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RESEARCH ARTICLE

Aamir Mehmood SHAH, Gengyuan LIU, Yu CHEN, Qing YANG, Ningyu YAN, Feni AGOSTINHO, Cecilia M. V. B. ALMEIDA, Biagio F. GIANNETTI

Urban constructed wetlands: Assessing ecosystem services and disservices for safe, resilient, and sustainable cities

Abstract Climate change and rapid urbanization are pressing environmental and social concerns, with approximately 56% of the global population living in urban areas. This number is expected to rise to 68% by 2050, leading to the expansion of cities and encroachment upon natural areas, including wetlands, causing their degradation and fragmentation. To mitigate these challenges, green and blue infrastructures (GBIs), such as constructed wetlands, have been proposed to emulate and replace the functions of natural wetlands. This study evaluates the potential of eight constructed wetlands near Beijing, China, focusing on their ecosystem services (ESs), cost savings related to human health, growing/maintenance expenses, and disservices using an emergy-based assessment procedure. The results indicate that all constructed wetlands effectively purify wastewater, reducing nutrient concentrations (e.g., total nitrogen, total phosphorus, and total suspended solids). Among the studied wetlands, the integrated vertical subsurface flow constructed wetland (CW-4) demonstrates the highest wastewater purification capability (1.63E+14 sej/m^2/yr) compared to other types (6.78E+13 and 2.08E+13 sej/m^2/yr). Additionally, constructed wetlands contribute to flood mitigation, groundwater recharge, wildlife habitat protection, and carbon sequestration, resembling the functions of natural wetlands. However, the implementation of constructed wetlands in cities is not without challenges, including greenhouse gas emissions, green waste management, mosquito issues, and disturbances in the surrounding urban areas, negatively impacting residents. The ternary phase diagram reveals that all constructed wetlands provide more benefits than costs and impacts. CW-4 shows the highest benefit–cost ratio, reaching 50%, while free water surface constructed wetland (CW-3) exhibits the lowest benefits (approximately 38%), higher impacts (approximately 25%), and lower costs (approximately 37%) compared to other wetlands. The study advocates the use of an emergy approach as a reliable method to assess the quality of constructed wetlands, providing valuable insights for policymakers in selecting suitable constructed wetlands for effective urban ecological management.

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Aamir Mehmood SHAH
State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China

Gengyuan LIU (✉)
State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China; Beijing Engineering Research Center for Watershed Environmental Restoration & Integrated Ecological Regulation, Beijing 100875, China
E-mail: liugengyuan@bnu.edu.cn

Yu CHEN
State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China

Qing YANG
Advanced Interdisciplinary Institute of Environment and Ecology, Beijing Normal University, Zhuhai 519087, China

Ningyu YAN
Key Laboratory for City Environmental Safety and Green Development of the Ministry of Education, Institute of Environmental and Ecological Engineering, Guangdong University of Technology, Guangzhou 510006, China; Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou 511458, China

Feni AGOSTINHO, Cecilia M. V. B. ALMEIDA,
Biagio F. GIANNETTI
State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China; Programa de Pós-graduação em Engenharia de Produção, Laboratório de Produção e Meio Ambiente, Universidade Paulista (UNIP), São Paulo 04026-002, Brazil

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Keywords constructed wetland, emergy, ecosystem services, disservices, ternary diagram

1 Introduction

The preservation, maintenance, and development of green–blue infrastructure in urban areas are crucial tactics to protect ecosystem services (ESs) and human well-being in the face of swift urbanization (Elmqvist et al., 2015). While the "green" elements of green and blue infrastructure (GBI) have received more attention in strategies, the significance of "blue" infrastructure is equally important for urban areas. Many cities face severe water-related sustainability issues, such as droughts, floods, and insufficient access to clean water (Haase, 2015). Blue city infrastructure includes various water bodies, such as lakes, rivers, artificial channels, constructed wetlands, and ponds (O'Donnell et al., 2021). In numerous countries, water-related sustainability issues are especially acute due to rapid city growth that often surpasses the development of sewerage infrastructure (Nagendra et al., 2018). Consequently, blue spaces, such as constructed wetlands, play a critical role. They act as recipients of untreated water, which could otherwise contribute to the spread of pollution and disease while simultaneously providing biological sewage treatment (Haase, 2015).

Constructed wetlands come in various varieties: Free water surface constructed wetland (FWS-CW) or surface flow, vertical subsurface flow constructed wetland (VSSF-CW), and horizontal subsurface flow constructed wetland (HSSF-CW) (Vymazal, 2011b), along with hybrid constructed wetland (HCW) systems that combine the previous three types (Maucieri et al., 2017). 1) FWS-CWs replicate natural wetlands, where wastewater is directed to flow over the surface, offering benefits such as flood prevention, shoreline erosion control, and wastewater quality improvement (Farooqi et al., 2008). Additionally, a wide variety of plants can be used as emergent species in this type of natural wetland (DBT, 2019). 2) HSSF-CW, also known as a reed bed system, is a type of constructed wetland where untreated wastewater flows horizontally through a bed. This system requires 5–10 m^2 of land area per population equivalent and involves aerobic and anaerobic conditions. Aerobic conditions take place at the root zone, whereas organic matter breakdown occurs through anaerobic conditions (DBT, 2019). HSSF-CWs have been shown to be highly effective at removing pollutants such as chemical oxygen demand (COD), biochemical oxygen demand (BOD), ammoniacal nitrogen, total suspended solids (TSS), and phosphate (Steer et al., 2002; Solano et al., 2004). Although the HSSF-CW demands more land area than the VSSF-CW, it provides better denitrification performance (Knight et al., 2000; Calheiros et al., 2012; Saeed and Sun, 2012; Sudarsan et al., 2018). 3) VSSF-CW is a type of wetland system where wastewater is introduced from the top of the wetland and flows through the bed in a vertical direction before being drained out from the bottom (Tilley et al., 2014). This design facilitates aerobic conditions that support high levels of nitrification, as well as the removal of pollutants such as COD and BOD. Whereas VSSF-CW requires less land area per population equivalent than HSSF-CW, it demands more maintenance (DBT, 2019). To achieve higher removal efficiency, particularly for nitrogen, a combination of various types of constructed wetlands is often employed in combined systems. Typically, these systems consist of several parallel vertical subsurface flow beds, followed by two or three horizontal flow beds in series (Vymazal, 2007).

Constructed wetlands offer various ESs to society (Ghermandi et al., 2010). These ESs include carbon sequestration, aesthetics, biodiversity conservation (Yang et al., 2008; Vymazal, 2011a), mitigation of urban heat island effects (Sun et al., 2012; Shah et al., 2020; Meng et al., 2023), flood risk reduction (Mitsch and Day Jr, 2006), improved water quality (Dhote and Dixit, 2009; Shah et al., 2021), support for food production (Lannas and Turpie, 2009), protection of coastal communities (Gedan et al., 2011), provision of dynamic cultural resources (McGregor et al., 2010), and opportunities for recreation and education (Cachelin et al., 2009).

However, the design of constructed wetlands in cities presents some challenges. For instance, they release gaseous compounds into the atmosphere during their pollutant abatement processes (Mander et al., 2003; VanderZaag et al., 2008). The most perilous gases for the environment, called greenhouse gases (GHGs), are methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O), and these gases are widely recognized as significant contributors to global warming. Additionally, under certain circumstances, constructed wetlands can increase mosquito populations, which are generally unwanted in urban settings due to their irritating bites and potential as disease vectors (Knight et al., 2003). Last, the wrong project design could lead to odor problems and the presence of water in subsurface systems (Stefanakis, 2018). However, when properly constructed and designed, constructed wetlands typically do not create odor problems (Stefanakis, 2018).

Calculating the ESs and ecosystem disservices (EDs) of constructed wetlands in urban areas is a complex task, and previous researchers have explored different methods, including economic or monetary approaches. For instance, Yang et al. (2008) assessed the economic values of a constructed wetland system's ES through the contingent valuation method in Hangzhou, China. The contingent valuation method measured the total economic value of the constructed wetland at 800000 yuan over a 20-year period. Similarly, Sharma et al. (2015) employed a hybrid approach that involved direct market price and unit-adjusted value transfer techniques to calculate the economic value of the primary benefits offered by the wetland ESs in the Koshi Tappu Wildlife Reserve, Nepal. Previous assessments of ESs mostly relied on monetary metrics as a standard unit of measurement (Murray, 2013), which are easier for decision-makers to comprehend and monitor policy results (Greenhalgh et al., 2017). However, this approach represents a limited viewpoint that solely considers human preferences (Brown and Ulgiati, 1997; 2011; Franzese et al., 2017) and overlooks the interests of future generations and other species (Brown and Ulgiati, 2011). Furthermore, this technique provides a restricted outlook on the environmental advantages (Häyhä and Franzese, 2014) and has a finite time frame (Mellino et al., 2015).

Evaluations centered on human perception aim to quantify the perspective of the recipient regarding various aspects of value (Yang et al., 2018). Therefore, it would be beneficial to have a universal framework that assesses ES value (ESV) from a production or supply standpoint (Yang et al., 2020). By adopting a donor-side perspective, the donor in this context is recognized as the Sun, given its crucial role as the primary driver of all geo-biosphere processes. Consequently, solar energy and deep heat have been identified as the fundamental reference points for evaluating ESV. The emergy method is based on this principle, where emergy represents the total available energy, encompassing both direct and indirect contributions, involved in the production of a particular good or service (product) (Odum, 1996). The emergy method offers several advantages for service accounting in constructed wetlands. First, it provides a comprehensive framework for quantifying and integrating multiple resources within a constructed wetland system. It allows for the assessment of not only water resources but also other inputs such as energy, materials, and labor (Brown and Ulgiati, 1997). By considering multiple resource inputs, the emergy method offers a more holistic understanding of the overall performance and efficiency of the system. Second, compared to the water footprint approach and other methods that primarily focus on water-related aspects, the emergy method incorporates a wider range of indicators. These indicators include the amount of solar energy utilized, the quantity of various materials involved, and the ESs provided by the wetland system. By considering multiple indicators, the emergy method enables a more comprehensive assessment of the system's sustainability and ecosystem functioning. Finally, one notable advantage of the emergy method is its ability to distinguish between artificial inputs and natural resources. It achieves this by quantifying inputs based on the amount of solar energy required to generate them (Brown et al., 2000). This feature is particularly relevant in the context of constructed wetlands, as it allows for a clear differentiation between human interventions (such as energy and material inputs) and the natural resources harnessed by the system. This differentiation facilitates a more accurate understanding of the system's reliance on external inputs and its potential impacts on the environment (Odum, 1996).

Previous researchers have evaluated ESs (e.g., urban heat islands, water purification, stormwater reduction, etc.) of constructed wetlands via the emergy accounting approach (Zhou, 2004; Chen et al., 2008; Zhou et al., 2009; Duan et al., 2011; Thompson, 2018); however, they did not consider the adverse effects or address a few benefits; for example, GHG emissions, mosquitoes, and carbon sequestration within the city area are usually disregarded from analysis. Examining the negative impacts is essential when systematically evaluating the costs and benefits of urban constructed wetlands. For instance, GHGs have significant environmental and health impacts and cannot be disregarded. They trap heat and contribute to respiratory ailments resulting from smog and air pollution (source). Furthermore, the selected services and disservices are particularly relevant and significant in addressing the specific environmental challenges faced by Beijing, China. By focusing on these services, you can directly contribute to tackling the key issues and meeting the city's environmental goals. Therefore, the present study aims to fill these research gaps by developing a new nonmonetary ES framework and identifying and calculating the vital ESs (and disservices) of constructed wetlands around Beijing, China.

2 Methods

2.1 Emergy diagram of the urban constructed wetland

The FWS-CW is characterized by a densely vegetated area through which the wastewater flows above the substrate bed. On the other hand, in vertical and horizontal wetlands, wastewater flows below the surface of porous media, such as biochar, soil, sand, or other materials (Stefanakis et al., 2014; Dotro et al., 2017; Hadidi, 2021). Each typology of wetland employs different mechanisms of pollutant removal, which in turn govern the treatment procedure and resulting performance of the wetlands.

Figure 1 presents the system diagram of an urban constructed wetland ES. The diagram illustrates the interactions among the inner processes within the wetland and the flows of ESs. In understanding the connections among provisioning services, regulating services, and supporting services (e.g., net primary productivity (NPP)), emergy analysis proves particularly suitable for these reasons. A typical constructed wetland comprises several components, including vegetation, soil, sand, gravel, activated sludge, organic components, iron ore powder, brick, cement, polyethylene (PE) pipe, steel griller, and machinery. These components work together to facilitate the

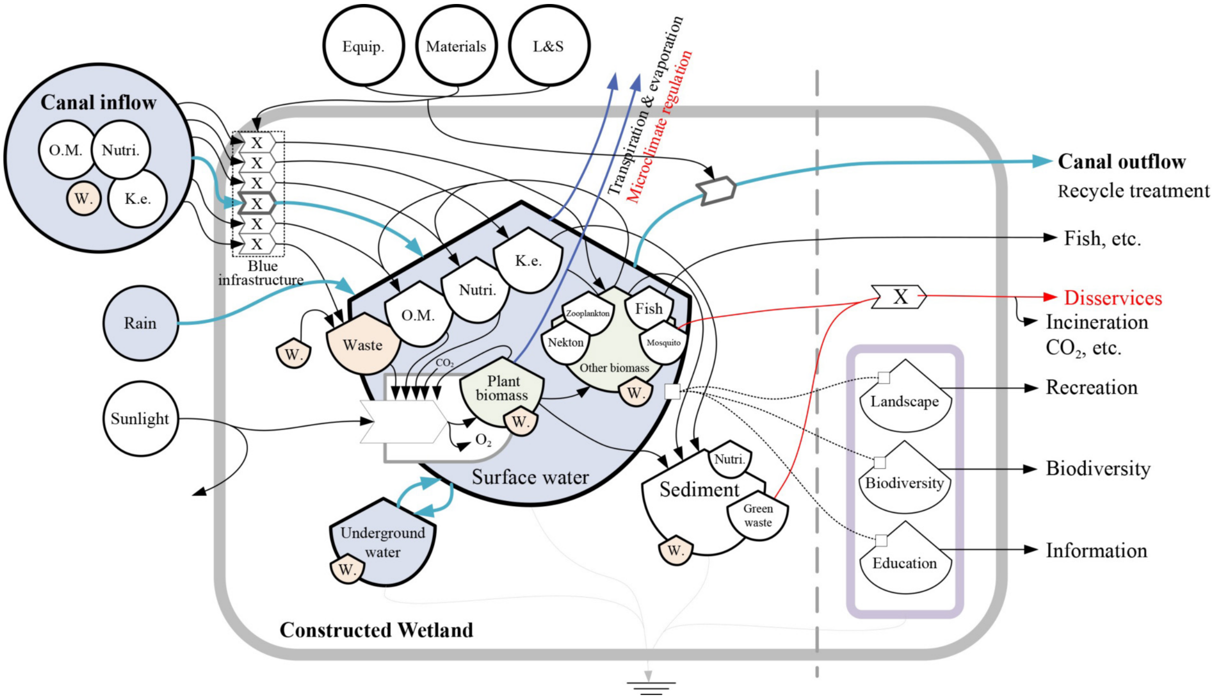

Fig. 1 Emergy diagram of a constructed wetland ecosystem: O.M. = organic matter; W. = waste; K.e. = potassium and other inorganic matter; L&S = labor and services; Equip. = equipment; Nutri. = nutrients; red line shows disservices; blue line shows water flows.

purification and treatment of wastewater. Water evaporation from rain and plant transpiration collaborate to regulate the microclimate within wetland zones. Moreover, the vegetation in wetlands provides benefits at various scales, ranging from micro to macro, including recreational and educational opportunities and promoting biodiversity. The benefits of resource concentration at higher hierarchies are depicted cumulatively on the right side of the boundary in the diagram. Additionally, byproducts of wetlands, such as waste from constructed wetlands, can be recycled and treated to produce compost and bioenergy, adding further value to the system.

2.2 Emergy-based valuation methods of constructed wetland

2.2.1 Ecosystem services (ESs)

(1) Net primary productivity (NPP)

The net carbon gain by plants, also known as NPP, is determined by the balance between the carbon gained through photosynthesis and the carbon released through respiration (Chapin III and Eviner, 2007). The emergy involved in driving NPP increase can be determined using the following formula:

$$U_{\mathrm{NPP}} = \mathrm{Max}(R_i) + S_i P(x_i), \tag{1}$$

where U_{NPP} shows the emergy required by NPP per area (sej/m^2/yr); $\mathrm{Max}(R_i)$ is the sum of all renewable emergy inflows to the constructed wetland ecosystem i (sej/yr), which is calculated as:

$$\mathrm{Max}(R_i) = \mathrm{Max}[\mathrm{Sum}(U_{\mathrm{solar}}, U_{\mathrm{geoth}}), U_{\mathrm{wind}}, U_{\mathrm{rain.geo}}, U_{\mathrm{rain.chem}}, U_{\mathrm{runoff}}], \tag{2}$$

where $U_{\mathrm{rain.chem}}$ is associated with the chemical energy of evapotranspired rain, and U_{runoff} is associated with the chemical and geopotential potential energy of run-off water (Odum, 1996); S_i is the area of constructed wetland (m^2); $P(x_i)$ represents the emergy of inflows used in a constructed ecosystem for construction/maintenance; and x_1 to x_n represent all specific resources used (gravel, soil, sand, vegetation, PE liner, PE pipe, brick and cement, machinery, electricity, and maintenance). The sej/m^2/yr values of emergy flows are computed in this study. The corresponding actual values for the case study can be found in the following tables.

(2) Carbon sequestration

Wetlands, which only cover 5%–8% of the Earth's surface, are a crucial component of the carbon cycle, but they store approximately 35% of the plant's carbon (Mitra et al., 2005; Mitsch and Gosselink, 2015). When wetlands dry out or drain, they can become carbon sources and emit methane and carbon dioxide into the ambient atmosphere (Hemes et al., 2018; Mozdzer and Megonigal, 2013). In response, wetland restoration and rewetting efforts are being made as a strategy for reducing carbon emissions and using them as carbon sequestration systems (Hemes et al., 2018; Joosten et al., 2012). Therefore, the carbon sequestration equation of the constructed wetland is as follows:

$$U_{\mathrm{CS}} = \sum_i (C_{\mathrm{FR}} \times UEV_{\mathrm{CS}i}), \tag{3}$$

where U_{CS} is the total emergy supporting the carbon sequestration process (sej/m^2/yr), C_{FR} represents the annual average carbon fixation rate of constructed wetland (g/m^2/yr), and $UEV_{\mathrm{CS}i}$ is the unit emergy value (UEV) of carbon uptake (sequestration) (sej/g) by the *i*th constructed wetland ecosystem.

(3) Microclimate regulation

Water surfaces have the ability to reduce the temperatures of nearby land surfaces by 0.54 °C per 100 m and over water by 1.76 °C per 100 m. This study evaluates the degree to which constructed wetland supports maintaining microclimates and reducing the local urban heat island effect through evapotranspiration (ET) processes. The method for calculating microclimate regulation, which is related to ET, is as follows:

$$U_{\mathrm{MR}} = \sum_i (E_i \times 1000 \times 275 \times UEV_{\mathrm{ET}}), \tag{4}$$

where U_{MR} shows the emergy used for microclimate regulation (sej/m^2/yr), E_i represents ET capacity (kg/m^2/day), 1000 and 275 are the conversion factors from kg to g and day to year, respectively, and UEV_{ET} is the UEV of ET (sej/g).

(4) Stormwater reduction

Urban constructed wetland hydrology is extremely dynamic, with wetlands completely inundated for months or exposed to drought extremes. Depending on the geomorphology and regional hydrogeology, constructed wetland can play a significant role in storing rainwater, controlling groundwater levels, and reducing stormwater runoff. The equation of stormwater runoff is as follows:

$$U_{\mathrm{SWR}} = \sum_i (R_{\mathrm{v}} \times \rho \times G \times UEV_{\mathrm{RW}}) / S_i, \tag{5}$$

where U_{SWR} represents the emergy applied to stormwater reduction (sej/m^2/yr), R_{v} shows the amount of retention volume of water (m^3/yr), ρ is the density of water (kg/m^3), G represents the Gibbs chemical energy of water (J/kg), and UEV_{RW} is the UEV of rainwater (sej/J).

(5) Water purification

Constructed wetlands can improve water quality by removing phosphorus, nitrogen, and BOD, which would lead to unnecessary algal growth that reduces constructed wetland quality, recreation, and functionality value (Irwin et al., 2018). This study focuses on phosphorus, nitrogen, and BOD for simplicity purposes, but they can also remove other pollutants during operation, including TSS. The equation of water quality is as follows:

$$U_{\mathrm{WP}} = \sum_i (P_{\mathrm{a}} \times UEV_{\mathrm{poll}}), \tag{6}$$

where U_{WP} shows the emergy applied to water purification (sej/m^2/yr), P_{a} is the amount of pollutant accumulated (kg/m^2/yr), and UEV_{poll} represents the UEV of pollutant (sej/g).

(6) Groundwater recharge

Among all ESs provided by constructed wetland to the surrounding environment, perhaps the most important is the underground water recharge service. Since constructed wetland receives a huge amount of wastewater and stagnant water, and becomes stored in the soil, it can also recharge underground water storage. The equation of groundwater recharge is:

$$U_{\mathrm{GW}} = R \times \rho \times G \times 1000 \times k \times UEV_{\mathrm{GW}}, \tag{7}$$

where U_{GW} is the emergy applied to groundwater recharge (sej/m^2/yr), R is the amount of rainfall in the constructed wetland (m/yr), G represents the Gibbs free energy (J/g), 1000 is the conversion factor from kg to g, k is the infiltration coefficient of the case study, and UEV_{GW} is the UEV for groundwater (sej/J).

2.2.2 Ecosystem disservices (EDs)

(1) Greenhouse gas emissions

There are services and disservices in constructed wetlands because they mostly depend on human or nonrenewable inputs to deliver the desirable services. Nonrenewable inputs, when used unsustainably, can result in the generation of disservices such as GHG emissions (van Zanten et al., 2014). GHG emissions, such as CO_2, N_2O, and CH_4, are categorized as disservices because of their adverse impact on the environment. These gases are the main GHGs responsible for global warming, with 100-year global warming potentials of 28 and 265, respectively (IPCC, 2014). Microbial activity produces N_2O and CH_4. Furthermore, N_2O is primarily produced from natural soil via biologically driven processes such as nitrification and denitrification, as well as nonbiological processes such as chemodenulation (Granli and Bockman, 1995).

In this study, the Eco-Indicator 99 of the life cycle assessment technique is used to evaluate the initial damage generated by losses. The disability-adjusted life years (DALYs) calculate the damage to human health loss, whereas damage to ecosystem quality loss is calculated by the potentially disappeared fraction (PDF) of species (Goedkoop and Spriensma, 2001; Ukidwe and Bakshi, 2007).

Health loss due to GHG emissions is estimated as follows:

$$U_{\mathrm{HHGHG}} = \sum_i (f_i \times DALY_i) \times UEV_{\mathrm{health}}, \tag{8}$$

where U_{HHGHG} is the emergy needed to fix the pollution-induced human health loss (sej/m^2/yr), f_i represents the capacity of the constructed wetland system to absorb the *i*th emission (kg/m^2/yr), $DALY_i$ refers to the DALY of people generated by the *i*th emission (person·yr/kg), and UEV_{health} is the emergy transformity for health services loss (sej/person/yr).

Ecosystem quality loss due to GHG emissions is calculated as follows:

$$U_{\mathrm{EQ}} = \sum_i (f_i \times PDF_i) \times UEV_{\mathrm{PDF}}, \tag{9}$$

where U_{EQ} indicates the emergy needed to fix the pollution-induced ecosystem quality degradation (sej/m^2/yr), PDF_i is the PDF of species caused by emission i (%·yr/kg), and UEV_{PDF} means the emergy transformity of ecosystem biomass (sej/yr).

Finally, the total emergy cost (U_{AP}) to fix damages due to pollution-induced human loss can be calculated as:

$$U_{\mathrm{AP}} = U_{\mathrm{HHGHG}} + U_{\mathrm{EQ}}. \tag{10}$$

(2) Mosquito problem

Constructed wetlands offer significant potential for providing habitats for wildlife and improving water quality. However, they have been identified as potential breeding grounds for mosquitoes, leading to conflicts with nearby residents. These conflicts arise due to the design features of constructed wetlands, such as shallow water and emergent vegetation, which are essential for treating wastewater but can also facilitate mosquito breeding (Knight et al., 2003). Additionally, constructed wetlands can attract a large number of birds, which increases the risk of viral infections spreading to nearby human populations. In regions with limited natural mosquito populations, conflicts are often highest near newly urbanized areas (Knight et al., 2003).

Mosquitoes can be controlled via various strategies, such as Mosquito-specific bacteria, Larvivorous fish, Source reduction, and Chemical control. Due to a lack of data, we have used only conventional chemical pesticides, such as the organophosphate compound temephos, to control the mosquitoes. The emergy equation is as follows:

$$U_{\mathrm{mosq}} = O_{\mathrm{amount}} \times UEV_{\mathrm{pest}}, \tag{11}$$

where U_{mosq} is the emergy of mosquito issue (sej/m^2/yr), O_{amout} shows the amount of organophosphate compound temephos in the constructed wetland ecosystem (g/m^2/yr), and UEV_{pest} is the UEV of pesticides (sej/g).

(3) Green waste from the constructed wetland

Green waste is produced after clipping (by machine or hand) the grass from the constructed wetland. The equation of green waste is as follows:

$$U_{\mathrm{GW}} = D_{\mathrm{cost}} \times EMR, \tag{12}$$

where U_{GW} is the UEV of green waste (sej/m^2/yr), D_{cost} represents the amount of green waste disposal cost in land (\$/m^2/yr), and EMR (emergy to money ratio) shows the UEV of disposal waste through labor (sej/\$).

2.2.3 Ternary diagram

To enhance the understanding of emergy analysis outcomes for policymakers and readers, Giannetti et al. (2006) proposed a ternary phase diagram as a graphical tool. This diagram enables the representation of emergy results, facilitating comparisons of various systems and processes with ESs. It also allows for the assessment of improvements and tracking system performance over time. The ternary diagram is a versatile and adaptable tool that is applicable to represent countries, systems, processes, products, and different time periods.

In Fig. 2, the three corners of the triangle are labeled *E*, *D*, and *I*, creating a three-dimensional plot on a two-dimensional plane. Point *I* represents 100% of the emergy urban cost of constructed wetland growth and maintenance. Similarly, point *E* and point *D* represent 100% of EDs and 100% of ESs + avoided cost for human health, respectively (Shah et al., 2022). At point *I*, the composition of *I* is at its maximum, equal to 100%. As we move downward, the percentage of *I* decreases and becomes zero on line *DE*. Point *D*, on the other hand, is the bottom-left vertex of the triangle, with percentages of 100% at point *D* and zero along line *EI*. The composition of *D* decreases as we move away from point *D* and increases as we get closer to it. The line intersecting point *X* corresponds to 30%*D*, 20%*I*, and 50%*E*. Along the line *ED*, the concentration of *I* is zero, and the lines parallel to *ED* represent increasing concentrations of *I* from 0% to 100%. The line intersecting point *X* corresponds to 20%*I*. Consequently, the concentration of *E* at point *X* can be calculated as $100\% - (D + I)/100 = 100\% - (30\% + 20\%) = 50\%$. Additional examples are illustrated in Fig. 2, where point *Y* corresponds to 30%*E*, 10%*D*, and 60%*I*.

2.3 Case description and data sources

Beijing, a city facing significant water pollution and water resource scarcity, made the "Green Olympics" its primary focus during the Beijing Olympics in 2008. Since then, the municipal government of Beijing has put tremendous efforts into various environmental engineering projects to tackle water pollution and promote ecological restoration. As part of our research, we have chosen eight commonly constructed wetlands situated around Beijing to study their effectiveness in addressing these challenges. The data for this study were collected from multiple sources, including the *Beijing Statistical Yearbook 2017*, the *China Biodiversity Research Report*, and various government reports and scientific literature. For further information and specific details about the case study and the collected data, please refer to Table 1.

3 Results

3.1 Emergy for construction and maintenance of constructed wetlands

The results of the emergy evaluation values (expressed in sej/m^2/yr) for CW-1 are presented in Table 2. Among the

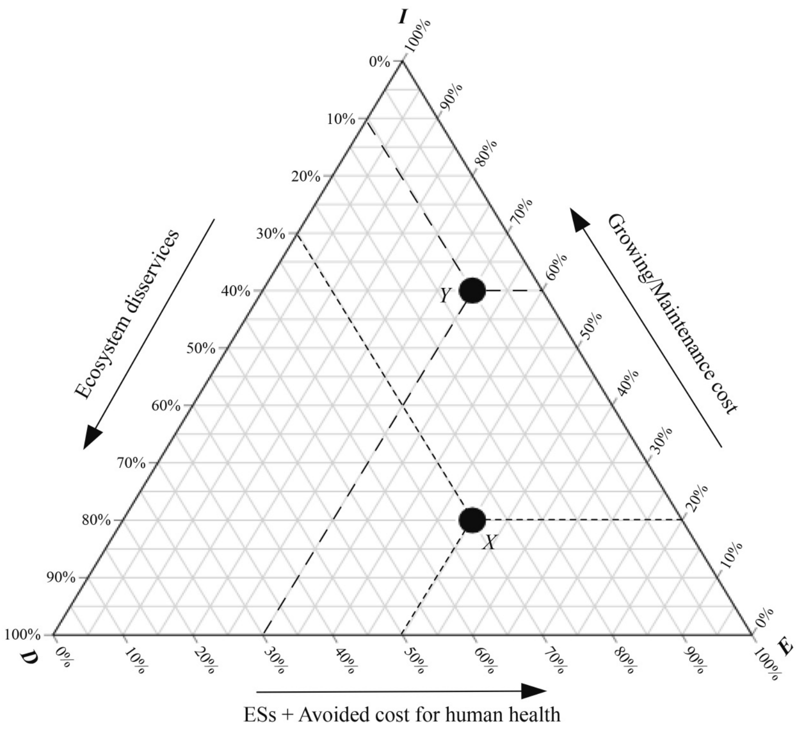

Fig. 2 A ternary phase diagram is used to compare the growing/maintenance cost with the ESs + Avoided cost for human health and disservices.

Table 1 Types of constructed wetlands located in Beijing

Constructed wetland types	Location	Area/m^2	Vegetation	Characteristics	Ref.
CW-1	Longdao River VSSF-CW	600	*Typha latifolia*, *Phragmites australis*, *Zizania aquatica*	The ability to deal with water pollution	Chen et al. (2008)
CW-2	Wildlife Rescue and Rehabilitation HSSF-CW	411	*Lythrum salicaria*, *Iris tectorum*, *Scirpus validus*	The ability to deal with water pollution	Cui et al. (2016)
CW-3	Wildlife Rescue and Rehabilitation FWS-CW	280	*Typha orientalis*, *Acorus calamus*, *Iris tectorum*	The ability to deal with water pollution	Li et al. (2019)
CW-4	Olympic Forest Park IVCW	45000	*Phragmites communis*, *Typha latifolia L.*, *Zizania caduciflora*	The ability to deal with water pollution	Xie et al. (2012)
CW-5	Shicheng Town, Miyun District, HSSF-CW	2700	*A. donax*, *Phragmites communis*, *A. calamus*, *T. sacchariflora*, *T. angustifolia*, *Iris pseudacorus*, *A. plantago-aquatica*, *S. planiculmis*, *L. salicaria*	The ability to deal with water pollution	Wang et al. (2008)
CW-6	Shunyi District HCW	1449	*Phragmites communis*, *Typha latifolia L.*	The ability to deal with water pollution	Zhang et al. (2011)
CW-7	Changping District VSSF-CW	1.20	*Salix babylonica*	The ability to deal with water pollution	Wu et al. (2011)
CW-8	Yongding River HSSF-CW	450	*Phragmites communis*	The ability to deal with water pollution	Xie et al. (2016)

Note: IVCW — Integrated vertical constructed wetland.

inputs in the CW-1 system, renewable inputs account for approximately 0.03% of the total inputs, totaling 2.88E+10 sej/m^2/yr. On the other hand, human inputs encompass various components, such as gravel, soil, sand, vegetation, PE liner, PE pipe, bricks and cement, and maintenance cost.

The VSSF-CW (CW-1) ecosystem shows an emergy value of 1.07E+14 sej/m^2/yr for nonrenewable inputs, making up nearly 99% of all other inputs. This indicates that the structure and management of the CW-1 ecosystem are predominantly the result of human engineering, with significant human intervention.

Within the category of renewable inputs, natural rainfall has the largest value, recorded at 1.36E+10 sej/m^2/yr. Meanwhile, the values of sand (55.4%) and gravel (35%) are the most significant among both renewable and nonrenewable inputs. To reduce human inputs, urban managers may consider using proper management techniques for sand and gravel to decrease input costs or explore alternative materials with lower emergy values that perform equally well, such as gravel, rock, and organic materials (Wang et al., 2018). Similar calculations

Table 2 Emergy evaluation table of a constructed wetland ecosystem in Beijing

CW-1 ecosystem (input)	Raw data	Unit	UEVs (sej/unit)	Emergy (sej/m^2/yr)	Ref. for UEVs
Renewable resources					
Sunlight	3.54E+09	J/m^2/yr	1.00	3.54E+09	Brown and Ulgiati (2016)
Geothermal energy (deep heat)	1.90E+05	J/m^2/yr	4.90E+03	9.31E+08	Brown and Ulgiati (2016)
Wind	9.77E+06	J/m^2/yr	7.90E+02	7.72E+09	Brown and Ulgiati (2016)
Rainwater (chemical)	1.94E+06	J/m^2/yr	7.01E+03	1.36E+10	Brown and Ulgiati (2016)
Rainwater (geopotential)	4.12E+04	J/m^2/yr	7.37E+04	3.04E+09	Odum (1996)
Human inputs					
Gravel	2.95E+04	g/m^2/yr	1.27E+09	3.75E+13	Nelson et al. (2001)
Soil	6.75E+04	J/m^2/yr	9.41E+04	6.35E+09	Brown and Bardi (2001)
Sand	4.17E+04	g/m^2/yr	1.42E+09	5.93E+13	Odum (1996)
Vegetation	3.45E−02	\$/m^2/yr	1.47E+13	5.09E+11	Jiang (2007)
PE liner	1.24E+06	J/m^2/yr	1.41E+05	1.75E+11	Nelson et al. (2001)
PE pipe	2.73E+05	J/m^2/yr	1.41E+05	3.86E+10	Nelson et al. (2001)
Bricks and cement	3.67E+03	g/m^2/yr	2.50E+09	9.18E+12	Brown and Bardi (2001)
Maintenance	1.91E−02	\$/m^2/yr	1.47E+13	2.82E+11	Jiang (2007)

Note: The calculation process of renewable resources and human inputs of CW-1 is available in the Supplementary Materials.

are performed for other aspects of CW-1, and the detailed calculation process is provided as follows.

All the selected constructed wetlands are located in Beijing, and for the purpose of this study, we assume that the renewable inputs are consistent across all wetlands. Since the selected wetlands vary in size, we consider the renewable value per square meter to ensure a fair comparison. Additionally, we assume that the VSSF-CW, HSSF-CW, and FWS-CW utilize the same quantity of PE liner, PE pipe, and bricks and cement, resulting in constant values for these inputs (measured in g/m^2/yr or J/m^2/yr).

Gravel and sand are utilized in vertical and horizontal subsurface flow wetlands (Vymazal et al., 2006) to enhance porosity and prevent clogging, which can negatively impact the functioning of constructed wetlands (Chen et al., 2008). Moreover, these substrates possess the ability to filter and absorb pollutants, especially phosphorus (Chen et al., 2008). For FWS-CWs, a substantial amount of soil (9.95E+11 sej/m^2/yr) is used since they rely solely on the free water surface as a substrate for emergent plants and spontaneous vegetation (Vymazal, 2011a). As a result, wetland plants play a crucial role in absorbing pollutants and creating favorable conditions for bacteria, which are instrumental in pollutant removal. CW-3 stands out with a high vegetation value (5.13E+13 sej/m^2/yr) compared to other wetlands, as reported by Li et al. (2008), where eight *Typha angustifolia L.* plants are planted per square meter in FWS-CW, more than in vertical and horizontal constructed wetland. Based on Table 3, the total emergy values of renewable resources and human inputs per unit area in Beijing are ranked as follows: CW-4 > CW-7 > CW-6 > CW-1 > CW-8 > CW-2 > CW-5 > CW-3. The total emergy value of inputs for all the constructed wetlands is displayed in Table 3, providing valuable insights into their resource utilization and input efficiency.

3.2 Emergy for services

To evaluate the ESs of the urban constructed wetland ecosystem, this study adopts a widely recognized framework that considers both the ESs and the costs associated with avoiding damage to human health. Table 4 presents the emergy values of the ESs and the avoided costs for the selected constructed wetlands.

The results show that all constructed wetlands demonstrate the maximum value for NPP compared to other services. Among the wetlands, CW-7 exhibits the highest carbon sequestration value (2.82E+12 sej/m^2/yr), closely followed by CW-3. Additionally, CW-8 demonstrates a higher average microclimate regulation value (1.58E+11 sej/m^2/yr) than the other wetlands. This is attributed to its rapid and dense vegetative growth, primarily comprising common reed (Milani et al., 2019). Studies have shown that common reed exhibits the highest ET values, which contribute significantly to microclimate regulation (Rozkošný et al., 2006; Milani et al., 2019).

Wetland plants play a crucial role in the constructed wetland system by facilitating pollutant removal and providing a favorable environment for pollutant-removing bacteria. CW-4, although improving overall water quality, demonstrates relatively lower TSS removal efficiency compared to CW-2 (Xie et al., 2012). However, it is worth noting that CW-4 shows excellent removal efficiency for total phosphorus (TP) and total nitrogen

Table 3 Emergy flows for the eight studied constructed wetland systems

Constructed wetland typologies	Total emergy value (sej/m^2/yr)							
	CW-1	CW-2	CW-3	CW-4	CW-5	CW-6	CW-7	CW-8
Renewable resources								
Sunlight	3.54E+09	3.54E+09	3.54E+09	3.54E+09	3.54E+09	3.54E+09	3.54E+09	3.54E+09
Geothermal energy (deep heat)	9.31E+08	9.31E+08	9.31E+08	9.31E+08	9.31E+08	9.31E+08	9.31E+08	9.31E+08
Wind	7.72E+09	7.72E+09	7.72E+09	7.72E+09	7.72E+09	7.72E+09	7.72E+09	7.72E+09
Rainwater (chemical)	1.36E+10	1.36E+10	1.36E+10	1.36E+10	1.36E+10	1.36E+10	1.36E+10	1.36E+10
Rainwater (geopotential)	3.04E+09	3.04E+09	3.04E+09	3.04E+09	3.04E+09	3.04E+09	3.04E+09	3.04E+09
Human inputs								
Gravel	3.75E+13	4.00E+13	–	1.65E+14	1.60E+13	8.52E+13	3.20E+13	9.03E+13
Soil	6.35E+09	–	9.95E+11	–	–	9.95E+11	–	–
Sand	5.93E+13	3.99E+13	–	1.77E+14	3.99E+13	–	1.03E+14	–
Vegetation	5.09E+11	6.49E+12	5.13E+13	5.34E+12	3.98E+12	2.80E+13	1.47E+12	5.34E+12
PE liner	1.75E+11	1.75E+11	1.75E+11	1.75E+11	1.75E+11	1.75E+11	1.75E+11	1.75E+11
PE pipe	3.86E+10	3.86E+10	3.86E+10	3.86E+10	3.86E+10	3.86E+10	3.86E+10	3.86E+10
Bricks and cement	9.18E+12	9.18E+12	9.18E+12	9.18E+12	9.18E+12	9.18E+12	9.18E+12	9.18E+12
Maintenance	2.82E+11	3.01E+11	1.47E+11	3.76E+09	3.01E+11	2.82E+11	2.82E+11	3.01E+11
Total inputs value (*U*)	**1.07E+14**	**9.61E+13**	**6.18E+13**	**3.57E+14**	**6.96E+13**	**1.24E+14**	**1.46E+14**	**1.05E+14**

Note: "–" means data not applicable.

Table 4 Emergy of ESs for the eight constructed wetlands studied

Constructed wetland typologies	Total emergy value (sej/m^2/yr)							
	CW-1	CW-2	CW-3	CW-4	CW-5	CW-6	CW-7	CW-8
ESs								
NPP	1.07E+14	9.61E+13	6.18E+13	3.57E+14	6.96E+13	1.24E+14	1.46E+14	1.05E+14
Carbon sequestration	9.30E+10	1.34E+12	1.86E+12	9.30E+10	1.40E+12	9.76E+11	2.82E+12	1.44E+11
Microclimate regulation	3.39E+10	2.47E+09	2.96E+10	3.39E+10	5.16E+10	3.18E+10	6.98E+10	1.58E+11
Stormwater reduction	3.74E+09	1.64E+10	8.00E+09	4.98E+08	8.30E+08	1.55E+09	1.87E+12	4.98E+09
Water purification								
TP	8.56E+12	5.32E+10	7.88E+10	1.68E+13	1.76E+11	1.46E+12	1.98E+12	–
TN	9.05E+12	1.78E+12	4.51E+11	1.46E+14	2.22E+11	9.03E+12	3.99E+12	2.24E+10
TSS	3.15E+12	6.59E+13	4.38E+12	–	–	–	4.37E+12	–
Groundwater recharge	8.26E+09	8.26E+09	8.26E+09	8.26E+09	8.26E+09	8.26E+09	8.26E+09	8.26E+09
Total ESs = Max (ES_i)	**1.07E+14**	**9.61E+13**	**6.18E+13**	**3.57E+14**	**6.96E+13**	**1.24E+14**	**1.46E+14**	**1.05E+14**
Avoided cost for human health								
Global climate change	1.68E+08	2.42E+09	3.36E+09	1.68E+08	2.52E+09	1.76E+09	5.09E+09	2.61E+08
Total ESs value (*U*)	**1.07E+14**	**9.61E+13**	**6.18E+13**	**3.57E+14**	**6.96E+13**	**1.24E+14**	**1.46E+14**	**1.05E+14**

Notes: The calculation process of ESs of constructed wetland is available in the Supplementary Materials. "–" means data unavailable or not calculated.

(TN) contaminants, likely due to the selection of specific vegetation. Studies have highlighted that cattail and common reed plants exhibit better removal efficiency for TN and TP than other species (Parde et al., 2021).

Another important service provided by the constructed wetlands is groundwater recharge, which shows consistent values across all the selected case study areas. The constructed wetlands efficiently recharge groundwater (8.26E+09 sej/m^2/yr) because they directly connect with the ground, unlike other green–blue infrastructures such as green roofs and walls, which cannot recharge underground water. The total emergy value of all ESs for each constructed wetland is displayed in Table 4, reflecting the comprehensive benefits and contributions of the constructed wetlands in providing valuable ESs to the urban environment.

3.3 Emergy for disservices

Wetland systems can produce both positive and negative outcomes, leading to conflicts among various stakeholders (von Döhren and Haase, 2015). In the current case study, the selected constructed wetlands may have negative effects on some individuals or communities due to the complexity and size of the city. Municipal officials, who are not biological scientists, have expressed concerns about artificial wetlands, stating that they require more land, generate unpleasant odors, and create mosquito problems near built-up areas, which can be harmful to city inhabitants. However, it is essential to note that these issues arise when wetlands are not properly managed. Some researchers have highlighted the EDs generated by constructed wetlands, such as GHG emissions, production of green waste, and mosquito issues (Knight et al., 2003; Maucieri et al., 2017).

The results in Table 5 reveal that the selected constructed wetlands release significant amounts of GHGs, including N_2O, CH_4, and CO_2, into the surrounding environment. The value of CO_2 (1.69E+09 sej/m^2/yr) is higher in several wetlands compared to CW-3 (FWS-CW). Studies have shown that CO_2 emissions are notably lower in FWS-CWs (ranging from 29.4 to 176.0 mg/m^2/h, with an average value of 95.8 mg/m^2/h) than in subsurface flow constructed wetlands (VSSF-CW and HSSF-CW: 51.9 to 567.0 mg/m^2/h, average 184.7 mg/m^2/h) (Mander et al., 2014). Additionally, the emergy values of N_2O and CH_4 for some constructed wetlands (CW-2, CW-5, and CW-8) are higher compared to others. For vertical constructed wetlands (e.g., VSSF-CW), CH_4 emissions (ranging from 0.3 to 5.4 mg/m^2/h, average 2.9 mg/m^2/h) are significantly lower than those in horizontal constructed wetlands (e.g., HSSF-CW) (0.048 to 17.5 mg/m^2/h, average 7.4 mg/m^2/h) and FWS-CWs (0.15 to 27 mg/m^2/h, average 5.9 mg/m^2/h) (Mander et al., 2014).

Moreover, the value of mosquito control (6.03E+10 sej/m^2/yr) is larger than GHG emissions. This may be due to specific design features, such as shallow water and emergent vegetation, which are necessary for optimizing water quality but can also lead to an undesired increase in mosquito populations (Knight et al., 2003). However, it is important to note that EDs such as bad odors were not computed due to a lack of available data.

4 Discussion

4.1 Emergy value comparisons for inputs, ESs, and EDs of the studied constructed wetlands

Tables 2 and 3 present the transformities, raw data, and solar emergy values for the selected constructed wetlands. The analysis revealed that the sand component itself made the largest emergy contribution, constituting 55%, 42%, 50%, and 57% of the total inputs for CW-1, CW-2, CW-4, and CW-5, respectively. This finding is consistent with a study by Zhou et al. (2009), which analyzed constructed wetland and conventional wastewater treatments using the emergy method and found that sand also contributed significantly to the emergy values. Moreover, the results also show that the vegetation value of CW-3 is the largest compared to other wetland types because more plants have been used per square meter in CW-3.

When evaluating the ESs provided by the constructed wetlands, the NPP values, which encompass short-term NPP and long-term NPP used for water purification, bioenergy generation, and direct burning on the open field or residue left on the field for soil fertility, were found to increase. The NPP values of the selected wetlands are ranked as follows: CW-4 > CW-7 > CW-6 > CW-1 > CW-8 > CW-2 > CW-5 > CW-3. Similarly, the ranking of carbon sequestration values among the different constructed wetlands is as follows: CW-7 > CW-3 > CW-5 > CW-2 > CW-6 > CW-8 > CW-1 > CW-4.

Furthermore, the value of groundwater recharge is calculated, as other green infrastructure ecosystems may not provide this service to the same extent or not at all. Despite the relatively small proportion of recharged water

Table 5 Emergy of disservices for the eight constructed wetlands studied

Constructed wetland typologies	Total emergy value (sej/m^2/yr)							
	CW-1	CW-2	CW-3	CW-4	CW-5	CW-6	CW-7	CW-8
EDs								
Greenhouse gasses emission								
N_2O	5.50E+08	9.44E+08	5.11E+08	5.50E+08	9.44E+08	1.32E+08	–	9.44E+08
CH_4	5.66E+08	1.44E+09	1.15E+09	5.66E+08	1.44E+09	1.56E+07	–	1.44E+09
CO_2	1.69E+09	1.69E+09	8.47E+08	1.69E+09	1.69E+09	3.21E+08	–	1.69E+09
Mosquitoes' issues	6.03E+10	6.03E+10	6.03E+10	6.03E+10	6.03E+10	6.03E+10	6.03E+10	6.03E+10
Green waste	1.91E+13	3.82E+13	3.82E+13	1.91E+13	1.91E+13	1.91E+13	9.54E+12	1.91E+13
Total EDs value (*U*)	**1.92E+13**	**3.83E+13**	**3.83E+13**	**1.92E+13**	**1.92E+13**	**1.92E+13**	**9.60E+12**	**1.92E+13**

Notes: The calculation process of EDs of constructed wetland is available in the Supplementary Materials. "–" means data unavailable or not calculated.

compared to the total wastewater entering the constructed wetland, this contribution is of significant importance in maintaining groundwater resources.

In addition, water purification services are assessed based on their purification efficiency in this study. Compared with other constructed wetlands, CW-4 achieves higher purification efficiency. Specifically, it can remove 44% of TP and 20% of TN, although its removal efficiency for TSS is relatively lower than that of CW-2. In fact, the effluent TSS levels in CW-4 occasionally exceed those of the influent, which may be attributed to plant dieback during autumn and winter (Xie et al., 2012). Our findings align with previous research that indicates that the physical processes of sedimentation and filtration are the primary mechanisms responsible for TSS removal in constructed wetlands, as opposed to biological processes.

Constructed wetland typologies also generate EDs in the form of GHG emissions. HSSF-CWs (e.g., CW-2) exhibit significantly higher CH_4 and N_2O emissions than FWS-CWs (e.g., CW-3) and VSSF-CWs (e.g., CW-1). Additionally, FWS-CWs were found to emit significantly less CO_2 than horizontal and vertical subsurface flow wetlands. Teiter and Mander (2005) also compared HSSF-CWs and VSSF-CWs and found slightly higher emissions of N_2O from VSSF-CWs (35.6–44.7 g (N_2O N)/m^2/h) than from HSSF-CWs (4.4–19.5 g (N_2O N)/m^2/h), with no significant differences in CO_2 emissions. HSSF-CWs had higher CH_4 emissions than VSSF-CWs, and within the HSSF-CWs bed, methane emissions were significantly higher in the inlet zones (640–9715 g(CH_4 C)/m^2/h) than in the outlet zones (30–770 g(CH_4 C)/m^2/h). Similarly, Bateganya et al. (2015) found significant CH_4 emissions from HSSF-CWs compared with VSSF-CWs (30.5 and 8.5 mg/m^2/h, respectively), with no significant difference considering CO_2 fluxes, and higher N_2O emissions were observed from HSSF-CWs (0.22 mg(N_2O)/m^2/h) than from VSSF-CWs (0.08 mg(N_2O)/m^2/h). The higher CH_4 emissions from HSSF-CWs than VSSF-CWs are due to the prevalence of anoxic-anaerobic conditions in HSSF-CWs, which is demonstrated by negative redox potential and low dissolved oxygen concentrations (< 2 mg/L) (Vymazal and Kröpfelová, 2008). Moreover, future calculations of the bad odor value are necessary to evaluate this disservice more accurately.

4.2 Emergy ternary diagram

The ternary phase diagram (Fig. 3) provides valuable information that can facilitate decision-making processes and serve as a useful tool for comparing and contrasting the significant features of a system. In this particular diagram, we can observe that CW-4, CW-7, and CW-1 represent maximum benefits of 50%, 48%, and 47%, respectively, when compared to costs and impacts. On the other hand, CW-5 and CW-8 show benefits of approximately 44% and 43%, respectively, which are closer to their inputs at approximately 44% and 47%,

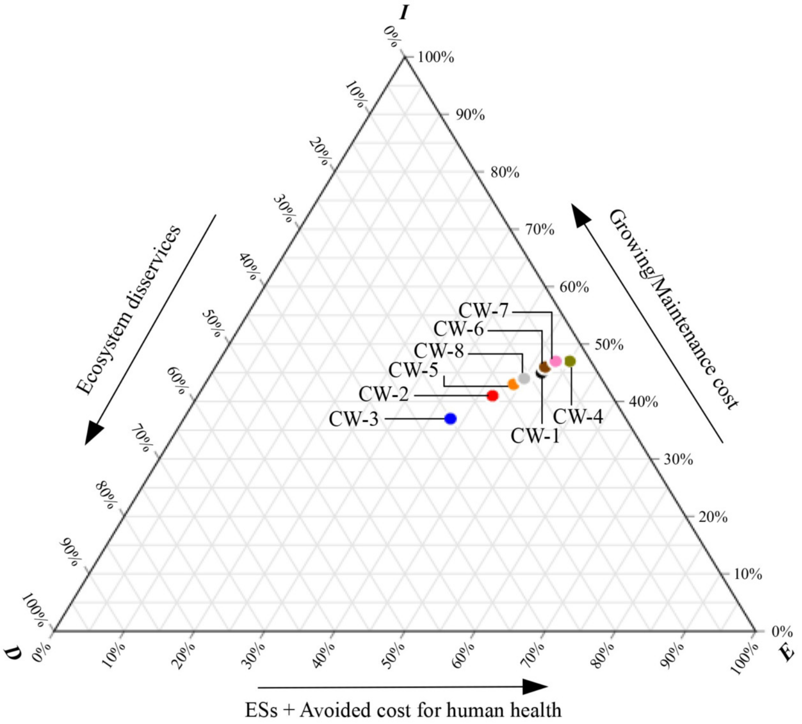

Fig. 3 Ternary diagram of different constructed wetlands, including ESs + Avoided cost for human health, Growing/Maintenance cost and Disservices.

respectively. CW-3, however, exhibits the minimum benefits of approximately 38% compared to other wetlands, with impacts and costs of approximately 25% and 37%, respectively.

Overall, most wetlands in the study generate more benefits than impacts and costs. Based on this analysis, we suggest that policymakers and urban administrators consider constructing wetlands similar to CW-4 in urban zones. CW-4 demonstrates higher benefits and requires less investment due to its feature of not needing power-lifting equipment, and the water flows by gravity. Moreover, the presence of other organisms in its environment contributes to better ecological control of mosquitoes, which is conducive to reducing negative services.

4.3 Limitations of this study

While our study may not have specifically focused on biodiversity assessment, it is crucial to recognize the significance of biodiversity within the broader context of urban constructed wetland management. Acknowledging this limitation, we can propose potential avenues to compensate for it, encouraging discussions on the potential trade-offs and synergies between ESs and biodiversity conservation. By highlighting the positive outcomes of managing constructed wetlands for ESs such as water purification, flood control, and recreational amenities, we indirectly support biodiversity by creating more favorable habitats for various species. This perspective underscores the importance of adopting a balanced approach that considers both ESs and biodiversity conservation in the management of urban constructed wetlands. In addition, it is essential to obtain more data on average air purification per unit area in constructed wetlands, as this information is crucial for evaluating the air purification service more accurately. Having reliable data on air purification by constructed wetland plants will enhance our understanding of the environmental benefits provided by these wetlands. Furthermore, cultural services were not considered in our study due to a lack of data. To improve future assessments, it is essential to seek better data from responsible agencies to estimate the cultural services provided by constructed wetlands. By incorporating cultural services, we can better appreciate the societal and cultural values associated with these ecosystems and their contributions to human well-being.

5 Conclusions

To achieve sustainable development for all inhabitants and lasting economic benefits from water resources, it is essential to enhance the quality of wastewater. The objective of this study was to assess the construction and maintenance costs, potential benefits (referred to as services), and potential damages (referred to as disservices) provided by constructed wetlands. Constructed wetlands can be a valuable aspect of a holistic approach to reduce nutrient loads and enhance water quality, thereby benefiting the urban environment. Among the services estimated in this study, carbon sequestration was found to be the leading service generated by constructed wetlands in Beijing, China. However, CW-3 (FWS-CW) was not deemed suitable due to its relatively lower benefits (ESs) compared to other wetlands, likely resulting from its complex human-engineered landscape, which generated some disservices.

The study also revealed a higher value of mosquito issues compared to GHG emissions, but this challenge can be addressed by incorporating appropriate design features, such as shallow water and emergent vegetation, to maximize water quality treatment while minimizing the undesired growth of mosquito populations.

Furthermore, the emergy ternary tool demonstrated that all the constructed wetlands generated more benefits than impacts. Among these wetlands, integrated vertical flow CW-4 produced fewer impacts than benefits. Therefore, urban administrators should consider constructing CW-4 type wetlands in or around the city for better urban ecological management. This approach would not only benefit the city's environment but also enhance its economic and social values.

Despite the valuable findings, there are some limitations in the present research due to incomplete data and CW management problems. For instance, certain ESs and EDs were not quantified due to insufficient data on air purification, biodiversity, and odor issues. Therefore, future studies may require additional data to enable a more comprehensive evaluation of services/disservices provided by constructed wetlands.

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Competing Interests The authors declare that they have no competing interests.

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