Constructed Wetlands for Wastewater Treatment: A Scientometric Review of Research Trends

Happison Muzioreva*[1], Trynos Gumbo[2], and Innocent Musonda[1]
[1]University of Johannesburg, Centre for Applied Research + Innovation in the Built Environment (CARINBE), 55 Beit Street, Johannesburg, South Africa (*Corresponding Author)
[2] University of Johannesburg, Department of Urban and Regional Planning, 55 Beit Street, Johannesburg, South Africa
happymuzioreva@gmail.com (H. Muzioreva),tgumbo@uj.ac.za (T. Gumbo), imusonda@uj.ac.za (I. Musonda)

Neema Kavishe
Ardhi University, Department of Building Economics, PO Box 35176, Dar Es Salaam, Tanzania
neykluvert@yahoo.com (N. Kavishe)

Abstract

In recent times, interest in decentralized sanitation alternatives, especially constructed wetlands (CWs), has spiked because of the need for wastewater treatment systems that allow effluent reuse, all in an effort to try and meet the rising demand for new water sources. Therefore, due to the increase in research in the subject area, the present study aimed to identify the research trends and prevailing themes in the existing literature on constructed wetlands as domestic wastewater treatment systems. A scientometric methodology was adopted in the study. The scientometric review was conducted using the VOSviewer and Citespace software. A total of 68 peer-reviewed journal articles were quantitatively analyzed using Various methods such as co-authorship analysis, co-citation analysis, and keyword analysis. Constructed wetlands were found to be very effective and efficient in pollutant removal, nutrient recycling, and water recycling through the identified clusters. The advancement and modification of CWs to make them better at treating new toxins was a welcome notion in the field. However, the lack of extensive collaboration among researchers needs to be improved for the betterment of the field through ideas and information exchange. The study was limited because it was conducted using the Scopus database and only focused on domestic wastewater. Therefore, future research can be centred around other types of wastewater using databases other than Scopus.

Keywords
Constructed wetlands, Domestic wastewater treatment, Decentralized sanitation, Sustainable sanitation, Scientometrics

1. Introduction
The increasing demand for water brought on by urbanization around the world has a variety of socioeconomic repercussions that have put further strain on scarce natural resources. According to Waly et al. (2022), in the last 50 years, the world's water demand has tripled, diminishing the available water supplies. As a result, non-traditional water resources are now required to manage water sources sustainably. Wastewater reuse is one of the options that can cover the gap of water shortage globally. However, this approach needs careful consideration because it is controlled by the reuse plans, which demand ad hoc effluent quality with the planned water use (Abdullah et al., 2020). As a result, it is believed that to avoid any potential adverse effects resulting from the various wastewater usage applications, a high-efficiency treatment system with low to minimal risks is needed (Waly et al., 2022).
Constructed wetlands (CWs) are, therefore, one of the systems that can potentially be the treatment technology that allows water reuse. CWs are a rapidly expanding class of wastewater treatment techniques built to mimic natural wetlands' physical, biological and chemical processes (Machado et al., 2017). In agreement, Hassan et al. (2021) state that these systems are artificial wetlands constructed to function and resemble natural wetlands utilizing plants, microorganisms, and soil to treat wastewater. Therefore, CWs are seen as low-cost technologies with little operating and maintenance needs that can be used in various socioeconomic contexts because they rely on indigenous plants

and microorganisms. Because of this, CWs are a cost-effective treatment alternative compared to conventional systems and other decentralized sanitation alternatives.

1.1 Background

Constructed wetlands depend on biological processes like plant assimilation and biodegradation, chemical processes like adsorption and precipitation, and physical processes like filtration and sedimentation for the treatment of wastewater (Pinninti et al., 2022). Plants play a significant role in CWs processes. However, due to the low oxygen concentration of wetlands, it has to be noted that only vascular plants are used in CWs as they thrive in low-oxygen environments (Shukla et al., 2021). High-density vegetation in CWs offers pollutant adsorption sites and creates microenvironments that act as microbe attachment sites (Machado et al., 2017). Furthermore, Oliveira et al. (2021); Shukla et al. (2021) add that plant waste is also a good source of nutrients (nitrogen and phosphorus) and organic carbon for the metabolism of microorganisms. Apart from plants, microorganisms are also crucial to the degradation of contaminants and the transition of contamination from the environment to the plant (Oliveira et al., 2021). According to Machado et al. (2017), the processes of pollutant degradation in CWs typically involve microbial consortia, each with a unique degrading mechanism for each particular pollutant. In design, CWs are characterized by slow water flow and shallow water depth (Nivala et al., 2018). The lengthy retention times caused by the slow water flow enable sedimentation and lengthen the time that the wastewater is in touch with the components of the wastewater (Hassan et al., 2021). Therefore, selecting the appropriate flow velocity in any CW is crucial to give the microorganism adequate time to break down the pollutants.

The primary purposes of CWs are to improve the quality of effluent and recycle nutrients. The significant advantages of wetlands include low maintenance and operation costs, low construction costs, and high flexibility in the landscape design to provide shelter for organisms and wildlife, their environmentally friendly approach, and their ability to facilitate the reuse of treated water (Hassan et al., 2021; Waly et al., 2022). Table 1 below summarizes the economic values of CWs based on their direct, indirect, option, and existence value.

Table 1. Economic value of CWs

Direct values	Indirect values	Option values	Existence values
Resources	Function and Services	Future applications	Intrinsic significance
Recreation	Water quality attenuation and supply	Industrial	Biodiversity
Irrigation	Energy saving	Agricultural	Landscape
Water	Carbon sequestration	Pharmaceutical	Aesthetic
		Other application	

Adopted from (Waly et al., 2022)

Even though they have many benefits, CWs have some limitations to their applications, such as low tolerance for conditions of near-complete drying, inability to treat if discharge meets specific standards, large land requirements, and inconsistent treatment (Machado et al., 2017). Despite these few minor setbacks, CWs have been used all over the world as wastewater treatment systems. According to Hassan et al. (2021); Waly et al. (2022), CWs have been in use since the second part of the 20th century, with service in large numbers in European nations such as Denmark, Turkey, Austria, the United Kingdom, Slovenia, and Switzerland; several African countries such as Kenya, Seychelles, South Africa, and Tanzania; Asian nations such China (with more than 400 CWs), India, Pakistan; South American countries such as Brazil, Colombia, and Argentina. Numerous academics have described the apparent benefits of using CWs for wastewater treatment as green and sustainable technology, and as a result, there have been enormous gains in both research and applications (Waly et al., 2022). Therefore, due to the increase in research in the subject area, this study seeks to map out and identify the research trends and prevailing themes in the existing literature on constructed wetlands as domestic wastewater treatment systems.

2. Materials and Methods

This work used a quantitative approach based on scientometric methods to asses, depict, and discuss the defined research objectives. The methodology was used to look for novel patterns in the behaviour of published literature, mainly journal articles, patterns of collaboration and research components, and the theoretical underpinnings of constructed wetlands as domestic wastewater treatment systems. Although scientometric reviews are novel in completed wetlands studies, few examples have previously employed them. Zhang et al. (2021) used scientometrics in their research on *"A review on China's constructed wetlands in the recent three decades: Application and practice"*. The approach was also used by (Oliveira et al., 2021) in their review on *"Floating treatment wetlands in domestic wastewater treatment as decentralized sanitation alternative"*.

2.1 Scientometric review

Early studies on scientometrics (Karami et al., 2011) define it as the quantitative analysis of scientific fields based on communication and published literature, all of which includes discovering new fields of scientific study, analyzing how research has evolved through time, or analyzing how research is distributed geographically and organizationally. According to Donthu et al. (2021, scientometrics is the application of quantitative methods to bibliometric data, such as bibliometric analysis or citation analysis. Moreover, scientometrics typically employs mathematical and statistical examination of bibliographic data through scientific mapping techniques (Cooper, 2015). Scientific mapping techniques, according to Oliveira et al. (2021), are data visualization techniques that help scientists compare and contrast the structure and dynamics of scholarly knowledge and include methods such as bibliographic coupling, citation analysis, keyword analysis, and co-citation analysis.

As highlighted by Cooper (2015); Donthu et al. (2021), to make it easier to analyze bibliographic data in a reasonable practical manner, bibliometric software tools such as VOSviewer, Citespace, or Gephi are used. This study used VOSviewer and Citespace to produce scientific maps. VOSviewer is an analysis software that provides visually comprehensible, aesthetically beautiful, and decipherable bibliometric maps and graphs, which allow users to see interactions, links, networks, and comparisons among bibliographic data (Onososen & Musonda, 2022). Furthermore, Donthu et al. (2021); Oliveira et al. (2021) state that it is advantageous because it is user-friendly and can use different databases simultaneously. Citespace, on the other hand, much like VOSviewer, integrates clustering and social network analysis techniques as software for data mining and visualizing scholarly publications primarily drawing on the concepts of community factor analysis and pathfinder network scaling (Niu et al., 2022). According to Che (2017), Citespace is very advantageous because it has sound visualization effects, fast processing speeds and strong readability in data analysis. Hence, the researcher chose to use the two software for the present study. Figure 1 below shows the methodological scheme followed in the scientometric analysis.

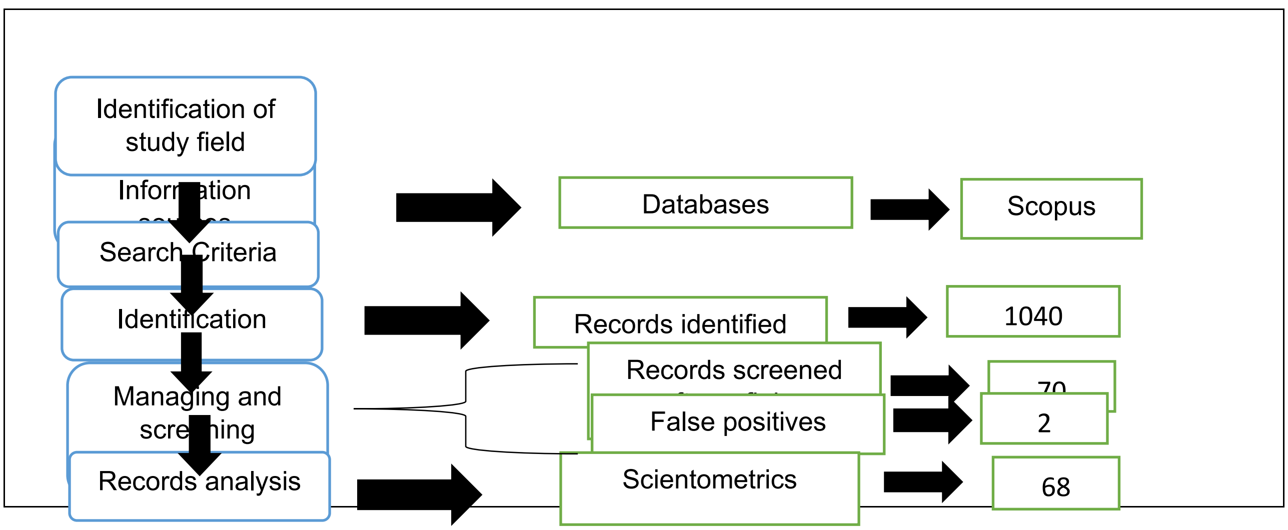

Figure 1: Schematic of the scientometric process

There are a host of databases where researchers can obtain data for scientific enquiry, chief amongst them are the most popular google scholar, Web of Science, and Scopus. The researcher in this study used Scopus as the database for data retrieval, as shown in figure 1. Web of science was disqualified as a database for data retrieval because almost all of the scientific publications in Web of Science are also found in Scopus. Google Scholar is a much more extensive repository than both Scopus and Web of Science, but as (Onososen & Musonda, 2022) highlighted, it has issues indexing publications since it counts conference abstracts, and this inevitably leads to an enormous increase in the number of papers, therefore, making it difficult to conduct a scientometric review. Hence, the choice to use Scopus.

Therefore, search words were entered in Scopus, as shown in Table 1, and the results showed about 1040 documents. The years were limited to two decades, from 2002 to 2022. The search was left to include all countries as the study's objective is to try and understand the recent research trends in constructed wetlands as domestic wastewater treatment systems. The search was then refined to the subject area of engineering and the English language; the resulting tab showed about 70 relevant documents, as illustrated in Fig 1. Further refinery was done through abstract filtering. The researcher read through the abstracts of all 70 documents to eliminate all the documents irrelevant to the subject area. Two documents were identified as false positives and were removed; the remaining 68 documents were retrieved for analysis. The 68 documents were then analyzed in Vosviewer and Citespace software using the following analysis techniques: Co-occurrence, Co-authorship, and Co-citation. Table 2 below shows the essential parameters of the search strategy used in Scopus for data retrieval.

Table 2 Parameters of the search strategy

Search Words	Constructed wetlands and Domestic wastewater treatment
Document Type	Journal Article
Subject Area	Engineering
Period time	≤ 2022
Language	English
Limit to (Query)	Scopus: Title-Abs-Key (Constructed wetlands and Domestic wastewater treatment) and publication year >2001 and publication year < 2023 and refined by (Document type: Article; Subject Area: Engineering; Key Words: Wastewater treatment, wastewater management; Language: English; Source Type: Journal)
Search Date	November 2022

3. Results and Discussion

The results from the analysis are presented below. The first section covers the overview of the research publications, followed by co-citation analysis in section 3.2. The next section covers the results of the co-occurrence analysis. The penultimate section covers the results of the results of the co-authorship analysis. Finally, the last section summarizes the results by giving an overview of the lessons learnt and the recommendations.

3.1 Oversight of publications

Regarding publication trends in the past two decades, China leads the research outputs with 21 papers in the subject area as shown in Figure 2 below. India and the United States of America followed with eight and six publications, respectively. Brazil, Turkey, and the United Kingdom followed with four research outputs in the subject area. Africa was also represented in research outputs by countries like Tunisia, with two publications, and Morocco and Uganda, with a single publication each. A developing country like China leads in research outputs in CWs mainly because of the need of the country to find sanitation alternatives for their large populations. The same can be said about India and nations like Brazil. However, developed nations like the USA can be considered anomalies to this general notion. But it can be argued that the increased research outputs in the subject area from these countries are because of the push for sustainable alternatives to the energy-intensive conventional systems. Only a few African nations are present; this is concerning as these countries particularly need solutions to the problems posed by poor sanitation frameworks, which in turn cause health risks amongst the majority of all African countries. The future allows more research in the subject area, especially for the African nations, to try and turn theory into practice.

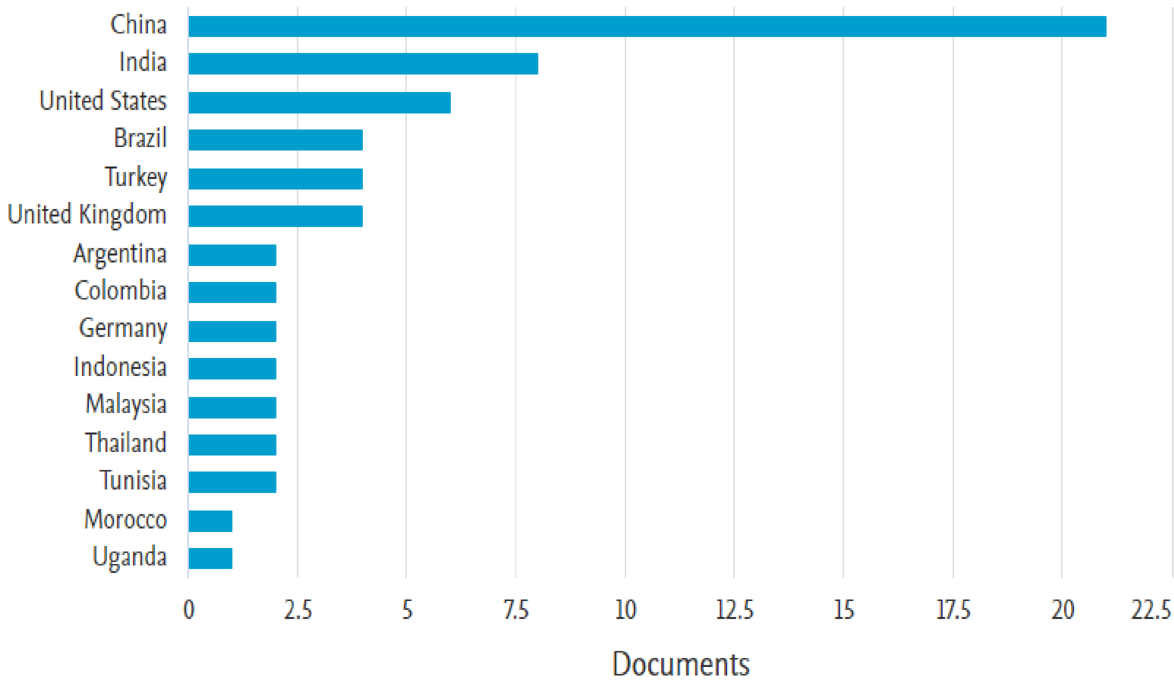

Figure 2. Research publications by country

3.2 Co-citation analysis

The first analysis which was run in the software was co-citation analysis. Co-citation analysis is a scientific mapping method that assumes that papers that are frequently cited together have similar themes, and the analysis can be used to discover the study's underlying hypotheses (Donthu et al., 2021). This study used author co-citation analysis, as illustrated in the visualization in Figure 3. For an accurate analysis, the minimum number of citations per author was set at 10. Out of the 5178 authors identified, only 77 met the threshold. The most cited authors in the subject area were Vyzmal, J with 101 citations; Brix, H with 75 citations and Zhang, J with 35 citations. One of the studies by Vymazal (2009) describes the performance of two horizontal subsurface flow-constructed wetlands in the Czech Republic. The study's findings suggested that when suspended particles and organics are the predominant pollutants, horizontal-flow constructed wetlands are a viable alternative to the modest sources of contamination. Being one of the most influential authors in the subject area, (Vymazal, 2010) study on constructed wetlands as domestic wastewater treatment concluded the same also, stating that the removal of organics and suspended particles are quite effective in constructed wetlands while nutrient removal is poor. However, poor nutrient removal in CWs can be offset by combining different types of CWs and using a medium with high adsorption capacity. Zhang et al. (2010)also had a study with the same underlying themes as Vyzamal, J. The study showed that artificial aeration in CWs is an innovative or cost-effective technology for treating domestic wastewater because it is more productive technologically and economically, especially in nutrient removal. Both Vyzamal, J and Zhang, J seem to agree that besides the traditional advantages of CWs, such as being substantially cheaper in operation and maintenance and environmentally sustainable, they also provide many functions, such as carbon sequestration, flood control, or wildlife habitat.

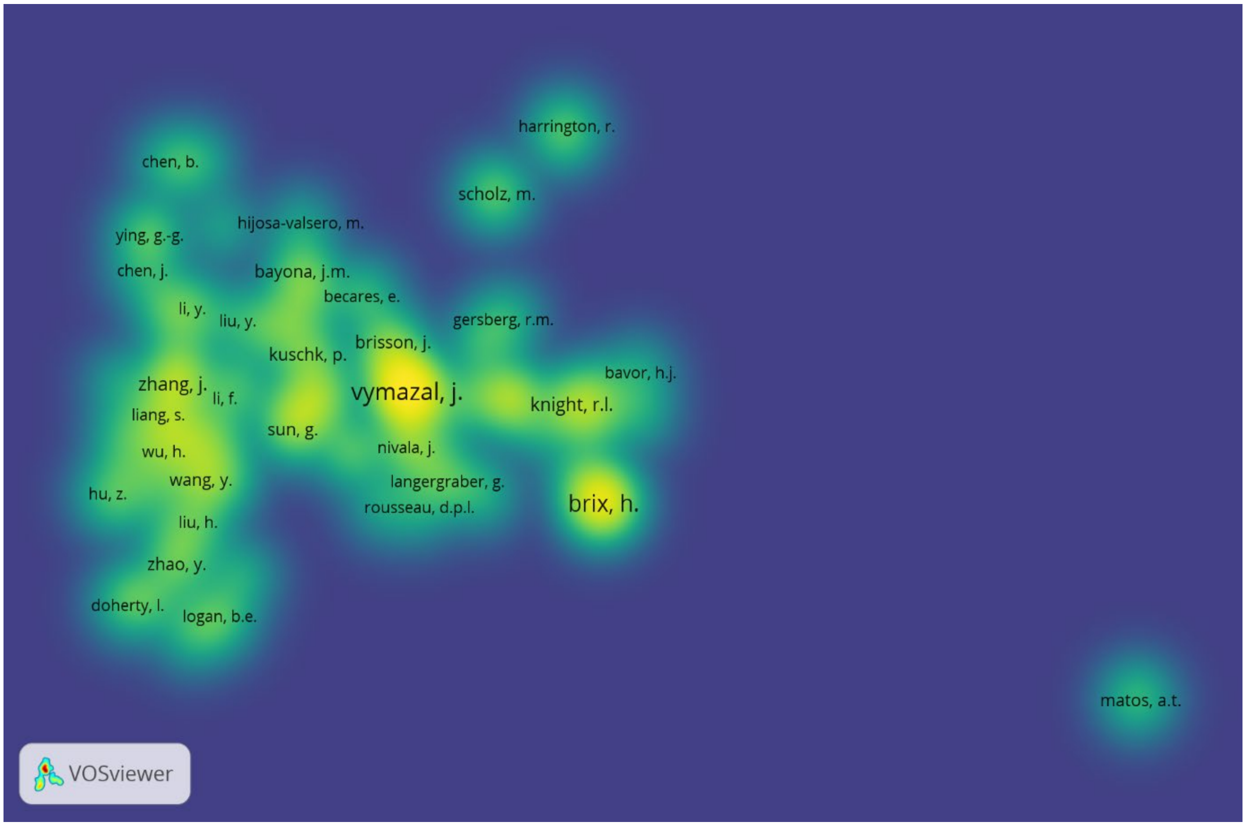

Figure 3. Author co-citation density map

3.3 Co-occurrence analysis

Co-occurrence analysis is a method that examines the text of a publication, sometimes referred to as keyword analysis. According to Donthu et al. (2021), co-occurrence analysis indicates that words that commonly occur together have a thematic relationship. However, it has to be noted that the technique has drawbacks in the sense that certain words can be termed as keywords even though they are out of context, and in addition, general words can be termed as keywords. The first analysis was run in Citespace. The analysis was done using only one splice from 2002 to 2022. Figure 4 and 5 represent the keyword analysis in Citespace. Figure 4 shows the network for keywords, including the clusters, formed, whilst Fig 5 shows the neural network of the keyword analysis. The second analysis was done in Vosviewer. Fig 6 shows the co-occurrence analysis in the VOSviewer software. For this analysis, for a word to be included, the minimum number of co-occurrences of that particular word was supposed to be five. Out of 796 words, only 38 met the threshold.

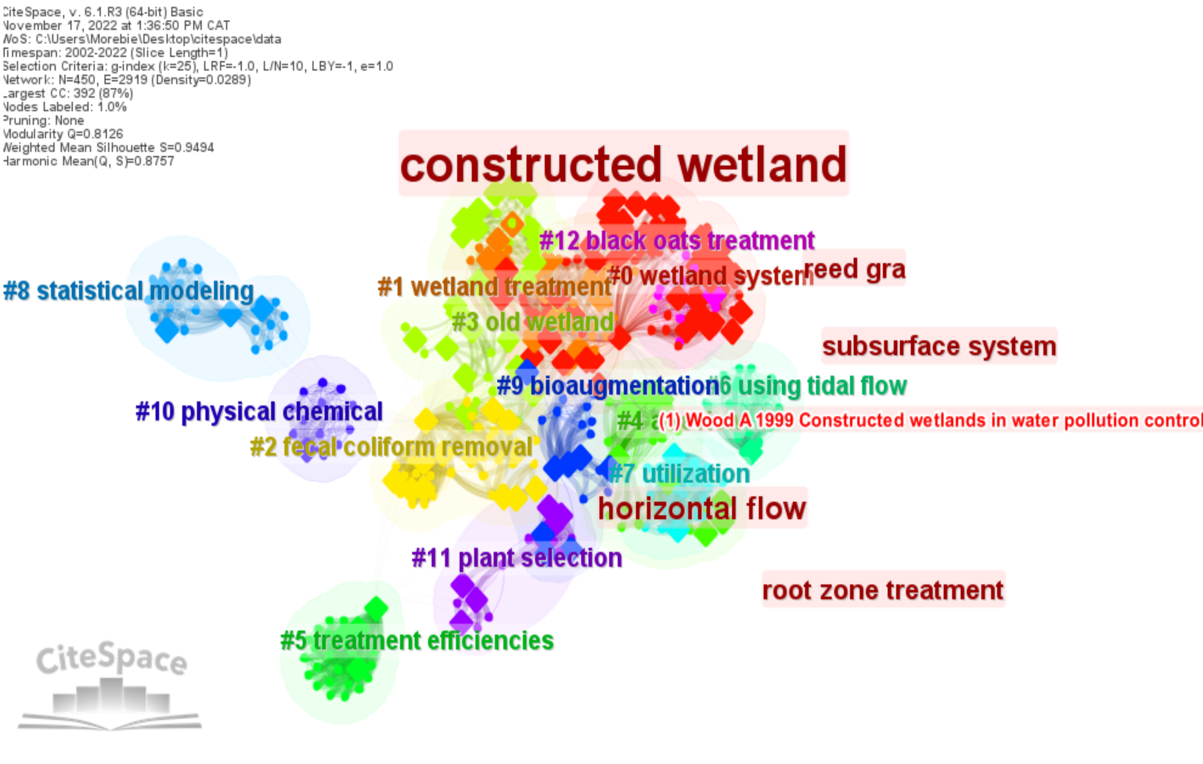

Figure 4 Key words network including clusters

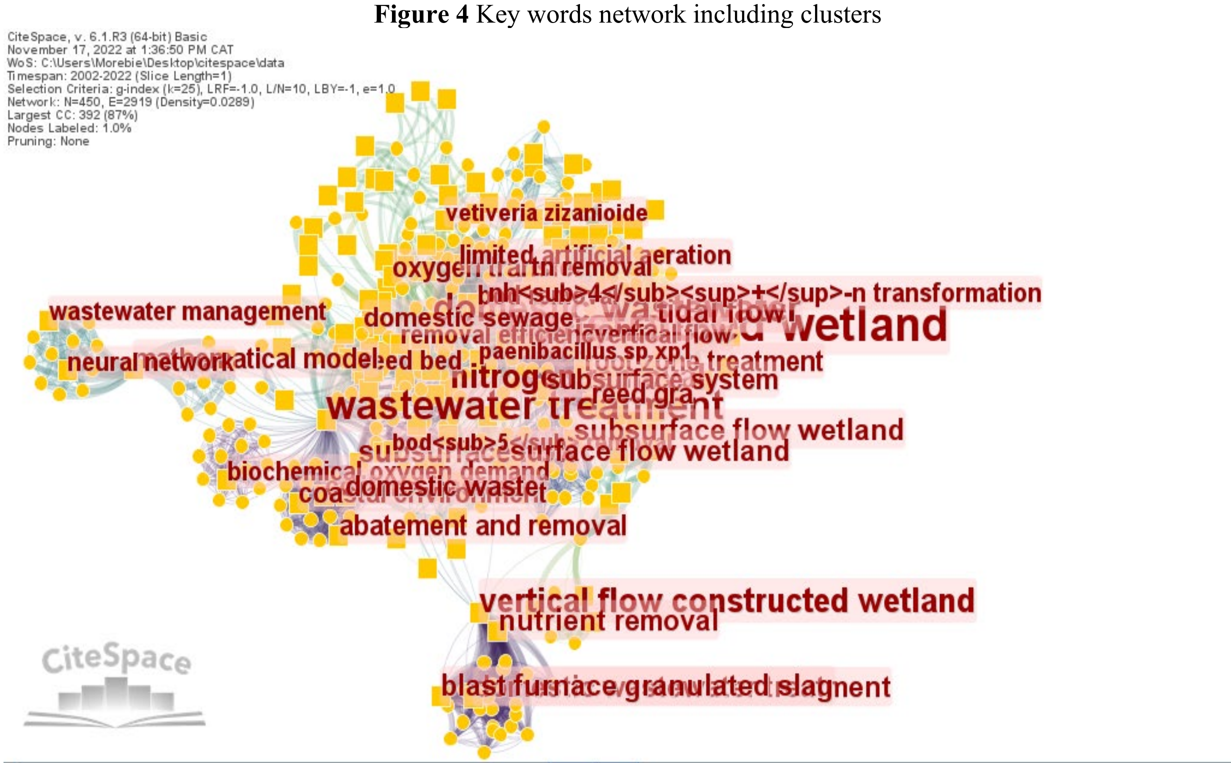

Figure 5. Keyword neural network

<u>Citespace analysis</u>

The clusters identified by the Citespace software, as illustrated in, Figure 4, include wetland treatment, plant selection, bioaugmentation, statistical modelling, treatment efficiencies etc. It has to be noted that Citespace struggles to label its clusters when compared to VOSviewer. However, from the analysis of the keywords in Fig 5, there are apparent keywords that stick out. The types of CWs are clearly shown in Figure 5; the most prevalent types are the tidal flow CW, the horizontal flow CW, and the subsurface flow CW. A study by Kabbour et al. 2022) specifically looked at domestic wastewater treatment by a tidal flow CW in Casablanca, Morocco. The results showed steady treatment efficiencies of 70% BOD (Biological Oxygen Demand), 80% for COD (Chemical Oxygen Demand), and 73% for SS (Suspended Solids), and the effluent from the CW was within Morocco's legal guidelines for discharge. Delgado et al. (2020) also looked at the removal of new pollutants like personal care products from domestic wastewater using a subsurface flow CW in Medellin, Colombia. The abatement and removal efficiency was above 95% for the organic load. Plant selection was also one of the significant clusters in Figure 4. The plant that sticks out here is *vetiveria zizanoides,* as illustrated in Figure 6. The study by Abdullah et al. (2020) looked at the performance of CWs using *vetiveria zizanoides* in Malaysia and showcased the effectiveness of the plant in pollutant removal. This is, however, different from the VOSviewer software analysis, as will be shown later in the discussion. Generally, from the keywords identified, one can conclude that CWs offer reliable pollutant removal, faecal coliform removal, and nutrient removal satisfactory enough to warrant the application of the various types of CWs in multiple countries across the globe.

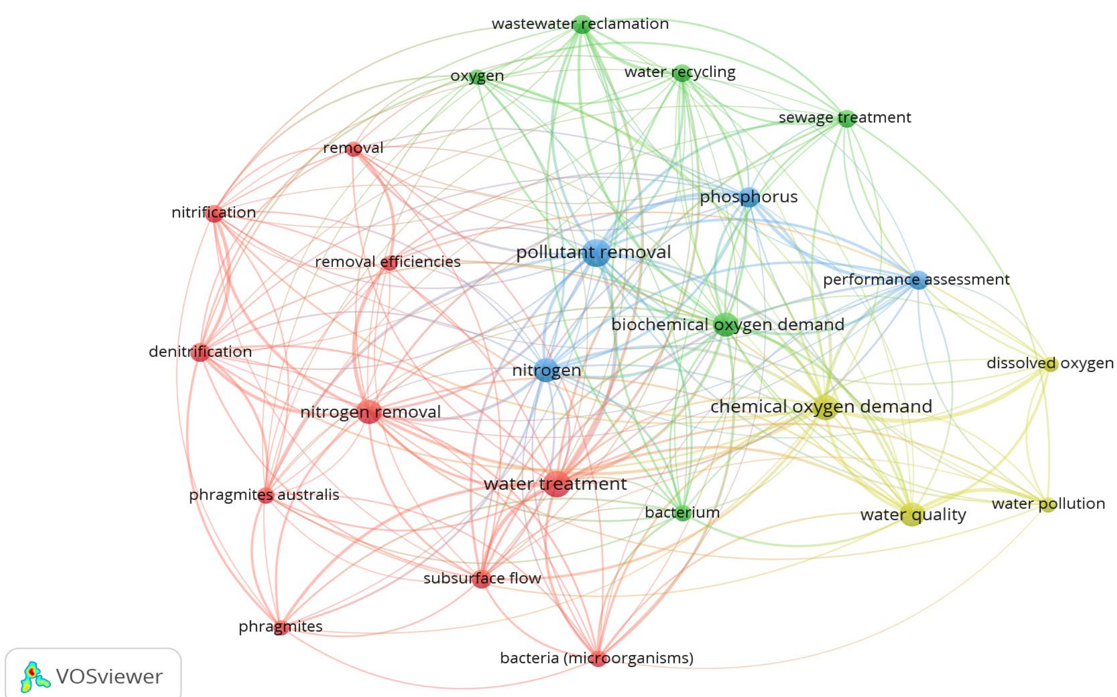

Figure 6. Co-occurrence analysis

<u>VOSviewer analysis</u>

As mentioned earlier, the main difference between keyword analysis using Citespace or VOSviewer is that the latter clearly shows cluster items and groups them according to the prevailing theme of the key terms in that particular cluster. The keyword analysis using VOSviewer revealed about four clusters, as shown in Fig 6. Cluster one mainly describes the functionality of CWs and is represented by the colour red. Cluster two primarily speaks on water reclamation and is represented by the colour green. Cluster three, represented by the colour blue sub-theme, is nutrient removal. Finally, cluster four, represented by the colour yellow underlying theme, is effluent quality. Cluster one shows all the keywords in the processes of CWs. Contrasting to the Citespace analysis, the most popular plant type used in CWs, as illustrated in Fig 6, is *phragmites australis,* commonly known as the common reed. A number of studies indicated the varied use of the plant type. Mesquita et al. (2018) demonstrated the effectiveness of the plant in a full-scale horizontal subsurface flow CW in Sarnadas Rodao, Portugal. Besides aquatic plants, bacteria (microorganisms) also play a significant role in breaking down pollutants in CWs. A clear indication of the importance of bacteria is illustrated in the study by (Shao et al., 2013), where bio augmentation (specifically the addition of

Paenibacillus sp. XP1) was used to improve the removal efficiency of nitrogen in a CW in Shanda, China. Due to the poor nutrient removal abilities of CWs, the result of the study clearly showed that bioaugmentation improved nitrates and TN (Total Nitrogen) removal efficiencies. The other biological processes that take place in CWs include nitrification and denitrification, where ammonia is converted into nitrates and then reduced to nitrogen gas. It is, therefore, essential to note that for wastewater treatment, CWs employ a lot of biological and physiochemical processes based on the type of bacteria, media or plant available in the CW.

Cluster two is mainly speaking on wastewater reclamation and water recycling. One of the main advantages of CWs, as suggested by various authors, is their water-saving capabilities. De Simone Souza et al. (2017) looked at the feasibility of CWs in treating grey water for reuse. The study concluded that CWs as water-saving technologies need water utilities, the state government, and the local authorities to provide some subsidy if they do not attain the required economic viability. This can be justified because these systems produce favourable externalities that increase social welfare, such as crop irrigation and fish farming. The reclaimed water can also irrigate green spaces in cities to enhance the local microclimate, encourage energy conservation, and promote public health (da Silva et al., 2017). Cluster three's sub-theme is nutrient removal. It has to be noted that the poor removal of nitrogen and phosphorous in CWs has been well documented in scientific literature. However, steps have been taken to improve the removal of TN and TP in CWs; bioaugmentation is one of the methods used to enhance nutrient removal, as mentioned earlier. Besides the innovative methods, there are other types of CWs that are generally good in nutrient removal, as illustrated by (Cheng et al., 2021); tidal flow CWs are good in \nutrient removal, especially nitrogen. Nutrient removal can also be enhanced using plant types with high adsorption capacities, like *vetiveria zizanoides* (Abdullah et al., 2020). Finally, the last cluster focuses on water quality. The water quality mentioned herein is the effluent quality from the effluent from CWs. The consensus with CWs is that they produce effluent free from pollutants due to their high removal efficiencies, which is why it is safe for reuse. Ayaz et al. (2015) did a performance analysis of two full-scale hybrid CWs treating domestic wastewater near a water source in Kocaeli, Turkey. The results indicated that the CWs complied with the effluent discharge standards and never compromised the water quality of the nearby water source. Another perfect example is the study by (Kabbour et al., 2022) in Morocco which was mentioned earlier. Therefore, CWs are one of the best options for wastewater reuse because of their high-quality effluent.

3.4 Co-authorship analysis

Co-authorship analysis looks at how researchers connect with each other. According to Donthu et al. (2021), understanding how academics engage with one another is crucial because it is a formal way of measuring and assessing collaboration among researchers and identifying leading countries, organizations, or individual scientists in a particular research area. A co-authorship network for the present study is shown in Figure 7. A co-authorship network analysis was done using VOSveiwer for researchers who contributed significantly to constructed wetlands. The investigation was conducted as follows; the minimum number of documents per author was set at 1, and the minimum number of citations per author was set at 20. Out of the 280 authors in the 68 documents analyzed, only 96 met the threshold.

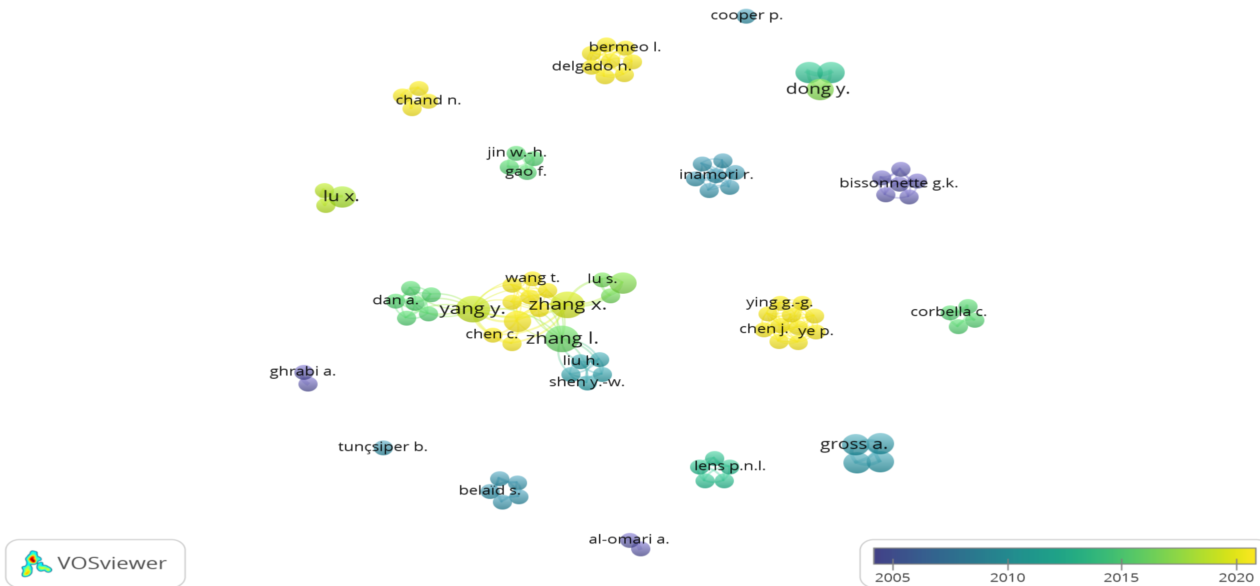

Figure 7. Co-authorship analysis visualization

The most active researchers in the area, as shown by the big nodes, are Zhang X, Zhang Y, and Zhang L, all with three documents each. One of the most recent works of Zhang X looked at the performance of a recirculating standing hybrid CW in treating wastewater mixed with heavy metals. In one of his earlier works. In the findings, X. Zhang et al. (2020) note that the recirculating standing hybrid CWs were influential in the co-precipitation of heavy metals, reducing their toxicity to plants and microbes. Regarding the timeline of the publications, the most recent ones are represented by the colour yellow. Bermeo L, Delgado N, Li K, and Chen J are some of the authors with the most recent publications. The current trends in CWs research, as highlighted by (Delgado-González et al., 2021), include trials in the improvement of phosphorus removal by using granulated apatite filters as the media in the systems. Li et al. (2021)also recently did an interesting study that looked at the role of wetland plants on wastewater treatment and electricity generation in a constructed wetland coupled with microbial fuel cells. The recent trends show a bit of progress in the betterment of CWs as wastewater treatment systems. However, it has to be noted that the highly disconnected nodes between authors in Figure 7 are a cause for concern as it shows little collaboration amongst the researchers in the field. There is only high interconnectivity between Asian authors, specifically Chinese researchers; this can be bad for the growth of the field in general as there is no passing on of information and exchange of ideas. With the introduction of new toxins to wastewater, the advancement of treatment methods is significant in combating these pollutants to protect and preserve human health. This duty mainly falls to scientific researchers. Therefore, there is a need for more information exchange collaboration to come up with new ideas and refine the old ones.

3.5 Lessons learnt and Recommendations

The review covered a lot of aspects, but there were a few critical and noteworthy points. The first point to note was the lack of research publications on the subject area from African nations. This can be attributed to many factors, like the lack of funding for research. Sanitation is sometimes the least pressing issue in these countries as they have a host of other social and economic problems that need immediate solutions. The second lesson from the review regarding the CWs themselves is that the choice of plant and media is significant for effective pollutant removal. The choice of plant and media will determine the microbial community responsible for the biodegradation of pollutants. The selection of plants and media also has a bearing on the overall performance of the systems; as showcased already, there other plants that facilitate better pollutant removal than others, whereas there are others that are better enhancers in nutrient removal than others. Thirdly, poor nutrient removal in CWs has also pushed researchers to experiment with different types of systems to make them well-rounded and efficient. Lastly, it can be seen that the research trends in the subject area are pushing for more technologically advanced techniques that can do multiple things at once, whether it is to produce renewable energy, deal with new toxins, or serve as wastewater reuse systems. The most cited and discussed themes as found in the analysis are listed below in Table 3

Table 3. Most cited themes

I.D	Theme
1	Effectiveness of CWs in treating physical, chemical and microbial contaminants in domestic wastewater
2	Impacts of different media on CWs in sewage treatment
3	Bio-elecricity generation in CWs
4	Effects of different weather conditions on CWs
5	Effectiveness of different types of CWs in treating domestic wastewater

Therefore, with all these things in mind, a few recommendations can be made to further the application and research on CWs.

- The discussion on CWs needs more African researchers because African nations are in dire need of cheap sanitation alternatives which are economically sustainable.
- In terms of application, careful consideration has to be done on the type of CW, the kind of plant and the media to use and consideration of the weather of the area also has to be taken into account.
- Finally, researchers in the field need to collaborate more with each other and pass on ideas on the advancement of the systems to deal with new toxins that come with the ever-expanding global environment.

4. Conclusion

Constructed wetlands offer a sustainable option for wastewater treatment. The interest in constructed wetlands as decentralized sanitation alternatives has garnered much interest recently, mainly because of their environmentally friendly approach to domestic wastewater treatment. This paper identified the research trends on domestic wastewater treatment using constructed wetlands. Developing countries like China and India lead the research publication the research area mainly because of the need to find sanitation alternatives to their hugely populated cities. Constructed wetlands have been concluded to be effective and efficient in pollutant removal, nutrient recycling, and water recycling. The advancement and modification of CWs are welcome in the field as it is crucial, especially in this day in age where new toxins are emerging daily. However, it has to be noted that a lack of collaboration among the researchers in the field is concerning as information and idea exchange is necessary to advance the research field. The presence of only a few African researchers is also a cause for concern as the continent is in dire need of cheap, sustainable alternatives to the centralized systems, which are not economical to these nations. However, it is important to note that the study was limited in that it was conducted using only the Scopus database and only focused on domestic wastewater treatment. Future research can therefore be conducted using other databases and should focus on the various types of waste water.

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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Biographies

Happison Muzioreva holds an Honours Degree in Quantity Surveying from the National University of Science and Technology in Zimbabwe. He is currently doing his Master's in Civil Engineering with the University of Johannesburg within the Faculty of Engineering and the Built Environment. His research interests include sustainability, sanitation, and wastewater systems.

Professor Trynos Gumbo is a C2 NRF rated researcher and a SACPLAN Registered Professional Planner; who is currently working as a Full Professor and leader of the Sustainable and Smart Cities and Regions (SSRC) research group within the Department of Urban and Regional Planning within the Faculty of Engineering and the Built Environment at the University of Johannesburg (UJ), South. Prof Gumbo holds a PhD from Stellenbosch University, South Africa, masters and honours degrees from the University of Zimbabwe in Rural and Urban Planning. He has published in a wide range of research areas that include smart and sustainable cities and regions, intelligent transport systems & infrastructure planning, integrated and sustainable human settlements, spatial analysis using geographical information systems to statistical analysis using statistical package for social sciences.

Professor Innocent Musonda is a C2 NRF rated researcher, who is currently working as a Full Proffessor in the department of Construction Management and Quantity within the Faculty of Engineering and the Built Environment at the University of Johannesburg. Professor Innocent Musonda holds a PhD in Engineering Management and qualifications in Construction Management and Civil Engineering. He is a registered Civil Engineer, a professional Construction Manager and a full member of the Chartered Institute of Building (CIOB). He has worked in the public and private sector in Botswana, South Africa and Zambia. He is a researcher, invited speaker, founder and director of the Centre for Applied Research and Innovation in the Built Environment (CARINBE) at the University of Johannesburg. He has served as a chairperson of an international conference series on infrastructure development and investment in Africa from its inception in 2014. Prof Musonda is also a roaming scholar at the University of Toronto, Canada, on the Engineering Education for Sustainable Cities in Africa Project (EESC-A). Research Interests include, Construction health and safety, BIM and digital applications in the Built environment, Infrastructure development and sustainability, Energy efficiency and environmental protection in built infrastructure, and Skills development and new knowledge areas for the Built environment.

Doctor Neema Kavishe holds a PhD in Civil Engieering. She currently works at Ardhi University in Dar es Salaam Tanzania as a lecturer at Ardhi University within the department of Building Economics. Dr Neema Kavishe did her PhD at the School of Civil Engineering, University of Birmingham in the UK. She does research in Construction and Project Management. Her research interests include Public Private Partnership, sustainability, and housing.