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Constructed Wetlands as Domestic Decentralized Wastewater Treatment Systems - A Systematic Review

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Abstract

Constructed wetlands (CWs) have recently gained significant interest in urban wastewater treatment as decentralized sanitation alternatives. This paper seeks to understand the practices, principles, and emerging themes in constructed wetlands as domestic wastewater treatment systems. The PRISMA methodology and the archival research methods were used to identify papers published in the last ten years through Scopus and Google Scholar. The results showed that about 29% were performance analysis studies, and 60 % were pilot studies, indicating genuine interest in the systems but a very low implementation rate. Pollutant removal in CWs is influenced by the plant species, microorganisms, and media type. Water reuse is the significant advantage of CWs, with agriculture being the most reuse activity. The study was limited in that it focused mainly on domestic wastewater. Therefore, future research is encouraged to see the performance of CWs in treating high-strength wastewater.

Keywords

Constructed wetlands, Domestic wastewater treatment, Decentralized sanitation, Onsite wastewater treatment, Wastewater reuse

1. Introduction

Sanitation is one of the most crucial and essential infrastructural pillars for ensuring human health, happiness, and environmental sustainability (Kazora & Mourad, 2018). Poor sanitation systems worldwide have several consequences, including a negative impact on the quality of water and health risks for the communities impacted (Nansubuga et al., 2016). One estimate suggests that over 70% of all the global water used ends up as wastewater, which is then dumped into freshwater bodies like lakes and rivers without adequate treatment (Shukla et al., 2021). Therefore, the issues with the qualitative and quantitative scarcity of water resources led to increased concern and a quest for effluent treatment improvements that are suitable in terms of quality and cost compared to conventional treatment methods (Oliveira et al., 2021). According to Zhu et al. (2013), it is apparent that the current sanitation systems are inefficient and have gaps, which stresses the need for a change in wastewater management to include sustainable interventions that would make basic sanitation attainable for everyone and reduce stress on water sources. Meerholz & Brent (2013) reiterate that water is internationally acknowledged as a valuable resource; due to limited water supplies across the globe, water optimization and reuse are becoming increasingly important, especially in the wastewater sector.

Castañer et al. (2020) Posit that the high costs of conventional systems prevent the construction of wastewater treatment facilities, mainly because the raw wastewater must be transported over long distances and frequently requires pumping stations to get to the treatment stations. Due to this, shortage of water sources around the globe, and a push for climate change mitigation from organizations like the United Nations (Sustainable Development Goals, especially SDG 6), there is a high demand for the construction of new wastewater treatment facilities that are not energy intensive but are environmentally friendly (Mucha et al., 2018). At the forefront of this change are decentralized, onsite sanitation systems. Decentralized wastewater sanitation is the treatment and disposal of relatively modest volumes of wastewater from small communities at or near the point of generation (Capodaglio et al., 2017). Several technologies have been developed pertaining to decentralized sanitation and water reuse, as these are crucial for a more sustainable approach to wastewater management. One of the technologies that have stood out in recent years regarding decentralized sanitation is constructed wetlands (CWs), which entails wastewater treatment systems designed to use and even increase the biological, physical, and chemical mechanisms for the water purification processes (Abdullah et al., 2020).

Constructed wetlands (CWs) have gained significant interest in urban wastewater treatment recently, especially in decentralized sanitation, since they are dependable, inexpensive, easy to construct and operate, and provide an environmentally beneficial method to treat wastewater (Andreo-Martínez et al., 2017; Machado et al., 2017; Valipour & Ahn, 2016). By definition, Jácome et al. (2016); Muduli et al. (2022) state that constructed wetlands are engineered systems that treat different types of wastewater through processes like microbial degradation, adsorption, assimilation, precipitation, sedimentation, assimilation, plant absorption, and volatilization. However, due to the proliferation of studies in the area in recent times, there is a need to understand the state of the art. Therefore, this paper seeks to understand the practices, principles, and emerging themes in constructed wetlands as decentralized sanitation alternatives.

2. Materials and Methods

To achieve the objectives, the authors conducted a systematic literature review of constructed wetlands as domestic decentralized wastewater treatment systems. The authors used the PRISMA methodology coupled with the Archival Research Method. These methods use secondary data, which is acquired by searching databases. The eligibility criteria was as follows: Studies that met the following criteria were included in the review (a) the study that explored the topic of constructed wetlands; (b)the study that dealt with domestic wastewater treatment using constructed wetlands; (c) the study could be empirical or theoretical, and (d) the study should have been written in English.

2.1 Search strategy, Data Source, and Article Selection

Initially, a literature search was conducted using Google Scholar and Scopus. The steps of this research followed are presented below.

1. Defining database source: This review covered the well-established database of Scopus and Google Scholar; the Web of Science database was excluded because Scopus and Google Scholar contain most of the articles therein.
2. Delimitation of the scope: The timeframe covered is ten years, from 2012 to 2022; the last date the database was screened for new papers was the 14th of December 2022. The time frame was limited to ten years because of the need for recent studies in the subject area.
3. Defining a unit of analysis and sampling: All search results were accepted at first. The sample of documents was defined by searching the following keywords in Scopus "*Constructed wetlands and domestic wastewater treatment*."
4. Applying filters: Keyword filters for domestic wastewater treatment in engineering and environmental science subject areas were applied, and a language filter, "*English*" was used; the search results returned 179 results.
5. Conducting a general compilation: ten articles were removed for duplicity, and the remaining studies were 169.
6. Screening: The title and abstract of all articles were read, and papers not related to constructed wetlands were dismissed; 70 were dismissed, and 99 remained. The second screening: review papers, conference papers, and book chapters were dismissed. The dismissed papers were 40, and the remaining sample comprised 59 articles. Conference papers and books were removed because they do not necessarily go through the rigorous peer-review process of journal articles. The third screening: All the remaining articles were read to confirm their relation to constructed wetlands as domestic wastewater treatment systems. Four papers were dismissed as they were not discussing domestic wastewater; the sample was 55.
7. Defining the sample: the final sample was 55 papers, thorough reading was done to extract the necessary information, and information was logged in an excel sheet.

The steps are shown in the Figure 1 PRISMA flow diagram.

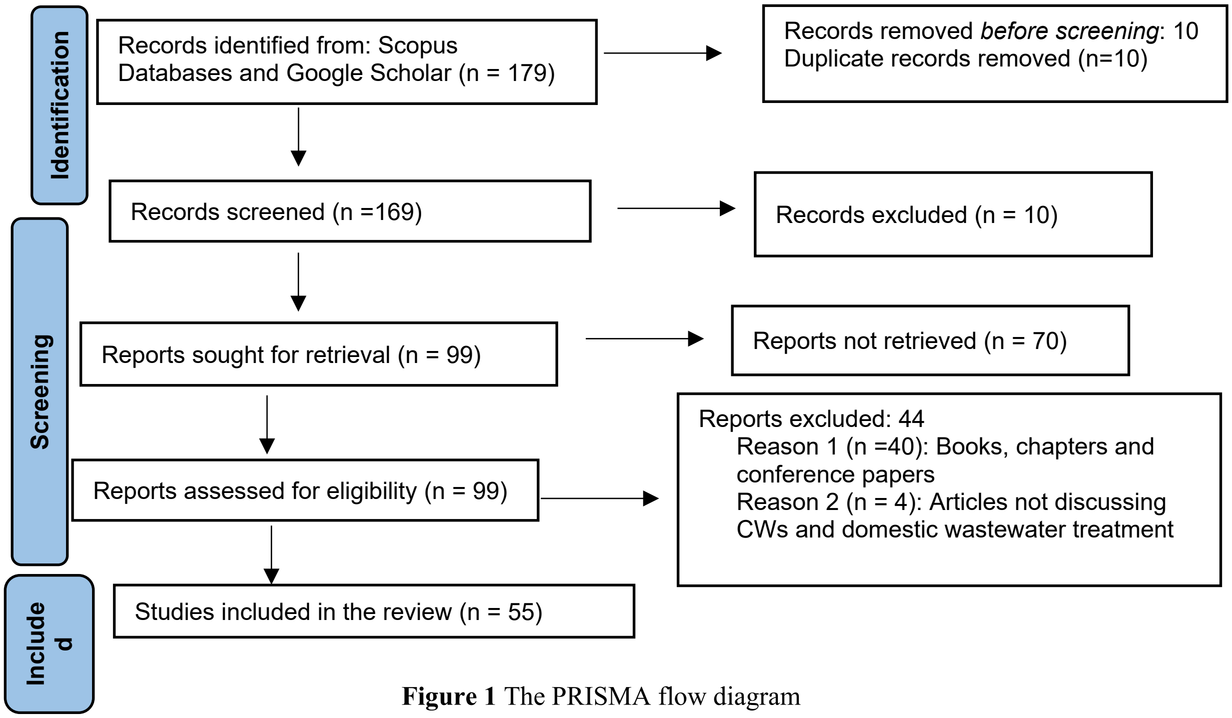

Figure 1 The PRISMA flow diagram

3. Results and Discussion

The content analysis and data interpretation from the final 55 papers was conducted to see the practices, principles, and emerging themes in CWs as domestic wastewater treatment systems globally over the past decade. First, the authors present an overview of the studies on CWs as wastewater treatment systems. A summary of the type of CWs used and the aquatic plants used for wastewater treatment follows. The penultimate section reviews the principles that govern wastewater treatment in CWs. Finally, the discussion ends with the appraisal of the emerging thematic areas in CWs as alternative wastewater treatment systems.

3.1 Overview of publications on CWs as domestic wastewater treatment systems

Over the past decade, research outputs on constructed wetlands have been on the rise. This can be attributed to several reasons. The main ones are economic (especially for developing countries), population growth putting a strain on existing sanitation infrastructure, and the push for sustainable alternatives to conventional approaches in wastewater treatment by organizations like the United Nations through the Sustainable Development Goals (SDG 6 for sanitation). Over the past decade, the researcher identified about 55 papers that discussed domestic wastewater treatment by CWs. Table 1 summarizes their main features.

Table 1 Summary of Research Publications

Number	*Type of Study*	*CW type and plant specie*	*Country of Application*	*Authors and year*
1	Pilot study	Horizontal Flow CW: *Vetiveria Zizanioides*	Malaysia; suggestions on the application	(Abdullah et al., 2020)
2	Performance analysis	Vertical flow and Horizontal flow CWs: none	Spain; Full-scale application	(Adrados et al., 2014)
3	Performance analysis	Hybrid CW: *Typha latifolia, Phragmites australis and Vetiver grass*	Pakistan; Full-scale application	(Ali et al., 2018)
4	Performance analysis	Horizontal subsurface flow constructed wetland	Spain; Full-scale application	(Andreo-Martínez et al., 2017)

		(HF-CW): *Phragmites australis*		
5	Pilot study	Horizontal Flow CW: *Juncus maritimus, Typha angustifolia, Cyperus papyrus, and Canna indica*	Algeria: suggestions on application	(Bekkari et al., 2022)
6	Pilot study	Hybrid-CW: *Hymenachne grumosa*	Brazil: suggestions on application	(Horn et al., 2014)
7	Pilot study	Vertical flow constructed wetland: *Cyperus alternifolious*	Turkey: Suggestions on application	(Bilgin et al., 2014)
8	Pilot study	Vertical Flow Constructed Wetland: *Heliconia psittacorum*	Colombia: suggestions on application	(Bohórquez et al., 2017)
9	Pilot study	Vertical Flow Constructed Wetlands: *Oenanthe javanica*	China: Suggestions on application	(Cao et al., 2022)
10	Pilot study	Vertical-flow constructed wetland (VFCW): *Juncus spp. ('Junco')*	Brazil: Suggestions on application	(Carneiro et al., 2022)
11	Pilot study	Horizontal flow-CW; Vertical & Horizontal subsurface flow-CW: *Thalia dealbata Fraser and Iris tectorum Maxim*	China: suggestions on application	(J. Chen, Ying, et al., 2016)
12	Pilot study	Horizontal subsurface flow-CW: *Cyperus alternifolius*	China: Suggestions on application	(J. Chen, Wei, et al., 2016)
13	Pilot Study	Hybrid-CW: *Anthurium andraeanum, And Dieffenbachia sequina (Linn.) Schott*	China: Suggestions on application	(Lai et al., 2021)
14	Performance analysis	Horizontal subsurface flow CW: *Typha latifolia and Canna indica*	India: Full-scale application	(Datta et al., 2021)
15	Pilot study	Horizontal Flow-CW: none	Spain: Suggestions on application	(Corbella & Puigagut, 2018)
16	Performance analysis	Integrated subsurface flow-CW: *phragmites and typha*	India: Suggestions on application	(Deeptha et al., 2015)
17	Pilot study	Horizontal Flow-CW: *halophytes Juncus acutus, Sarcocornia*	Greece: Suggestions on application	(Fountoulakis et al., 2017)
18	General study	Vertical subsurface flow-CW: *Phragmites*	China	(Huang et al., 2015)
19	Performance analysis	Hybrid-CW*: Glyceria maxima, Phalaris arundinacea*	Poland: Full-scale application	(Jucherski et al., 2017)
20	Pilot Study	Horizontal subsurface flow-CW: *Phragmites australis*	Germany: Suggestions on application	(Kahl et al., 2017)
21	Performance analysis	Horizontal subsurface flow CW: *water spinach, chinese celery, cress*	China: Full-scale application	(Khairalla et al., 2016)
22	Pilot study	Vertical Flow-CW: *Phragmites australis*	Kenya: Suggestions on application	(Kilingo et al., 2022)
23	Pilot study	General CWs: *Canna indica, Iris pseudacorus Vetiveria zizanioides*	China: Suggestions on application	(Li et al., 2013)

24	Pilot study	Vertical subsurface flow-CW: *common reed*	China: Suggestions on application	(Lu et al., 2016)
25	General study	General CWs: Various	Brazil	(Machado et al., 2017)
26	Pilot study	Horizontal subsurface flow-CW: *macrophyte Cyperus papyrus*	Kenya: Suggestions on application	(Mburu et al., 2013)
27	Performance analysis	Kickuch Horizontal Subsurface flow-CW: *Phragmites australis*	Poland: Full-scale application	(Mucha et al., 2018)
28	Performance analysis	Decentralized multistage- CW: *Canna lily*	India: Full-scale application	(Muduli et al., 2022)
29	Performance analysis	Hybrid CW: *Typha angustifolia and Canna indica*	India: Field-scale application	(Munavalli et al., 2022)
30	Pilot study	Horizontal and Vertical subsurface flow-CW: *Phragmites australis*	Germany: Suggestions on application	(Nivala, Boog, et al., 2019)
31	General study	General CWs: *Common reed (Phragmites spp.)*	Germany	(Nivala et al., 2018)
32	Performance analysis	Vertical Flow-CW: *Juncus acutus and Cyperus laevigatus, Phragmites spp*	Jordan: Full-scale application	(Nivala, Abdallat, et al., 2019)
33	General study	Floating treatment- CW: various macrophytes	Brazil	(Oliveira et al., 2021)
34	Performance analysis	Hybrid-CW: *Canna species, and Alpinia purpurata*	Brazil: Full-scale application	(Paulo et al., 2013)
35	Pilot study	Hybrid-CW: *Phragmites inoculated with Paenibacillus sp.*	China: Suggestions on application	(Pei et al., 2016)
36	Pilot study	Vertical flow-CW: *Canna Indica*	India: Suggestions on application	(Pinninti et al., 2021)
37	Performance analysis	Horizontal subsurface flow-CW: *Phragmites australis*	Turkey: Full-scale application	(Çakir et al., 2015)
38	Performance analysis	Horizontal subsurface flow-CW: *T. latifolia and Commelina benghalensis*	India: Full-scale application	(Shukla et al., 2021)
39	Pilot study	Vertical flow-CW: *Typha latifolia*	Cuba: Suggestions on application	(Salgado et al., 2018)
40	Pilot study	Horizontal and Vertical subsurface-CW; Hybrid-CW: *Phragmites australis*	Turkey: Application in various cities	(Ayaz et al., 2015)
41	Pilot study	General CWs: *Typha latifolia and Cyperus rotundus*	India: Suggestions on application	(Shingare et al., 2017)
42	Performance analysis	Horizontal subsurface flow CWs :*Bulrush (Phragmites communis)*	China: Full-scale application	(Song et al., 2021)
43	Performance analysis	Horizontal subsurface flow-CW: *J. acutus and C. selloana*	Turkey: Full-scale application	(Aydın Temel et al., 2018)
44	Pilot study	Microbial fuel cells-CWs: *Canna Indica*	India: Suggestion on application	(Thakur & Das, 2021)
45	Pilot study	Vertical flow-CW: none	Spain: Suggestions on application	(Torrijos et al., 2016)
46	General study	General-CWs: various macrophytes	South Korea	(Valipour & Ahn, 2016)

47	Pilot study	Horizontal subsurface flow-CW: *Phragmites australis*	Italy: Suggestions on application	(Verlicchi et al., 2013)
48	Pilot study	Vertical subsurface flow-CW: *Phragmites australis*	China: Suggestions on application	(H. Wu et al., 2016)
49	Pilot study	Microbial fuel cells CW: *J. effuses, T. orientalis, and S. validus*	China: Suggestions on application	(Wang et al., 2017)
50	Pilot study	Vertical flow-CW: *Arundo donax and Canna indica*	China: Suggestion on application	(S. qing Wu et al., 2013)
51	Pilot study	Tidal flow-CW: none	China: Suggestions on application	(Tan et al., 2019)
52	Pilot study	Vertical flow-CW: *Typha angustata and Canna indica*	India: Suggestions on application	(Yadav et al., 2018)
53	Pilot study	Vertical flow, Horizontal subsurface flow-CW: *Thalia dealbata*	China: Suggestions on application	(Zeng et al., 2021)
54	General study	General CWs: Various macrophytes	China	(Z. Chen et al., 2016)
55	Pilot study	General CW: *Paspalidium flavidum*	Pakistan: Suggestions on application	(Rehman et al., 2022)

From Table 1, it can be seen that various countries are interested in CWs as wastewater treatment systems. Asian countries lead the pack due to the number of publications from the continent, particularly from China and India. However, the lack of African countries is concerning, especially as the nations from the continent suffer the most from the effects of inadequate sanitation. From the studies reviewed, there are only three studies from Africa. These were pilot studies from Kenya (Mburu et al., 2013); (Kilingo et al., 2022) and Algeria (Bekkari et al., 2022). However, it has to be noted that it is not entirely accurate to assume that a lack of publication is a lack of practice. South American and European nations were fairly represented in the study, with countries like Brazil, Greece, Turkey, and Colombia, to name a few. Generally, besides the disruptions caused by the Covid-19 pandemic, there is a steady increase in interest in CWs as decentralized sanitation alternatives. This bodes well for international organizations like the UN, particularly the 2030 Agenda for Sustainable Development.

3.2 Practices of domestic wastewater treatment by CWs around the globe

Regarding the practice and implementation of CWs, there is a relatively low application of full-scale systems around the globe. As shown in Figure 2 below, the most studied systems in the review are pilot systems, with 60%, and full-scale systems follow, with about 29%. About 11% of the studies were general studies that included reviews and design papers. The general studies include bibliometric reviews by (Oliveira et al., 2021) in the Brazilian context of CWs in domestic wastewater treatment. Another general study in Germany by (Nivala et al., 2018) crucially looked at the standards for dimensioning, construction, and operation of constructed wetlands for domestic and municipal wastewater. As stated, most studies in the review are pilot studies, indicating the intent of full-scale application of CWs as wastewater treatment systems. Various pilot scale systems experimented with different types of CWs. S. qing Wu et al. (2013) investigated the treatment performance of an integrated vertical flow constructed wetland for domestic wastewater treatment in central China. The pilot study showed removal efficiencies of 81.03 % for COD, 51.66 % for total nitrogen (TN), 42.50 % for NH4+-N, and 68.01 % for TP, indicating the system's effectiveness. In Asia, pilot studies by Shingare et al. (2017) in India and Abdullah et al. (2020) in Pakistan demonstrated the efficiency of CWs and how well they can help the water-stressed communities in the continent. Even though there are not many studies in the African context, (Kilingo et al., 2022) showcased the satisfactory performance of a vertical flow CW for treating domestic wastewater in Kibera Slum, Kenya. South American nations also had pilot studies in the subject area (Carneiro et al., 2022) looked at raw sewage treatment by a vertical flow CW in the city of Joao Pessoa in north-eastern Brazil. However, it has to be noted that pilot studies sometimes fail in field implementations because of the use of synthetic wastewater instead of raw wastewater (Thakur & Das, 2021).

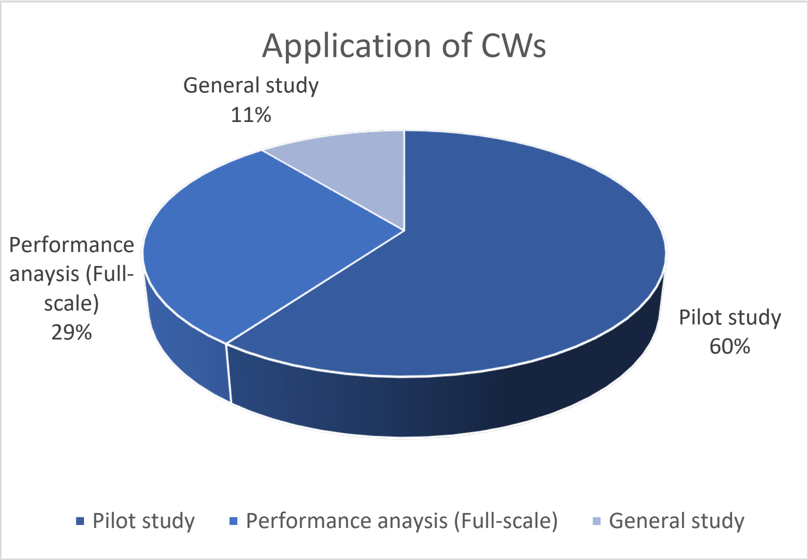

Figure 2 Practice and application of CWs in the studies

As shown in Figure 2, about 29% of the studies reviewed were performance analyses of full-scale constructed wetlands indicating a poor practice rate. It must be noted that primarily Asian and European countries have adopted CWs as wastewater treatment systems, followed by South American nations. It is visible from Table 1 that countries like China and India mostly lead when it comes to wastewater treatment using CWs. Muduli et al. (2022) conducted a study analyzing the performance of multistage CW in Gujarat, India, over three seasons. The results indicated the efficiency of the CW, albeit with average removal efficiencies in seasons with low radiation hours, but overall, the CW was able to handle the pollution load. Another interesting study was done by (Khairalla et al., 2016), who conducted the performance analysis of a horizontal subsurface flow-CW under different loading rates in Wuxi City, China. The findings showed that lower hydraulic loading rates and higher temperatures boosted the removal efficiencies of the CW. The HF-CW was a practical solution in places with inadequate sanitation, combining high removal efficiencies for pollutants with effective nutrient removal. Turkey and Spain are some of the European countries with studies on performance analysis in the review. Andreo-Martínez et al. (2017); Aydın Temel et al. (2018) conducted performance analyses on horizontal subsurface flow-CWs in treating domestic wastewater in Samsun, Turkey, and South Eastern Spain, respectively. For South America, Brazil is one of the nations that have adopted CWs as wastewater treatment systems, as illustrated by (Paulo et al., 2013), who looked at the performance of hybrid-constructed wetlands in treating both greywater and blackwater in Campo Grande. The few performance analysis studies of full-scale CWs in this study show that the systems are efficient and effective in treating wastewater. However, it has to be noted that sometimes, CWs are seen as secondary treatment methods that work with other primary decentralized methods. Of the 55 studies in the review, about 23 studies mentioned a primary treatment method. These included septic tanks (Aydın Temel et al., 2018; Kahl et al., 2017; Rehman et al., 2022), anaerobic baffled reactors (Ali et al., 2018; Ayaz et al., 2015), settling ponds (Mburu et al., 2013; Nivala et al., 2018), up-flow anaerobic sludge blankets (Ayaz et al., 2015), biofilters (Adrados et al., 2014), Imhoff tanks (Nivala et al., 2018), sedimentation tanks (Deeptha et al., 2015; Fountoulakis et al., 2017; Khairalla et al., 2016), activated sludge (Bilgin et al., 2014; Verlicchi et al., 2013), and moving bed bioreactors (Lai et al., 2021).

3.3 Wastewater treatment principles in CWs

As mentioned earlier, aquatic plants have a significant role in wastewater treatment in CWs. However, besides plants, other things contribute to the biodegradation of pollutants, including bacteria, the type of media used, etc. Regarding aquatic plants, the specie and kind used also has a bearing on pollutant removal efficiencies. As mentioned by Pinninti et al. (2021), aquatic plants help in wastewater treatment by absorbing nutrients, heavy metals, toxic substances, and oxygen transfer for metabolism and improving the hydraulic properties of the media. Of the 40 species identified in Table 1, about 10 of them were used twice or more. Figure 3 below shows the different plant species used more than once in the studies reviewed. The most used plant species in constructed wetlands for domestic wastewater treatment is *phragmites australis*. It was mentioned about 15 times. As illustrated by Andreo-Martínez et al. (2017), Kilingo et al. (2022), and (Çakir et al., 2015), *phragmites australis,* popularly known as the common reed has very high removal efficiencies in both organic and inorganic pollutants. In the pilot study by (Kilingo et al., 2022) in Kenya, the average removal efficiencies for the main wastewater parameters; COD (Chemical Oxygen Demand), TN (Total Nitrogen), Nitrates, TP (Total Phosphorous), Phosphates, TSS (Total Suspended Solids) were 93%, 37%, 39%, 74%, 79%, and 98% respectively. The study's second most used plant species was *canna indica,* with nine mentions. A pilot study by Pinninti et al. (2021) in India used *canna indica* as the plant species, and the removal rates for Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD) were 87% and 91%, respectively. Similarly, nutrient removal efficiency for total nitrogen (TN) and total phosphorus (TP) was found to be 97% and 98%, respectively, indicating the effectiveness of the plant.

Typha Latifolia followed with about six mentions in the studies. *Typha angustifolia, Juncus maritimus*, and *Cyperus artenifolious* had three mentions each. Finally, species with two mentions were *Vetiveria Zizanoides, Cyperus papyrus, Juncus acutus,* and *Halia dealbata*. Aquatic plants are one of the reasons that make CWs a cheap and sustainable wastewater treatment option. Most plant species are found locally in any region or part of the world; therefore, there is no expense.

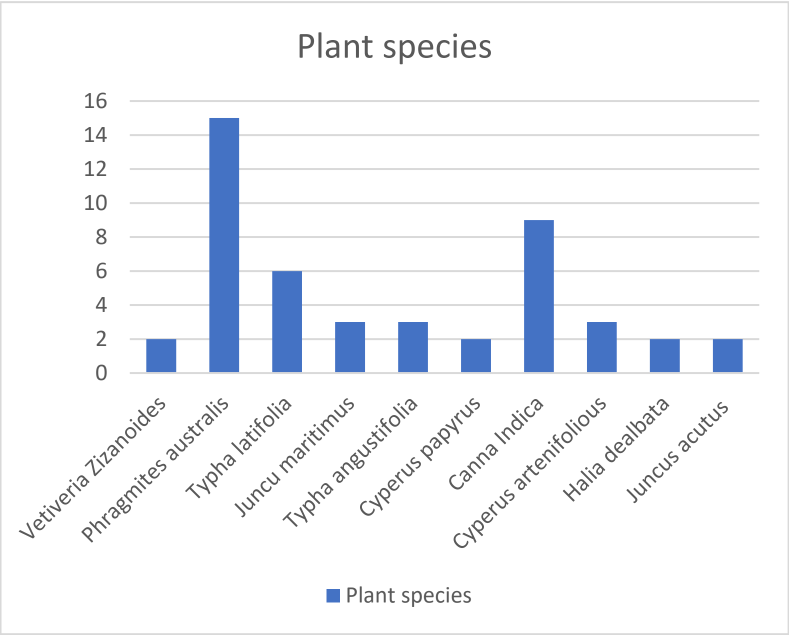

Figure 3 The most used plant species in the studies

The other two most important elements besides plants for pollutant degradation in CWs are microbial and media. Although not mentioned in many studies, a few highlighted the paramount importance of microorganisms and media in pollutant removal. Of the 55 studies in the review, besides general studies, only five outrightly looked into the role of bacteria in pollutant degradation in CWs. Adrados et al. (2014) in Spain looked into microbial communities in both VF-CWs and HF-CWs; (Salgado et al., 2018) study in Cuba focused on domestic wastewater treatment by constructed wetlands enhanced with bioremediating rhizobacteria; (Lai et al., 2021) looked at the microbial community in a CW integrated with a moving bed bioreactor (MBBR) in China; (S. qing Wu et al., 2013) also looked at the microorganism community of an integrated vertical-flow constructed wetland; Finally, (Zeng et al., 2021) study looked into the microbial community that promotes COD, TP, and TN removal in CWs. The study by Salgado et al. (2018) concluded that rhizospheric bacteria contain detoxifying enzymes that allow them to cope with polluted environments. The role of bacteria is clearly outlined by (S. qing Wu et al., 2013); the study indicated that facultative or obligatory aerobic/ anaerobic bacteria control the biodegradation of organic materials while aerobic respiration is more effective and feasible for the removal of organic contaminants. Nutrient removal by bacteria in CWs, especially nitrogen, heavily depends upon three biological processes: denitrification, nitrification, and ammonification (Lai et al., 2021). However, the study by Zeng et al. (2021) concluded that while CWs are great in nitrogen removal, they are very poor in phosphorous removal because phosphorus does not have an atmospheric component that facilitates and encourages microbial activities. The general study by (Valipour & Ahn, 2016) also stated that the bacteria's role in CWs either as attached biofilm or as suspension bacteria is crucial because of the quick generation time, high metabolism, and versatile metabolic pathways, all of which favour pollutant degradation.

The role of media in the treatment of wastewater in CWs is poorly mentioned in the studies reviewed. Of the 55 studies, only four out rightly looked into the role of different substrates in removing pollutants in CWs. H. Wu et al. (2016) looked into sludge-ceramsite as a substrate in an effort to enhance nitrogen removal in CWs. The results concluded that sludge-ceramsite significantly intensified the removal of organic pollutants and nitrogen with removal rates of COD (97.2%), NH_4^+-N (98.9%), and TN (85.8%). The other study by Tan et al. (2019) looked into using activated alumina as a substrate to enhance organic and nutrient removal in a tidal flow CW. The study again concluded that using activated alumina is advantageous in pollutant removal; the average removal efficiencies were 85.9% COD, 85.4% NH_4^+-N, 72.8% TN and 96.4% TP, respectively. In India, Shingare et al. (2017) looked into the performance of different substrates in treating domestic wastewater. The study found sand to be highly efficient in the removal of BOD and TSS, while marble chips had a very high removal percentage rate in COD. However, it has to be noted that the regularly used media material in CWs is soil, sand, and gravel. In contrast, alternate media can be dolomite, laterite, zeolite, limestone (as already stated), norlite, polonite, coal fly ash, etc. (Valipour & Ahn, 2016). The choice of media to be used is crucial because the media can strongly affect hydraulic conductivity, macrophyte growth, and the biofilm's attachment.

3.4 Emerging themes in domestic wastewater treatment by CWs

One of the most prevalent themes in the studies is water reuse. As mentioned earlier, one of the advantages of using CWs for wastewater treatment is they allow water reuse for different activities, relieving stress on the already strained water sources. However, it has to be noted that from the 55 studies in the review, only 12 out rightly mentioned water reuse. As mentioned in the studies, the most reuse activity for the water from CWs is irrigation, with 12 mentions (Andreo-Martínez et al., 2017; Ayaz et al., 2015; Bekkari et al., 2022; Datta et al., 2021; Fountoulakis et al., 2017; Kilingo et al., 2022; Muduli et al., 2022; Nivala, Abdallat, et al., 2019; Oliveira et al., 2021; Paulo et al., 2013; Shingare et al., 2017; Song et al., 2021). The second most cited activity was landscaping, with three mentions (Bekkari et al., 2022; Kilingo et al., 2022; Oliveira et al., 2021); the reuse of purified effluent for urban green spaces and golf courses is widespread, as illustrated by (Bekkari et al., 2022) in the village of Temacine, Algeria. Lastly, gardening, recreation, and landscaping had a single mention (Kilingo et al., 2022) in the studies reviewed. According to Muduli et al. (2022), the treatment efficiency of CWs is generally high, and the purified water is free from toxins and pollutants while being rich in nutrients. Therefore, it can be used for crop irrigation and a host of other activities. Biomass use was one of the other interesting issues in the studies. The nutrient-rich plants used in CWs, according to the studies by (Datta et al., 2021; Oliveira et al., 2021), can be used as livestock fodder. This is clearly illustrated in the city of Kothapally, India, where 500 kgs of biomass were harvested after 45 days and were used to feed the livestock of the nearby farmers (Datta et al., 2021). Besides biomass, the study by (Song et al., 2021) mentions the use of sludge as applied fertilizer to improve the yield in crop irrigation. Biomass can also be used for bio-electricity generation with a setup that includes constructed wetlands coupled with microbial fuel cells; however, this system is still novel in the subject area. This was illustrated in the studies by (Thakur & Das, 2021; Wang et al., 2017) in China and India, respectively. The energy-recovering abilities of the constructed wetland coupled with a microbial fuel system make it one of the best CWs options in domestic wastewater treatment.

4. Conclusion

The systematic review identified 55 publications on domestic wastewater treatment by constructed wetlands over the last ten years. There has been a recent steady rise in publications, particularly in Asian countries such as India and China. However, there is a lack of research in Africa, which is concerning as the continent is greatly affected by inadequate sanitation. Most of the studies in the review were pilot studies, comprising 60% of the 55 papers. Using raw wastewater in pilot studies is encouraged to avoid failures in field-scale implementation as it better represents the reality on the ground. About 29% of the studies were performance analysis studies, indicating few field-scale applications of constructed wetlands as domestic wastewater treatment. The most commonly used plant species in constructed wetlands was found to be *phragmites australis*. One setback of constructed wetlands is their poor phosphorus removal. Water reuse, specifically for agricultural use, was one of the most prevalent topics in the studies. Additionally, bio-electricity generation is also an emerging trend in the field. Constructed wetlands potentially offer a sustainable decentralized sanitation alternative. However it has to be noted that this study was limited because it only included the Scopus and Google Scholar databases and focused only on domestic wastewater. Therefore, future research should include other databases to understand further the efficiency of constructed wetlands in treating high-strength wastewater such as industrial wastewater.

Declaration of Competing Interest

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

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