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REVIEW PAPER

The integration of nature values and services in the nature-based solution assessment framework of constructed wetlands for carbon–water nexus in carbon sequestration and water security

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Abstract As the climate change impacts are expected to become increasingly disruptive, affecting water security, environmental health and ecosystem, constructed wetlands receive attention for their functions in delivering various life-sustaining services to human and environmental systems. In this article, a systematic review was conducted through the Preferred Reporting Items for Systematic Reviews and Meta-Analyses standard to identify the current research on constructed wetlands' nature values and services from 2011 to 2020 of two databases, namely Scopus and Web of Science. The criteria of assessment focus on holistic deliberation of subject matters, namely carbon sequestration and water security as regulating and provisioning services, as well as nature values of constructed wetlands, namely instrumental and intrinsic values. As a result, 38 articles were selected and comprehensively examined. As the lack of an interdisciplinary approach makes data and information integration difficult, this study derived an integrated classification of constructed wetlands' services and mapped with its nature values, guided by the Millennium Ecosystem Assessment framework. Besides, mechanisms and factors affecting carbon sequestration and water security were also discussed. The carbon–water nexus was then conceptualised as interlinkages between engineered and natural physicochemical processes at the interface between carbon and water cycles. To fill the gaps, based on the carbon–water nexus concept, a new framework was synthesised at the end of the deliberation for constructed wetlands in regulating local climate through carbon sequestration and ensuring water security through water treatment and purification as well as influencing socio-cultural values, which needs an integrated approach that is the novelty of this work. The framework integrates the dichotomy of the instrumental-intrinsic nature values of constructed wetlands to evaluate the importance and benefit of the carbon–water nexus. The framework that reveals the vitality of nature values provided by constructed wetlands can help improve the decision-making to prioritise ecosystem services and conservation efforts,

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particularly in the sustainable management of constructed wetlands.

Keywords Carbon–water nexus · Constructed wetlands · Natured-based solution · Carbon sequestration · Water security · Sustainability

Introduction

Climate change and its impact

Global climate change is one of the current issues extensively debated internationally whereby many climate experts believe it is attributable to the increased release of greenhouse gases (GHGs) arising mainly from anthropogenic activities (Al-Ghussain, 2018; Goldberg et al., 2019; Letcher, 2019). The primary GHG, carbon dioxide (CO_2), has significantly contributed to global warming and subsequently climate change. According to the National Aeronautics and Space Administration (NASA), the CO_2 concentration in the Earth's atmosphere is almost 417 parts per million (ppm) (https://climate.nasa.gov/). It is observed that the concentration of CO_2 has increased gradually since the Industrial Revolution by 48% (280 ppm) and 12% (380 ppm) over the last two decades (Rosli et al., 2017). Furthermore, simulation and projection show that if the atmospheric CO_2 concentration is increased and maintained at 550 ppm, global annual CO_2 emissions need to be reduced by more than 75% over the next century (Emrouznejad et al., 2019; Schröder & Cabral, 2019). Rogelj et al. (2016) stated that CO_2 emission is estimated to reach about 65 Gt CO_2eq yr^{-1} by 2030. This phenomenon is expected to have catastrophic effects on natural and human environments if it is not addressed. The predicted impacts relate to habitat loss, the existence of unknown plant species, and the decline in the distribution of indigenous species that are poorly adapted to drought, heat and water insufficiency (Feistel & Hellmuth, 2021; Kabisch et al., 2016). Thus, it will likely become humanity's most important and nuanced environmental problem over time (Awange 2018; Intergovernmental Panel on Climate Change (IPCC) 2018). Thus, this area of research is under widespread scrutiny and investigation. Today's researchers and engineers' most significant challenge is to improve and develop systems for capturing CO_2 produced by anthropogenic activities and sequestering it securely from the atmosphere, to combat climate change and its impacts by 2030, as stated by the United Nations in Sustainable Development Goals (SDGs) (www.sustainabledevelopment.un.org).

Many efforts are made to limit CO_2 and other GHGs emissions into the environment to lessen climate change impacts (Azarkamand et al., 2020; Van Vuuren et al., 2018). The Paris Agreement acknowledges and offers a basis for ratcheting efforts to tackle global warming by balancing GHG removals and anthropogenic emissions to their parties. In general, all major GHGs State Parties pledged to reduce GHGs emissions from 26 to 28% of 2005 concentration levels by 2025, except for the United States of America (USA). This agreement strives for a vital, significant and feasible mitigation action towards global climate change through agreeable entire parties to reach a stipulated national governed response to decreasing anthropogenic emissions of CO_2 into the atmosphere.

Several research groups have been developing methods to mitigate and reduce the excess CO_2 in the atmosphere. Innovation by science and technology is the ordinary means to assess and propose how to tackle and solve these issues (Cai et al., 2021; Du et al., 2019). However, Bellamy (2015) affirmed that even though it would slow the effect, technology is expensive and needs sophisticated instruments and experts to handle, yet poses high risks and uncertainties to living life. Moreover, technology is not limited to technical aspects but must incorporate ethical and social concerns (Byskov et al., 2019). Hence, maximising the ecosystem's functions and services in climate mitigation and adaptation is seen as a nature-based solution to sustain human and environmental systems and deliver valuable benefits for people and nature (Marín-muñiz et al., 2014; Xiaoyan et al., 2019).

Constructed wetland as a nature-based solution

Wetlands have been demonstrated to be among the significant important, effective and no or low-cost alternatives for sequestering CO_2 (Derakhshan-Nejad et al., 2019; Harenda et al., 2018; Lorenz & Lal, 2018; Nahlik & Fennessy, 2016; Reddy et al., 2016). Wetland possesses a complex ecosystem that includes lakes, marshes and floodplains mainly covered with water-saturated soil, providing numerous services to human well-being and the environment, as classified by the Millennium Ecosystem Assessment (Table 1) (MEA, 2005). Wetlands can be portrayed as 'the kidney of the landscape' with great indirect value as resources, sinks and changes of many biological and chemical substances (Mitsch, 2020). Despite having a significant role in water quality improvement, wildlife protection and flood mitigation, several studies showed that wetlands are a natural system for sequestering excessive CO_2 in the atmosphere (Abdullahi et al., 2018; Graves et al., 2020; Lorenz & Lal, 2018). Wetlands comprise the highest carbon storage as the largest carbon pool and conclusively contribute to global carbon cycling (Lorenz & Lal, 2018). Even though central mitigation bank guidelines do not list carbon storage among the wetlands' functions, it must be acknowledged as a vital ecosystem service (Means et al., 2016).

However, according to Davidson (2014), the decline rate of world wetlands was 3.7 times faster during the twentieth and early twenty-first centuries, with 64–71% loss since 1900 AD. Industrialisation, land expansion for agriculture and urbanisation have contributed to this loss of natural wetlands worldwide (Junk et al. 2013). The intensifying rate of natural wetlands' failure has alternatively led to constructed wetlands that are intended to replicate and mimic the functions and values of natural wetlands that have been devastated (Metcalfe et al., 2018). Constructed

Table 1 Services provided by wetlands (MEA 2005)

Services	Examples	
Regulating		
Services that regulate the ecosystem process while maintaining environmental quality and outputs	Climate regulating	Source and sink GHGs, influence local and regional temperature, raining patterns and other climate processes
	Water treatment and purification	Water retention, water recovery and water removal of excess pollutants and nutrients
	Water hydrological	Groundwater recharge and discharge
	Natural hazard regulation	Storm protection and flood control
	Pollination	Habitat for pollinators
	Erosion regulation	Retention of soils and sediments
Provisioning		
Services that provide resources and products obtained from ecosystems	Freshwater	Storage and retention of water for domestic, industrial and agricultural use
	Food	Fish, fruits and wild grains production
	Biochemical	Extraction of medicines and other materials from biota
	Genetic materials	Genes for resistance to plant pathogens
	Fibre and fuel	Logs, peat, fuelwood and fodder production
Supporting		
Fundamental services that underpin the provision of services	Soil formation	Sediment retention and accumulation of an organic substance
	Nutrient cycle	Storage, cycle, process and acquisition of nutrients
Cultural		
Non-material services which provide benefits	Spiritual and inspirational	Source of inspiration, some religions attach spiritual and religious values to aspects of the wetlands ecosystems
	Aesthetic	Beauty and aesthetic value in aspects of wetland ecosystems
	Recreational	Opportunities for recreational activities
	Congnitive/educational	Opportunities for formal and informal education

wetlands are becoming increasingly important, whereby the specific ecosystem services do not have to be mutually exclusive, as both natural and constructed wetlands can perform a variety of ecosystem functions (Wong et al., 2018).

The nature values and services of constructed wetlands

The properties of constructed wetlands are similar to natural wetlands. It incorporates physical, chemical and biological processes, providing ecosystem services derived from the interactions between water, soil, aquatic organisms, plants and microbes, i.e. sedimentation, nutrient, carbon and water cycling. In addition, plant diversity contributes to increasing the landscape by creating significant wildlife habitats for various animals, such as amphibians, insects and songbirds and enhancing the site's aesthetics (Rajpar & Zakaria, 2014). Likewise, constructed wetlands show the great potential to exert CO_2 sequestration from the atmosphere and keep it in the form of organic matter and biomass to absorb pollutants and restore the quality of water through the carbon and water cycles (Bernal & Mitsch, 2013; Mitsch et al., 2008; Ward et al., 2017; Wong et al., 2018). Furthermore, the Ramsar Convention on Wetlands emphasises that 'climate change mitigation is all about carbon, but climate change adaptation is all about water' (Sherren & Verstraten, 2013). However, traditionally, carbon mitigation, water supply, pollution control, agricultural resource management and energy generation have all been viewed as separate issues to be resolved independently. Nevertheless, it is becoming clear that interconnections between water, carbon and nutrient cycles can now be utilised in systems that fulfil numerous roles while increasing ecosystem health (Avellan et al., 2017). Yet, less attention was given to researching constructed wetlands valuation to merge the processes of carbon sequestration and water rehabilitation as well as other values through the integrated approach of carbon and water cycles in its ecosystem services.

Commonly, constructed wetlands are used for water reuse projects on a local scale, such as gardening and nutrient and pollutants removal in domestic settings, or on a larger scale, for irrigation of crops, public parks, golf courses, or to restore natural wetlands and groundwater (Metcalfe et al., 2018; Nan et al., 2020; Rossa et al., 2019). Nevertheless, recent studies showed the possibility of leveraging constructed wetlands as a potential mitigation approach in addressing the carbon–water nexus, relating to those natural and engineered physicochemical processes at the interface of the atmosphere between carbon and water cycles (Clarens & Peters, 2016; Masi et al., 2018; Were et al., 2019). Thus, constructed wetlands can address at least two critical aspects of sustainable development through the carbon–water nexus: clean water and sanitation (SDG6) and climate action (SDG13). SDG6 sets the baseline for watershed resources management to ensure the ecosystem and human health are assured by sustaining the adequate quantity and acceptable quality of water supply (UN-Water, 2013). Hence, it is essential to assess the security of these resources by exploring the functions and values of constructed wetlands. In addition, Masi et al. (2018) showed that constructed wetlands help reduce the urban heat effect, positively influencing the community's health, offering integration of functions and values for people whereby the hidden benefits and values of constructed wetlands should be highlighted on top of the functions. However, functions and values are often puzzled and considered identical, whereby this may lead to a lack of sound constructed wetland management, which could negatively impact the ecosystem. Hence, two questions are raised in this review, i.e. 'how does constructed wetland function in performing carbon sequestration and ensuring water security?' and 'how does constructed wetland provide values to the wellbeing of human and the environment?'. Therefore, this review focuses on the concept of carbon–water nexus of constructed wetlands based on its nature values and services that need an integrated approach to strengthen the conservation as well as adaptation and mitigation planning to reduce the climate change vulnerability and enhance the sustainable management of constructed wetlands.

To the best of our knowledge, no systematic review has examined the carbon–water nexus of constructed wetlands and the interactions between the values and services of constructed wetlands just yet. Hence, this review aims to identify the current research patterns concerning constructed wetlands over the last decade (2011–2020) and provide insight into the values and services provided by constructed wetlands. Secondly, the carbon—water nexus is examined by assessing carbon sequestration and water rehabilitation services by constructed wetlands through carbon and water cycles to determine the mechanisms taking place in constructed wetlands. The functions are hypothesised to be influenced by the values perceived by the people. Since the values and services of constructed wetlands involve a multifaceted transaction between people and the environment, this review needs to understand intrinsic and instrumental values and provide necessary information and strategies to help direct the future valuation of constructed wetlands, especially paths to achieving SDG 6 and SDG 13. Moreover, this review potentially contributes to a better understanding of the vital nature benefits of constructed wetlands as a nature-based solution for mitigating and adapting to climate change as well as advocating for the long-term development of engineered wetland ecosystem.

Methodology

A systematic literature review (SLR) was conducted to understand a subject matter and obtain a solid and determined response that engages with a research question. Conducting a systematic review of the values and services of constructed wetlands is critical, as there is a growing global debate about it. The method used in this review identifies gaps and directs future research on the nature values and services of constructed wetlands as a nature-based solution in climate change adaptation and mitigation. A systematic review allows researchers to identify patterns in previous studies and aid the understanding of related issues that can provide insights into the nature values and services of constructed wetlands in the context of the carbon–water nexus (Abu Samah et al., 2021). In addition, Mallett et al. (2012) stated that the review process is strengthened by the transparent retrieval and selection process, covering more prominent research areas and controlling research bias based on the objectives. Hence, this review is guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standard (Moher et al., 2009) and the strategies listed by Bramer et al. (2018). The review is rooted explicitly in the literature on constructed wetlands' ecosystem services and their valuation. The search criteria were specified by combining the types of constructed wetlands, including agriculture pond, lake (ex-mining pond and land change), saltpan and engineered wetlands (water treatment basin, dam and reservoir), with each of the four possible ecosystem services classified in the Millennium Ecosystem Assessment (MEA, 2005). Figure 1 presents a schematic diagram of the summarised topics selected for this review. The literature search focused on two electronic databases, namely Scopus and Web of Science (WoS), to maximise the journal coverage. These two databases are the most wide-ranging database, encompassing more than 250 fields of study, including the environment (Mohamed Shaffril et al., 2019). Figure 2 shows the flow of the selection process and method used in the systematic review guided by PRISMA methodology, consisting

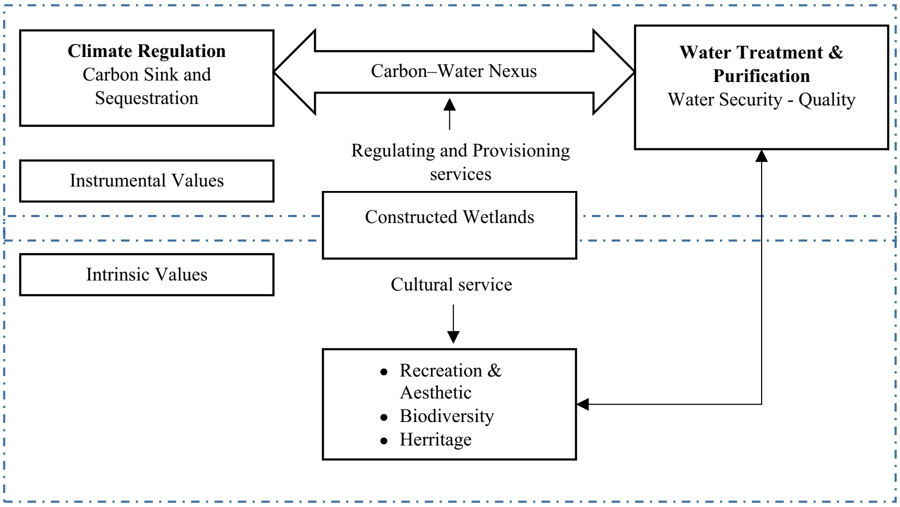


Fig. 1 A schematic diagram of the topics selected for the review in this paper

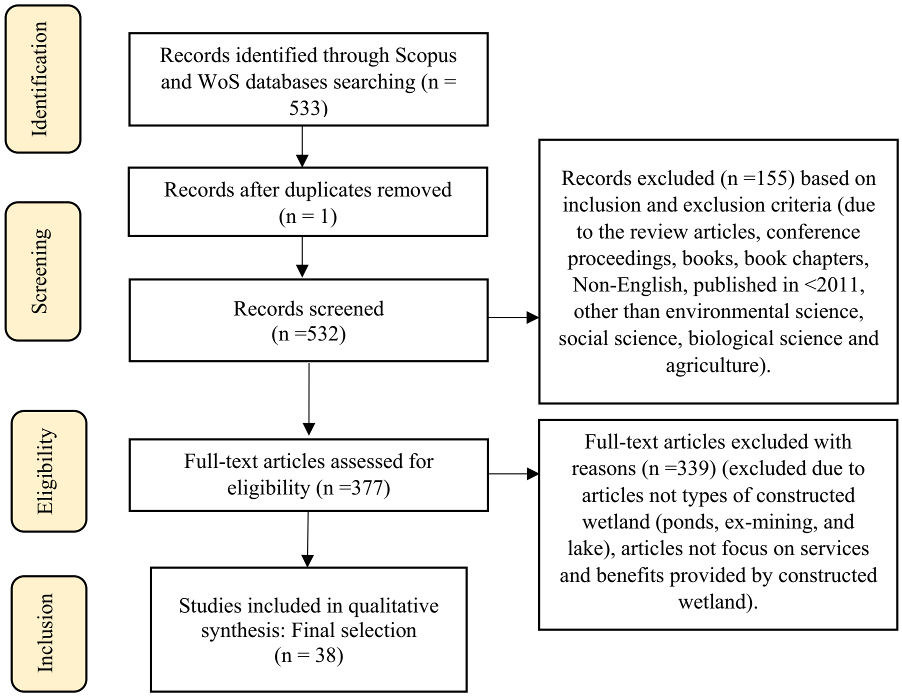


Fig. 2 A schematic diagram of the selection processes and methodology of the systematic review guided by PRISMA (Moher et al. 2009)

of four steps, i.e. identification, screening, eligibility and inclusion, which are described as follows.

Identification

The first step identified and searched related articles by identifying keywords on the databases using advanced search and search strings developed up to 31 August 2020. The search strings used were (‘wetlands’ OR ‘wetland’ OR ‘lake’ OR ‘ex-mining lake’ OR ‘mining lake’ OR ‘pond’ OR ‘human-made’ OR ‘manmade’ OR ‘artificial’) AND (‘carbon storage’ OR ‘carbon sequestration’ OR ‘carbon sink’ OR ‘carbon capture’) AND (‘values’ OR ‘valuation’ OR ‘intrinsic’ OR ‘relational’ OR ‘instrumental’) AND (‘water*’). In this step, a total of 533 articles were successfully retrieved from both databases.

Screening

Next, the screening step was conducted to remove duplicating papers whereby all articles retrieved were refined based on inclusion and exclusion criteria determined by the researcher. The first criterion was the literature type where this review only focuses on research articles because it represents the primary source that provides empirical data. Thus, other publications in the form of review articles, conference proceedings, books and book chapters were excluded. Besides, only articles published in English from 2011 to 2020 were selected because it is critical to observe the research trends and issues regarding constructed wetlands’ values and services over the past ten years. Based on these criteria, refined results excluded 155 articles and only 1 article was removed based on duplication screening. Most importantly, to increase the possibility of related articles, articles published in the research area of environmental science, social science, biological science and agriculture were selected.

Eligibility

A total of 377 articles were subsequently prepared for the eligibility step. The articles were further screened based on the titles, abstracts and main contents to ensure the articles fulfilled the criteria and could be used to review and achieve the aims. Consequently, 339 articles were excluded because some of the articles did not provide full access, did not discover the types of constructed wetlands and did not focus on the values and services provided by the constructed wetlands.

Inclusion

As a result, a total of 38 articles were ready to be analysed. Analysis of published papers included in this review, i.e. publication year, the types of constructed wetlands, the study's geographic area and other related information, was extracted and analysed. The analysis provided related information to the current research on constructed wetlands' values and services, especially in carbon sequestration and water security. Microsoft Office Excel 2019 was used to analyse all the selected articles.

Results and discussion

Main findings of the study

Table 2 provides an overview of ecosystem services provided by constructed wetlands. The number of studies for regulating and provisioning services in climate regulation as well as water purification and treatment is high. However, there is not much study that integrates cultural services, like aesthetic, recreational and heritage. Thirty-eight articles were published between 2011 and 2020 in peer-reviewed journals regarding constructed wetlands' ecosystem services, comprising 27 studied sites. These papers reported studies from 15 countries where 37% were conducted in Asia and North America, respectively, followed by 21% of which were recorded in Europe and only 5% of articles were from South America. The largest number of studies were conducted in the United States of America (USA) with 31.5%. Figure 3 shows the geographic distribution of the constructed wetlands' ecosystem services studies where the number of studies shows in parentheses. Globally, studies on the constructed wetlands' ecosystem services were relatively heterogeneous regarding the services and purposes. As shown in Fig. 4a, the number of publications assessing constructed wetlands increased exponentially over the first three years (2011–2014). After that, it fluctuated until 2020, with an average number of publications being 4 per year. Researchers had evaluated engineered wetlands (82%) more frequently than other constructed wetland types. The articles had been published in 27 journals with the highest percentage, 18% ($n=7$) being published in Ecological Engineering (Fig. 4b). The quantification approach was the major type of analysis, including experiment or modelling (95%), qualitative assessments and mixed studies (2.5%).

Implication and explanation of findings

The lack of an interdisciplinary approach makes data and information integration difficult. Most of the publishing efforts came from environmental fields focusing on instrumental value. Meanwhile, social sciences, crucially not only for the study of cultural services but also for most valuation methodologies and intrinsic value, are underrepresented in constructed wetlands' ecosystem services. Comparisons between assessments have been challenging and inconsistent due to the variety of existing classifications of ecosystem services and value categories. Since this review identifies the constructed wetland's values and services, we thus derived and mapped an integrated classification of constructed wetlands' ecosystem services and nature values guided by the Millennium Ecosystem Assessment (MEA) framework. The detail of specific matter provided by constructed wetlands' ecosystem services is described in Table 3, directly highlighting the functions and their benefits. The classification listed also guides the review of constructed wetlands' ecosystem services and introduces the conceptual framework of carbon–water nexus, allowing the ecosystem services to be translated into suitable institutional and social responses.

Mechanism of carbon sequestration in constructed wetland

Constructed wetlands' capacity in carbon sequestration is a vital function that provides an impetus undertaking for large-scale restoration and improvement of the ecosystem. However, it is often hindered and mostly taken for granted. As illustrated in Fig. 5, the constructed wetland has been seen as a potential carbon sink, demonstrating the necessity of explicitly designed to store as much carbon as possible (Fennessy et al., 2018). Generally, carbon sequestration in constructed wetland involves several processes, utilising the carbon dynamics and other elements within the systems at different scales to capture, sink and

Table 2 List of selected articles mapping with constructed wetlands' ecosystem services

No.	Plants	Country	CWES						Journals	Authors
			RS				PS	CS		
			CWR	WP	CWP	BI	WSP	ARH		
1	Typha, Phragmites and Miscanthus	Korea		√					Ecological Engineering	Reyes et al. (2020)
2	*Senecio bonariensis*	Argentina		√			√		Journal of Hydrology	Siniscalchi et al. (2020)
3	Macrophytes	Argentina		√	√	√			Ecological Engineering	Manzo et al. (2020)
4	*S. grosus* and *E. dulcis*	Malaysia		√					Journal of Natural Sciences	Sidek et al. (2020)
5	*Typha latifolia L*	US	√	√					Soil Science Society of America Journal	Iseyemi et al. (2019)
6	Black mangrove species, *Avicennia marina*	China	√						Water Science and Technology	Yang and Yuan (2019)
7	*J. effusus, S. lacustris, Spar ganium erectum, Iris pseudacorus, Carex riparia, Glyceria maxima*	Poland		√					Journal of Ecological Engineering	Rossa et al. (2019)
8	Mangroves	Taiwan	√						Marine Pollution Bulletin	Huang et al. (2019)
9	*Phragmites australis*	Iraq		√			√		Iraqi Journal of Agricultural Sciences	Rahi and Faisal (2019)
10	grassland	Portugal	√	√			√		Mitigation and Adaptation Strategies for Global Change	Santos et al. (2018)
11	*Phragmites & Typha latifolia*	China	√	√			√	√	Ecosphere	Wong et al. (2018)
12	NA	US		√				√	Journal of Environmental Management	Irwin et al. (2018)
13	*E. crassipes S. molesta & P. stratiotes*	Malaysia		√					Jurnal Teknologi	Sidek et al. (2018)
14	*Phragmites australis*	Labenon		√					Water and Environment Journal	Abi Saab et al. (2018)
15	*Typha L. Typha A.* and *Alisma plantago-aquatica, Bolboschoenus maritimus, Glyceria maxima, Eleocharis palustris,* and *Equisetum fluviatile*	Germany	√						Ecological Engineering	Overbeek et al. (2018)
16	*Nuphar, Nymphaea, Thalia, Pontederia, Eleocharis, Sagittaria, Cladium*	US		√	√				Ecological Engineering	Zhang et al. (2017)
17	*Phragmites australis, Typha P. and Clerodendrum schmidtii*	China	√				√		Ecological Engineering	Guo et al. (2017)

Table 2 (continued)

No.	Plants	Country	CWES						Journals	Authors
			RS				PS	CS		
			CWR	WP	CWP	BI	WSP	ARH		
18	Macrophytes	Spain		√					Science of the Total Environment	Hernández-Crespo et al. (2017)
19	*Phragmites karka*	India	√						International Journal of Applied and Pure Science and Agriculture	Kanungo et al. (2017)
20	*Phragmites australis*	China	√						Agricultural and Forest Meteorology	Zhang et al. (2016)
21	*Spartina alterniflora, Juncus roemerianus, and Spartina patens*	US	√						Wetlands	Shiau et al. (2016)
22	*C. vulpinoidea, E. obtuse, J. effusus, M. ringens*	US	√						Journal of Environemental Mangement	Means et al. (2016)
23	*Typha latifolia L. & (Schoenoplectus americanus*	US	√						Water Science and Technology	Reddy et al. (2016)
24	hardstem bulrush (*Schoenoplectus acutus*) & *Typha spp.*	US	√						Biogeosciences	Anderson et al. (2016)
25	21 emergent species, 15 floating-leaved species and 14 submerged species and dominated by *Cyndon dactylon*	China	√						Aquatic Botany	Xiao et al. (2015)
26	Vascular plants	Canada		√				√	Water Research	Rooney et al. (2015)
27	NA	Italy				√			Journal of Limnology	Sartori et al. (2015)
28	NA	China	√						PLoS ONE	Cao et al. (2015)
29	*Typha sp, Phragmites sp. & Chara sp.*	Spain				√			Aquatic Sciences	Español et al. (2014)
30	Agriculture crops and emergent vegetation	US	√	√		√			Wetlands	Maynard et al. (2014)
31	Typha/Leersia marsh	US	√						Journal of Environmental Quality	Bernal and Mitsch (2014)
32	Typha/Leersia marsh	US	√						Ecological Engineering	Mitsch et al. (2014)
33	Phragmites	Germany	√						Ecological Engineering	De Klein and Van der Werf (2014)
34	NA	Canada		√				√	Wetlands	Sherren and Verstraten (2013)
35	NA	China		√				√	Environmental Monitoring and Assessment	Zhang et al. (2013)
36	Typha/Leersia marsh	US	√						Landscape Ecology	Mitsch et al. (2013)

Table 2 (continued)

No.	Plants	Country	CWES						Journals	Authors
			RS				PS	CS		
			CWR	WP	CWP	BI	WSP	ARH		
37	reed bed	Germany		√					Wetlands	Boets et al. (2011)
38	*Polygonum lapathifolium*	US	√						Biogeosciences	Maynard et al. (2011)

CWES: Constructed wetlands' ecosystem services, RS: Regulating service, PS: Provisioning service, CS: Cultural service, CWR: Climate and weather regulating, WP: Water purification & treatment, CWP: Constructed wetlands protection, BI: Biodiversity, WSP: Water storage and provision, ARH: Aesthetic, recreational and heritage (ARH)

store atmospheric carbon dioxide for the long term into the wetlands' soil carbon pool with minimum possibilities of being released back into the atmosphere (Chen et al., 2017). Thus, a change in carbon stock in or between wetland environments is represented as carbon sequestration. Ultimately, the value of carbon uptake by constructed wetlands is referred to the maximum rate of carbon storage (for example, the rate of plant growth) and the greatest amount of carbon that may be stored (in plants or soil) on a given temporal and spatial scale (De Klein & Van der Werf, 2014; Lorenz & Lal, 2018).

The carbon balance is determined by two processes, photosynthesis and respiration, majorly mediated by plants. Plant communities are responsible for uptaking the atmospheric carbon dioxide through photosynthesis as their primary source and decay at the bottom soil, which can profoundly perform carbon sequestration (Luan et al., 2018). Mitsch et al. (2013) developed and ran a dynamic carbon model, showing carbon exchange occurs between the atmosphere and constructed wetlands (Fig. 6) in which soil carbon sequestration is determined by the cycle of CO_2 and CH_4 emissions exchange. With the aid of sunlight, wetland plants assimilate the biological CO_2 into their tissues and convert them to carbohydrates which are deposited into leaves, stems, roots and lastly in the soil as soil organic carbon or vice versa in soil respiration that occurs at the aerobic zone. Carbon sink and sequestration of constructed wetlands depend on the amount of dissolved organic matter enhanced by microbial activities in the soil (Rosli et al., 2017). A further change of this biomass is profoundly reliant upon hydrology whereby the slow rate of organic matter decomposition and high productivity of plants under saturated soil conditions may add to the sequestration of carbon caused by the anoxic wet condition of water inundation (Iseyemi et al., 2019).

Factors affecting carbon sequestration in constructed wetland

Several factors, such as the establishment of dominant plants over the age of constructed wetlands, hydrology (soil saturation) and seasonal climate (temperature) as described below, are important natural features facilitating wetland carbon pool and accumulation. Table 4 shows the literature regarding carbon

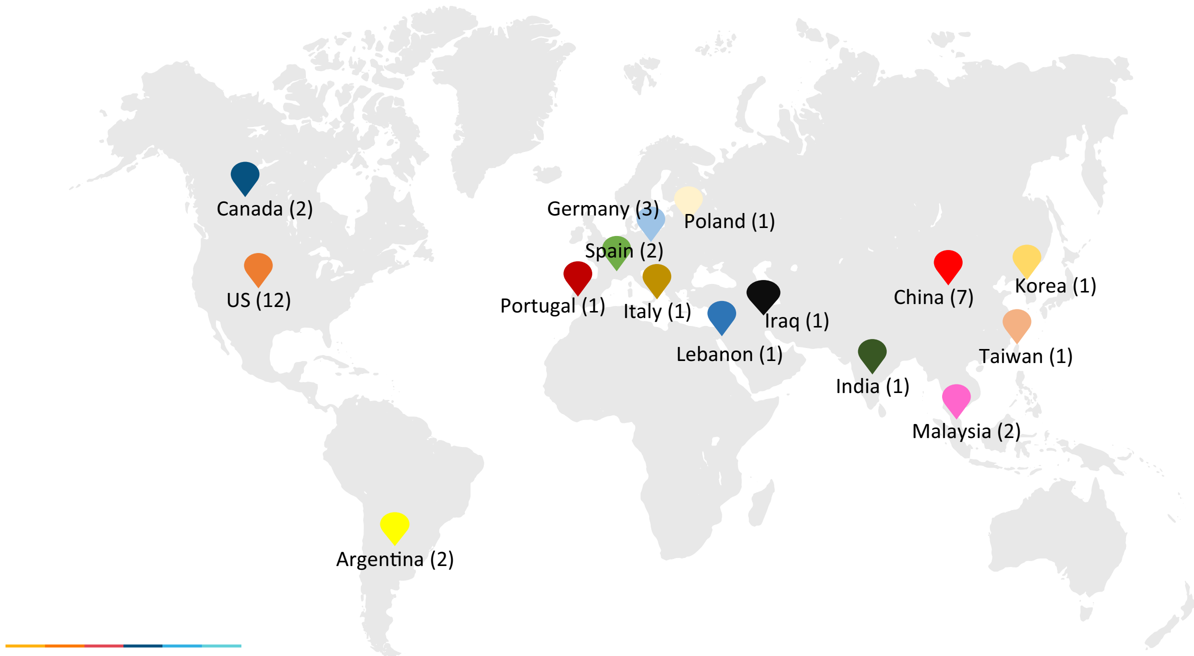


Fig. 3 Geographic distribution of relevant constructed wetland studies

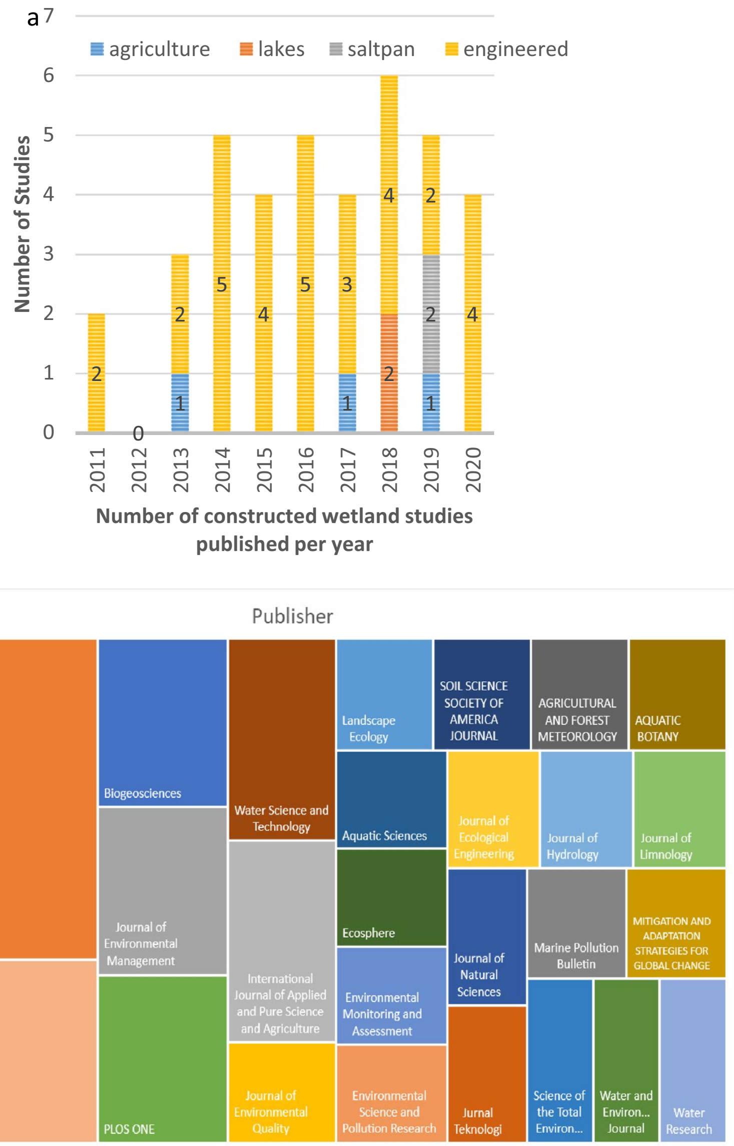
sequestration in constructed wetlands, including the dominant plants and the age of constructed wetlands.

Dominant plants over the age of constructed wetlands' ecosystem services

Plants are often employed in constructed wetlands whereby plant diversity always affects the potential of constructed wetland to store carbon by supplying the available substrate. Previous studies higher (Huang et al., 2019; Yang & Yuan, 2019) showed a relationship between plant types over the age of constructed wetlands in carbon accumulation enhancement. For example, the rates are higher in the saline constructed wetlands vegetated with mangrove species between 323 and 635 g C m^{-2} y^{-1}, showing significant carbon content in the soil of the mangrove habitat. In addition, researchers found cattail (*Typha* species) and common reed (*Phragmites* species) to be the most common plant species planted or naturally colonised in the constructed wetlands. These emergent plants are expected to introduce an important amount of carbon into the soil which is known as superior biomass producers (Avellan et al., 2017). Overbeek et al. (2018) found a higher fraction of organic matter even in the sediment of 3-year-old constructed wetlands planted with *Typha latifolia* and *Typha angustifolia*, and the linearity model shows the constructed wetlands have the potential to sequester carbon. The carbon accumulation recorded in constructed wetlands dominant with *Typha* species is between 23 and 267 g C m^{-2} y^{-1} (Bernal & Mitsch, 2014; Guo et al., 2017; Iseyemi et al., 2019; Reddy et al., 2016). Mitsch et al. (2014) showed plant succession for 20 years of constructed wetlands dominated by *Typha* species remarkably possesses a high nutrient content with greater productivity contributing to the carbon pool and sequestration rate.

Meanwhile, the carbon assimilation rate by *Phragmites* species is remarkable as this species can absorb up to 700 ppm of CO_2 concentration (Kanungo et al., 2017). Further, the roots of *Phragmites* may reach deeper than any other hydrophyte (root depth up to 3 m), helping the plant take up water and wetland nutrients (De Klein & Van der Werf, 2014; Zhang et al., 2016). This vascular plant consists of a high content of lignocellulosic components, such as carbon and nitrogen, that directly supplies the organic matter into sediment through decomposition (Maynard et al., 2011; Reddy et al., 2016). For instance,

Fig. 4 Data and analysis from the selected constructed wetland assessment. **a** Number of studies per year according to types of constructed wetland. **b** Breakdown of studies published in various journals



De Klein and Van der Werf (2014) recorded the highest carbon accumulation with net values in the range of 0.27–2.40 Mg C ha^{-1} y^{-1}, signifying 12 to 67% CO_2 fixation. The carbon pool significantly increases between 51 and 82% after 3 to 15 years with *Phragmites australis* established as dominant plant communities (Guo et al., 2017; Zhang et al., 2016).

Other species, such as *Juncus* and *Mimulus,* also show a significant capability to store the aboveground carbon even though at a young age of creation, which is about 2 to 3 years. In addition, their inclusion improves the relationship between plant cover, indicating that these species provide a non-negligible contribution to overall carbon storage (Means et al., 2016; Shiau et al., 2016). Thus, the carbon pool and accumulation are most likely based on plant types and local availability, climate adaptability and tolerance to influent water quality (Wu et al., 2015).

Hydrology (soil saturation)

Amount of water, water retention time and water depth are also key factors influencing wetland carbon storage. Due to their high productivity and slow

Table 3 The integrated classification scheme of constructed wetlands' ecosystem services and their nature values

Ecosystem services	Constructed wetland ecosystem services	MEA	General ecosystem services definition (MEA)	Specific matter provided by constructed wetland ecosystem services	Nature values
Regulating services (RS)	Climate and weather regulating (CWR)	Climate regulating	Regulation of GHG. The most common representations are the uptake, storage and sequestration of CO_2	The constructed wetlands act as a sink for GHGs, primarily CO_2. Organic and inorganic carbon is stored and sequestered and quantification as aboveground biomass (AGB), aboveground carbon (AGC), and belowground carbon (BGC). Influence on air moisture, formation of clouds and saturation point	Instrumental value
	Water purification (WP)	Water purification and waste treatment	Physicochemical and biochemical processes are involved in the removal of pollutants and wastes from the aquatic environment	Treatment of human and animal wastes (e.g. nitrate and phosphate retention); sedimentation, trapping, dilution; bioremediation, filtration and absorption, and decomposition (e.g. pesticide residues or industrial pollution)	
	Biodiversity (BI)	Pollination	Biological and physical support (habitat) to facilitate the healthy and diverse reproduction of species	The maintenance of key habitats that act as nurseries, spawning areas or migratory routes (e.g. grasses, mangroves, birds). These habitats and the connectivity among them are crucial for the successful life cycle of species. This also includes pollination (e.g. plants pollination), and seed and gamete dispersal by organisms. This service guarantees the maintenance of genetic diversity or gene pool protection	Objective intrinsic value
Provisioning services (PS)	Water storage and provision (WSP)	Freshwater	The provision of water for uses of water in agriculture, domestic, and industrial as well as human consumption	Water abstraction in constructed wetlands environments is mostly associated with lakes, saltpans and water treatment plants, be used for domestic, industrial processes or agriculture in ponds	Instrumental value
Cultural services (CS)	Aesthetic, recreational and heritage (ARH)	Aesthetic and heritage	The exaltation of senses and emotions by landscapes, habitats or species	The existence and beauty of charismatic habitats and species such as migratory birds and iconic landscapes. It can be related to wetlands activities (recreational fishing, birds watching)	Subjective intrinsic value
		Recreational	Opportunities that the constructed wetlands' environment provide for relaxation		

rate of organic matter decomposition caused by the anaerobic conditions created by water inundation, wetland plant materials sequester carbon more efficiently under saturated soil conditions. Furthermore, different gradients of water depth in the landscape affect vegetation distribution and aquatic species, thus influencing organic matter accumulation. For instance, Xiao et al. (2015) showed a significant difference in carbon pools in different submerged zones. The inundated zone for the whole year with a water depth greater than 1.50 m managed to pool about 55 g C kg^{-1} compared to the emergent and drawdown zones (0.3–1.5 m) where the average carbon is 41 g C kg^{-1} and 26 g C kg^{-1}, respectively.

Meanwhile, Bernal and Mitsch (2014), De Klein and Van der Werf (2014), and Maynard et al. (2011) showed the open water area has a high rate, indicating that they receive a vast amount of organic matter within the wetlands' plant organic waste and sequestration rates were found similar to that of natural wetland. The modification to the drainage system along with nutrient-rich water input not only stimulates the plants' growth but enhances soil saturation and anaerobic condition that influences biogeochemical mechanisms, like nutrients absorption, organic matter decomposition and denitrification, thus increasing carbon (Guo et al., 2017; Iseyemi et al., 2019). As a result, even a slight change in wetland equilibrium shows a different change in total wetland functioning in carbon sequestration.

Seasonal climate (temperature)

The local environment and seasonal climate relate to temperature control of the microbial activity affecting the soil organic matter decomposition in the wetlands. The microbial population directly shifts with the temperature and the oxygen available in the production of soil organic matter. Microbial decomposition rate is slow as soil respiration in high humidity and low temperature (anaerobic condition) may enhance the carbon content. The biological reaction is estimated to double for every 10 °C increase in temperature. Thus, warming is likely to increase world plant biomass, while decreasing the soil carbon pool (Jan et al., 2020). Bernal and Mitsch (2014) and Santos et al. (2018) showed that temperate freshwater wetland typically has more significant soil organic carbon accumulation than tropical wetland because of lower temperature and longer hydrological pulse. Furthermore, the current study shows that comparable carbon pools ranging between 27.30 and 28.48 kg C m^{-2} in summer and 23.98 and 31.09 kg C m^{-2} on average in winter are a good representation of temperate hydro-period wetland (Iseyemi et al., 2019).

Water security in constructed wetland

The UN-Water conceptual framework for water security is shown in Fig. 7, which encourages a collaborative approach to solving contemporary water-related issues. Good governance, transboundary cooperation, financing, peace and political stability are important components of aquatic system management to meet future water demands. As for good governance, adequate legal, infrastructure, institution and capacity should be in place. Transboundary cooperation needs sovereign states to consult and coordinate their actions to meet the diverse and, at times, competing interests of mutual benefit. Conflicts' negative consequences, such as reduced water quality and/or quantity, compromised water infrastructure, human resources, related governance and social or political systems, should be avoided to ensure water security peace and political stability. At the same time, innovative financing sources supplement public-sector funding, such as private-sector investments and micro-financing schemes.

Furthermore, these factors contribute to ecosystem protection, water-related hazard reduction, climate change adaptation, safe drinking water access, as well as human health and well-being advances (UN-Water, 2013). This approach directly emphasises the importance of understanding the diverse functions of aquatic ecosystems, such as constructed wetlands and their advantages in terms of health and well-being, livelihoods, water security, and more recently, climate change mitigation and adaptation (Kansoh et al., 2020). This approach also underlines the need for measures to reduce pollution that renders water unavailable or unsuitable for other purposes, contributing to water scarcity. Constructed wetlands are generally less expensive than complex infrastructure solutions for pollution abatement, stormwater management and coastal zone protection while providing various ecological functions and other values.

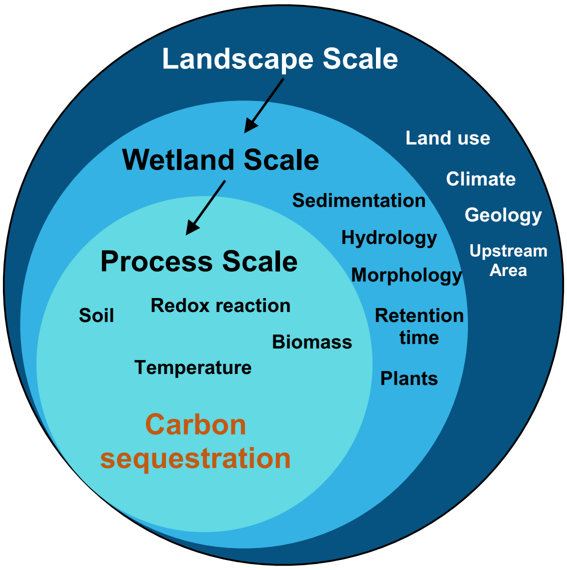


Fig. 5 Driving factors affecting the carbon sequestration capacity across three scales (adapted from Fennessy et al., 2018)

Constructed wetlands as pollution abatement

A literature survey shows that constructed wetlands not only behave like a carbon sink but a transformer of pollutants and nutrients, depending on the physical, chemical and biological characteristics of the constructed wetlands' environment. The constructed wetlands may also enhance the ecological carrying capacity of the ecosystem through sustainable treatment of wastewater (Galve et al., 2021; Rahi & Faisal, 2019; Sherren & Verstraten, 2013). Numerous studies (Abi Saab et al., 2018; Hernández-Crespo et al., 2017; Reyes et al., 2020) corroborated that the primary focus of constructed wetlands is to remove contaminants from wastewater, including biological oxygen demand, nutrients, suspended solids and heavy metals. In addition, microbial decomposition, assimilation, precipitation and adsorption to soil particles are all chemical and biological processes that function within the wetland environment, contributing to enhanced water quality. It is also an indicator of constructed wetlands' performance in ameliorating water quality and helps recover eutrophic water bodies (Hernández-Crespo et al., 2017; Irwin et al., 2018). In this context, constructed wetlands can assist local governments in finding a balance between watershed environmental protection, social and economic development, thereby helping in the development of sustainable policies (Abi Saab et al., 2018; Wong et al., 2018).

An interesting project was carried out in Yongding River Green Ecological Corridor, Beijing, China (Wong et al., 2018), which illustrates the potential of constructed wetlands and artificial lakes as a long-term green infrastructure solution. This green project is a core concept using the ecosystem approach to advance urban sustainability in improving ecosystem services, such as water storage, water purification, local climate regulation and expanded wetland-based nature reserves to preserve biodiversity and aesthetic values to meet high residents' demands.

Therefore, following the green infrastructure principles, phytoremediation becomes a significant and integral element to favour the constructed wetlands' improvement in a sustainable environment. Phytoremediation is the chemical and biological efficiency of plant activities in purifying, debilitating or removing environmental pollutants in water, wastewater, sludge and soil via biosorption (Jamion et al., 2021). However, studies showed that plant species may differ in their ability to absorb nutrients. Table 5 summarises over 15 dominant plant species established worldwide to remove pollutants and treat various water bodies. This review reveals that *Phragmites* are emergent plant species that are highly planted, particularly in Asia. In addition, Avellan et al. (2017) stated that, globally, wastewater treatment plants remove about 60 million kg of biochemical oxygen demand (BOD) every year, over 4 million kg of nitrogen and roughly a million kg of phosphorus.

Sediment trapping is a significant physical function of the constructed wetlands. By retaining sediment run-off flowing through the steady hydraulic substrate into nearby water bodies, constructed wetlands filter suspended particles and decrease erosion (Manzo et al., 2020). In addition, it encourages silt to settle out of suspension in the water column and collect in the wetland substrate by reducing flow velocity. Suspended solids are settled by chemical flocculation through the electrostatic interaction and microbial metabolism of colloidal solids correlated with the plants' roots (Rahi & Faisal, 2019). As a result, the purity of nearby water bodies improves. Rahi and Faisal (2019) assessed the performance of constructed wetlands planted with *Phragmites australis* to treat municipal wastewater and found that the

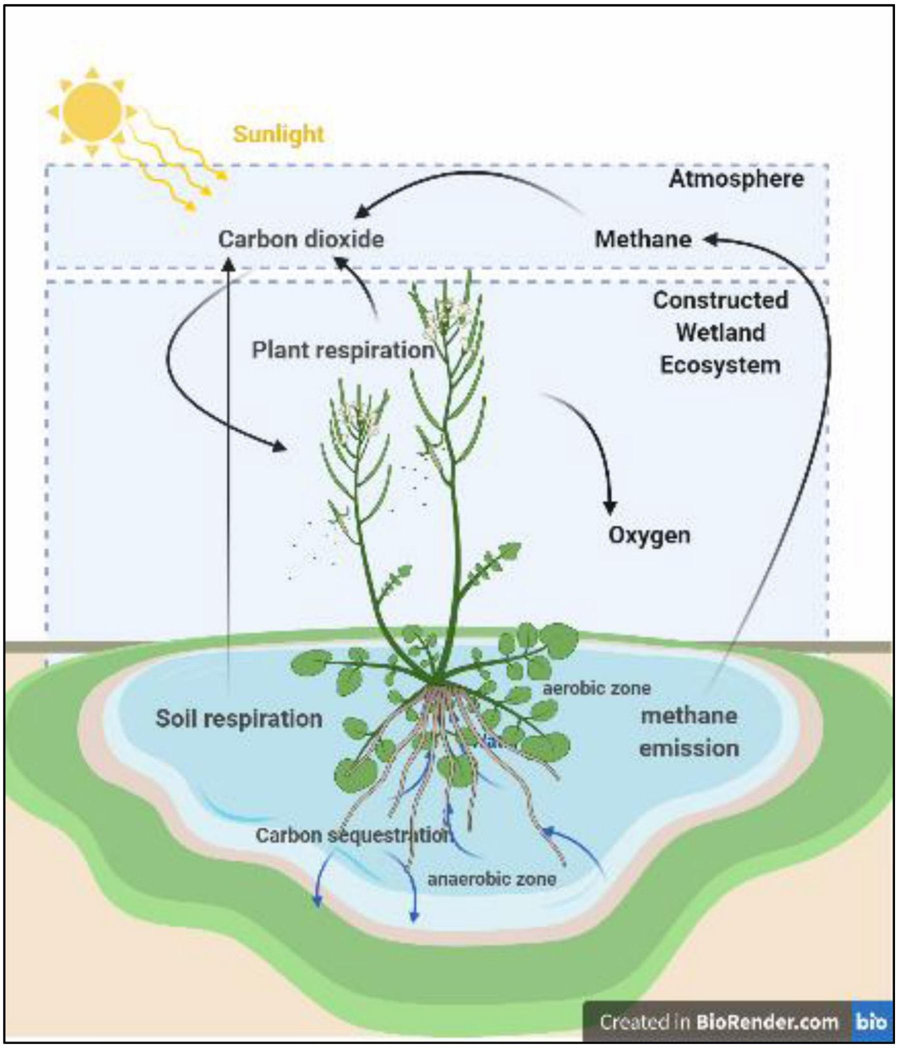


Fig. 6 The process involved in carbon sequestration (adapted from Mitsch et al., 2013)

average removal efficiencies of total suspended solids (TSS) typically range from 50 to 80%. The findings are in agreement with the results of Abi Saab et al. (2018) and Manzo et al. (2020) who obtained a more significant removal efficiency of TSS (> 80%), showing that constructed wetlands are efficient in the removal of suspended solids from various types of water.

Constructed wetlands are notable for removing various types of chemical pollutants, such as biological oxygen demand (BOD), nutrients and heavy metals. Biological oxygen demand (BOD) is removed from runoff water through aerobic and anaerobic microbial degradation processes (Rahi & Faisal, 2019). Wetland plants stimulate microbial activity by providing a leaf and root substrate for bacterial biofilms to grow on and further supply dissolved oxygen (Rahi & Faisal, 2019). Wetland plants have a unique adaptation to anaerobic soil conditions and transfer oxygen to the root systems. Furthermore, the wetland plants produce oxygen, resulting in greater dissolved oxygen concentration in the water and the soil around the plant roots. The presence of these oxidised microsites improves the system's ability to decompose pollutants through aerobic bacterial breakdown (Oleksińska, 2015). Generally, the previous study found that significant BOD removal efficiencies are between 30 and 70%, depending on the types of wastewater. For example, Reyes et al. (2020) reported the maximum load of BOD from livestock wastewater is reduced from 301.59 kg/d to 63.57 kg/d, contributing to up to 50% of removal. In addition, Abi Saab et al. (2018)

Table 4 Carbon sequestration in constructed wetlands reported in the literature

Dominant plant types	Pool	Site study	Constructed wetland ecosystem services age	Carbon accumulation (g C m^{-2} y^{-1})	Authors
Typha latifolia	BGC	Arkansas State University's (ASU) Agricultural Research Facility	9	23–30*	Iseyemi et al. (2019)
Black mangrove species, *Avicennia marina*		Datang Saline Constructed Wetland (DSCW)	–	323–460	Yang and Yuan (2019)
Mangrove—Rhizophora stylosa		Yuanjhongkong constructed a mangrove wetland	12	635	Huang et al. (2019)
Phragmites australis, Carex schmidtii, and Thelypteris palustris community		Paddy field in Jilin Longwan	15–30	270–491	Guo et al. (2017)
Cattail (Typha spp.) and Schoenoplectus americanus		North Carolina A&T State University swine unit	12	100–175	Reddy et al. (2016)
Leersia hexandra, Myriophyllum spicatum, Potamogeton spp. and Chara spp		Dam construction at Lashihai	20	56–146	Xiao et al. (2015)
Cattail (Typha spp.)		Olentangy River WetlandResearch Park	10	181–193	Mitsch et al. (2013)
			15	219–267	Bernal and Mitsch (2014)
Polygonum lapathifolium		Constructed wetlands at the San Joaquin River	13	179–249	Maynard et al. (2011)
Phragmites Karka	AGC	Constructed wetland in Ujjain city	2 and 8	–	Kanungo et al. (2017)
Juncus spp, Memulus spp, Eleocharis spp, Carex vulpinoidea spp.	AGB, AGC	Ahn Wetland Mesocosm Research Compound	2	30.8–78.2	Means et al. (2016)
Grassland	GHG flux	Artificial lake	7	75.22–82.27**	Santos et al. (2018)
Juncus roemerianus		Brackish marsh in Carteret County, North Carolina	3	0.014–0.037	Shiau et al. (2016)
Phragmites australis		Heihe watershed	–	940–1030	Zhang et al. (2016)
Phragmites vegetation		Lankheet lake constructed wetland	–	617–977	De Klein and Van der Werf (2014)

Constructed wetland ecosystem services age is the period of constructed wetland has been designed for land reclamation following mining or as a mitigation measure for natural areas lost to land development

BGC: Belowground carbon, AGB: Aboveground biomass, AGC: Aboveground carbon

*Measured in kg C $m.^{-2}$

**Measured in Mg $ha.^{-1}$

recorded that the constructed wetlands treat more than 20% of the Litani River flow compared to data obtained in 2016. A pretty similar result was obtained by Rahi and Faisal (2019) where their study shows the constructed wetlands have been successfully used to treat the municipal wastewater with 55.4 and

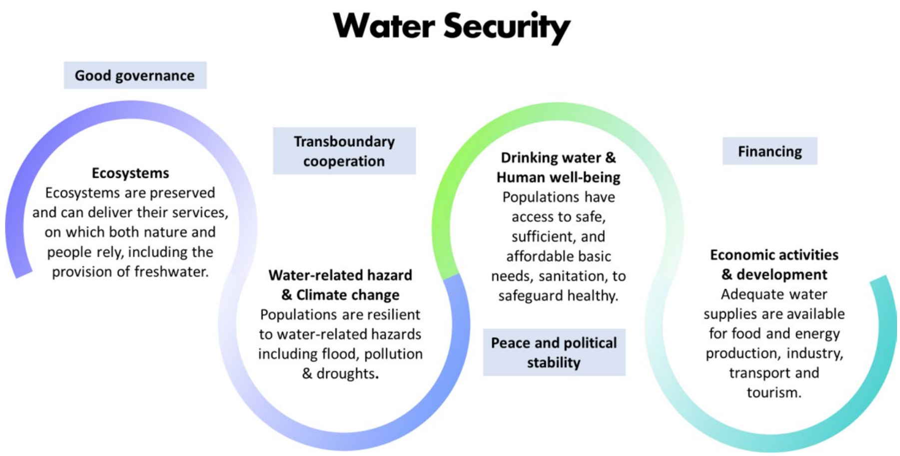


Fig. 7 The components of aquatic system management to meet future water demands in the UN Water's conceptual framework for water security (adapted from UN-Water, 2013)

Table 5 Summary of the established plants by region to remove pollutants and treat various water bodies

Regions	Countries	Plants	Water types	Removal of pollutants	References
Asia	Lebanon	*Phragmites australis*	River	COD, TSS, BOD_5, TP, TN, Cu, Zn, Mn, Fe, E-coli, Salmnonella, Faecal coliform	Abi Saab et al. (2018)
	Iraq	*Phragmites australis*	Municipal wastewater	TSS, BOD_5, TP	Rahi and Faisal (2019)
	Malaysia	*S. grosus & E. dulcis*	Constructed lake	COD,TP, Fe	Sidek et al. (2020)
		E. crassipes S. molesta & P. stratiotes			Sidek et al. (2018)
	Korea	*Typha, Phragmites, & Miscanthus*	Livestock wastewater	COD, TSS, BOD_5, TP	Reyes et al. (2020)
	China	*Phragmites & Typha latifolia*	Constructed lake	TP, TN	Wong et al. (2018)
Europe	Belgium	reed bed *(Phragmites species)*	Pig farmyard wastewater	COD, TP, TN	Boets et al. (2011)
	Spain	ND	Eutrophic water	TP, TN	Hernández-Crespo et al. (2017)
	Portugal	grassland	Artificial lake	TN	Santos et al. (2018)
	Sweden	*J. effusus, S. lacustris, Spar ganium erectum, Iris pseudacorus, Carex riparia, Glyceria maxima*	Cattle farm rainwater runoff	TP, TN	Rossa et al. (2019)
North America	USA	*Nuphar, Nymphaea, Thalia, Pontederia, Eleocharis, Sagittaria, Cladium*	Created freshwater wetland	ND	Zhang et al. (2017)
South America	Argentina	*Phragmites australis*	Wastewater and flood prevention	TSS, TN	Manzo et al. (2020)

COD chemical oxygen demand, *TSS* total suspended solids, BOD_5 biological Oxygen demand, *TP* total phosphorus, *TN* total Nitrogen, *Cu* Copper, *Zn* Zinc, *Mn* Manganese, *Fe* Iron, *ND* non-existent data

72.7%. Regarding nutrients removal, plants absorb and assimilate nutrients (nitrogen and phosphorus) in the constructed wetlands that exist in inorganic forms, such as nitrate and phosphate ions, allowing them to be used for biomass production (Rahi & Faisal, 2019). Some plant species have a high preference for one type of ionic form over another. For example, Abi Saab et al. (2018); Rahi and Faisal (2019); Reyes et al. (2020); and Wong et al. (2018) showed that the average removal of total phosphorus recorded by *Phragmites* and *Typha* species is around 55–66%. However, other species, such as *Scirpus, Eleocharis* and *Juncus,* show greater uptake and removal efficiencies between 50 and 90% (Rossa et al., 2019; Sidek et al., 2018, 2020). In addition, the removal efficiencies of total nitrogen vary from the lowest 0.4% by grass to the highest 90% by *Phragmites* species (Abi Saab et al., 2018; Rossa et al., 2019; Santos et al., 2018). Nitrogen removal is complex and redox potential is a critical parameter that affects nitrogen oxidation and reduction in constructed wetlands (Rahi & Faisal, 2019). Changes in nutrient uptake and removal between plant species are most likely due to differences in growth stages, nutrient absorption and use efficiencies.

Furthermore, trace heavy metals are removed from runoff wastewater through plants with different physiological processes that allow metal tolerance and absorption capacity (Sidek et al., 2018). For instance, studies showed *Scirpus* and *Eleocharis* species have an excellent removal efficiency for iron (Fe) which is greater than 80% (Sidek et al., 2018, 2020), and on average, for some metals, copper (Cu), zinc (Zn) and manganese (Mn) by *Phragmites species* (Abi Saab et al., 2018). Such performance might be due to metals cannot be removed from water directly by utilising biological processes like that of organic pollutants. Sidek et al. (2020) described heavy metal removal by plants from a solution involves two phases whereby the first phase consists of the processes, namely ion exchange, chelation and adsorption, while the second phase involves heavy metal precipitation induced by roots. In addition, the plants perform phytoremediation by a process called rhizofiltration.

Additionally, constructed wetlands are also shown to be highly effective for removing pathogens from river water. Pathogenic pollutants, such as bacteria, are eliminated and deactivated in the wetland system through several factors, such as vegetation, sorption to sediments, sunlight intensity, water retention and pH water (Abi Saab et al., 2018). Direct evidence shows that if the water chemistry is good, it precedes higher biological where taxa species are found during the treatment pathway as macro-invertebrates are directly affected by the physicochemical water environment. Yet, it is a significant indicator of treatment efficiency and biodiversity level. According to Sartori et al. (2015), macro-invertebrate taxa not only act as litter decomposers but also support other wetland functions, such as regulating plant communities and nutrient cycling. These valuable elements contribute to transferring nutrients from sediments, detritus and water columns, making a net contribution to the environmental system (Manzo et al., 2020).

The performance of constructed wetlands in pollution abatement is well established where *Typha*, *Phragmites* and *Eichhornia* are some of the identified wetland plants with good adaptability and tolerance to contaminated water and are effective phytoremediators for water treatment and purification. Additionally, the treated water and wastewater may supply for other water use, such as drinking and irrigation, after considering the required permissible levels for water as supporting the water shortage source of freshwater (Rahi & Faisal, 2019; Zhang et al., 2013). Besides, constructed wetlands provide biological functions that include productivity, biodiversity and life support. Therefore, the constructed wetlands need best management practices to ensure water security in which to enhance the quality of the ecosystem and human health on a local and regional scale.

Carbon–water nexus in constructed wetlands

There has been little study discussing the carbon–water nexus in which only 16% ($n=6$) articles collated are seen indirectly applying the carbon–water nexus concept in assessing the multi-functions of wetlands (Maynard et al., 2011, 2014; Mitsch et al., 2014; Santos et al., 2018; Wong et al., 2018; Zhang et al., 2016). For example, Santos et al. (2018) showed a significant correlation between carbon storage, water purification and sediment retention at the constructed lake, where its ecosystem can effectively provide long-term regulating and provisioning services to enhance water provision and increase carbon storage. Maynard et al., (2011, 2014) also found a similar result where through carbon–water nexus, two constructed wetlands with suitable and effective plant diversity have provided ecosystem services of carbon sequestration, nutrient retention and habitat support for 20 years (Mitsch et al., 2014).

Researchers had conducted various assessments to evaluate and increase the functions and services of constructed wetlands associated with climate change mitigation. The increase in carbon stored in soil and biomass is greatly beneficial for the ecosystem services and functions, directly helping in the provisioning and supporting services and maintaining biodiversity. Understanding the different use and management systems of constructed wetlands would enhance carbon storage and other ecosystem services. Healthy constructed wetlands with intact conditions will hugely contribute to increasing resilience towards the climate change impacts. However, there is a lack of study in assessing the integration of constructed wetlands' nature values and services whereby the regulating and provisioning services of constructed wetlands have gained more attention than socio-cultural services. The selection of ecosystem services to be evaluated may reflect the level of policy concern of these services in each country. For example, climate change is a challenge in the North American region, and hence, constructed wetlands have been extensively focused on carbon sequestration. However, constructed wetlands' ecosystem services mapping the importance of socio-cultural service is still less established (Xu et al., 2018). Socio-cultural services are assessed mainly by economic approaches (Dang et al., 2021). Therefore, further assessments that encompass multiple ecosystem services, especially socio-cultural services, are required to evaluate different values adequately in which constructed wetlands provide ecosystem services to different groups of stakeholders and support policymakers to manage and sustain constructed wetlands' ecosystem.

Optimisation of the interdependent constructed wetlands' ecosystem services is also needed, and it is critical to identify the entire bundle of constructed wetlands' ecosystem services related to increasing carbon storage, water security and other trade-offs when examining the multifaceted nature of livelihoods. Insufficient data and knowledge of the utilisation of carbon–water nexus in the constructed wetlands will limit the nature values of this ecosystem, consequently, hindering the definite benefits. Lack of information on the carbon–water nexus makes it difficult to assist wetland management, local and international model development efforts to regain the socio-ecological benefits from the nature values of constructed wetlands (Stringer et al., 2012). To draw an understanding of how the processes of carbon–water nexus in constructed wetlands contribute to climate change mitigation and water security, we highlight the concept, processes and mechanisms taking place through carbon and water cycles, and to realise the benefits provided by constructed wetlands, a conceptual framework of integrating ecosystem services dichotomy between the importance of nature values will be proposed at the subsequent section.

Definition of nexus

The original concept of nexus comes from physics where nexus is defined as the dynamic interrelationship of two or more objects or the motion forms through their interconnections and interactions (Li et al., 2020). (Abdi et al., 2020; de Grenade et al., 2016; Smajgl et al., 2016) had provided various definitions of nexus, but a comprehensive explanation could not be established just yet and many studies focused on the nexus between food, energy and water.

Generally, nexus can be defined in two definitions. First, nexus is described as the interactions between different sectors (or subsystems) within the system boundary, such as water and carbon systems (Zhang et al., 2018). Cai et al. (2018) further illustrated that nexus is regarded as interconnected physicochemical processes, input and output relationships of production, as well as infrastructure and institutions' interactions. This definition focuses on interpreting interactions between systems in understanding the complex system's overall characteristics through its components' interlinkages in which it emphasises that one system's deficiencies will pressure the other systems. Thus, the carbon–water nexus requires holistic management of these two systems as they are both critical in balancing the environment.

Second, nexus is defined as an analysis method or approach to quantify the nexus nodes' links, including water, food and energy (Abdi et al., 2020). For instance, nexus by FAO's approach analyses the nature–human system's relation and creates integrated management of natural resources across different scales and sectors by building up the synergies and trade-offs (FAO, 2014). Smajgl et al. (2016) illuminated this approach as dynamic relationships to identify the emergence of cross-sector linkages. Meanwhile, de Grenade et al. (2016) viewed the concept of nexus on environment systems needs an ideal engagement of ecological-social design and adaptive capacity research to focus on the constraints and

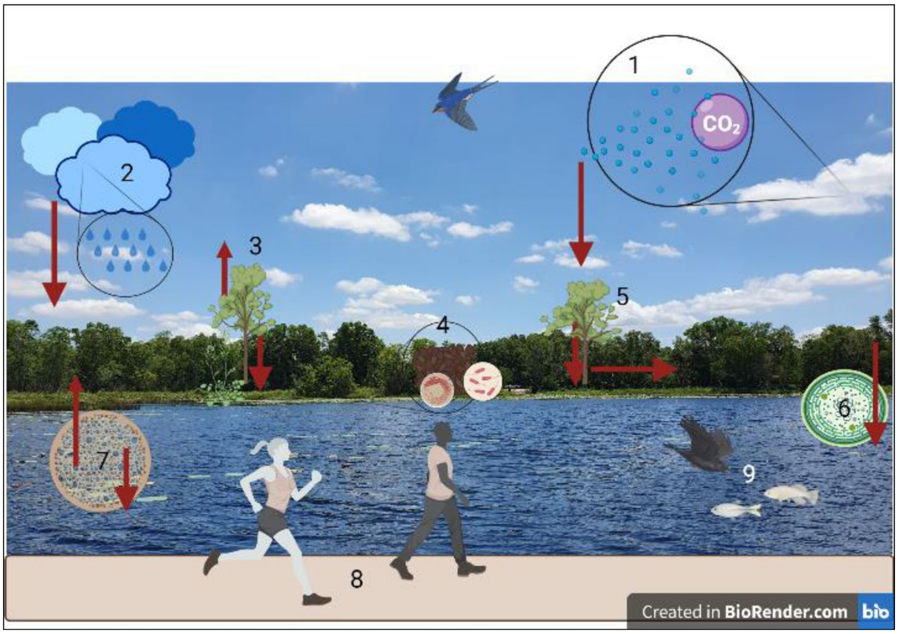


Fig. 8 The concept of carbon–water nexus in constructed wetland consisting carbon movement from the atmosphere across the landscape and soil into the water system as a watershed (adapted from Ward et al., 2017)

abilities of environment systems and human processes' complex existence, particularly in adaptation to climate change. However, Keskinen et al. (2016) argued that the concept of nexus is so intense that it could not be explained from a single standpoint. Thus, they provided the definition comprising an analytical technique, either quantitative or qualitative, governance tools in enhancing collaboration between related sectors and the emerging disciplines.

Processes and mechanisms of carbon–water nexus in constructed wetlands

By adopting the definitions, the carbon–water nexus is conceptualised as interlinkages between engineered and natural physicochemical processes at the interface between carbon and water cycles. The carbon–water nexus presents the interdependencies between the carbon and water systems as they are twosome in processing, supplying, distributing and using environmental resources. Anthropogenic climate change is driven by changes to the carbon cycle, one of the most immediate ways in which we can observe its impact is on the water cycle (Clarens & Peters, 2016). The advancement of carbon–water nexus knowledge in mitigating pollution effects would be crucial to developing long-term climate change adaptation strategies. A warmer atmosphere will alter precipitation patterns, reduce freshwater reserves and drive extreme weather. Endeavours to manage carbon emissions will have significant implications on water cycles whereby the carbon–water nexus calls for integrated management to promote sustainable development of constructed wetlands and reduce the unexpected effect on the socio-ecological system. Hereof, it diverges from the conventional decision-making practices which previously considered within separate disciplines (Liu et al., 2015).

Figure 8 illustrates the carbon–water nexus, showing the processes and mechanisms of constructed wetlands that consist of carbon movement from the atmosphere across the landscape and soil into the water system as a watershed (Ward et al., 2017). (1) First, atmospheric particles, including greenhouse gases, such as CO_2, coming from natural and anthropogenic activities, return to the atmosphere and some condense to form a cloud. (2) Second, raindrops capture organic and inorganic carbon during rain by scavenging particles and absorbing organic vapours as they fall towards the earth. (3) At the same time, plants fix atmospheric CO_2 by photosynthesis and release a portion of it back into the atmosphere through respiration. (4) Plant-derived organic carbon is converted and preserved by microbial and fungal activities in the organic soils when organic carbon combines with roots and sediment to form organic soils. (5) Plants absorb water dissolved organic and dissolved inorganic carbon and settle aerosols as it passes by forest canopies (throughfall), plant trunks and stems. Thus, water will seep into soils and groundwater reservoirs, triggering bio-physicochemical transformations, overland flow happens when soils are fully saturated or runoff occurs faster than soil saturation. (6) Organic carbon from the terrestrial and water biosphere is decomposed by microbial organisms in the constructed wetlands and physical decomposition, such as photo-oxidation, resulting in CO_2 fluxes on a scale comparable to the amount of carbon sequestered annually by the constructed wetlands. Decomposition of macromolecules, such as lignin from plants into smaller carbon components and monomers, contributes to CO_2 conversion, metabolic intermediates and biomass. (7) Constructed wetland stores organic carbon in sediment but it also has a lot of net heterotrophy in the water column, which results in a net CO_2 flux to the atmosphere and naturally sequestering a fraction of fixed CO_2. (8) and (9) Constructed wetlands may produce healthy air and improve water quality which directly enhances human well-being, such as providing recreation, leisure and the biodiversity growth of constructed wetland ecosystem.

Realising the carbon–water nexus approach practically will enhance the functions and services of constructed wetlands. The trade-off benefit is gained between the interchange of environmental sustainability and human well-being. However, the carbon–water nexus of artificial, constructed or restored wetlands is dealt with the major human intervention, making it different from natural wetlands whereby lack of knowledge of the values and services of this ecosystem will limit its use. The carbon–water nexus is influenced by management practices whereby many challenges limit the optimisation of ecosystem services, but looking at the fringe benefits provided by constructed wetlands, like nature values, it is possible (Maynard et al., 2011; Wong et al., 2018; Zhang et al., 2016).

Nature values of constructed wetlands

Constructed wetlands consist of vital nature values that provide various services and functions (regulating, provisioning and cultural services) that are mutually dependent. To a certain extent, constructed wetlands' ecosystem values benefit people differently, where different people view different values towards this ecosystem. The values can be antithetical by different philosophies and scholars whereby the values are from a strictly useful stand in which human thinks distinctly from the rest of nature and to a viewpoint where human and other living things are deemed to deserve equal recognition (Arias-Arévalo et al., 2018; Hejnowicz & Rudd, 2017; Lockwood, 1999). The United Nations-Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Service (IPBES) listed various value definitions in which the 'value' can be referred to as a simple measure, a preference of a person towards something, a belief or principle regarding culture or the importance of something to others or itself. Besides, values are also influenced and changed over time by social networking (Diaz et al., 2014), whereby the constructed wetlands' valuation spectrum is broad through the integration of values.

As outlined in the ecosystem framework by the Millennium Ecosystem Assessment (MEA, 2005) (Table 1), the ecosystem emphasises biodiversity and ecosystem for a human being; therefore from the beginning, it has a clear focus on nature's instrumental values. The concept of instrumental values is usually clear-cut in environmental valuation and ecosystem services in which the objects or things are means to some external end (Pascual et al., 2017) and it is always conditional (Sandler, 2012). This concept holds to the anthropocentric nature, representing a conjugal between science and economic view whereby the definite purpose has been validated to decision-makers why this ecosystem is essential and should be protected. Hence, it is a threat when only a part of services, functions and values are selected for further research because it is easy to convey or have a more direct policy or act relevance.

As a response to the MEA framework, environment ethicists (non-anthropocentric) in the field of conservation biology defended that the ecosystem that consists of biodiversity also has its values, namely intrinsic values (Rolston III, 2006; Sandler, 2012). Intrinsic values mean the values of an object in and of itself/themselves or as a means to an end. Natural entities, including biotic species in the ecosystem, have intrinsic values in the advantage of their independence from people's control. In ecosystem services, the grounding or foundation for intrinsic values is seen from two viewpoints, i.e. objective and subjective intrinsic values (Sandler, 2012). All living organisms have objective intrinsic value—the good of their own, relatives to its features or properties in virtue of which it is valuable, which is discovered rather than generated by a people.

In contrast to objective intrinsic value, subjective intrinsic value is valued for what it is, not for what it can do. People determine this value through their evaluative attitudes or judgements, and it does not exist before or without them. People widely appraise subjective intrinsic value for various reasons, such as cultural and spiritual significance, personal mementoes, historical sites or performances due to their embodies, rarity, beauty or representation. Therefore, subjective intrinsic value can be distinguished from someone's preferences and approachable by persuasion and education (Gómez-Baggethun et al., 2014). Hence, people's views of habitats and ecosystem services, like constructed wetlands, have been vital aspects of the social-ecological system and sustainability management. Nevertheless, research on socio-ecological systems and environmental management generally neglects the study of values on human perceptions. In assessing ecosystem services, financial valuation methods have gained more attention than other valuation methods, emphasising instrumental values and disregarding intrinsic values (Arias-Arévalo et al., 2017).

However, the current study shows that the assessments of ecosystem services mainly focus on supporting general sustainability management, land-use change planning and policies as well as conservation action. There is limited evidence that has been provided on valuing the nature values of constructed wetlands, especially intrinsic values that are rarely reported. The majority of the previous studies underpinning the MEA's framework emphasised the ecosystems for human wellbeing, aiming at nature's instrumental values and had insufficient empirical evidence of intrinsic nature values. Lack of study integrates the regulating-provisioning services and social services assessments for climate change mitigation and water security, where both are critical concerns as a climate vulnerable. These limitations were acknowledged by Español et al. (2014); Irwin et al. (2018); Manzo et al. (2020); Rooney et al. (2015); Sartori et al. (2015); Sherren and Verstraten (2013); Wong et al. (2018); Zhang et al. (2013). Several efforts had been made to assess the constructed wetlands' ecosystem services through a socio-ecological perspective under cultural services in adapting to climate change, compared to the mono-disciplinary valuation method as discussed previously. For example, it was pointed out by Sherren and Verstraten (2013) to understand how Cumberland County farmers perceive constructed wetlands and climate change. Despite the farmers being transparent about the significance of constructed wetlands on water management and occupied with its importance and challenge, they found that the farmers lack information about the constructed wetlands' benefits in adapting to climate change. However, the Yongding Green Ecological Corridor showed a significant correlation between citizens' perceptions of climate regulation, water quality and scenic beauty but insignificant in heritage value for future generations (Wong et al. 2018). In addition, constructed wetlands' ecosystem services with great self-mechanism also will enhance their ability to conserve biodiversity and positively reflect the perception of aesthetics and heritage values (Manzo et al. 2020; Rooney et al. 2015; Zhang et al. 2013).

Even though the interlinkages between ecosystem services and invaluable benefits are complex, using fragmented and disciplinary knowledge is insufficient to address the data and information gaps (Xu et al., 2018). This leads to unclear and unspecific management demands of the constructed wetlands. Integrated approaches are required to understand how to connect issues to identify strategic actions on connections. The assessment of the instrumental-intrinsic values can provide empirical evidence that offers new perspectives and insights into the analytical framework for valuing the constructed wetlands' ecosystem services (Jamion et al., 2022). To address these nature values, a more comprehensive underpinning knowledge through interdisciplinary research is required to craft the constructed wetlands' ecosystem values and evaluation. In this context, hard science that looks into instrumental values and soft science that looks into intrinsic values are needed to drive conservation management decisions as asserted by MEA in illustrating the relationships between ecosystem services and human well-being.

Conceptual framework

The ecosystem services and nature values of constructed wetlands can be framed into a framework of carbon–water nexus which fills the gaps and strengthens the benefits of constructed wetlands. Since constructed wetlands have been shown to possess high potential in storing carbon and are essential as water resources, incorporating the carbon–water nexus is a great mechanism to call for action in mitigating climate change. However, the constructed wetlands have yet to become an integral part of decision-making and management targets as a nature-based solution for climate change mitigation. Hence, optimising constructed wetland through regulating services for carbon sequestration and water security requires full consideration because the processes interrelate with provisioning and socio-culture services, which will affect the effectiveness of adaptation to climate change. The approach to addressing the gaps is through developing integrated evaluation models to understand the constructed wetlands' ecosystem services and values better. Most recent models (Santos et al., 2018; Siniscalchi et al., 2020; Waters et al., 2019; Wong et al., 2018) were established by converging only a few particular sectors, such as land use and land change, water supply and agriculture or matters bi-cross like biodiversity, and most of the existing models only able to simulate one type of ecosystem services. Hence, there is an urgent need to propose an integrated assessment model to estimate and evaluate the absolute values of constructed wetlands on an entirely structural basis under various management and regulation circumstances at the socio-ecological level. Indirectly, this model will provide adequate data and information, thus filling the knowledge gaps in constructed wetlands' ecosystem management.

Previous studies were found in lacking both quantitative and qualitative mixed approaches, whereby it is advisable with the principle of transdisciplinary research that connects scientific and societal practices in addressing sustainability issues (Lang et al., 2012) and eliminating bias in data collection (Saunders et al., 2009). Besides, data availability and sharing as well as parameterisation limiting the access will affect the ability to identify problems and strategies for mitigation. Therefore, assessments based on empirical data and evidence-based methods may transfer more appropriate, reliable and credible information for decision-making and planning processes.

Based on theory-driven studies (Arias-Arévalo et al., 2017; MEA, 2005; Sandler, 2012) circled around carbon sequestration, water security, carbon–water nexus, nature values and services of constructed wetlands, a conceptual framework is proposed in Fig. 9, setting out two core features dichotomy of the nature values and services for constructed wetlands. It is a simplified model of the integration between people's needs and constructed wetlands' ecosystem services in mitigating climate change. The conceptual framework can be complementary to science-based models and acts as a tool to achieve understanding across different disciplines. The conceptual framework has four functions which are interconnected to provide and enhance the practice of analysing the existing knowledge, as a catalyst to generate new knowledge, to guide and support the development and implementation of associated policies, as well as to develop abilities that are relevant to attaining the stakeholders' objectives.

The main feature in the conceptual framework, nature values consist of instrumental and intrinsic values interlinked elements, constituting all constructed wetlands' ecosystem services. The instrumental values of constructed wetlands benefit people through the regulating and provisioning services via carbon sequestration and water security. Besides, constructed wetlands possess intrinsic values, inheriting their nature objectives, such as regulating the environment's temperature, producing oxygen and regulating the quality and quantity of water resources while subjective intrinsic values interlink with the socio-cultural services for recreational and aesthetic, biodiversity and heritage purposes. The importance of benefits/values and services of constructed wetlands should be created between human and nature as in the notion of sustainability to live in tranquillity with nature. Hence, the fundamental importance is to translate the conceptual framework into practices and catalyse a positive transformation within the interlinking elements, particularly in the sustainable management of constructed wetlands. In this context, the call for action to carry out long-term conservation of constructed wetlands is needed to increase the resilience towards the impacts of climate change and ensure water security in which collaboration between scientists, administrators, authorities and societies could pave the path in safeguarding the ecosystem services for a sustainable environment.

Conclusion and recommendation for future study

Based on 38 studies retrieved from the Scopus and WoS databases, a systematic review has been conducted to explore constructed wetlands' functions in regulating services, especially climate regulating, which are carbon storage and sequestration as well as water purification for water security. This review derived an integrated classification of constructed wetlands' ecosystem services and mapped them with their nature values. Besides, this review depicts how nature values can be evaluated through constructed wetlands' cultural services as it is known to offer various ecosystem services and benefits that contribute to livelihood and wellbeing. Researchers have reviewed different types of constructed wetlands in examining the effectiveness of carbon sequestration and water purification through evaluation, driving factors and trade-off analyses. Plant diversity and sedimentation show a vital role in the carbon–water nexus as constructed wetlands have been critical in global climate change and conservation debates in virtue of increasing demand for research into which ecosystem services and benefits have the most significant value. This review has also enhanced the insight of nature values, namely instrumental and intrinsic values, as the socio-ecological valuation for constructed wetlands' ecosystem management. Besides, the review reveals some gaps, namely mono-disciplinary evaluation practices of ecosystem services, knowledge and methodology in valuing constructed wetlands' ecosystems. Lastly, a conceptual framework was synthesised based on the conceptualisation of the carbon–water nexus that integrates the dichotomy of the instrumental-intrinsic nature values to evaluate the importance and benefit of constructed wetlands. As a result, this review has provided insights into the body of knowledge on the benefits and values of constructed wetlands. Further, utilising the conceptual framework may lead to a future study in assessing the nature values provided by the constructed wetlands to sustain the ecosystems. All in all, enhancing the carbon–water nexus in climate change mitigation and water conservation requires collaborative efforts involving scientists, stakeholders and the public to provide a new path for a holistic approach to managing constructed wetland ecosystems towards environmental sustainability.

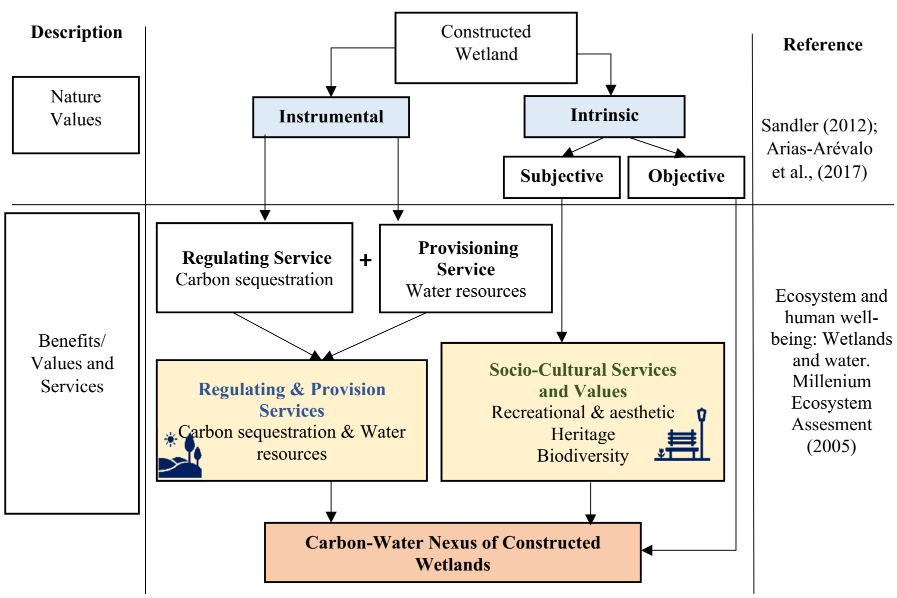


Fig. 9 A conceptual framework of carbon–water nexus of constructed wetland. *In the main panel, nature value is denoted in a blue box and ecosystem services in a yellow box; text in blue denotes the concept of hard science and text in green denotes the soft science that needs a transdisciplinary approach to achieve the aim of carbon–water nexus of constructed wetland

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Data availability Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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Consent to publish The authors affirm that all related participants have provided their consent for publication.

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