 documents. Information on author names, affiliations, journal titles, keywords, citations, the countries where studies were conducted, and publication years was retrieved. Only English-language documents were included in this study. By applying a threshold of 100 or more citations, 209 publications were selected, accounting for 5.1% of all publications.

VOSviewer is a powerful tool for constructing and visualizing bibliometric networks. Developed by NJ van Eck and L Waltman of the Centre for Science & Technology Studies (CWTS) at Leiden University, Netherlands, it offers an intuitive interface for exploring complex bibliometric networks. Nodes represent entities (e.g., authors, keywords), while links show relationships or collaborations. This allows researchers to map relationships between publications, authors, journals, institutions, and keywords, providing meaningful insights into research trends, collaboration patterns, and thematic clusters.

We used the VOSviewer V.1.6.18 to perform network analyses to identify co-authorship, keyword co-occurrence, and citation analysis of authors, sources, and the countries studied. The network analysis maps were created using the association strength method. By offering a clear and interactive way to analyse and interpret bibliometric data, VOSviewer has become an essential tool for researchers seeking insights into the structure and dynamics of the academic literature.

2.2. Geospatial and Statistical Analysis

QGIS V.3.26 was utilized to represent the spatial distribution of different studies on CWs and the plant species used across various regions. Raw data was collected from the Scopus database, and GIS maps were created. Statistical analyses were performed using Microsoft Excel 2016.

3. RESULTS

The results of the study revealed significant findings aligned with the objectives. Key trends and patterns emerged from the analysis, highlighting the increasing interest in CW research that likely stems from the growing need for cost-effective wastewater treatment options in both urban and rural settings. Furthermore, the results demonstrated the diverse nature of works on CWs, offering valuable insights into wastewater treatment using CWs. These findings are discussed in detail to draw meaningful interpretations and implications for the development of CWs.

3.1. Country-wise Publications

The bibliometric analysis highlights the global distribution of research contributions on CWs, revealing notable regional disparities. Asia and Europe dominate the field, indicating robust CW research in these regions. This trend reflects the significant environmental challenges these densely populated regions experience, such as water pollution and resource management, which necessitate innovative solutions like CWs. North and South America follow, while Africa and Australia contribute fewer publications.

China (1,054 publications) and the United States (807 publications) lead in CW research, highlighting their substantial investment in the field. China's prominence likely stems from its extensive infrastructure projects and urgent environmental challenges, particularly surrounding wastewater treatment and ecological restoration. The United States' significant contribution reflects its long-standing expertise in wetland management and technological innovation. European nations, including the United Kingdom, Germany, and Spain (each with over 200 publications), as well as France, Italy, and the Czech Republic (each exceeding 100 publications), have a strong tradition of research in environmental science and sustainability.

The representation of Australia, Canada, and India (each with over 100 publications) highlights their efforts to address region-specific environmental challenges. For instance, Australia's contributions are likely linked to its dry climate and the need for sustainable water management. At the same time, India's growing interest in CW research may reflect the increasing demand for cost-effective wastewater treatment options in both urban and rural settings.

In contrast, Africa and South America contribute fewer publications, possibly due to limited research funding and infrastructure. However, this smaller number does not necessarily imply lesser importance; instead, it highlights an opportunity for growth in CW research in these regions, where CWs can potentially address critical environmental and public health issues. The country-wise number of publications on CWs for the given period is shown in Figure 1.

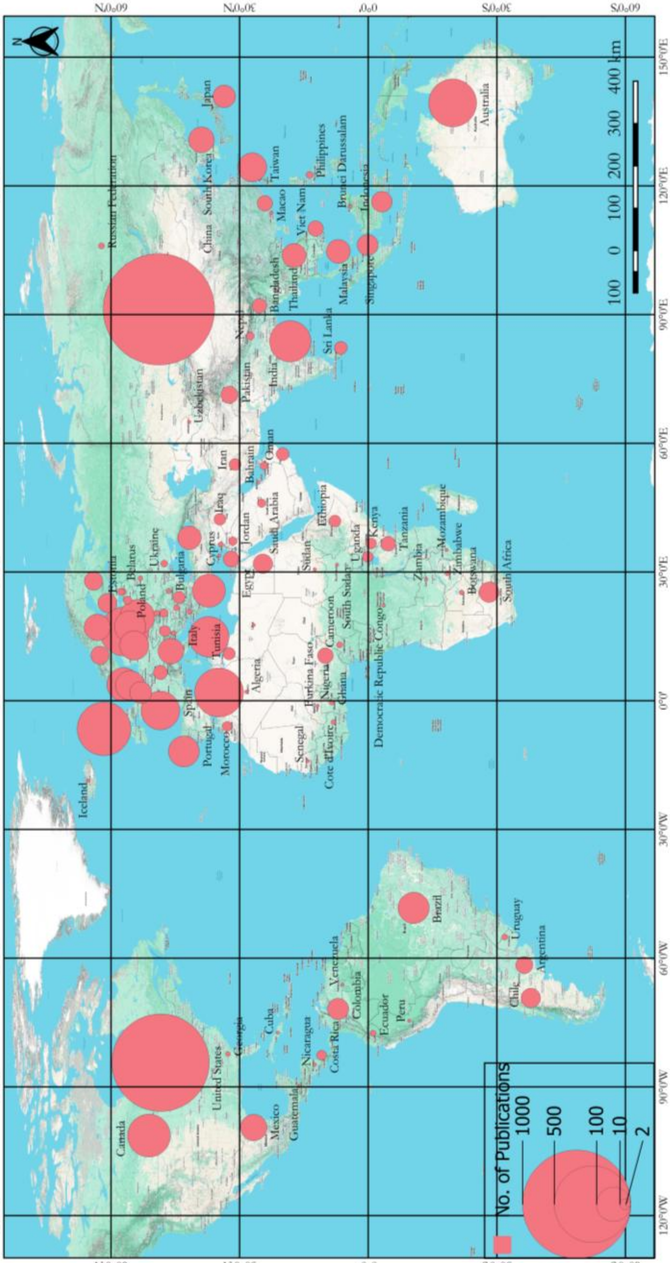
3.2. Annual Trends in Publications

The year-wise analysis of publications on CWs shows a clear upward trend in terms of research output, especially after 2009. This consistent increase reflects the growing global recognition of CWs as an effective and sustainable solution to environmental challenges, including wastewater treatment, habitat restoration, and climate adaptation.

The year-wise data shows that since 2009, the number of publications on CWs has consistently exceeded 100. The most publications occurred in 2020 (369 documents), while the lowest was in 1992 (2 documents). Since 2015, there has been a steady increase in publications. The peak in 2020 may also partially reflect a shift in research focus towards understanding the role of ecosystems in disease regulation and public health, highlighting the need for resilient natural systems during global crises.

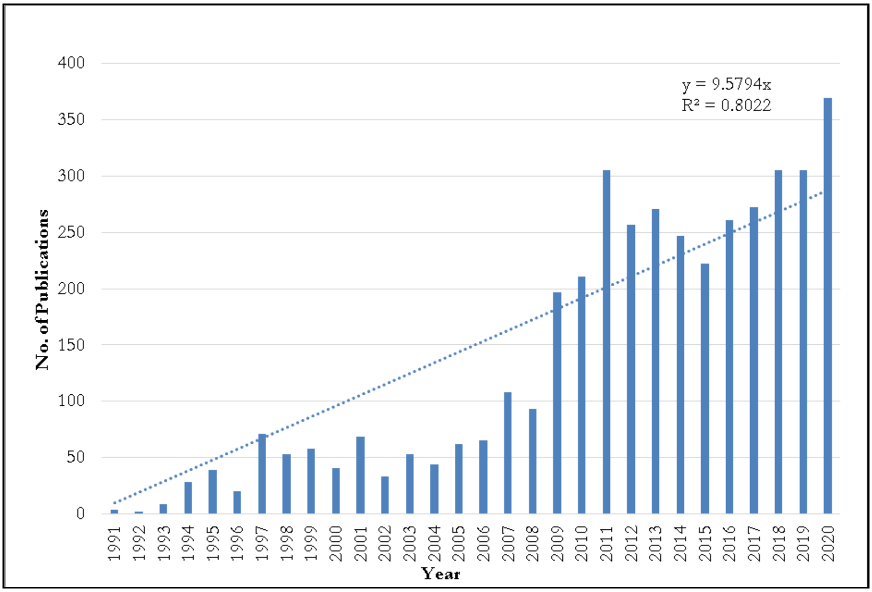
There was a decline in published research in 2000, 2002, 2004, 2008, 2012, and 2015. However, since then, the number of publications has nearly doubled from 197 in 2009 to 369 in 2020. A trend analysis (Figure 2) illustrates this increase in CW studies. This upward trend highlights the need for interdisciplinary approaches and international collaborations to

Figure 1: Country-wise Publications on Constructed Wetlands from 1991 to 2020



Data Source*:* Scopus. Created by the authors.

Figure 2: Year-wise Trend of Publications on Constructed Wetlands from 1991 to 2020



Data Source*:* Scopus. Created by the authors.

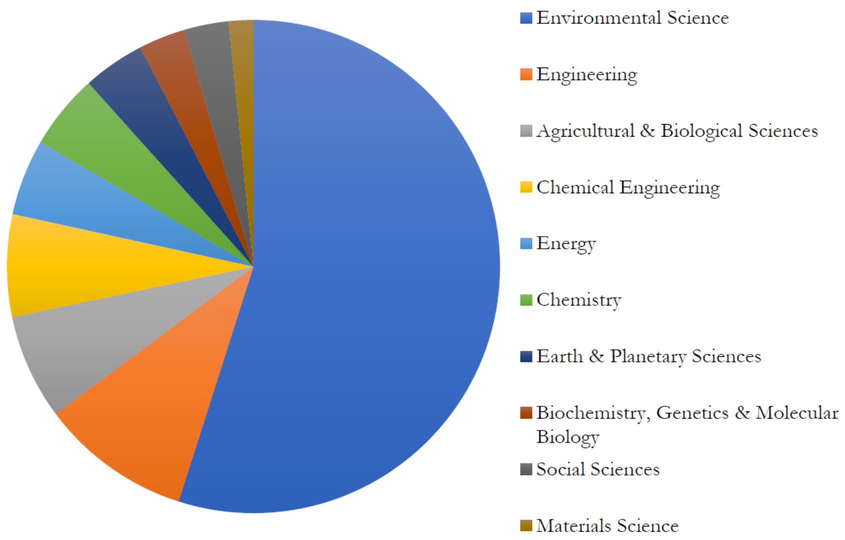
refine CW designs further, optimize performance, and expand their applicability in addressing twenty-first-century environmental challenges.

3.3. Subject Areas

Figure 3 highlights the interdisciplinary nature of the research retrieved from the Scopus database, with environmental science representing 51.45% of the total publications. This underscores its key role in addressing contemporary challenges like sustainability, climate change, and resource management. The substantial representation of engineering (9.26%) reflects its critical role in developing practical solutions and technologies for environmental applications such as wastewater treatment, renewable energy systems, and infrastructure design.

The contributions from agricultural and biological sciences (6.47%) and chemical engineering (6.29%) highlight the integration of natural and chemical processes in environmental research. These fields likely address topics such as soil and crop management, biotechnological solutions, and sustainable chemical processes. Similarly, the inclusion of energy (4.69%) reflects a growing focus on energy efficiency, renewable sources, and the environmental impact of energy systems.

Figure 3: Top 10 Study Areas Related to Publications on Constructed Wetlands from 1991 to 2020



Data Source*:* Scopus. Created by the authors.

The less dominant fields, such as chemistry, earth and planetary sciences, biochemistry, genetics, and molecular biology, provide niche contributions to environmental research. For instance, research in materials science may focus on developing sustainable materials or improving water filtration technologies.

The distribution across subject areas highlights the multidisciplinary nature of the research, emphasizing the importance of collaboration across diverse fields to address complex environmental issues. These trends provide a roadmap for future research funding and collaboration opportunities, particularly in fostering interdisciplinary studies that link environmental science with engineering, biology, and chemistry.

3.4. Journal- and Publisher-wise Analysis

Applying a citation threshold of over 100, 209 publications were retrieved, representing 5.1% of all publications. Table 1 shows that the most highly cited papers were published in journals by major academic publishers, with Elsevier leading with 22 publications. This dominance reflects Elsevier's extensive portfolio of environmental and engineering journals.

The presence of Springer (6), Wiley (3), and smaller contributions from Taylor & Francis (2) and others highlights the diversity of platforms hosting

Table 1: Major Sources Contributing to Publications Related to Constructed Wetlands

Sl. No.	Name of the Journal	Publisher	Cited by
1.	*Ecological Engineering*	Elsevier	9,579
2.	*Water Research*	Elsevier	5,222
3.	*Water Science & Technology*	International Water Association	4,844
4.	*Science of the Total Environment*	Elsevier	3,625
5.	*Bioresource Technology*	Elsevier	3,388
6.	*Environmental Pollution*	Elsevier	1,347
7.	*Chemosphere*	Elsevier	1,260
8.	*Environmental Science & Technology*	American Chemical Society	1,214
9.	*Critical Review in Environmental Science & Technology*	Taylor & Francis	795
10.	*Journal of Environmental Management*	Elsevier	782
11.	*Chemical Engineering Journal*	Elsevier	708
12.	*Environment International*	Elsevier	518
13.	*Water (Switzerland)*	Multidisciplinary Digital Publishing Institute	461
14.	*Aquaculture*	Elsevier	413
15.	*Hydrobiologia*	Springer	375
16.	*Desalination*	Elsevier	372
17.	*Engineering in Life Sciences*	Wiley	324
18.	*Journal of Cleaner Production*	Elsevier	234
19.	*Agricultural Water Management*	Elsevier	228
20.	*Water, Air, and Soil Pollution*	Springer	210
21.	*Agriculture, Ecosystems and Environment*	Elsevier	161
22.	*Biotechnology Advances*	Elsevier	151
23.	*Journal of Soils and Sediments*	Springer	150
24.	*Soil Biology and Biochemistry*	Elsevier	147
25.	*Biosensors and Bioelectronics*	Elsevier	146
26.	*Vertical Flow Constructed Wetlands: Eco-Engineering Systems for Wastewater & Sludge Treatment*	Elsevier	135
27.	*Journal of Environmental Sciences*	Elsevier	127
28.	*Process Biochemistry*	Elsevier	123
29.	*Journal of Environmental Quality*	Wiley	121
30.	*Journal of Industrial Microbiology and Biotechnology*	Springer	120
31.	*Journal of Hazardous Materials*	Elsevier	119
32.	*Vadose Zone Journal*	Wiley	114

33.	*Environmental Science and Pollution Research*	Springer	113
34.	*Metallomics*	Oxford University Press	107
35.	*Wetlands*	Springer	104
36.	*Renewable and Sustainable Energy Reviews*	Elsevier	103
37.	*Journal of Environmental Science & Health*	Taylor & Francis	101

Data Source*:* Scopus. Created by the authors.

impactful research. However, the limited representation of journals from institutions such as the International Water Association (1), American Chemical Society (1), Multidisciplinary Digital Publishing Institute (1), and Oxford University Press (1) suggests the underrepresentation of specialized publishers in this domain.

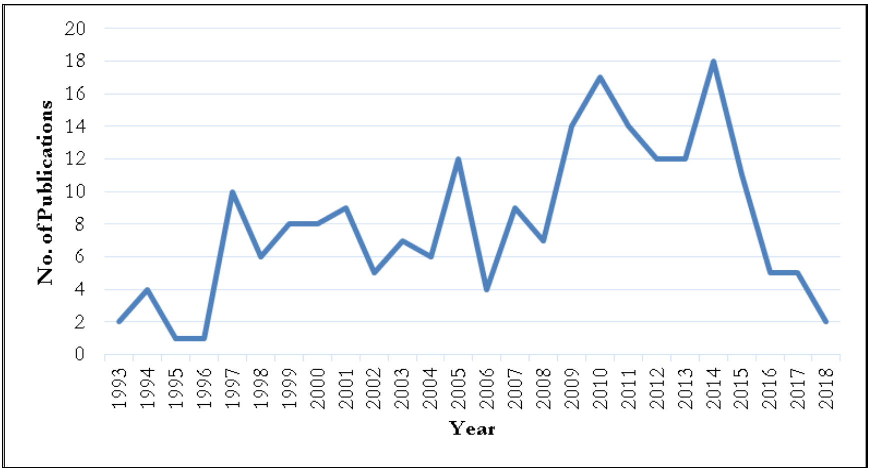
These results also indicate a concentration of influence among a few major publishers, which may reflect trends in publication preferences or journal quality standards in the field. However, the smaller contributions by other publishers highlight niche areas where impactful research is being conducted. A deeper exploration of the thematic focus of these highly cited publications provided valuable insights into the specific subtopics within CW research driving high citation rates, such as wastewater treatment, habitat restoration, and emerging technologies. Examining the publication years of these articles revealed trends in the evolution of CW research, highlighting periods of significant breakthroughs or shifts in focus.

The findings emphasize the pivotal role of major publishers in disseminating high-impact research on CWs while also highlighting the need to recognize and promote contributions from a wider range of publishers. A further meta-analysis, as outlined above, could provide a more nuanced understanding of the factors driving research impact, enabling researchers to identify key trends, gaps, and opportunities for future work in the field.

3.5. Analysis of Highly Cited Publications

The increase in publications reflects the growing interest in CW research, driven primarily by advances in modern methodologies and a broad understanding of CW applications (Figure 4). However, fluctuations in annual citation numbers indicate the variability in these studies' visibility and perceived impacts. This discrepancy calls for further investigation into factors influencing citation trends, such as the relevance of research topics to current environmental challenges, the geographic distribution of impactful research, and networks of scientific collaboration.

Figure 4: Total Number of Most Cited Publications from 1991 to 2020



Data Source*:* Scopus. Created by the authors

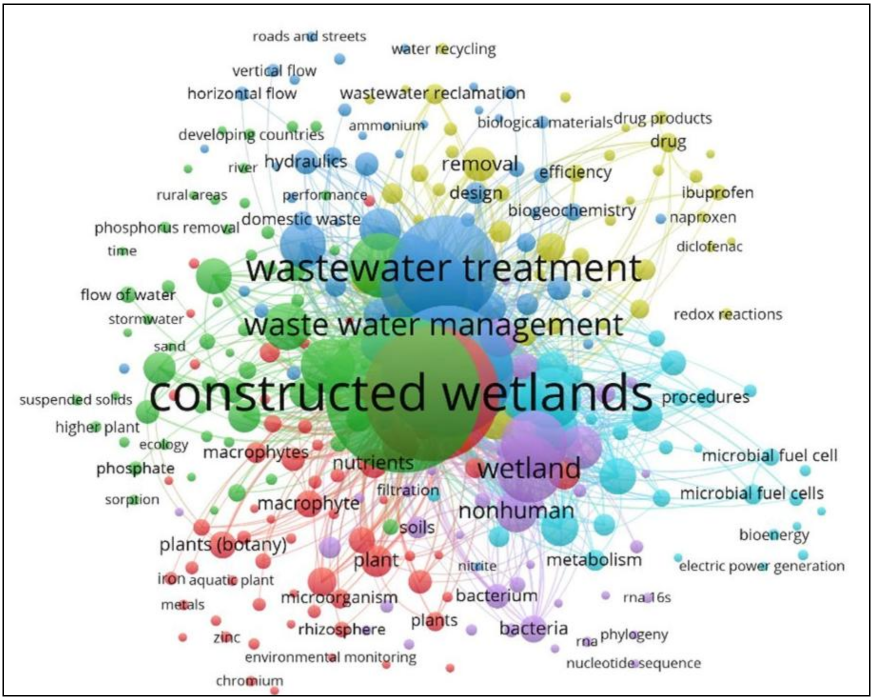
This analysis identifies themes or keywords correlated with high citation counts, examines interdisciplinary linkages, and maps the progression of research focus areas over time. Furthermore, a comparative analysis of high-impact and low-impact years reveals strategies for enhancing the visibility and influence of CW research.

3.6. Co-occurrence of All Keywords

An analysis of the co-occurrence of keywords in highly cited publications on CWs was conducted. The authors selected a threshold value of five for the minimum number of occurrences of a keyword for network analysis using the full counting method. This method counts a full publication for each of the co-authors, whereas in the case of the fractional counting method, a publication is counted in fractions with respect to the number of co-authors for that publication. Figure 5 shows the co-occurrence of all the keywords related to CW research generated using VOSviewer software. Six clusters, each in a different colour, are observed. The colours of the bubbles represent the cluster to which the items belong. The bubble and keyword size represents the weight assigned to each keyword, while the frequency of keyword occurrence is shown by lines connecting related keywords.

Among the keywords used more than five times, "constructed wetlands" stands out with 209 occurrences, highlighting its importance as a central research theme. It is followed by "constructed wetland", "wetlands", "wastewater treatment", "wastewater", and "waste water management", with frequencies of 173, 167, 127, 97, and 83, respectively. The

Figure 5: The Network Visualization Map of Keyword Co-occurrence for Publications Related to Constructed Wetlands

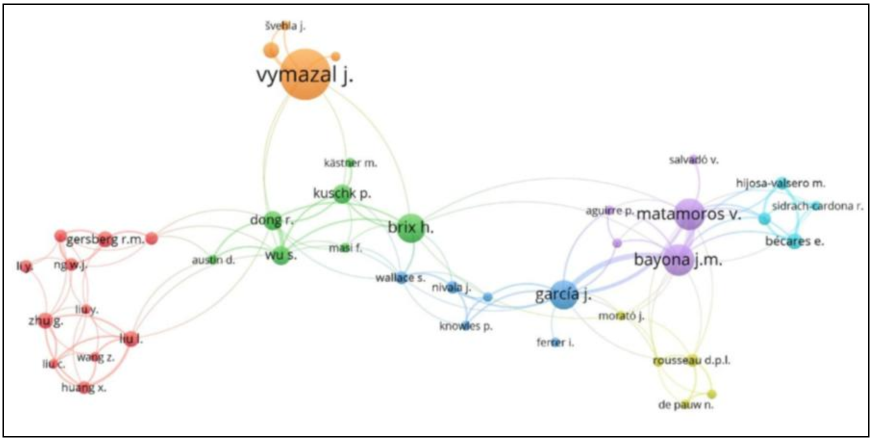


Data Source*:* Scopus. Created by the authors

co-occurrence lines connecting keywords, especially their thickness, reveal strong associations between certain themes. For instance, the frequent link between "constructed wetlands" and "wastewater treatment" emphasizes the ongoing focus on CWs' role in environmental remediation.

The word "constructed wetlands" (4241) has a stronger link with the other clusters than "wetlands" (3721), as evidenced by the green-coloured clusters, which show a higher frequency of co-occurrence with the other five clusters. Further analysis of the linkages between keywords could reveal specific applications such as industrial wastewater treatment and agricultural run-off management. The co-occurrence patterns suggest opportunities for integrating concepts from related fields such as ecology, chemical engineering, and socio-economic studies. By expanding on the observed clusters and their interrelations, this analysis offers a comprehensive overview of the intellectual landscape of CW research.

Figure 6: The Network Visualization Map of Co-authorship Citations for Publications Related to Constructed Wetlands



Data Source*:* Scopus. Created by the authors

3.7. Co-authorship Analysis

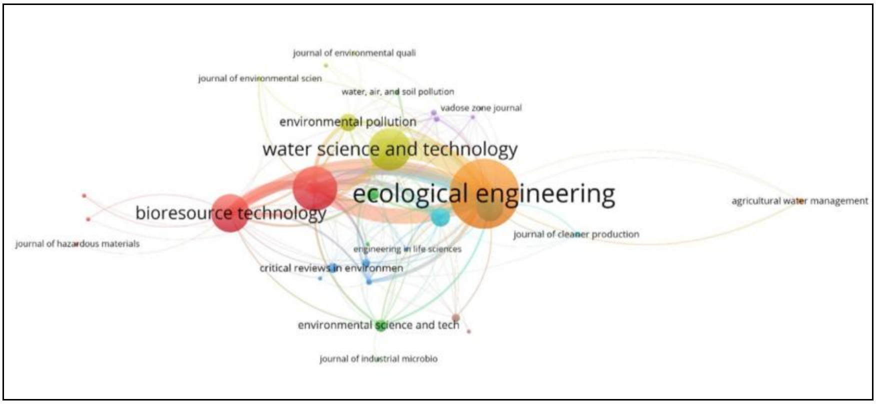
To interpret the interconnection between the authors of highly cited publications on CWs, a co-authorship analysis map for authors has been created. A threshold of two, as the minimum number of documents for an author, using the full counting method, was applied for the network analysis. Of the 578 authors identified from the highly cited publications, 112 have at least two jointly published documents (Figure 6). The clusters reveal that 112 of the 578 authors are well-connected. The purple cluster centred around "Bayona J M" has the highest link strength of 29, indicating strong collaborative networks. This is followed by another purple cluster, which is centred around "Matamoros V", with the second-highest link strength of 27, alongside authors from the green, blue, and yellow clusters.

In terms of documents and citations per author, "Vymazal J" (represented by the orange cluster) has the highest number of documents (10) and citations (6427), highlighting a potentially wide-reaching influence that intersects with other clusters or fields. "Brix H" (represented by the green cluster) has the second-highest citation count (2583), indicating pivotal contributions to CW research.

3.8. Citation Analysis of Source

Figure 7 shows a network analysis of the most frequently cited CW sources, with bubble size representing the total number of citations. Different colours highlight clusters of sources retrieved primarily on the basis of the

Figure 7: The Network Visualization Map of Source Citations for Publications Related to Constructed Wetlands



Data Source*:* Scopus. Created by the authors

frequency of their occurrence. This analysis provides valuable insights into the influence and interconnections of various journals in the CW field.

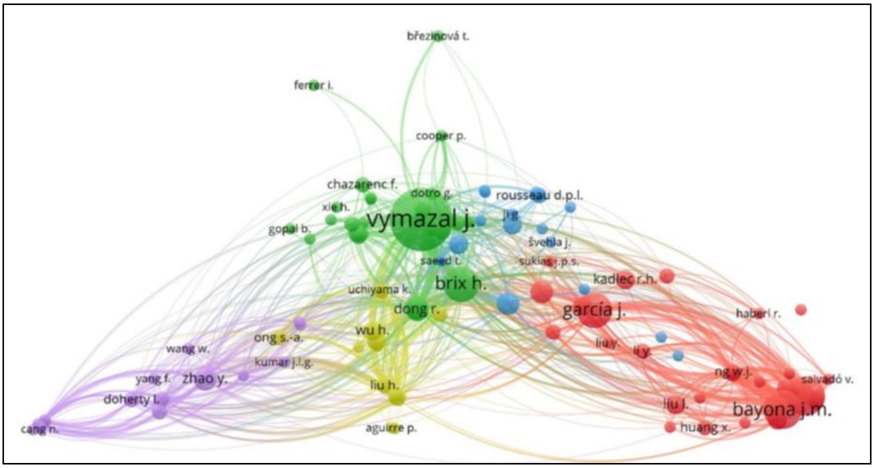
The dominance of *Ecological Engineering*, with a link strength of 268 across 51 documents, highlights its key role in advancing CW research, likely due to its focus on ecological restoration and engineering solutions. Similarly, *Water Research*, with a link strength of 213 from 28 documents, reflects its importance in water quality and management, making it a natural fit for CW-related studies. The strong position of *Water Science and Technology*, with a link strength of 160 from 26 documents, can be attributed to its interdisciplinary approach to water technology challenges.

The geographic distribution of the authors contributing to these journals highlights regional research priorities. Understanding the relationship between clusters and journals from fields like environmental science, engineering, and biology could reveal the extent of interdisciplinary collaboration in CW research.

3.9. Citation Analysis of Authors

A citation analysis map of the authors of the included publications was prepared to analyse the academic structure of highly cited publications on CWs. A threshold of two was set as the minimum number of documents for an author, using the full counting method, for the network analysis. Of the 578 authors identified from highly cited publications, 112 have published at least two documents jointly (Figure 8). This highlights key contributors and reveals patterns of collaboration and influence. Identifying

Figure 8: The Network Visualization Map of Author Citations for Publications Related to Constructed Wetlands



Data Source*:* Scopus. Created by the authors

whether these collaborations are interdisciplinary or regionally concentrated could provide valuable context for advancing the field.

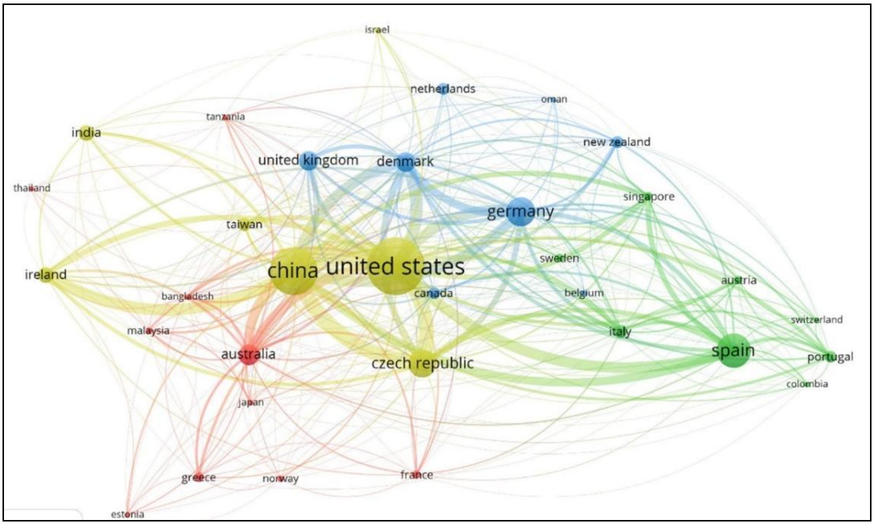
The results indicate that the most significant green cluster is led by the author "Vymazal J", who has the highest number of citations and demonstrates the strongest link strength (340), highlighting extensive collaboration and influence in the field. This is followed by "Brix H", another prominent figure in the green cluster, with a link strength of 253. These two authors emerge as leading contributors, with a total of 6,427 and 2,583 citations, respectively. Additionally, authors such as "Bayona J M" (1,776 citations) and "Matamoros V" (1,747 citations) also made significant contributions, albeit with slightly lower link strengths.

Evaluating the thematic contributions of leading authors could reveal underexplored areas in CW research, such as the role of nitrogen, phosphorus, and SSF CWs, and aspects like microbial processes or climate resilience, which deserve greater attention.

3.10. Citation Analysis of Countries

A citation analysis map for countries has been prepared for highly cited publications on CWs to provide significant insights into global collaboration patterns, knowledge dissemination, and research influence in the field. A threshold value of two for the minimum number of documents from a country was applied for network analysis using the full counting method. Among the 57 countries identified among the highly cited

Figure 9: The Network Visualization Map of Country Citations for Publications Related to Constructed Wetlands



Data Source*:* Scopus. Created by the authors

publications, 33 met the minimum threshold of two documents (Figure 9). The clustering patterns indicate regional groupings of countries, likely influenced by geographical proximity, shared environmental challenges, or economic partnerships.

The yellow cluster, representing the United States with the highest link strength of 523, serves as a central hub for global collaborations, highlighting its significant influence and reach within the research community. This dominance may reflect the country's robust research infrastructure, ample funding opportunities, and strong institutional collaborations. Similarly, China and the Czech Republic, with notable link strengths of 470 and 271, respectively, play pivotal roles in advancing CW research and contributing to global research. Investigating whether specific clusters focus on particular research areas—such as nutrient removal, biodiversity conservation, or water reuse—could reveal specialization patterns.

4. DISCUSSION

Bibliometric research, particularly citation analysis, is crucial for understanding research trends and identifying key contributions across fields. It enables the visualization of significant research documents, aiding the identification of advanced trends and innovative approaches. In the context of CWs, bibliometric analysis highlights the interplay between socio-economic conditions and climatic factors, which often constrain the development of CWs in a given region. For instance, in China, the development of CW follows a diverse pattern, which stands out as one of its key characteristics (Y Zhang *et al.* 2021). Bibliometric analysis results indicate that, since 2009, the application of CWs and related research have increased. The analysis identified four research hotspots in CW studies: nitrogen, phosphorus, macrophytes, and SSF CWs (M Zhang *et al.* 2021).

Ji *et al.* (2021) found that CW-related research exhibits greater diversity and increased cross-group associations, highlighting a broader interdisciplinary approach. The authors used bibliometric analysis to identify leading journals that are significantly contributing to CW research. For instance, *Bioresource Technology* emerged as the most important journal, with 25 records retrieved from the WoS database (2012–2020) (Ji *et al.* 2021) and 655 citations recorded in the Scopus database (1995–2021) (Niknejad *et al.* 2023). The present study's findings reveal that *Ecological Engineering* (Elsevier) and *Water Science and Technology* (International Water Association) have the highest citation counts. These findings emphasize the growing prominence and interdisciplinary nature of CW research, offering a foundation for exploring advanced applications and developing innovative management strategies.

In recent years, there has been an increased application of low-cost CWs. At the same time, more research and improved management strategies are needed. In a bibliometric study based on the Scopus database from 1992 to 2019, Colares *et al.* (2020) found that the keyword "macrophyte" is directly connected to nearly all other terms. Other key terms include "sediment", "biomass", and "nutrient removal". Colares *et al.* (2020) show that wastewater treatment and management are the most crucial topics in publications on CWs. Vymazal J and Brix H have the largest co-author networks in their studies. In a bibliometric study using the Scopus and WoS databases, Yu *et al.* (2021) identified key connections in the literature and highlighted important aspects for optimizing CWs. Further research is needed to assess the toxicity of major pollutants and apply new technologies for CW optimization (Yu *et al.* 2021).

5. IMPORTANCE/ APPLICABILITY OF CWS

The growth of urbanization and industrialization, particularly in developing countries, poses challenges for water management. Water reuse has now become essential due to the global scarcity in freshwater resources. The quality and quantity of reclaimed water can be managed through reclamation and reuse. However, numerous biohazards and concerns are associated with using reclaimed water (Arora, Sudhir, and Raghubir 2009). CWs offer a feasible, natural, and cost-effective alternative to conventional wastewater purification and treatment methods, benefiting developing and developed countries (Arora *et al.* 2009).

CWs can treat various waste streams, including industrial effluents (Chang *et al.* 2021; Skrzypiecbcef and Gajewskaad 2017; Vymazal 2014), storm-water run-off (Choi, Lee-Hyung, and Kyung-Duk 2016; Li *et al.* 2017; Jie Wang *et al.* 2021), grey water (Prasad *et al.* 2021), domestic wastewater (Lu *et al.* 2016; Y Zhang *et al.* 2021), landfill leachate (Bakhshoodeh *et al.* 2020), and saline wastewater (Q Wang *et al.* 2021).

CWs offer great potential as the ideal substitute for wastewater treatment, particularly in small and medium-sized towns or cities (Zhang, Richard, and Tan 2009). Their low operational costs and energy efficiency make CWs an appealing and stable alternative worldwide. According to Vymazal (2011), the wastewater treatment technologies in CWs in the twenty-first century can be described as follows:

- Using a hybrid system that combines multiple CW types to improve water treatment efficiency, particularly for nitrogen reduction.
- Treating specific compounds already present in effluent wastewater.
- Finding an effective medium with higher phosphorus removal efficiency in SSF.
- Identifying bacteria that assist in treatment processes.
- Pollution removal and hydraulic modelling in different types of CWs.

As a wastewater treatment system, CWs offer several advantages, including flexibility in terms of site location, low pre-application treatment requirements, simple operation, low maintenance, and no modification of the natural wetland environment. They also provide stable performance in diverse environmental conditions (Polprasert 2004). CWs are cost-effective to develop and operate, and they can create wildlife habitats in free water surface (FWS) systems (Polprasert 2004).

Although mosquitoes are a potential hazard with FWS systems (Polprasert 2004), efficient and comparably sophisticated systems are cost-effective to implement in cities and towns, especially where land is scarce and the dense population helps lower household sewerage costs (Denny 1997). The key prerequisites for promoting the application of CWs in developing countries are raising awareness of their potential and encouraging nations to develop their own technologies (Denny 1997).

5.1. Major Types

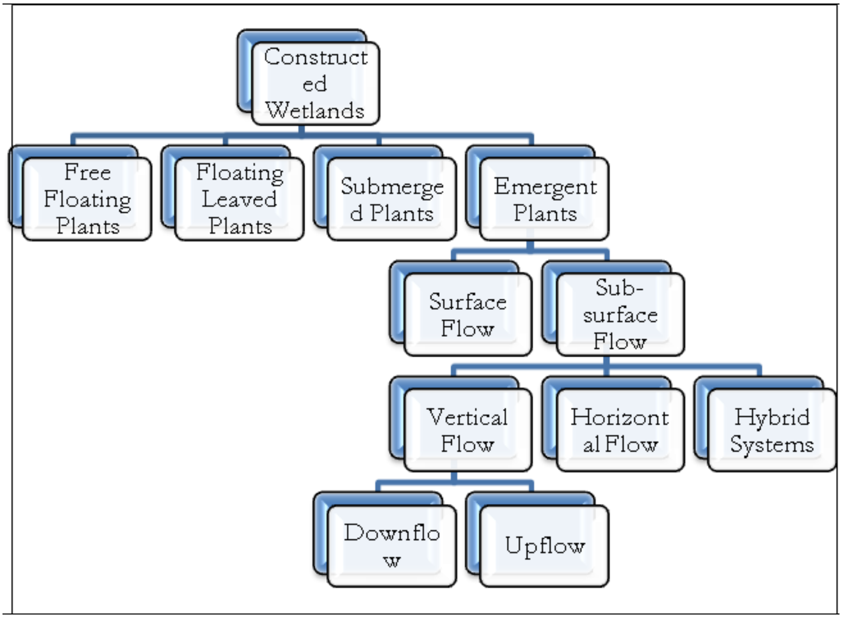
For wastewater treatment, CWs are typically categorized based on various characteristics. One classification divides CWs into four types based on the dominant macrophyte: (1) free-floating macrophytes, (2) rooted emergent macrophytes, (3) floating leaved macrophytes, and (4) submerged macrophytes (Vymazal 2010). Additionally, CWs are further subdivided based on the hydrological features of the wetland, including FWS and subsurface systems. CWs can also be classified by flow direction as either horizontal or vertical (Vymazal 2010). According to Stottmeister *et al.* (2003), CWs encompass aquaculture, hydrobotanical, and soil systems.

Based on the dominant plant species, Dordio and Carvalho (2013) classified four types of CWs: floating macrophytes (for example, *Lemna minor*, *Eichhornia crassipes*); floating macrophytes with leaves (for example, *Potamogeton gramineus*, *Nymphaea. alba*); submerged macrophytes (for example, *P. crispus*, *L. uniflora*); and rooted, emergent macrophytes (for example, *Typha latifolia*, *Potamogeton australis*). The CW classification for wastewater treatment, according to Vymazal (2007), is shown in Figure 10.

A horizontal SSF CW is a large basin filled with gravel, sand, and wetland vegetation. In horizontal SSF CWs, biochemical oxygen demand (BOD), total suspended solids (TSS), and pathogens are significantly reduced. Oxygen availability in horizontal SSF CWs is often low in summer and may become even more limited when plants are dormant in winter. Unlike FWS CWs, horizontal SSF CWs do not cause mosquito problems. In a 2006 study by Ouellet-Plamondon *et al.* (2006), artificial aeration was found to be a promising method for improving removal efficiency in horizontal SSF CWs, particularly in freshwater farms in cold regions where aeration is readily available. Because water primarily flows beneath the bed surface, the risk of hydraulic failure due to freezing is reduced in horizontal SSF CWs. It has several benefits, including no need for electrical energy and low operating costs. However, it also has drawbacks such as requiring a large amount of land, effecting limited nutrient removal, posing risks of clogging depending on the primary treatment, requiring a long time to reach full capacity, and needing expert design and construction supervision.

FWS CWs effectively remove organics through microbial degradation and colloidal particle settling (Vymazal 2010). VF CWs, also known as “reed bed systems” or “soil filters”, are a common urban wastewater treatment system. They are particularly useful in areas where other natural water treatment systems are challenging to implement. VF CWs are highly

Figure 10: Different Types of Constructed Wetlands for Wastewater Treatment



Source: Based on Vymazal (2007)

beneficial due to their minimal surface area requirements and effectiveness in removing organic matter and ammonia, though their phosphorus removal efficiency is relatively lower (Prochaska and Anastasios 2006). According to Prochaska and Anastasios (2006), VF systems are typically flooded and drained regularly, which saturates the soil bed's pores. However, not all VF systems operate on a fill-and-drain basis; some function entirely under unsaturated conditions, while others maintain a portion of the substrate in a partially saturated state. In these systems, the wastewater percolates through the substrate, which functions like a filter.

5.2. Role of Wetland Vegetation

The primary functions of plants in CWs include supplying oxygen; removing nitrogen and phosphorus; reducing chemical oxygen demand (COD), BOD, and TSS; and enhancing overall removal efficiency (Zhang *et al.* 2009). Commonly used plant species for leachate treatment in CWs are *P. australis*, *T. latifolia*, and *Chrysopogon zizanoides*, although other genera, such as Glyceria, Scirpus, and Eleocharis, are also utilized (Bakhshoodeh *et al.* 2020). According to Zhang *et al.* (2009), key considerations for CW development include the design, the specific role of plants, weather impacts, costs, energy efficiency, and long-term sustainability. Using local and renewable resources lowers ecological costs, enhances economic benefits through reduced energy consumption, and mitigates environmental stress (Zhang *et al.* 2009).

The ability of various aquatic plants, such as lemna, reed-grass, Salvinia, Eichhornia, and Azolla, to grow in polluted waters and reduce nutrient and contaminant loads have been studied (Arora *et al.* 2009). Compared to conventional treatment systems, macrophyte-based wastewater treatment systems offer several advantages. However, they also have limitations, such as their sensitivity to potentially toxic elements like high ammonia concentrations in wastewater (Arora *et al.* 2009).

Various experiments have determined that helophytes, commonly known as marsh plants, perform best in semi-natural wastewater treatment systems (Stottmeister *et al.* 2003). This is due to their unique growth physiology, which allows them to survive in extreme rhizosphere conditions (Stottmeister *et al.* 2003). Plants enhance overall treatment efficiency, directly and indirectly, making selecting the most suitable vegetation species a critical design decision.

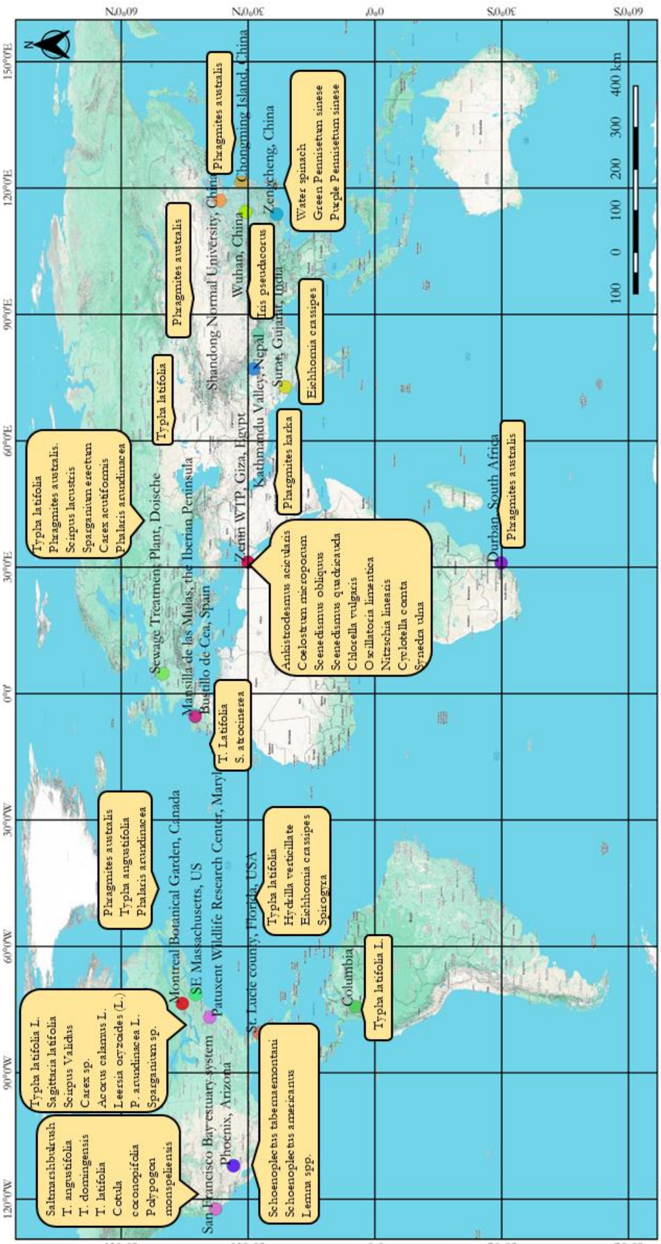
Improved nitrogen removal in CWs planted with vegetation results from active and passive oxygen transfer from the atmosphere to the roots, which supply oxygen to the rhizosphere (Lin, Dong, and Mo 2002). Aerated CWs also remove more nitrogen than non-aerated CWs (Nivala *et al.* 2013). To evaluate microbial density and activity in the rhizospheres of three plant species, Gagnon *et al.* (2007) planted six replicates in four different microcosms, including *Typha angustifolia*, *Phalaris arundinacea*, *P. australis*, and one unplanted control. The major plant species found in CWs within the selected study areas are shown in Figure 11.

The types and species of aquatic plants are influenced by water depth and the extent of inundation (Greenway 2004). A mix of emergent, submerged, and floating plant species should be selected to evaluate the performance of CWs with regards to plant diversity. Typical wetland species used in interior China include *Typha orientalis, P. australis, Zizania latifolia, Canna generalis, Acorus calamus, Echinochloa cruss-galli, Juncus effusus*, and *E. crassipes* (Yan and Xu 2014). According to Yan and Xu (2014), in cold climates, *P. australis, T. orientalis,* and *Z. latifolia* are better suited to SSF CW environments, while species like *E. crassipes* thrive in warmer climates.

5.3. Design and Construction

CWs mimic natural wetland systems and effectively remove various pollutants from wastewater (Ansola, Paula, and Luis 2014). CW systems are categorized into three types based on their design and operation: surface

Figure 11: Different Species of Plants Used in Constructed Wetlands across Various Study Areas Worldwide



Data Source*:* Scopus. Created by the authors flow, SSF, and VF systems (Farooqi, Farrukh, and Rahat 2008). Numerous studies have examined and reviewed the key design parameters, removal mechanisms, and treatment performance of CWs (Akratos and Tsihrintzis 2007; Albers and Camardese 1993; Ansola *et al.* 2003; Bayati *et al.* 2021; Dordio and Carvalho 2013; El-Mekkawi *et al.* 2021; Green *et al.* 1997; Guo *et al.* 2021; Lu *et al.* 2016; Maltais-Laundry *et al.* 2009; Mthembu *et al.* 2013; Prochaska and Anastasios 2006; Shrestha *et al.* 2001; Vandevenne 1995; Jie Wang *et al.* 2021, Jinqi Wang *et al.* 2021; Wu *et al.* 2021; Y Zhang *et al.* 2021).

To ensure the process is completely waterproof, the CWs are placed in a basin enclosed on all sides, with the substrate and bottom shielded by rubber foils (Farooqi *et al.* 2008). This precaution is crucial in any environmental setting to prevent water leaks that could disrupt system operation or contaminate the source water. Plants, gravel, or sand serve as substrates in these systems (Farooqi *et al.* 2008). Persson, Somes, and Wong (1999) examined the effects of various pond and wetland shapes as well as inlet and outlet locations. The results indicated that hydraulic efficiency, process effectiveness, and optimization of water quality treatment are the three main design components. Details of selected publications related to CWs are provided in Table 2.

Various fillers, such as steel slag, limestone, bamboo charcoal, and maifanite (with maximum adsorption capacity), have been used to create substrata for CW systems. Their effects on pollutant degradation in rural household sewage treatment systems were assessed by Lu *et al.* (2016), who found that removal efficiencies were positively impacted. In the CW developed by Mthembu *et al.* (2013), the medium consisted of multiple strata: fine sand at top, crushed rocks in the middle, and coarse rocks at the bottom. Various plants were planted in the wetland to analyse their effects on the pathogen, nutrient, and metal levels in wastewater (Mthembu *et al.* 2013).

Certain design parameters of CWs, such as deeper and larger beds, along with a natural or artificial insulation layer made of snow, rock wool, or polystyrene, can enhance protection against freezing (Ouellet-Plamondon *et al.* 2006). According to Greenway (2004), the key parameters to consider when designing a CW for wastewater treatment are shown in Figure 12.

Before constructing a CW for wastewater treatment, it is essential to select a suitable site that considers the wetland's objectives, soil type, land topography, local climate, total operational and maintenance costs, and potential future management changes (Cronk 1996). Key factors in constructing CW systems include the pre-treatment stage, choice of vegetation, porous media, and operation strategy (Skrzypiecbcef and Gajewskaad 2017). Further research and exploration of new potential and

Table 2: Details of Selected Publications Related to Constructed Wetlands

Sl. No.	Study area	Type of CW	Type of work	Type of water	Size of CW	Macrophytes used	References
1.	Columbia	SF CW	Removal of pharmaceuticals and personal care products	Treated wastewater	Area: 53 ha	*Typha latifolia L.*	Bayati *et al.* (2021)
2.	Zenin WTP, Giza, Egypt	—	Effective use of microphytes	Wastewater	Area of algal pond: 5.4 m^3; volume of water: 525.6 m^3; inflow rate: 1.44 m^3/d; HRT: 2 days	*Ankistrodesmus acicularis* *Coelostrum microporum* *Scenedismus obliquus* *Scenedismus quadricauda* *Chlorella vulgaris* *Oscillatoria limentica* *Nitzschia linearis* *Cyclotella comta*	El-Mekkawi *et al.* (2021)
3.	Zengcheng, China	VSSF CW	Purifying effect of biochar and zeolite	Biogas slurry	Area: 392 m^2	*Water spinach* *Green Pennisetum sinese* *Purple Pennisetum sinese*	Guo *et al.* (2021)

4.	SVNIT, Surat, Gujarat, India	—	Grey-water treatment	Grey water	Area: 0.3 m^2; depth and width: 0.3 m each; length: 1 m; water volume: 80 L; water depth: 0.27 m; capacity of overhead tank: 250 L	*Eichhornia crassipes*	Prasad *et al.* (2021)
5.	St. Lucie county, Florida, USA	—	Cleaning contaminated storm-water in urban areas	Contaminated run-off/ storm water	Area: 2 ha	*Typha latifolia* *Hydrilla verticillate* *Eichhornia crassipes* *Spirogyra*	Jie Wang *et al.* (2021)
6.	Wuhan, China	—	Endogenous denitrification and denitrifying dephosphatation	Municipal wastewater	Height: 120 cm; diameter: 20 cm	*Iris pseudacorus*	Wu *et al.* (2021)
7.	Chongming Island, China	—	Dissimilatory nitrate reduction processes	River water	Length: 6.0 m; width: 5.2 m; height: 2.0 m	*Phragmites australis*	Zhang *et al.* (2021a)
8.	Shandong Normal University, Jinan, China	SSF CW	Phosphorus removal efficiency	Saline wastewater	Height: 48 cm; diameter: 30 cm	*Phragmites australis*	Q Wang *et al.* (2021)
9.	Municipal WTP, China	Composite VSSF (upwards)	Rural household sewage treatment	—	Length: 3 cm; width: 1.7 cm; height of concrete pond: 160 cm	—	Lu *et al.* (2016)

10.	Durban, South Africa	Multi-designed (VF CW, HF CW, SSF CW)	Wastewater treatment	—	Length: 8 m; width: 4 m; volume: 3,000 L; flow rate: 0.2–2 l/s	*Phragmites australis*	Mthembu *et al.* (2013)
11.	Nehru Vihar Pumping station in Delhi, India	—	Nutrient removal from wastewaters	Partially treated municipal effluents	—	*Azolla microphylla*	Arora *et al.* (2009)
12.	Montreal Botanical Garden, Canada	HSSF CW	Nitrogen transformations and retention	—	Height: 0.3 m; width: 0.8 m; length: 1.25 m	*Phragmites australis* *Typha angustifolia* *Phalaris arundinacea*	Maltais-Laundry *et al.* (2009)
13.	Mansilla de las Mulas, northwest of the Iberian Peninsula	SSF CW	Municipal wastewater treatment	Municipal wastewater	Surface of glass fibre Tank: 1.1 m^2; depth of glass fibre tank: 0.55 m; volume of glass fibre tank: 0.6 m^3; water height: 20 cm	*Typha latifolia*	Ansola *et al.* (2003)
14.	Kathmandu Valley, Nepal	Two-staged SSF CW (HF followed by VF bed)	Wastewater treatment	—	Area (settlement tank): 18 m^3; area (horizontal flow bed): 140 m^2; length: 7 m; width: 20 m; height: 60 cm; area (vertical flow bed): 121 m^2; length: 11 m; width: 11	*Phargmites karka*	Shrestha *et al.* (2001)

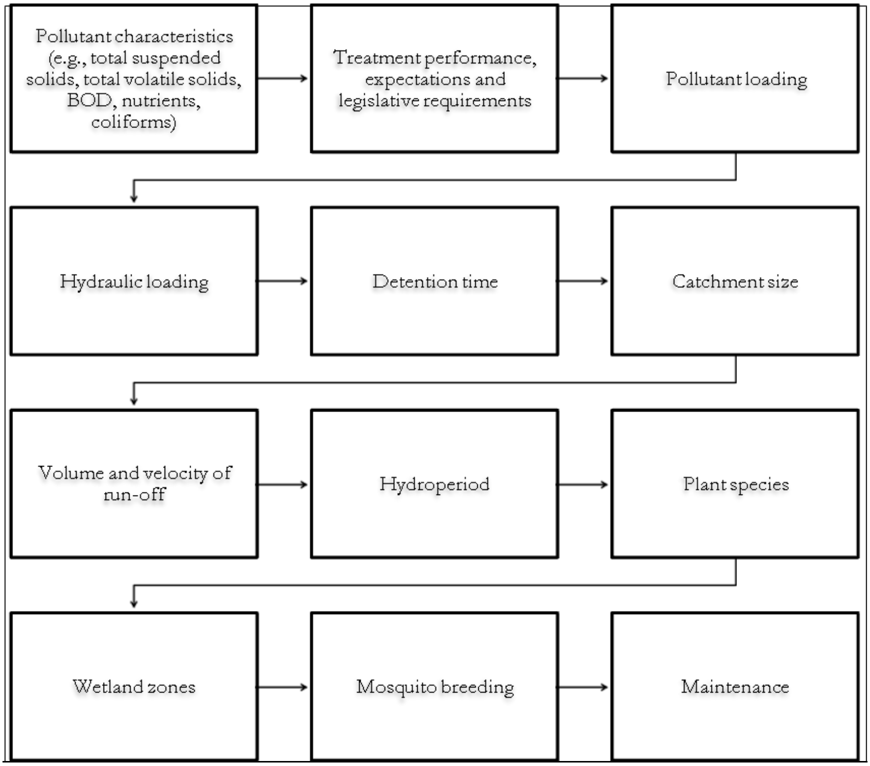
[39] Roy, Saha and Roy

					m; height: 90 cm; flow rate: 20 m^3/day		
15.	Sewage Treatment Plant, Doische, Belgium	—	Operational survey of a natural lagoon treatment facility	Wastewater	Area: 3,050 m^2; area of free water zone: 375 m^2	*Typha latifolia* *Phragmites australis.* *Scirpus lacustris* *Sparganium erectum* *Iris pseudacorus* *Carex acutiformis* *Phalaris arundinacea*	Vandevenne (1995)

Note: CW: constructed wetland; HRT: hydraulic retention time; WTP: water treatment plant; SF: surface flow; SSF: subsurface flow; VSSF: vertical subsurface flow; VF: vertical flow; HF: horizontal flow; HSSF: horizontal subsurface flow.

Source*:* Authors' compilation

Figure 12: Parameters Considered in the Design of Constructed Wetlands



Source*:* Based on Greenway (2004)

solutions are necessary for CW applications in contemporary scenarios.

5.4. Role of Microorganisms

Bacteria, protozoa, fungi, algae, and other microorganisms play a crucial role in the biogeochemical transformation of nutrients (Hoppe, Sang-Jin, and Klaus 1998). Indigenous (autochthonous) and foreign (allochthonous) microorganisms commonly coexist with the bacterial communities of CWs (Truu, Jaanis, and Jaak 2009). Autochthonous microbes exhibit metabolic activity, surviving and thriving in wetland systems while contributing to purification processes. In contrast, allochthonous microorganisms, such as pathogens, rarely survive and lack functional relevance in wetland environments (Ansola *et al.* 2014).

Ottova (1997) found that the retention of coliform bacteria was exceptionally high, exceeding the typical values observed in conventional systems. To evaluate the microbiological properties of various CWs, five

CWs were selected representing diverse design parameters, including CW area, media type, and vegetation. Monthly samples of inflowing and outflowing water were collected and analysed for microbial properties (Ottova 1997).

According to Kang *et al.* (1998), the low activity of soil enzymes is partly attributable to improved water quality. In two CW sites in the United States, four soil enzyme activities and microbial activity were measured along a transect from upland soil to wetland sediment. The hydrochemistry of the wetlands' inflow and outflow was also analysed. Results showed that enzyme activities in the sediments were significantly lower in both wetlands compared to the adjacent upland soils (Kang *et al.* 1998).

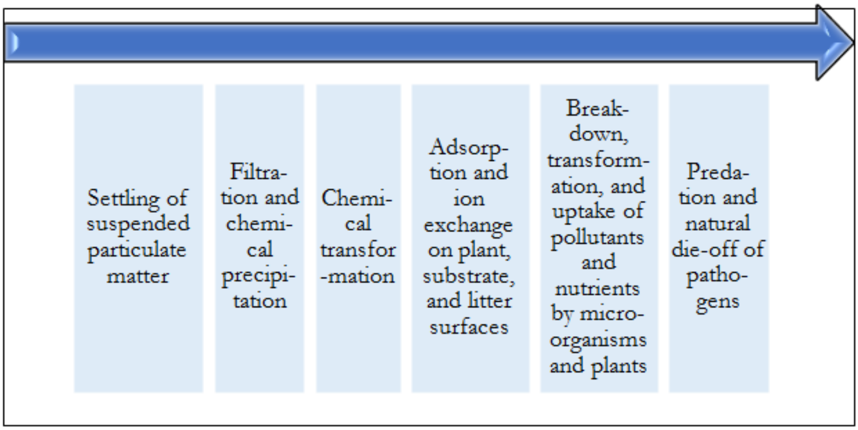
Microbial biomass carbon, denitrification enzyme activity, soil respiration, and related factors were compared across two constructed systems and three natural wetland settings (Duncan and Groffman 1994). The primary goal was to assess whether microbial biomass and activity were comparable across different wetland types (Duncan and Groffman 1994). The findings suggested that using organic substrates and establishing vigorous plant communities during wetland construction likely contributed to the successful development of microbial communities in these systems (Duncan and Groffman 1994).

5.5. Physical, Chemical, and Biological Processes for Organic Pollutants and Nutrient Removal

CWs are used for wastewater treatment because of their low operating costs and high pollutant removal efficiency. Primary pollutants include nutrients, organic contaminants, metals, and metalloids, which can accumulate in various mediums such as surface water, soil, sediment layers, and groundwater. In recent years, numerous strategies and technologies for water and wastewater treatment and the remediation of contaminated areas have been developed (Dordio and Carvalho 2013). Numerous advanced technologies have been developed for treating wastewater, such as oxidative processes, membrane filtration, and adsorption by activated carbon. Dordio and Carvalho (2013) have evaluated these mechanisms for removing organic xenobiotics from water. Despite their improved removal capacity, these treatment processes are used sporadically, primarily due to their cost-effectiveness.

As a result, there is growing demand for a substitute that effectively treats wastewater and helps eliminate organic xenobiotics from both the soil and natural waters at low operating and maintenance costs.

Figure 13: Mechanisms to Improve Water Quality in Constructed Wetlands



Source*:* Based on Haberl *et al.* (2003)

Researchers have explored various treatment technologies, including natural water treatment methods and biological and physiochemical processes. Biological water treatment involves the use of aerated bioreactors and biological aerated filters, while physical treatment primarily consists of filtration (Prasad *et al.* 2021). Chemical treatment methods, including chemical coagulation and electrocoagulation, were also investigated (Prasad *et al.* 2021). Phytotechnologies have successfully removed many organic xenobiotics from contaminated soils, waters, and wastewater (Dordio and Carvalho 2013). According to Haberl *et al.* (2003), the following mechanisms help improve water quality in CWs (Figure 13).

The phytoremediation process is a key method for wastewater treatment, involving the removal of contaminants through the interaction of soil, water, plants, and microorganisms (Prasad *et al.* 2021). The choice of plants is critical for the process's effectiveness. Key requirements for these plants include rapid growth, high nutrient absorption capacity, ease of harvesting, and significant biomass content (Prasad *et al.* 2021). This approach seeks to capitalize on plants' ability to absorb and metabolize organic xenobiotics (Dordio and Carvalho 2013). Dordio and Carvalho (2013) have also conducted several successful experiments analysing the removal of xenobiotics from contaminated source water using secondary and tertiary wastewater treatment methods.

The physical processes of sedimentation and decantation are crucial for removing various contaminants, some of which may remain largely unaltered in winter environments, such as particulate organic matter (Ouellet-Plamondon *et al.* 2006). While temperature significantly influences biological processes, the efficiency with which nitrogen and soluble organic matter are removed are reduced in winter conditions (Ouellet-Plamondon *et al.* 2006). The following factors influence CW wastewater treatment efficiency: CW area, depth, flow pattern, plant type, site selection, material porosity, and hydraulic budget (Polprasert 2004). Mosquito control and plant harvesting are two operational considerations for wetlands used in wastewater treatment. Green *et al.* (1997) investigated the nitrification of a secondary effluent using a VF bed system variant.

The life-cycle approach can be used to assess the environmental impact of various wastewater treatment technologies in greater detail (Brix 1994). The plant species and microorganisms in CWs are considered key biological components. These organisms are crucial in removing pollutants, including organic matter, from wastewater (Dordio and Carvalho 2013). In addition to biological processes and activities, CW systems can remove pollutants such as potentially toxic elements. Two examples are ammonia adsorption and organic nitrogen burial (Vymazal 2007). Figure 14 illustrates various studies on CWs published by different authors.

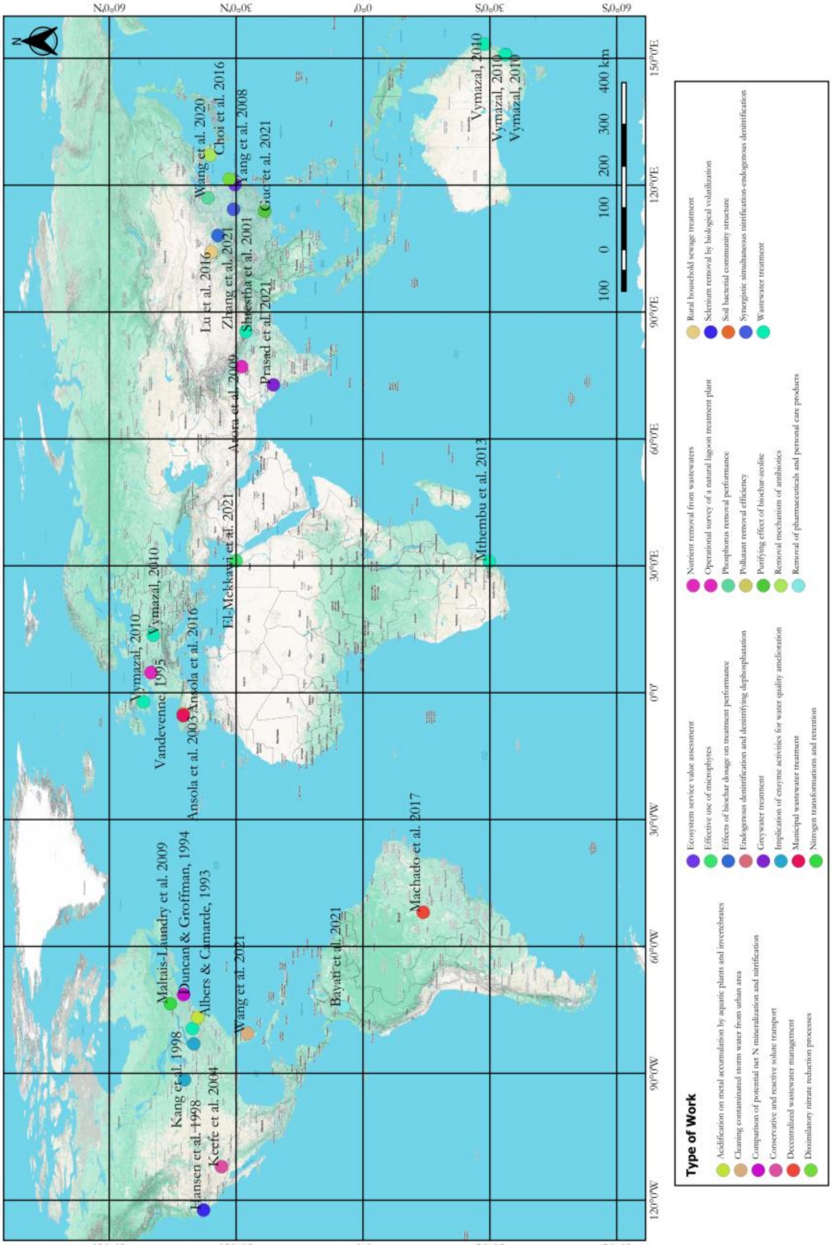
5.6. Operation and Maintenance

The set-up of a CW requires expert design and construction supervision. CWs need periodic maintenance to operate at full capacity without issues related to wetland processes. In an experimental study, Lu *et al.* (2016) designed various CW fillers for rural household sewage treatment based on an analysis of natural wetlands and the challenges associated with ineffective operation and treatment. Using a natural zeolite, gravel, and sandstone-based filler enhances nitrification and denitrification in CW systems, improving nitrogen removal efficiency (Lu *et al.* 2016). The intensity of these processes reflects the denitrifying capacity and potential of wetland systems (Lu *et al.* 2016). This experiment offers a solid basis for optimizing substrate filler selection in wetlands (Lu *et al.* 2016).

According to Greenway (2004), improving treatment effectiveness requires balancing two key parameters: the pollutant loading rate and the hydraulic retention time. The quantity and quality of wastewater effluents play a major role in affecting these parameters (Greenway 2004). Several factors, including the run-off volume, the properties of pollutants, the required treatment level, and the wetland's function as a flood retention basin, all influence the wetland's size (Greenway 2004).

Yan and Xu (2014) examined current engineering practices in cold climates, including case studies on improving water treatment effectiveness. They explored various measures such as optimizing system set-up, improving

Figure 14: Various Works on Constructed Wetlands by Authors Worldwide



Data Source*:* Scopus. Created by the authors winter operations, refining internal system design, and analysing pre-treatment and post-treatment technologies (Yan and Xu 2014). Pre-treatment and detention times are critical parameters to maximize pollutant removal efficiency (Greenway 2004). In storm-water wetlands, sedimentation ponds play a key role in removing particulates from the water. At the same time, dense vegetation in the macrophyte zone is essential for enhancing the removal of suspended solids and nutrients (Greenway 2004).

5.7. Major Challenges

Despite the numerous benefits CWs offer communities, they also face several challenges. The issues encountered during CW implementation, operation, and maintenance, as outlined by Shrestha *et al.* (2001), are as follows:

- Starting the first CW system required significant effort due to a lack of awareness.
- Although the system is natural and the materials needed for treatment are locally available, the initial capital investment is high, though lower than that of primary wastewater treatment plants.
- The sealing material for the beds is still not readily available.
- Filter media such as sand and gravel are difficult to obtain.
- There is also a security issue, particularly regarding the distribution pipes of the VF bed, which are exposed on the ground.

Other issues related to CW implementation include insufficient funding for further research to improve treatment systems and neglect in their operation and maintenance. However, wastewater treatment remains a low priority for both the public and industries due to weak effluent regulations.

Controlling mosquitoes in CWs remains a major issue. In CWs, mosquitoes are significant vectors of diseases in surrounding areas (Russell 1999). The design and operation of CWs should consider the potential for disease outbreaks via mosquitoes and implement measures to minimize their occurrence (Reddy and Elisa 1997). Flight range, blood host preferences, pathogen susceptibility, and their intrinsic capacity for population growth, which vary among species, are essential factors determining their characteristics (Russell 1999). To accurately assess the dangers and risks associated with mosquito development in CWs, proper species identification and knowledge of their biology are required (Russell 1999).

SSF CWs are more favourable for the health of nearby populations because insect invasions and odour issues are less likely in SSF than in FWS CWs (Machado et al. 2017). However, due to support matrix clogging—one of the main limiting factors—SSF CWs have a shorter lifespan than FWS CWs (Machado et al. 2017).

The quality of water plays a major role in mosquito production. For instance, storm water with minimal organic pollution tends to cause fewer mosquito problems (Russell 1999). In contrast, domestic sewage, which contains higher nutrient levels, fosters increased vegetation and mosquito production (Russell 1999). Predators are less likely to survive in heavily polluted water (Russell 1999). The nutrients in polluted wastewater may enhance conditions that support mosquito growth while reducing the effectiveness of factors that typically control larval populations, such as predators and surface vegetation (Tennessen 2020).

In a 2016 study on FWS CW by Walton *et al.* (2016), the impact of alkali bulrush on raised water levels, mosquito production, and water quality was investigated. In the summer of 2012, after converting a hectare of CW into six systems, bulrush was planted in the centre of three 5 m bands (0.5 m wide) in each system (Walton *et al.* 2016). Mosquito larvae require vegetation in wetlands for protection from predators and physical disturbances, as well as to increase food resources (Russell 1999). Mosquito populations are generally low in wetlands without vegetation (Russell 1999). In addition to mosquito production, wetland development and processes involve issues such as the need for larger areas, poor nutrient removal, substrate saturation, and odour control.

6. CONCLUSION

CWs are systems designed to use the natural processes of wetland vegetation, microbial communities, and soil to treat wastewater. CW ecosystems provide essential goods and services that benefit human welfare, including run-off water management, groundwater recharge, habitats for diverse species, and educational and scientific value. Primarily, CWs offer a sustainable and cost-effective solution for wastewater treatment, especially in areas facing urbanization, industrialization, and water scarcity.

The evolution of CW technology has seen significant advancements, from early experiments in the mid-twentieth century to modern hybrid systems optimized for nitrogen removal, pollutant management, and hydraulic efficiency. CWs have proven versatile in treating various waste streams, including industrial effluents, storm water, and grey water, demonstrating their adaptability to diverse climatic conditions and regional needs.

The Scopus online database was used for bibliometric analysis. Using the keyword "constructed wetlands", 4,407 documents published over a 30-year period were identified. A citation threshold of more than 100 citations was applied, resulting in 209 publications. Investigating how these highly cited works have influenced policy-making, technological advancements, and practical applications provided insights into the real-world impact of CW research.

VOSviewer software has been used for various citation-related network analyses. The co-occurrence analysis of the keywords used in highly cited publications on CWs offered valuable insights into the field's thematic focus and research trends. Among all the keywords, "constructed wetlands", "constructed wetland", "wetlands", "wastewater treatment", "wastewater", and "wastewater management" showed the highest frequency of co-occurrences. Citation analysis revealed that the journal *Ecological Engineering* had the most citations, followed by *Water Research* and *Water Science and Technology*.

To interpret the academic structure of highly cited publications on CWs, a citation analysis map focusing on authorship collaboration and influence was created. The co-authorship network analysis revealed that Bayona J M has the strongest link, followed by Matamoros V. An analysis of emerging authors and their collaborative networks aimed at understanding their integration into the global research community was also conducted. The citation-author network analysis showed that Vymazal J received the most citations and had the highest link strength (340), followed by Brix H. Regarding citations per author, Vymazal J (6427) and Brix H (2583) are followed by Bayona J M and Matamoros V.

Understanding the evolution of international partnerships provided insights into the growing globalization of CW research. The analysis of citations by country highlighted that the United States, China, and the Czech Republic dominate CW research, illustrating how these leading nations shape global trends and outcomes, particularly in citations and cross-disciplinary studies.

Bibliometric analysis revealed a growing research interest in CWs and their interdisciplinary applications, reflecting their increasing global relevance. Keywords like "constructed wetlands" and "wastewater treatment" dominate the research landscape, highlighting CWs' potential to address pressing environmental and water management challenges. However, as this review suggests, there is significant room for innovation, particularly in optimizing design, enhancing phosphorus removal, and integrating emerging technologies.

A detailed discussion on the importance of CWs captured several key characteristics related to their design and construction, the role of macrophytes and microorganisms, the physical and chemical processes involved in organic pollutant and nutrient removal, and their operation and maintenance. All these factors should be considered when constructing a CW for wastewater treatment.

To summarize, CWs for wastewater treatment can provide a sustainable source of bioenergy without depleting water resources or competing with energy crops. Successful implementation requires technical refinement, awareness, and policy support to maximize their ecological and socio-economic benefits. By harnessing the natural processes of wetlands, CWs offer a harmonious blend of ecological sustainability and engineering ingenuity, promising a greener future.

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