Carbon Storage and Sequestration in Constructed Wetlands: A Systematic Review

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국내 및 국외 적용된 인공습지 내 Bibliometric Analysis을 이용한 탄소저장 및 탄소격리 능력 분석

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Abstract

The use of constructed wetlands (CWs) to sequester carbon has been a topic of interest in recent studies. However, CWs have been found to be both carbon sinks and carbon sources, thus leaving uncertainties about their role in carbon neutrality initiatives. To address the uncertainties, a bibliometric and comprehensive review on carbon sequestration in CWs was conducted. Upon forming various scripts using CorText Manager, it was found that a majority of the studies focused on the effectiveness of CWs to remove nutrients, particularly nitrogen. The results of the comprehensive review revealed that high carbon concentrations and carbon sequestration rates in CW soils are dependent on the vegetation types used, the ages of the CWs, and the organic content of inflow water entering the CWs. The *Typha* genus was the most dominant plant genus used in the CWs from the reviewed studies and was associated with the highest carbon sequestration rates documented in this review study. Furthermore, the relatively high ability of tree species, in comparison to emergent plants, to sequester carbon was observed. Therefore, incorporating tree species into CW designs and adding them to emergent plants is seen as a potential breakthrough approach to improve the ability of CWs to sequester carbon and ultimately contribute to mitigating climate change.

Key words : carbon sequestration, constructed wetlands, soil organic carbon

요 약

최근 인공습지(Constructed Wetlands, CWs)를 이용한 탄소격리에 대한 연구가 활발히 진행되고 있으나 인공습지는 미생물, 식생, 여재 등 소규모 생태계로 탄소흡수원과 탄소 공급원 두가지 기능을 수행하기에 탄소중립을 위한 인공습지의 기능이 확실하지 않다. 따라서 본 연구에서는 인공습지의 탄소격리에 대한 기능을 파악하고자 계량서지학 분석(Bibliometric analysis)을 통해 다양한 논문 및 보고서를 기반으로 다양하고 포괄적으로 검토를 수행하였다. 계량서지학 분석(Bibliometric analysis) 결과 인공습지의 기능은 질소를 초점에 두어 영양염류 제거 효과가 높은것으로 분석되었으며, 인공습지는 토양 내 탄소함유량 및 탄소 격리는 토양 내 조성된 식생, 조성연도 및 유입수 내 유기물 함량에 따라 다른것으로 나타났다. 인공습지 내 적용되어진 식생 중 부들과(*Typha*)가 많이 적용되었으며, 탄소격리율에 기여도가 높은것으로 분석되었다. 목본류는 관목류에 비해 상대적으로 탄소격리율이 높아 인공습지 설계시 단일식생보다는 목본류와 관목류의 복합적으로 조성하여 인공습지 내 탄소격리율과 기후변화를 완화하는데 기여할 것으로 분석되었다.

핵심용어 : 탄소격리, 인공습지, 토양 유기 탄소

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1. Introduction

As climate change continues to emerge as a leading environmental concern worldwide, carbon emission is seen as a significant contributing factor to global warming. Although carbon emission reduction targets have been increased since the Paris COP in 2015, CO_2 emissions have also continued to increase every year since, until the global shutdown brought by the Coronavirus disease 2019 (COVID-19) pandemic in 2020 (BP p.l.c., 2023). In the said year, the estimated global carbon emission was estimated to be 36.8 billion tons. However, with economies recovering in most parts of the world, carbon emission by the year 2030 is estimated to reach around 40 billion tons (International Energy Agency, 2020).

Carbon capture, utilization, and storage (CCUS) technologies have been considered a pivotal contribution to achieving carbon emission reduction targets. However, the high cost and energy consumption of such carbon capture technologies impose a huge challenge in promoting its usage (Wilberforce et al., 2019). Previous literature also revealed that the storage time of CO_2 in CCUS can be limited due to the short lifespans of chemicals and fuels used in such technologies (Cuéllar-Franca & Azapagic, 2015). Moreover, the current global industrial capacity to channel, process, and convert CO_2 emissions is seen as extremely limited (Gür, 2022). Given the economic and feasibility challenges that come with conventional CCUS technologies, recent research endeavors revolved around the exploration of alternative technologies for carbon capture and storage. Nature-based technologies, in particular, became a major point of discussion in recent studies due to their potential as cost-effective carbon sequestration systems. Recent studies validated the ability of constructed wetlands (CW), a type of nature-based technology, to decrease the amount of pollutants (i.e., nitrogen and phosphorus) in wastewater and stormwater runoff (Dalsgaard et al., 2021; Hang et al., 2020; Malyan et al., 2021). In addition, the concept of CWs as treatment systems for wastewater and stormwater runoff has been highlighted in previous studies, primarily due to their low construction costs and maintenance requirements (Kayranli et al., 2010). Although the ability of wetlands to remove nutrients in stormwater runoff has been widely studied, its capability to sequester carbon remains unclear, as wetlands are widely considered as both carbon sinks and carbon sources (Ding et al., 2023). A previous study denoted that carbon budgets in CWs still have high variabilities, due to variable precipitation patterns and man-made disturbances (Helfter et al., 2022). Moreover,

a recent study found that constructed wetlands may potentially be sources of carbon due to the processes associated with denitrification, depending on inflow quality and the CWs' environmental conditions (Zhang et al., 2022). It was also previously noted that wetlands emit methane gas (CH_4), which indicates the potential of CWs to be net carbon sources (Lolu et al., 2020).

In order to address the uncertainties regarding the effectiveness of nature-based technologies as carbon-storing and -sequestering infrastructures, it is critical to determine the current state of knowledge regarding the carbon sequestration function of constructed wetlands. A bibliometric review was conducted to determine the trend and status of research concerning the use of constructed wetlands for carbon sequestration and storage. Furthermore, a comprehensive review was done to assess the carbon sequestration ability of constructed wetlands, through synthesizing and analyzing data from previously published articles obtained from the Scopus database. Knowledge gaps and future research directions regarding the utilization of nature-based solutions for carbon capture and storage were also determined through the bibliometric and comprehensive review.

2. Materials and Methods

2.1 Bibliometric Review

The research articles used for the bibliometric review were obtained from the Scopus database. The string inputted on the Scopus search was "TITLE-ABS-KEY ("carbon" AND "constructed wetland*" OR "artificial wetland*" OR "engineered wetland*" OR "treatment wetland*"). The search results were filtered further by limiting the list to English articles published from 2000 to 2023. The 1,345 articles retrieved from the query were downloaded as a Research Information System (RIS) file, which was parsed into a corpus using the CorText Manager, an online software that generates various scripts for bibliometric analysis. The scripts generated for this bibliometric review included the number of articles per journal, a network map of keywords and years, and a contingency matrix of keywords and countries.

To determine the most productive journals that publish articles related to carbon and constructed wetlands, the list builder feature, with "Journal" selected as the script parameter, was used. For the script parameters of the network map, "keywords" was selected as the first field, and "time steps" or years was selected as the second. The

contingency matrix was created to illustrate the magnitude of co-occurrence between keywords and countries. For the network map and contingency matrix, chi^2 was selected as the specificity measure. Chi^2 is a statistical measure that is typically used to determine the independence and relevance of the variables from each other (Nihan, 2020).

2.2 Comprehensive Review

The resulting articles from the first Scopus search were further filtered by adding keywords relevant to carbon sequestration, capture, and storage. The additional keywords were obtained from the resulting network map from the bibliometric review and are shown in the methodology framework in Fig. 1. After the additional filtration of the Scopus search, the final number of articles obtained was 97. Non-review articles written in the English language were utilized for the data collection process. The information and data collected from the articles included wetland type and area, year of construction, biomass or plant species used, carbon concentration data, and carbon
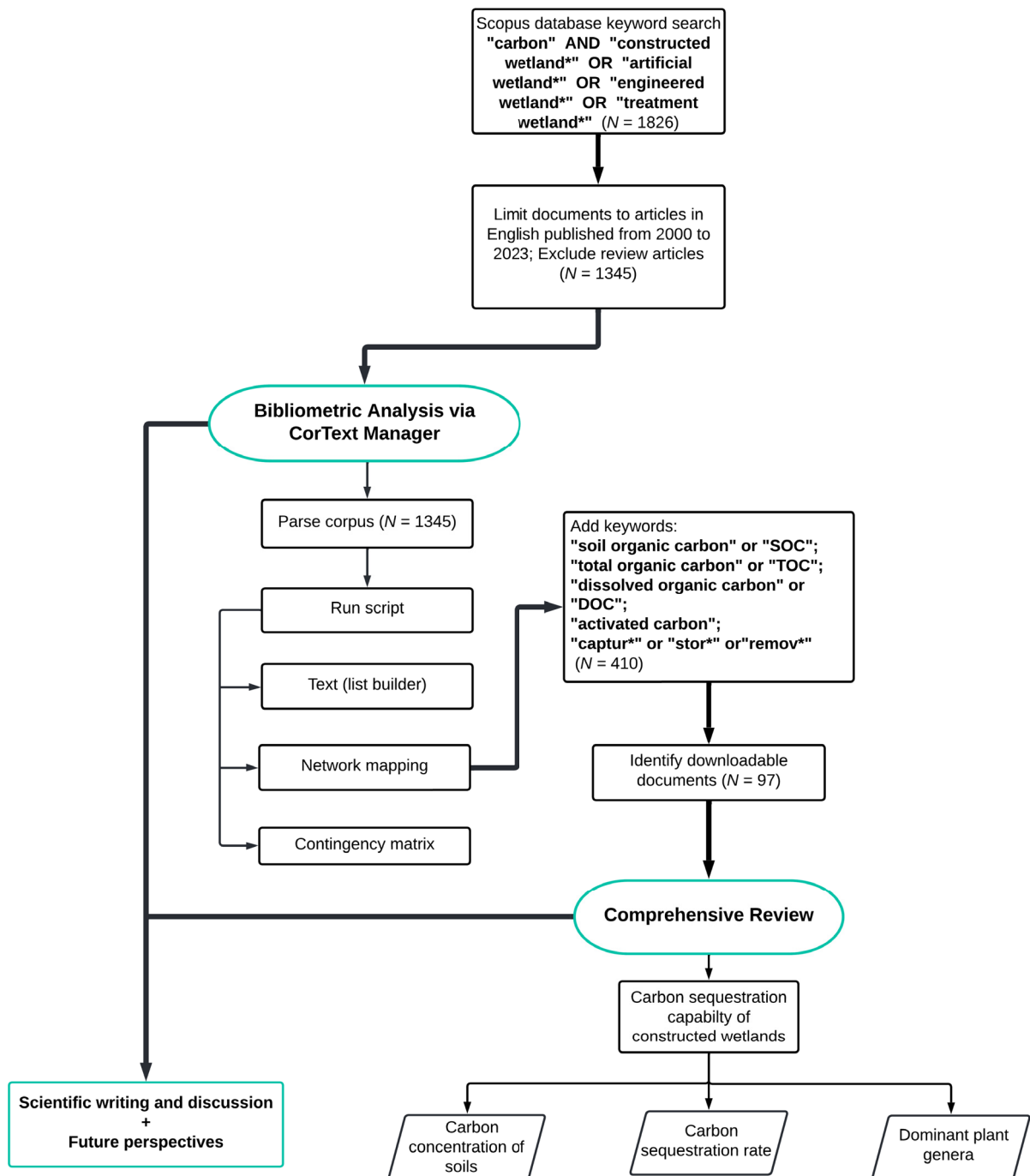

Fig. 1. Methodology framework of the review study on carbon sequestration in constructed wetlands

sequestration rates. After the data curation process, the ability of constructed wetlands to sequester and store carbon was estimated by creating plots and tables. A box plot was made to summarize the average carbon concentration of various soils examined in the obtained articles. Furthermore, carbon sequestration rates were summarized by creating a table of descriptive statistics. The creation of the box plot and summary table was done using OriginPro 2023.

3. Results and Discussions

3.1 Bibliometric Review

3.1.1 Most productive journals and Contingency Matrix

The distribution of the number of documents per journal was shown in Table 1. Results revealed that articles from the top 20 most productive journals in the list constituted about 67% of the 1,345 articles obtained from the Scopus search. The three most productive journals that published articles related to carbon and constructed wetlands were Ecological Engineering with 152 articles, Science of Total Environment with 119, and Bioresource Technology with

Table 1. The number of articles per journal for the Scopus keyword search "carbon" and "constructed wetland*" or "artificial wetland*" or "engineered wetland*" or "treatment wetland*"

Journal	Number of articles
Ecological Engineering	152
Science of the Total Environment	119
Bioresource Technology	103
Journal of Environmental Management	64
Environmental Science and Pollution Research	62
Chemosphere	58
Water Science and Technology	48
Water Research	48
Chemical Engineering Journal	44
Journal of Cleaner Production	29
Environmental Science and Technology	20
Environmental Pollution	20
Water, Air, and Soil Pollution	19
Wetlands	18
Water (Switzerland)	18
Journal of Environmental Quality	15
Journal of Water Process Engineering	14
Journal of Hazardous Materials	13
Desalination and Water Treatment	12
Water Environment Research	10
Others	448

103. Identifying the most productive journals is seen as a potential approach for researchers in the field of Nature-based Solutions to determine journals that are likely to accept their work. Furthermore, the list of the most productive journals can serve as a reference for researchers with the same focus of study to target their submissions and find future collaborations (Priem & Hemminger, 2012).

The contingency matrix highlighting the co-occurrence of keywords and countries was shown in Fig. 2. Red cells denote a high magnitude of co-occurrence between two fields, whereas blue cells indicate a low magnitude of co-occurrence between the two fields. Furthermore, White cells indicate neutrality between the two fields (Breucker et al., 2016). The numbers on the top and right side of the matrix refer to the number of articles from the country (vertical axis) and number of articles with a specific keyword (horizontal axis). From the generated contingency matrix, it was noted that the keyword "carbon" had the highest co-occurrence with China. However, it was observed that China had a negative magnitude of co-occurrence with the keywords "constructed wetland" and "constructed wetlands." This relationship suggested that a huge number of studies on carbon are conducted in China, but only a small fraction of existing studies focused on the utilization of constructed wetlands. The United States, Germany, and France were found to have a high magnitude of co-occurrence with "organic carbon." Moreover, these countries also exhibited high magnitudes of co-occurrence with the keyword "constructed wetland" or "constructed wetlands." This indicated that most of the studies obtained from the aforementioned countries performed extensive research on constructed wetlands. However, their correlation with the keyword "carbon" was observed to be neutral.

3.1.4 Network mapping and evolution of keywords

The network map of keywords related to carbon sequestration and constructed wetlands were illustrated in Fig. 3. Furthermore, time steps or years were added to the map to analyze the most relevant terms or keywords within a particular time frame. The network map generated serves as a visual representation of the relationships between keywords from the obtained articles in the Scopus search. Triangles represent publication years and circles represent the keywords frequently found in the obtained articles. The thickness of a node denotes a high frequency in the obtained articles. Furthermore, nodes that belong to the same cluster, which is represented by a larger circle with a lighter color are closely related to one another, while keywords from different clusters may denote different themes of study.
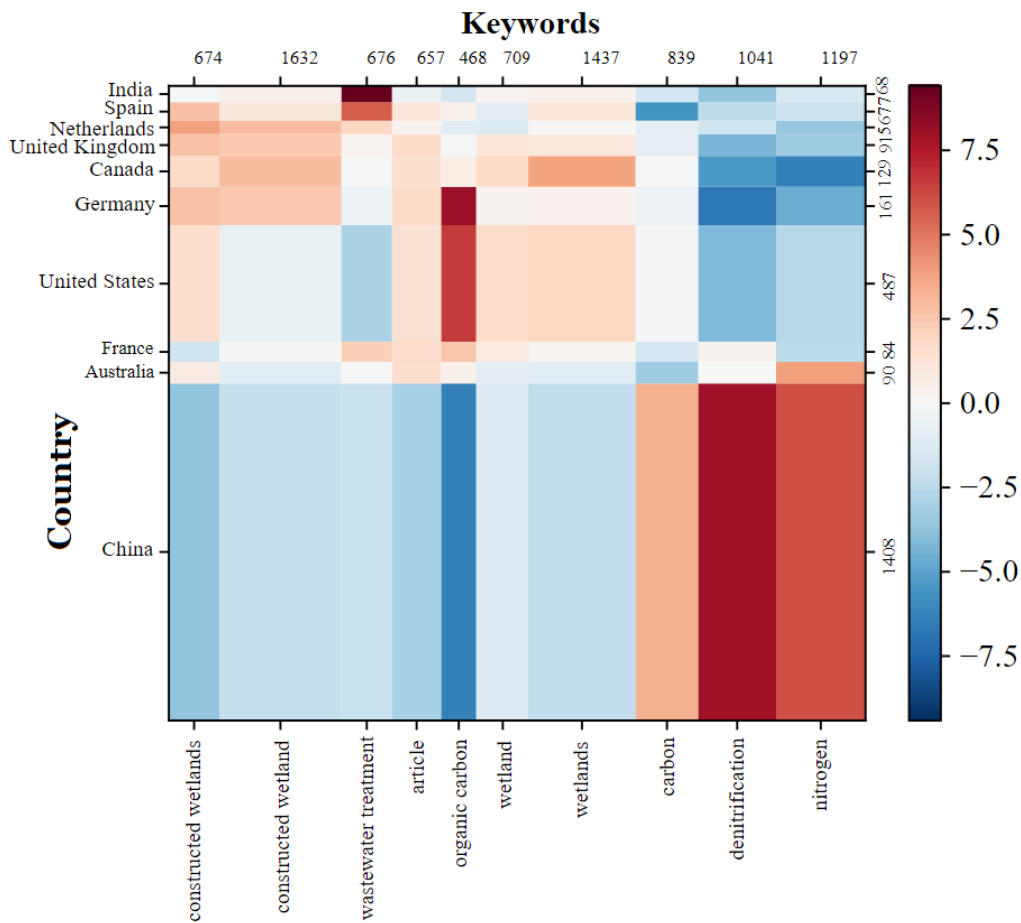
Fig. 2. The contingency matrix generated from CorText Manager using research articles related to carbon sequestration and constructed wetlands

From the network map, it was found that the keyword "wetlands" had a high co-occurrence with "nitrate" and "nitrates," denoting that nitrogen is the most commonly investigated parameter in studies related to wetlands. It was also observed that carbon sequestration and constructed wetlands have been topics of interest since the early 2000s. The keywords "carbon sequestration" and "efficiency" also had a high co-occurrence with the year 2018. This particular relationship between the mentioned keywords denoted that the efficiency or effectiveness of constructed wetlands as carbon-sequestering infrastructures has emerged as a field of study in more recent years. The keywords "activated carbon," "nitrogen removal," and "greenhouse gas" were also observed to have a high co-occurrence with recent years (i.e., 2021, 2022, and 2023), implying that the reduction of carbon and nitrogen continues to emerge as a central topic of studies related to constructed wetlands.

3.2 Comprehensive Review

3.2.1 Carbon storage and sequestration

The ability of constructed wetlands to store carbon has been investigated and validated in recent studies (Liu et al., 2022, Monge-Salazar et al., 2022). However, the extent to which CW can store carbon varied among sources. A box plot of the total carbon (TC), soil organic carbon (SOC), and soil inorganic carbon (SIC) concentrations in constructed wetlands was shown in Fig. 4. A majority of the reviewed studies recorded the average carbon concentration (concentration per year) of the constructed wetland soils from the date of construction to the date of sample collection. For carbon concentration values that were recorded several years after the construction of the wetland, the total value was divided by the constructed wetland age to get the average concentration. The mean TC concentration was 2.16% and the median was 1.59%. Varying factors affecting high TC concentration on CW soils were found, particularly on soil samples with a concentration above the 75th percentile of the recorded values. The presence of heterotrophs in some of the studied CW, for instance, was seen as a major contributing factor to high TC concentrations. Puttock et al. (2018) found that beaver invasion in the study site resulted in higher sediment accumulation and enhanced
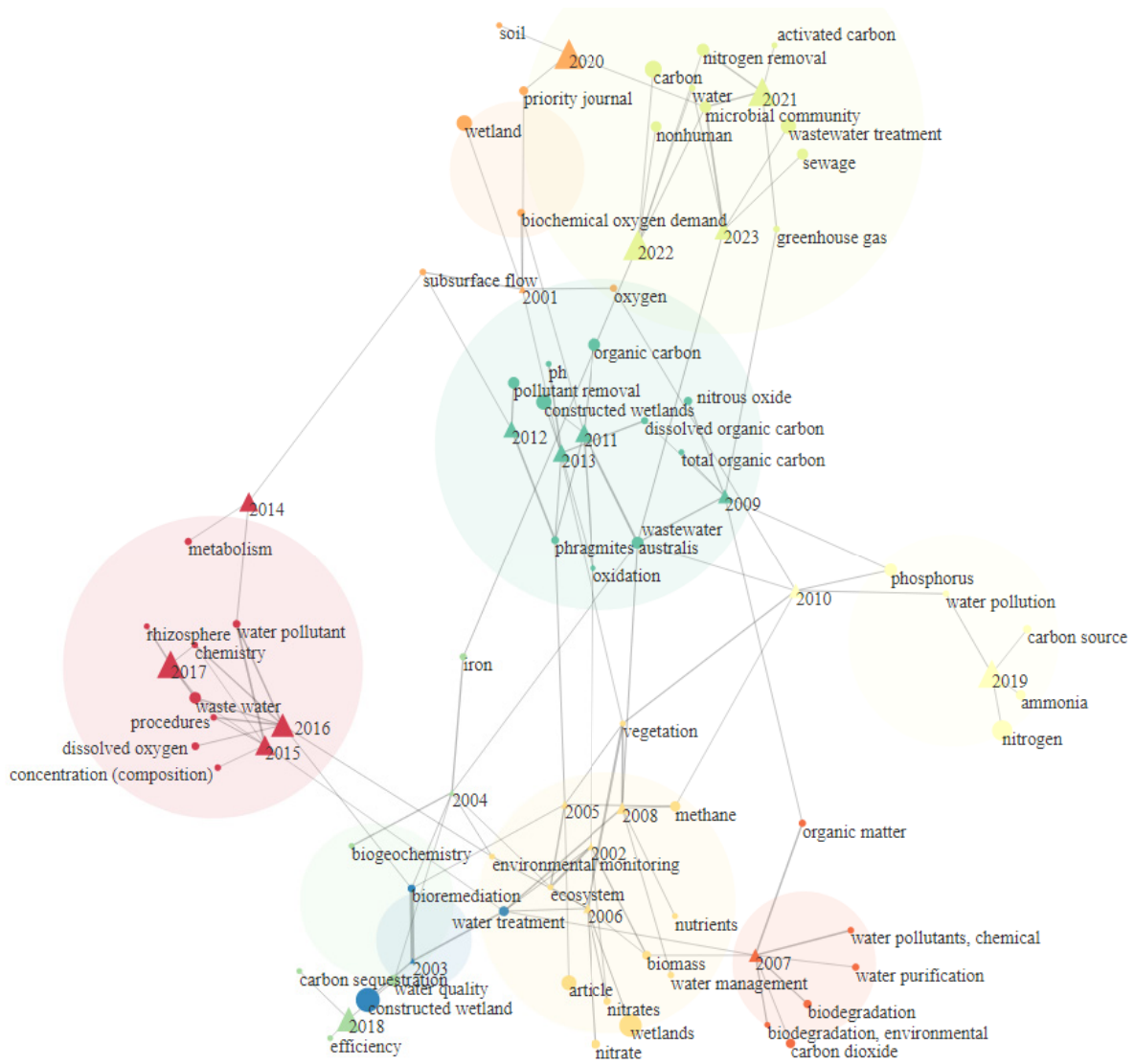
Fig. 3. The network map of keywords and years generated from CorText Manager using research articles related to carbon sequestration and constructed wetlands
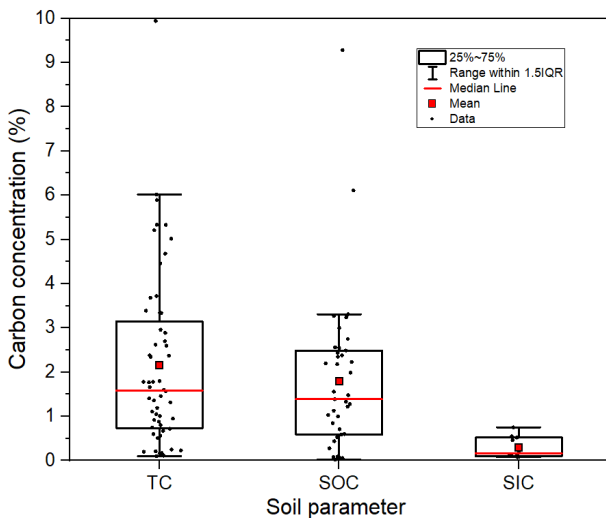

Fig. 4. Carbon concentration (%) of soils from constructed wetlands studied in the reviewed articles

soil carbon storage in the CW. TC concentrations from the beaver-impacted site ranged from 88 to 160 gC/kg, three years after the construction of the CW. The presence of organic residues in a majority of the CW was also found to result in a high TC concentration in CW soils. The increased soil accumulation and carbon storage in the site was associated with the dams built by beavers, which resulted in slower water flows and sediment accumulation. Among the reviewed articles, the maximum TC concentration (9.94%) was reported in the study conducted by Overbeek et al. (2020). This relatively high TC concentration was attributed to the conversion of CW plants from from a relatively similar vegetation composition to a heterogeneous composition. Specifically, the addition of aquatic vegetation in the wetland system was found to have increased TC concentration. Results from the reviewed studies also

indicated that the type of aquatic vegetation could potentially be a driving factor to increased TC concentrations of CW soils. It was revealed that soils with emergent aquatic vegetation had higher TC, SOC, and SIC concentrations, as compared to soils with submerged aquatic vegetation (Reddy et al., 2021). Furthermore, the alteration of CW soil properties, primarily through microbial diversity, after vegetation invasion was observed to be a significant factor in storing high amounts of carbon (Jamwal & Shirin, 2021; Yang et al., 2020). The factors that resulted in high TC were found to have similar effects to the SOC concentration of CW soils. High concentrations of SOC recorded in some studies exceeded a majority of recorded TC concentrations. A study by da Silva et al. (2022) remarked that incorporating high organic matter into CW soils resulted in increased microbial activity, thus increasing the soil's carbon mineralization capabilities. The presence of terrestrial plants on CW was also noted to have resulted in increased organic carbon storage in soils (Cao et al., 2017). Relatively low concentrations of TC, SOC, and SIC were noted in studies that involved newly-constructed CWs (Ramond et al., 2014).

The carbon sequestration rates of constructed wetlands studied in the reviewed articles are shown in Table 2. In contrast to the carbon concentration values recorded from the reviewed studies, there was no notable variation found between the carbon sequestration rates for all parameters, having a coefficient of variation of 0.6, 0.9, and 1.3 for TC, SOC, and SIC, respectively. The ranges of carbon sequestration rates for TC and SOC were 0.116 to 0.900 kg $m^{-2}yr^{-1}$ and 0.002 to 0.590 kg $m^{-2}yr^{-1}$, respectively. Although the range of C sequestration rates for TC and SOC appeared to be wide, the extremely high values differed greatly from the mean values by 64%, 72%, and 64% for TC, SOC, and SIC, respectively. Despite the relatively low variation of C sequestration rates gathered from the reviewed studies, the mean values were still found to have major differences from C sequestration rates from some studies

Table 2. Carbon sequestration rates in the constructed wetlands studied in the reviewed articles

	TC	SOC	SIC
Number of articles (n)	19	12	5
Mean (kg $m^{-2}yr^{-1}$)	0.324	0.167	0.068
Standard Deviation	0.197	0.151	0.088
Coefficient of Variation	0.6	0.9	1.3
Minimum (kg $m^{-2}yr^{-1}$)	0.116	0.002	0.004
Median (kg $m^{-2}yr^{-1}$)	0.252	0.141	0.008
Maximum (kg $m^{-2}yr^{-1}$)	0.900	0.590	0.189

not included in the comprehensive review, particularly those focused on long-term carbon sequestration estimates. Deverel et al. (2014) estimated the carbon sequestration rates from the Twitchell Island demonstration wetland project from 1997 to 2008 and recorded values ranging from 1.2 to 1.5 kg $m^{-2}yr^{-1}$, which exceeded the maximum value recorded in this review study. Relatively high C sequestration rates were often associated with high organic inputs in the CW throughout its operation (Maynard et al., 2011). Moreover, particularly high C sequestration rates recorded in this review study were observed in CWs where the inflow water was treated with coagulants. C sequestration rates were high for sites where the inflow was treated with polyaluminum chloride (PAC) (Stumpner et al., 2018). In the aforementioned study, the carbon sequestration rates in the CW increased by 50–100% after treating the inflow water with PAC and $FeSO_4$. Results from the reviewed studies also revealed that utilizing submerged aquatic vegetation on CW could potentially sequester 64% more carbon in the soil than using emergent aquatic vegetation (Reddy et al., 2018). This conclusion was found to be contradicting with the findings from the same study, wherein soils with emergent aquatic vegetation had higher C concentrations than those with submerged aquatic vegetation. This also confirms findings from a previous study that although carbon storage and carbon sequestration are related, they are not necessarily directly proportional (Post & Kwon, 2000). Emergent vegetation has a wider range of nutrient source, as they draw nutrients from both the soil and water columns. Although the high nutrient availability in soils with emergent vegetation tends to promote plant growth and increased carbon concentration, it was also found to result in increased microbial decomposition, which leads to reduced SOC sequestration rates (Strickland et al., 2009). The available data for SIC concentration of CW soils in this study is very limited. However, the results suggest that SIC concentration in CW soils are less than SOC concentration. This may be attributed to the high biomass input and litter accumulation in the reviewed CWs. A previous study found that SOC is closely related to biological processes such as biomass input, while SIC is associated with abiotic factors such as chemical processes (Du & Gao, 2020). In the same study, SOC comprised 91% of TC concentration of the examined soils. A similar proportion of SOC to TC is observed in this review study.

3.2.2 Dominant plant genera and carbon sequestration potential of tree species

Vegetation is a critical component of constructed wetlands

(Merriman et al., 2016; Zhao et al., 2020). Findings from the obtained carbon concentration and sequestration rates indicate that the type of vegetation, as well as its placement in the CW system, holds an important role in the efficiency of the CW as a carbon-storing and sequestering mechanism. A wide variety of plant genera was found on the constructed wetlands studied in the obtained research articles. The summary of the frequency of each plant genus is shown in Figure 5. A total of 43 unique genera were found, with *Typha* being the most common biological genus used in operating CWs. Among the other frequently found genera are *Phragmites*, *Schoenoplectus*, *Juncus*, *Alternanthera*, *Potamogeton*, and *Carex*. *Typha*, being the most dominant genus in the reviewed studies, was also attributed to the highest carbon sequestration rates and concentration recorded in this comprehensive review. A study by Harpenslager et al. (2018) observed that *Typha* species *T. latifolia* and *T. angustifolia* had high carbon sequestration potentials, reaching up to 0.590 kg m^{-2}yr^{-1}. However, the C sequestration rates of soils with the *Typha* species also varied with respect to soil types, with sand exhibiting the highest carbon sequestration rate among soil types. A previous study also found that using cattails (*Typha spp.*) is more effective than tule (*Schoenoplectus spp.*) in achieving accretion and carbon sequestration goals in CWs (Hernes et al., 2020). Apart from its noteworthy ability to sequester carbon, the *Typha* was also found to be effective in treating inflow water on CWs by uptaking nutrients and heavy metals (Soosaar et al., 2009; Sun et al., 2019; Vijay et al., 2017; Yu et al., 2020). Generally, plant invasions tend to increase carbon storage in constructed wetlands. However, the relatively high capability of the *Typha* species to sequester carbon may be associated with its large biomass, as *Typha* tends to be taller and more productive than the plant species they replace (Bansal et al., 2019). Moreover, the high capability of the *Phragmites* species, which is the second most commonly found species in this review, to sequester carbon was associated with its aerial leaves similar to terrestrial plants (Dong et al., 2012). The leaves from the said species, according to the study, can directly use the available CO$_2$ in the air for photosynthesis. In addition, the Phragmites species tend to have high-strength transpiration, thus slowing down respiration and increasing carbon storage.

Constructed wetland soils with plant genera other than *Typha* also exhibited high concentrations of carbon. CW soils with *Juncus effusus* had C concentrations reaching up to 4.68%, which is higher than a majority of the recorded values in this review (Yoon et al., 2011). Another study that investigated a CW covered with 53% *Juncus acutus* was found have a mean SOC sequestration rate of 0.42 ± 0.29 kg m^{-2}yr^{-1}, which was higher than the mean SOC sequestration rate obtained in this review (0.167 kg m^{-2}yr^{-1}) (Maziarz et al., 2019). The observed high C concentration and sequestration rates in this review indicated *Juncus* plants have the potential of storing and sequestering high amounts of carbon in CW soils, despite the genus being less studied in the reviewed articles. Tifton 85 grass (*Cynodon spp.*) was also found to be capable of mineralizing organic carbon in the study of Silva et al. (2019). Specifically, it was estimated that this specific type of plant is capable of sequestering carbon at a rate of 2.27 to 3.09 gC kg^{-1}yr^{-1}.

Apart from emergent plants, tree species have been growing as a topic of interest in recent studies due to their carbon-sequestering capabilities. Previous studies found that incorporating tree species increase constructed wetlands' capability to treat wastewater and store phosphorus and sediments (Bolton & Greenway, 1997; Vymazal, J., 2022). However, studies focusing on incorporating tree species to CW designs with the aim of increased carbon sequestration are still very scarce. Nevertheless, tree species, in general, have been found to exhibit high carbon stocks. It was found in a previous study that tree species *Syzygium cumini* and *Eucalyptus camaldulensis* exhibited high carbon stocks, in which maximum values of 10.32 Mg ha^{-1} and 13.5 Mg ha ha^{-1} were recorded, respectively (Zubair et al., 2022). Moreover, a study conducted in the United States recorded a total of 139.9 tons of sequestered carbon in 1,997 trees for one year (Sharma et al., 2021). The relatively high capability of tree species to sequester carbon may be associated with their enhanced above-ground biomass and longer life span. Recent studies indicate that tree biomass and age have a direct relationship with carbon sequestration (Ali et al., 2023; Darmawan et al., 2022). In addition to biomass differences, the variation of tree species was found to be a major factor in the carbon-sequestering capabilities of trees. It was found in previous studies that native tree species have greater carbon sequestration capacities than exotic species (Lu et al., 2014; Rodríguez-Loinaz et al., 2013). Information on the ability of tree species to sequester carbon from the examined articles in this review study was very scarce, as most of the found biological genera found in the studies were emergent and submerged plants. However, a wide range of findings on the carbon sequestration abilities of tree species was found outside the obtained articles, particularly their capability to sequester higher amounts of carbon. Thus, incorporating tree species, instead of or in addition to emergent plants, is seen a potential
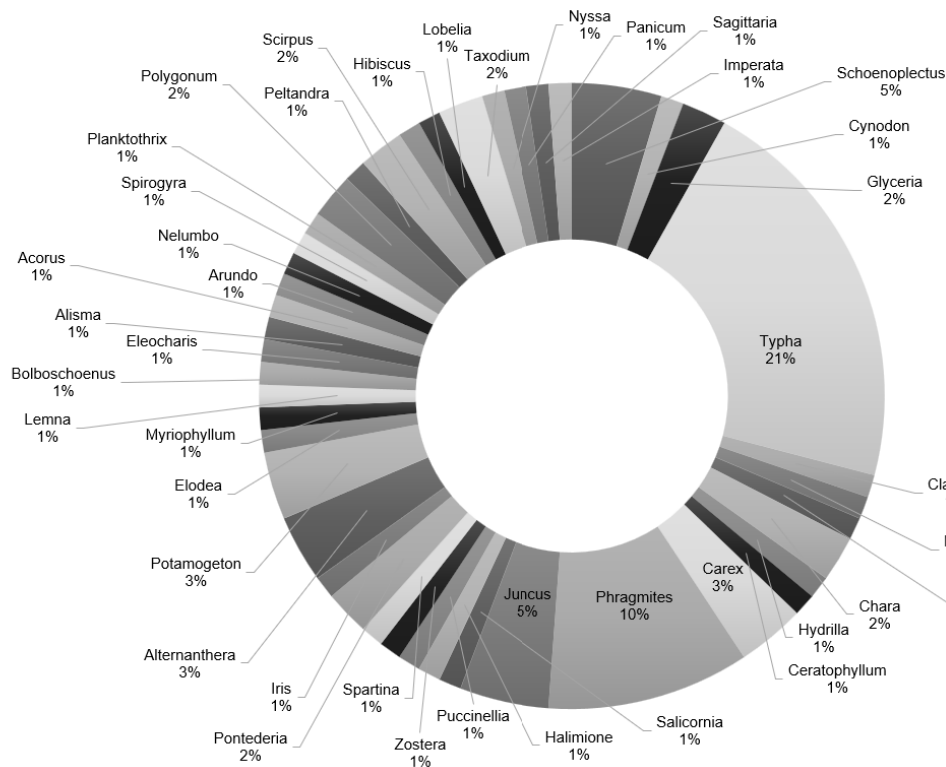
Fig. 5. Frequency of each biological genus used in the studied constructed wetlands from the reviewed articles

breakthrough approach to increase the carbon sequestration capabilities of CWs.

3.2.3 Relevance of constructed wetland age

The results of this comprehensive review suggested that several factors may affect the ability of constructed wetlands to store and sequester carbon. One varying attribute of CWs studied in the reviewed articles was the CW age. CW ages recorded in this study ranged from 24 days to 17 years. The linear plot of the ages and TC concentrations of CWs in the reviewed studies is shown in Fig. 6. The R^2 value of almost 0.7 suggested a linear relationship between CW age and TC concentration in CW soils. However, it can also be observed that recorded soil TC concentrations varied greatly in CWs that were older than 10 years. Relatively low TC concentrations in these older CWs were associated with high phosphorus loading in the CW soil resulting in high accretion of materials with high bulk density (Reddy et al., 2018). It was previously found that bulk density is negatively correlated to C concentration in CW soils (Cao et al., 2015). Despite the high variability of TC concentrations of soils in older CWs, the proportional relationship of CW age and TC concentration was still evident. This confirms conclusions from previous studies indicating that TC concentration in CWs tend to increase with the wetland's age (Shiau et al., 2022; Wang et al., 2021). The high
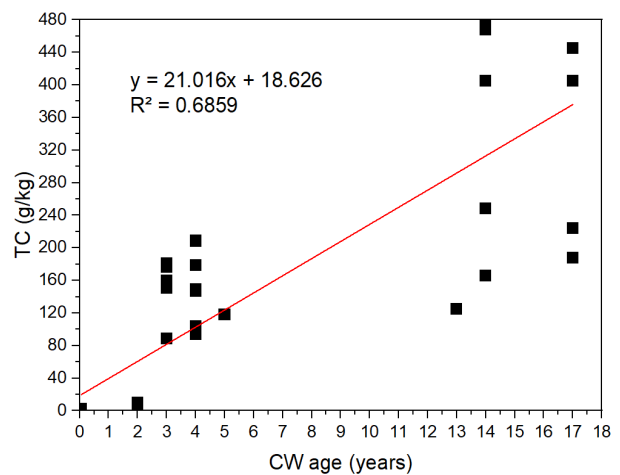

Fig. 6. Linear regression of age and TC concentration of constructed wetlands studied in the reviewed articles.

variability of TC concentrations in CWs also indicated the complexity of CWs' ability to sequester carbon long-term. Previous studies suggested that definite findings on carbon sequestration in CWs could take a long period of time, particularly decades or even centuries (Were et al., 2019). The capability a CW to be a carbon sink was also found to change depending on the vegetation cover in the CW. Valach et al. (2021) found that a minimum of 55% vegetation cover was needed for a CW to become a carbon sink, which was immediately achieved in the wetlands upon construction

or restoration. Another study determined that it would take a constructed wetland several decades to be considered as a carbon sink, primarily due to methane releases (Kayranli et al., 2010).

4. Conclusions

A bibliometric and comprehensive review on carbon sequestration in constructed wetlands has been conducted. Through a bibliometric analysis using CorText Manager, it was found that most studies conducted for constructed wetlands mainly focused on removing pollutants, particularly nitrogen. In addition, most of the countries included in the contingency matrix were developed nations, suggesting a research gap between carbon sequestration and developing countries.

Through the comprehensive review, the ability of CWs to store and sequester carbon was confirmed. However, sequestration rates varied depending on the vegetation types used, the ages of the CWs, and the organic content of inflow water entering the CWs. The *Typha* genus was associated with the highest carbon concentration and sequestration rates recorded in this review study. Although emergent plants have been proven to sequester carbon, their capability to do so is still seen as less than that of tree species, which exhibited much higher carbon sequestration rates in recent studies. Thus, incorporating tree species, instead of or in addition to emergent and submerged plants, in the design of CWs is seen as a potential way to increase carbon sequestration in CWs. Furthermore, the results of this review study suggest that carbon concentration in CW soils does increase over time. However, further studies are needed on the ability of CWs to sequester carbon long-term, as C concentrations of CW soils were observed to vary greatly in older CWs. Overall, the findings in this review study are believed to have potential benefits in designing CWs with the aim to sequester more carbon and ultimately contribute to reaching climate change mitigation targets.

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References

Ali, S., Khan, S. M., Ahmad, Z., Siddiq, Z., Ullah, A., Yoo, S., Han H., & Raposo, A. (2022). Carbon sequestration potential of different forest types in Pakistan and its role in regulating services for public health. *Frontiers in Public Health*, *10*. https://doi.org/10.3389%2Ffpubh.2022.1064586.

Bansal, S., Lishawa, S. C., Newman, S., Tangen, B. A., Wilcox, D., Albert, D., Anteau, M. J., Chimney, M. J., Cressey, R. L., DeKeyser, E., Elgersma, K. J., Finkelstein, S. A., Freeland, J., Grosshans, R., Klug, P. E., Larkin, D. J., Lawrence, B. A., Linz, G., Marburger, J., ··· Windham-Myers, L. (2019). *Typha* (cattail) invasion in North American wetlands: Biology, regional problems, impacts, ecosystem services, and Management. *Wetlands*, *39*(4), 645–684. https://doi.org/10.1007/s13157-019-01174-7.

Bolton, K. & Greenway, M. (1997). A feasibility study of trees for use in constructed wetlands in Subtropical Australia. *Water Science and Technology*, *35*(5). https://doi.org/10.1016/s0273-1223(97)00075-9.

BP p.l.c. (2023). *bp Energy Outlook 2023 edition*.

Breucker P., Cointet J., Hannud Abdo A., Orsal G., de Quatrebarbes C., Duong T., Martinez C., Ospina Delgado J.P., Medina Zuluaga L.D., Gómez Peña D.F., Sánchez Castaño T.A., Marques da Costa J., Laglil H., Villard L., Barbier M. (2016). CorTexT Manager (version v2). URL: https://docs.cortext.net.

Cao, Q., Wang, H., Zhang, Y., Lal, R., Wang, R., Ge, X., & Liu, J. (2017). Factors affecting distribution patterns of organic carbon in sediments at regional and national scales in China. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-06035-z.

Cao, Q., Wang, R., Zhang, H., Ge, X., & Liu, J. (2015). Distribution of organic carbon in the sediments of Xinxue River and the Xinxue River Constructed Wetland, China. *PLoS ONE*, *10*(7). https://doi.org/10.1371/journal.pone.0134713.

Cuéllar-Franca, R. M., & Azapagic, A. (2015). Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. In *Journal of CO2 Utilization* (Vol. 9, pp. 82–102). Elsevier Ltd. https://doi.org/10.1016/j.jcou.2014.12.001.

da Silva, Diogo André Pinheiro, Matos, M. P., Marques, M. V. A., de Matos, A. T., & de Alencar Neves, T. (2022). Kinetics and mineralization fraction of organic

matter from sewage sludge mixed with soil under controlled laboratory conditions. *Scientific Reports*, *12*(1). https://doi.org/10.1038/s41598-022-25121-5

Dalsgaard, J., von Ahnen, M., & Pedersen, P. B. (2021). Nutrient removal in a slow-flowing constructed wetland treating aquaculture effluent. *Aquaculture Environment Interactions*, *13*, 363–376. https://doi.org/10.3354/aei00411.

Darmawan, A. A., Ariyanto, D. P., Basuki, T. M., Syamsiyah, J., & Dewi, W. S. (2022). Biomass accumulation and carbon sequestration potential in varying tree species, ages and densities in Gunung Bromo Education Forest, Central Java, Indonesia. *Biodiversitas*, *23*(10), 5093–5100. https://doi.org/10.13057/biodiv/d231016.

Deverel, S. J., Ingrum, T., Lucero, C., & Drexler, J. Z. (2014). Impounded marshes on subsided islands:: Simulated vertical accretion, processes, and effects, Sacramento-San Joaquin Delta, CA USA. *San Francisco Estuary and Watershed Science*, *12*(2), 1–23. https://doi.org/10.15447/sfews.2014v12iss2art5.

Ding, Y., Wang, Y., Gu, X., Peng, Y., Sun, S., & He, S. (2023). Salinity effect on denitrification efficiency with reed biomass addition in salt marsh wetlands. *Bioresource Technology*, *371*. https://doi.org/10.1016/j.biortech.2023.128597.

Dong, W., Shu, J., He, P., Ma, G., & Dong, M. (2012). Study on the carbon storage and fixation of Phramites Autralis in Baiyangdian Demonstration Area. *Procedia Environmental Sciences*, *13*, 324–330. https://doi.org/10.1016/j.proenv.2012.01.031.

Du, C., & Gao, Y. (2020). Opposite patterns of soil organic and inorganic carbon along a climate gradient in the alpine steppe of northern Tibetan Plateau. *CATENA*, 186, 104366. https://doi.org/10.1016/j.catena.2019.104366.

Gür, T. M. (2022). Carbon Dioxide Emissions, Capture, Storage and Utilization: Review of Materials, Processes and Technologies. In *Progress in Energy and Combustion Science* (Vol. 89). Elsevier Ltd. https://doi.org/10.1016/j.pecs.2021.100965.

Hang, Q., Wang, H., He, Z., Dong, W., Chu, Z., Ling, Y., Yan, G., Chang, Y., & Li, C. (2020). Hydrilla Verticillata-sulfur-based heterotrophic and autotrophic denitrification process for nitrate-rich agricultural runoff treatment. *International Journal of Environmental Research and Public Health*, *17*(5). https://doi.org/10.3390/ijerph17051574.

Harpenslager, S. F., Overbeek, C. C., van Zuidam, J. P., Roelofs, J. G. M., Kosten, S., & Lamers, L. P. M. (2018). Peat capping: Natural capping of wet landfills by peat formation. *Ecological Engineering*, *114*, 146–153. https://doi.org/10.1016/j.ecoleng.2017.04.040.

Helfter, C., Gondwe, M., Murray-Hudson, M., Makati, A., & Skiba, U. (2022). From sink to source: High inter-annual variability in the carbon budget of a Southern African wetland. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *380*(2215). https://doi.org/10.1098/rsta.2021.0148.

Hernes, P. J., Miller, R. L., Dyda, R. Y., & Bergamaschi, B. A. (2020). Vegetation vs. Anoxic Controls on Degradation of Plant Litter in a Restored Wetland. *Frontiers in Environmental Science*, *8*. https://doi.org/10.3389/fenvs.2020.564603.

International Energy Agency. (2020). *Global Energy Review 2020*. www.iea.org/corrigenda.

Jamwal, P., & Shirin, S. (2021). Impact of microbial activity on the performance of planted and unplanted wetland at laboratory scale. *Water Practice and Technology*, *16*(2), 472–489. https://doi.org/10.2166/wpt.2021.017.

Kayranli, B., Scholz, M., Mustafa, A., & Hedmark, Å. (2010). Carbon storage and fluxes within freshwater wetlands: A critical review. *Wetlands*, *30*(1), 111–124. https://doi.org/10.1007/s13157-009-0003-4.

Lu, W., Yang, S., Chen, L., Wang, W., Du, X., Wang, C., Ma, Y., Lin, G., & Lin, G. (2014). Changes in carbon pool and stand structure of a native subtropical mangrove forest after inter-planting with exotic species Sonneratia apetala. *PLoS ONE*, *9*(3). https://doi.org/10.1371/journal.pone.0091238.

Lolu, A. J., Ahluwalia, A. S., Sidhu, M. C., Reshi, Z. A., & Mandotra, S. K. (2020). Carbon Sequestration and Storage by Wetlands: Implications in the Climate Change Scenario. In *Restoration of Wetland Ecosystem: A Trajectory Towards a Sustainable Environment* (pp. 45–58). Springer Singapore. https://doi.org/10.1007/978-981-13-7665-8_4.

Malyan, S. K., Yadav, S., Sonkar, V., Goyal, V. C., Singh, O., & Singh, R. (2021). Mechanistic understanding of the pollutant removal and transformation processes in the constructed wetland system. In *Water Environment Research* (Vol. 93, Issue 10, pp. 1882–1909). John Wiley and Sons Inc. https://doi.org/10.1002/wer.1599.

Maynard, J. J., Dahlgren, R. A., & O'Geen, A. T. (2011). Soil carbon cycling and sequestration in a seasonally saturated wetland receiving agricultural runoff. *Biogeosciences*, *8*(11), 3391–3406. https://doi.org/10.5194/bg-8-3391-2011.

Maziarz, J., Vourlitis, G. L., & Kristan, W. (2019). Carbon and nitrogen storage of constructed and natural freshwater wetlands in southern California. *Ecological Engineering: X*, *2*. https://doi.org/10.1016/j.ecoena.

2019.100008.

Merriman, L. S., Hunt, W. F., & Bass, K. L. (2016). Development/ripening of ecosystems services in the first two growing seasons of a regional-scale constructed stormwater wetland on the coast of North Carolina. *Ecological Engineering*, 94, 393–405. https://doi.org/10.1016/j.ecoleng.2016.05.065.

Nihan, S. T. (2020). Karl Pearsons chi-square tests. *Educational Research and Reviews*, *15*(9), 575–580. https://doi.org/10.5897/err2019.3817.

Overbeek, C. C., Harpenslager, S. F., van Zuidam, J. P., van Loon, E. E., Lamers, L. P. M., Soons, M. B., Admiraal, W., Verhoeven, J. T. A., Smolders, A. J. P., Roelofs, J. G. M., & van der Geest, H. G. (2020). Drivers of Vegetation Development, Biomass Production and the Initiation of Peat Formation in a Newly Constructed Wetland. *Ecosystems*, *23*(5), 1019–1036. https://doi.org/10.1007/s10021-019-00454-x.

Priem, J., & Hemminger, B. H. (2010). Scientometrics 2.0: New metrics of scholarly impact on the social web. First Monday. https://doi.org/10.5210/fm.v15i7.2874.

Post, W. M., & Kwon, K. C. (2000). Soil carbon sequestration and land-use change: Processes and potential. Global Change Biology, 6(3), 317–327. https://doi.org/10.1046/j.1365-2486.2000.00308.x.

Puttock, A., Graham, H. A., Carless, D., & Brazier, R. E. (2018). Sediment and nutrient storage in a beaver engineered wetland. *Earth Surface Processes and Landforms*, *43*(11), 2358–2370. https://doi.org/10.1002/esp.4398.

Ramond, J. B., Welz, P. J., Le Roes-Hill, M., Tuffin, M. I., Burton, S. G., & Cowan, D. A. (2014). Selection of Clostridium spp. in biological sand filters neutralizing synthetic acid mine drainage. *FEMS Microbiology Ecology*, *87*(3), 678–690. https://doi.org/10.1111/1574-6941.12255.

Reddy, K. R., Hu, J., Villapando, O., Bhomia, R. K., Vardanyan, L., & Osborne, T. (2021). Long-term accumulation of macro- and secondary elements in subtropical treatment wetlands. *Ecosphere*, *12*(11). https://doi.org/10.1002/ecs2.3787.

Rodríguez-Loinaz, G., Amezaga, I., & Onaindia, M. (2013). Use of native species to improve carbon sequestration and contribute towards solving the environmental problems of the timberlands in Biscay, northern Spain. *Journal of Environmental Management*, *120*, 18–26. https://doi.org/10.1016/j.jenvman.2013.01.032.

Sharma, R., Pradhan, L., Kumari, M., & Bhattacharya, P. (2021). *Assessment of Carbon Sequestration Potential of Tree Species in Amity University Campus Noida*. 52. https://doi.org/10.3390/iecf2020-08075.

Shiau, Y. J., Chen, Y. A., You, C. R., Lai, Y. C., & Lee, M. (2022). Compositions of sequestrated soil carbon in constructed wetlands of Taiwan. *Science of the Total Environment*, *805*. https://doi.org/10.1016/j.scitotenv.2021.150290.

Silva, Diogo André P., Matos, A. T., & Matos, M. P. (2019). Mineralization of organic matter and productivity of tifton 85 grass (Cynodon spp.) in soil incorporated with stabilized sludge from a vertical flow constructed wetland. *Journal of Water Sanitation and Hygiene for Development*, *9*(2), 309–318. https://doi.org/10.2166/washdev.2019.133.

Soosaar, K., Maddison, M., & Mander, Ü. (2009). Water quality and emission rates of greenhouse gases in a treatment reedbed. *WIT Transactions on Ecology and the Environment*, *125*, 105–125. https://doi.org/10.2495/WRM090111.

Strickland, M. S., Lauber, C., Fierer, N., & Bradford, M. A. (2009). Testing the functional significance of microbial community composition. *Ecology*, 90(2), 441–451.

Stumpner, E. B., Kraus, T. E. C., Liang, Y. L., Bachand, S. M., Horwath, W. R., & Bachand, P. A. M. (2018). Sediment accretion and carbon storage in constructed wetlands receiving water treated with metal-based coagulants. *Ecological Engineering*, *111*, 176–185. https://doi.org/10.1016/j.ecoleng.2017.10.016.

Sun, M., Tian, X., Zou, Y., & Jiang, M. (2019). Ecological aesthetic assessment of a rebuilt wetland restored from farmland and management implications for National Wetland Parks. *PLoS ONE*, *14*(10). https://doi.org/10.1371/journal.pone.0223661.

Vijay, M. V., Sudarsan, J. S., & Nithiyanantham, S. (2017). Sustainability of constructed wetlands in using biochar for treating wastewater. *Rasayan Journal of Chemistry*, *10*(3), 1056–1061. https://doi.org/10.7324/RJC.2017.1031738.

Vymazal, J. (2022). The historical development of constructed wetlands for wastewater treatment. *Land*, *11*(2), 174. https://doi.org/10.3390/land11020174.

Wang, C., Li, H., Cai, T., & Sun, X. (2021). Variation of soil carbon and nitrogen storage in a natural restoration chronosequence of reclaimed temperate marshes. *Global Ecology and Conservation*, *27*, e01589. https://doi.org/10.1016/j.gecco.2021.e01589.

Were, D., Kansiime, F., Fetahi, T., Cooper, A., & Jjuuko, C. (2019). Carbon Sequestration by Wetlands: A Critical Review of Enhancement Measures for Climate Change Mitigation. In *Earth Systems and Environment* (Vol. 3, Issue 2, pp. 327–340). Springer. https://doi.org/10.1007/s41748-019-00094-0.

Wilberforce, T., Baroutaji, A., Soudan, B., Al-Alami, A.

H., & Olabi, A. G. (2019). Outlook of carbon capture technology and challenges. *Science of the Total Environment, 657*, 56－72. https://doi.org/10.1016/j.scitotenv.2018.11.424.

Yang, R., Li, K., Fang, J., Quan, Q., Zhang, C., & Liu, J. (2020). The Invasion of Alternanthera philoxeroides Increased Soil Organic Carbon in a River and a Constructed Wetland With Different Mechanisms. *Frontiers in Ecology and Evolution, 8*. https://doi.org/10.3389/fevo.2020.574528.

Yoon, J., Kim, H., Nam, J. M., & Kim, J. G. (2011). Optimal environmental range for Juncus effusus, an important plant species in an endangered insect species (Nannopya pygmaea) habitat in Korea. *Journal of Ecology and Field Biology, 34*(2), 223－235. https://doi.org/10.5141/JEFB.2011.024.

Yu, B., Huang, J. C., Zhou, C., He, S., & Zhou, W. (2020). Selenium removal by clam shells and gravels amended with cattail and reed litter. *Science of the Total Environ-ment, 742*. https://doi.org/10.1016/j.scitotenv.2020.140661.

Zhang, Y., Dong, W., Yan, G., Wang, H., Wang, H., Chang, Y., Yu, S., Chu, Z., Ling, Y., & Li, C. (2022). Plant Carbon Sources for Denitrification Enhancement and Its Mechanism in Constructed Wetlands: A Review. In *Sustainability (Switzerland)* (Vol. 14, Issue 19). MDPI. https://doi.org/10.3390/su141912545.

Zhao, D., Dong, J., Ji, S., Huang, M., Quan, Q., & Liu, J. (2020). Effects of contemporary land use types and conversions from wetland to paddy field or dry land on soil organic carbon fractions. *Sustainability, 12*(5), 2094. https://doi.org/10.3390/su12052094.

Zubair, M., Yasin, G., Qazlbash, S. K., Ul Haq, A., Jamil, A., Yaseen, M., Rahman, S. U., & Guo, W. (2022). Carbon Sequestration by Native Tree Species around the Industrial Areas of Southern Punjab, Pakistan. *Land, 11*(9). https://doi.org/10.3390/land11091577.