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Review: Potential and strategies for implementing constructed wetland technology to mitigate water pollution in Ha Noi's lakes and ponds, Viet Nam

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Abstract. Constructed wetland (CW) technology emerges as a highly effective, sustainable, and eco-friendly solution for tackling water pollution. This report provides an overview of CW technology and its potential applications in treating water pollution in Ha Noi's lakes and ponds in Viet Nam. Based on existing research, the report synthesizes CW systems' definition, classification, and treatment efficiency while proposing appropriate implementation strategies for Ha Noi's lakes. Low-pollution lakes should utilize cost-effective free-floating plants, whereas highly polluted lakes require subsurface flow or hybrid CW systems to achieve high treatment efficiency. The implementation roadmap consists of three phases: assessing the current status, piloting the model, and scaling up the application alongside source control measures and operational monitoring. Although CWs technology is a sustainable and viable solution, their widespread adoption in managing water quality in Ha Noi's lakes and ponds requires thorough evaluation, careful selection of suitable technologies, and integration with comprehensive and long-term policies.

Keywords: Ha Noi's lakes and ponds, free floating plant, subsurface flow, constructed wetland, hybrid constructed wetland.

Classification numbers: 3.3.1, 3.4.2, 3.7.2

1. INTRODUCTION

Ha Noi currently has 125 lakes across 12 urban districts, covering a total area of 1,158 hectares [1], playing a crucial role in climate regulation and urban landscape enhancement. However, many of these lakes are facing severe pollution. According to a 2015 report by the Center for Environmental and Community Research (CECR), among the surveyed lakes, 11 exhibited signs of pollution, 8 were classified as heavily polluted, and 6 were identified as severely polluted. Notably, some of the most severely polluted lakes include Van Chuong, Linh Quang, Thien Quang, Kim Lien, and Ba Mau [2]. The primary cause of this pollution is the increasing discharge of domestic and industrial wastewater, along with other pollution sources. P. V. Quan *et al*. (2010) found that rainwater and runoff entering central Ha Noi's lakes contain high levels of indicator bacteria such as *E. coli* and total coliform, primarily due to untreated wastewater discharge and leakage from septic tanks [3]. Organic pollution is also a significant concern. B. T. Nguyen *et al*. (2016) identified Ba Mau Lake as the most severely affected by organic pollution, while other lakes, including West Lake, Hoan Kiem Lake, and Truc Bach Lake, exhibited moderate levels of pollution [4]. Additionally, heavy metal contamination in the To Lich and Kim Nguu Rivers has reached alarming levels, with toxic elements such as Pb, Cu, Zn, Cr, Cd, and Ni exceeding Viet Nam's surface water quality standards, posing serious risks to aquatic ecosystems and irrigation water sources [5]. A recent study by N. Da Le *et al*. (2024) reported severe microbiological contamination in 15 urban lakes, with total coliform and *E. coli* significantly exceeding the QCVN 08-MT:2015/BTNMT standards, posing a substantial risk to public health [6]. These findings highlight the critical need for wastewater treatment improvements and the strengthening of environmental management measures in Ha Noi.

Constructed wetlands (CW) are a promising pollution treatment technology that has been applied since the 1990s and early 2000s, primarily functioning as a secondary treatment system through chemical, biological, and physical processes [7]. They offer an environmentally friendly, cost-effective solution with simple operation and maintenance, making them highly suitable for application in developing countries [8]. While CWs have been effectively utilized for various wastewater types, they demonstrate particularly high treatment efficiency for wastewater rich in organic matter and nutrients [7]. The CW technology has been employed to treat a wide range of pollutants, including biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids (SS), total nitrogen (TN), total phosphorus (TP), total coliform (TC), and heavy metals. These contaminants are removed through microbial degradation, plant uptake, substrate adsorption, filtration through filter media, and biological control mechanisms. Additionally, the CWs contribute to enhancing ecological landscapes and creating urban green spaces. Given the severe pollution in Ha Noi's lakes and ponds, the implementation of CW technology presents an effective, sustainable, and environmentally friendly solution. This report provides a comprehensive review of the CW technology and its potential applications in mitigating water pollution in Ha Noi's lakes and ponds, Viet Nam. The study aims to explore the practical application of constructed wetlands as an affordable and eco-friendly solution for improving urban water quality in Ha Noi. It seeks to identify optimal design strategies tailored to different pollution levels of city lakes, while providing a structured roadmap for scaling up the technology within an integrated urban water management framework. The research highlights both the environmental benefits and operational considerations to support evidence-based policy making.

2. DEFINITION AND CLASSIFICATION

Constructed wetlands are an ecological technology that simulates various physical, chemical, and biological processes occurring in natural environments to treat wastewater. Fundamentally, the CWs operate by interacting with three main components: water, substrate, and plant species. The water component is characterized by flow regime, water source characteristics, and hydraulic loading rate. The substrate consists of filtration materials that serve as a structural support for plant, provide a habitat for microbial communities responsible for degrading pollutants in wastewater, and function as the primary mechanism for contaminant removal in CW. According to L. C. Sandoval Herazo *et al*. (2023), the most commonly used substrates were gravel (32 %) and sand (23 %) [9]. Additionally, depending on treatment requirements, wastewater characteristics, cost, and application location, various materials are also used, including limestone, zeolite, plastic, seashells, rice husk, granite, and coal slag [9-13]. By arranging or blending suitable materials, the substrate provides support for biofilms and plants, as well as facilitates physicochemical adsorption processes to maximize pollutant removal efficiency [14]. Common plant species in the CWs consists of aquatic plant species that can withstand polluted conditions and contribute to pollutant removal through hyperaccumulation mechanisms or rhizosphere processes. The selection of plant species is based on their biological structure and physiological functions, tailored to the specific design of the CW systems. For example, some plant species do not anchor their roots in the substrate but instead float freely on the water surface. Notable examples include *Ipomoea aquatica*, *Pontederia crassipes*, *Eichhornia crassipes*, *Pistia stratiotes* L., and members of the Lemnoideae family. In contrast, species with extensive root systems, such as *Typha latifolia*, *Phragmites australis*, and *Vetiveria zizanioides*, are typically planted in the substrate layer, where they effectively absorb nutrients and remain firmly anchored in flooded environments. *Cyperus alternifolius* is a versatile species that can be cultivated both on floating rafts and in filter media, making it widely utilized in the CW systems for treating various types of wastewater, including urban water-lake [15], domestic wastewater [16], and swine wastewater [11]. Additionally, certain native plant species are incorporated into the CW systems to enhance aesthetic appeal, such as: *Dracaena fragrans*, *Philodendron hastatum*, *Caladium bicolor*, *Catharanthus roseus (L.)* G.Don, *Canna hybrids*, *Canna indica*, *Canna generalis*, *Portulaca grandiflora*, *Dracaena sanderiana*, and *Melampodium paludosum*.

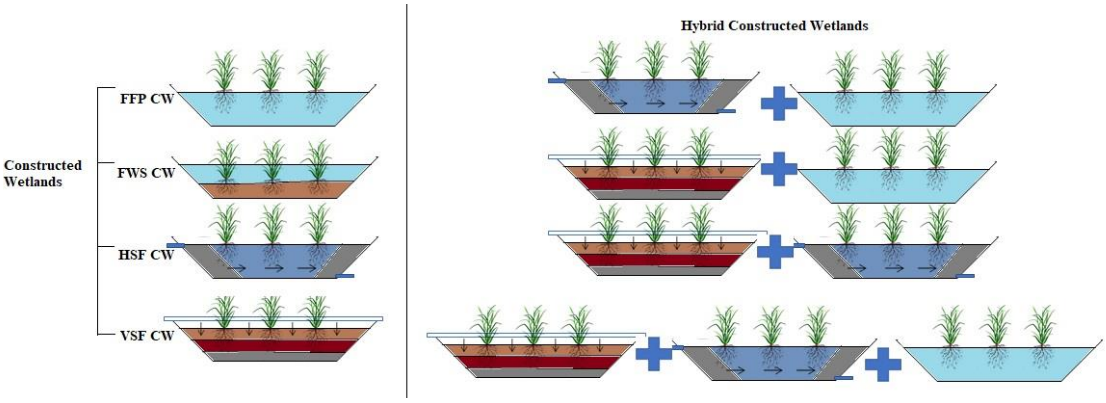


Figure 1. Classification of constructed wetlands. FFP: free-floating plant, FWS: free-water surface, VSF: vertical subsurface flow, HSF: horizontal subsurface flow, CW: constructed wetland.

Different types of the CWs vary in structure and operational principles, leading to differences in treatment objectives, implementation sites, and operational costs [17]. In general, CWs can be categorized into four main types: free-floating plant (FFP), free-water surface (FWS), subsurface flow (SSF), and hybrid-constructed wetlands (Figure 1). The FFP system utilizes aquatic plants that float freely or are grown on rafts, contributing to water quality improvement, habitat provision for aquatic organisms, and enhancing the aesthetic value of lakes and ponds. Its cost-effective and straightforward design makes the FFP system suitable for deployment in various locations. The FWS CW system consists of aquatic vegetation planted in a substrate layer, with surface water flow directly exposed to air, sunlight, and plants. This design mimics natural wetland ecosystems and is particularly effective in large areas. The SSF CW system is designed so that wastewater flows beneath the surface through a filter substrate, which is covered with aquatic plant species. This structure allows wastewater to interact with the substrate and plant roots, creating optimal conditions for microbial growth. As a result, organic matter decomposition and nutrient uptake are enhanced, improving treatment efficiency. The SSF CW system is further classified into two types based on flow direction: vertical subsurface flow (VSF) and horizontal subsurface flow (HSF) CWs. To optimize treatment efficiency, hybrid CW systems can be implemented by combining multiple CW types in sequence. This approach enables the treatment of a broader range of wastewater sources with higher efficiency and cost-effectiveness. Depending on wastewater characteristics, installation site, and investment budget, each CW type can be flexibly selected and applied to achieve the best possible treatment performance.

3. APPLICATION OF CONSTRUCTED WETLAND TECHNOLOGY IN POLLUTION TREATMENT

The treatment performance of CWs depends on wastewater characteristics, system type, and environmental conditions. Studies indicate that CWs can remove 79 - 99 % of TSS, 65 - 96 % of BOD_5, and 70 - 97 % of COD, significantly improving wastewater quality before effluents are discharged into the environment [18]. Regarding nutrient removal, CWs can eliminate 50 - 99 % ammonium nitrogen (NH_4-N), 40 - 80 % TN, and 40 - 80 % TP through plant uptake and microbial activity [19]. Additionally, the CWs exhibit a high capacity for pathogen removal, achieving 90 - 99 % elimination of pathogenic bacteria such as *E. coli* and *Salmonella* through sedimentation, plant absorption, and natural UV exposure [20].

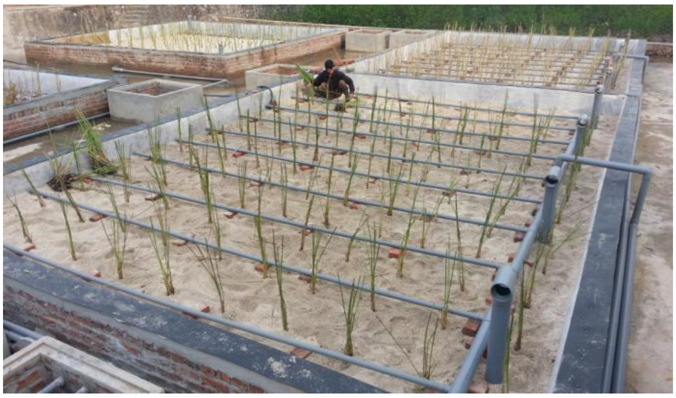
Constructed wetlands are a suitable technology for restoring and improving the water quality of urban lakes. These systems function as natural filters, effectively removing pollutants from stormwater, domestic wastewater, and industrial effluents before discharging to lakes. Additionally, the CWs help control eutrophication by absorbing excess nitrogen and phosphorus, thereby limiting algal blooms [21]. Practical studies have demonstrated the high efficiency of CWs in urban lake treatment. For instance, a project at Lake Qaroun (Egypt) successfully improved water quality by integrating the CW technology with a community-based management and monitoring program [22]. In China, a study at the Jinshan Lake showed that the CWs effectively removed TN in summer and nitrate-nitrogen (NO_3-N) in winter, although their phosphorus retention capacity remained limited [23]. Moreover, a pilot study at Xing-Qing Lake (Xi'an, China) reported the CW removal efficiencies of 84.2 % for COD, 53.8 % for NH_3-N, 47.9 % for TN, 73.3 % for TP, and 86.6 % for TSS [24].

The CWs have been widely adopted worldwide, with approximately 50,000 systems in Germany, 160 in Austria, 180 in Czech Republic, 956 in the United Kingdom, 8,000 in United States, 140 in Ireland, and 120 in the Netherlands and Portugal [25]. In Vietnam, the CWs have been applied to treat various types of wastewater, primarily domestic wastewater, pig farm effluents, and industrial wastewater (Figure 2). For pig farming wastewater, traditional treatment methods include biogas digesters and biological ponds (FFP CWs). However, effluent quality from these systems often fails to meet the Vietnamese environmental standards. Studies have proposed integrating aerobic and anoxic treatment processes with CW systems - particularly SSF and hybrid CWs - as post-treatment solutions for biogas effluents, ensuring improved wastewater quality and regulatory compliance. The CW systems for wastewater treatment at Formosa Ha Tinh Steel Corporation, with a capacity of 36,000 m³/day, was commissioned in 2017 and is one of the largest CW systems in Viet Nam. This model utilizes a SSF CW system designed with filtering materials, including limestone, riprap, and sand. The selected vegetation species used in the system include *Cyperus tegetiformis*, *Typha angustifolia* L., *P. australis* Cav, and *C. alternifolius*. The plant species in the CW systems were planted alternately. After seven years of operation, the system has developed into an artificial ecosystem supporting a diverse range of fish, birds, and small animals.

a. Constructed wetlands at Formosa Ha Tinh Steel Corporation, Ha Tinh province, Viet Nam.

b. Constructed wetlands at a 150 m³/day pig farming facility, Tot Dong Commune, Chuong My District, Ha Noi, Viet Nam

Figure 2. Selected applications of constructed wetland technology.



c. Vertical subsurface flow constructed wetland (VSF CW) at Quang Ninh Seafood Export Joint Stock Company, Quang Ninh province, Viet Nam.

d. Horizontal subsurface flow constructed wetland (HSF CW) system at Quang Ninh Seafood Export Joint Stock Company, Quang Ninh province, Viet Nam.

f. Free-floating plant constructed wetland (FFP CW) at Pacific Crystal Textiles Limited, Hai Duong province, Viet Nam.

Figure 2. Selected applications of constructed wetland technology (*continue*)

Another CW model for treating pig farming wastewater, with a capacity of 150 m³/day, was studied and implemented in Tot Dong commune, Chuong My district, Ha Noi. This model employs a hybrid CW system, integrating HSF and FFP CW systems. *C. alternifolius* was cultivated on floating rafts and alternated with *P. australis* Cav in the HSF system. The system achieved removal efficiencies of 79 % for COD, 82 % for TSS, 54 % for TN, and 83 % for TP, with the treated effluent meeting the Vietnamese regulatory standards for livestock wastewater discharge. Additionally, floating rafts planted with *C. alternifolius* have been widely deployed in urban rivers and lakes across Ha Noi, Viet Nam. These floating systems operate based on the absorption and transformation of pollutants through plant roots, effectively reducing excess nutrients such as nitrogen and phosphorus, thereby mitigating eutrophication and excessive algal growth. However, the effectiveness of this approach in Ha Noi's lakes and ponds remains insufficiently validated, primarily due to a lack of long-term data assessing pollutant removal efficiency, the adaptability of *C. alternifolius* to urban aquatic environments, and its long-term ecological impacts. Moreover, there has been no comprehensive technological design, operational management plan, or strategic framework for scaling up the implementation of these systems.

Table 1. Investment and operational costs of plant-based wastewater treatment technologies.

System	Wastewater type	Flow rate (m^3/d)	Investment cost (USD/m^3)	Operational cost (USD/m^3)
CWs in Guangdong, China	Polluted river water	14000	58	0.01
CWs in Wuhan, China	Polluted lake water	1500	32.19	0.007
CWs in Yuehu Lake, Wuhan, China	Polluted lake water	2000	72.5	0.017
CWs in Shiyan City, Shenzhen, China	Domestic wastewater	15000	77.33	0.026
CWs in Chongqing, China	Domestic wastewater	500	217.5	0.013
CWs in Sichuan, China	Domestic wastewater	3000	141.52	0.051
CWs in Chengdu, Sichuan, China	Domestic wastewater	2000	279.13	0.116
CWs in Fujian, China	Domestic wastewater	130	369.86	0.017
CWs in Chuong My, Ha Noi, Viet Nam	Livestock wastewater	150	289.85	0.014
CWs in Bun Banh Da Mai, Bac Giang, Viet Nam	Wastewater from traditional noodle production village	10	230	0.012

B. T. K. Anh *et al*., compiled from the project UQSNMT.01/20-21, 2022 [31].

Advantages and limitations of CW technology: One of the key advantages of CW technology is its low cost and simple operation. When land availability is not a constraint, investment costs for the CWs range from 32.19 to 369.86 USD per cubic meter, while operation and maintenance costs vary between 0.013 and 0.116 USD per cubic meter, making the CWs significantly more cost-effective than many conventional treatment technologies (Table 1).

Some reports indicate that the cost of CW for wastewater treatment in Africa is approximately 5 USD per person, which is significantly lower than mechanical treatment systems that can cost around 50 USD per person [26]. Additionally, treatment systems can be enhanced as green spaces, contributing to landscape improvement. They also support biodiversity by creating habitats for various forms of wildlife [27]. Beyond their high removal efficiency for nutrients, organic matter, and heavy metals, recent studies have reported the potential of the CWs to treat emerging contaminants [28]. Another significant advantage is their environmental friendliness, as they rely on natural treatment mechanisms that minimize secondary pollution and reduce energy consumption [29, 30].

However, a major limitation of constructed wetlands is their large land requirement, making them less feasible in densely populated areas with limited land availability [32]. The substantial land requirements pose a significant constraint, particularly for small water bodies situated within the densely built environment of Ha Noi. Despite this, the CW technology has been widely adopted in major cities worldwide due to its environmental and economic benefits. Optimal design is the key to maximizing the efficiency and applicability of CW systems [32]. Many CW models are designed with a gravity-driven flow mechanism, minimizing energy consumption and significantly reducing operational costs. In addition, the post-treatment management of biomass and substrate materials warrants careful consideration. Uncontrolled rapid growth of vegetation in constructed wetlands can lead to adverse ecological and environmental impacts. For example, *Eichhornia crassipes* is a common aquatic plant in Viet Nam, known for its high pollutant removal capacity and its frequent application in FFP CW. However, due to its rapid growth, if the dead biomass is not harvested in a timely manner, it can lead to secondary pollution. Therefore, it is recommended that biomass be harvested periodically during system operation, in accordance with the plant's growth cycle. Plant biomass generated from constructed wetlands may constitute a valuable resource. Several studies have proposed its potential for reuse in various applications, including composting, biofuel production, livestock feed, and solid fuel [33, 34]. Another concern associated with long-term operation is the potential for substrate clogging, which often necessitates complete replacement of the filter media. This significantly increases technology costs. However, operational evidence has demonstrated that substrate media generally maintain functional integrity over extended operational periods; for instance, the Formosa biological pond in Ha Tinh, which has been in continuous operation since June 2017, still delivers high treatment efficiency without necessitating media replacement. Should replacement become necessary, the exhausted filter media typically contaminated with organic matter can be partially repurposed following appropriate washing procedures or recycled into construction materials, contributing to resource recovery and circular economy objectives.

Overall, constructed wetlands align well with the requirement for low investment costs, mainly as operational expenses are minimal. This makes the CW technology a highly viable solution for pollution control in developing countries like Viet Nam.

4. PROPOSED SOLUTIONS FOR APPLYING CONSTRUCTED WETLAND TECHNOLOGY IN POLLUTED LAKES AND PONDS IN HA NOI

Ha Noi has approximately 125 lakes and ponds, many of which are severely polluted due to various causes. In urban lakes, the primary sources of pollution include direct discharge of untreated domestic wastewater and effluents from traditional craft villages, as well as limited water flow and poor self-purification capacity [2, 35]. Long-term sediment accumulation without regular dredging has also led to oxygen depletion, resulting in foul odors and deteriorating water quality. Algal blooms (eutrophication) are also common in many lakes due to excessive nutrient concentrations [36, 37]. The primary pollution issue in Ha Noi's urban lakes and ponds is organic matter and nutrient overload [4, 37]. Severe pollution, characterized by high ammonia concentrations, pH levels exceeding 9, low dissolved oxygen levels, and the additional release of phosphate from sediments, is the primary cause of mass fish mortality in urban lakes in Ha Noi [38, 39]. Therefore, applying the CW technology is a suitable and effective solution that offers economic, environmental, and urban landscape benefits.

The FFP CW systems are particularly suitable for large lakes with open spaces. In this model, wastewater flows through a vegetated area consisting of floating rafts or free-floating aquatic plants, which absorb pollutants and enhance photosynthesis, thereby increasing oxygen enrichment in the water. The FFP CW systems remove excess nutrients, mitigate eutrophication, and contribute to urban greening while maintaining extremely low operational costs. Several lakes in Ha Noi, such as Thanh Cong Lake, West Lake, Linh Dam Lake, and Nghia Tan Lake, have implemented FFP CW technology for wastewater treatment. However, these applications have been limited to partial pollution mitigation, with no systematic design considerations, such as plant species density optimization or detailed performance evaluations to determine the most suitable CW technology for different lake conditions. A critical aspect of the FFP CW technology is the selection of appropriate plant species, regulation of planting density, and control of plant growth, along with the integration of complementary treatment measures to optimize efficiency [40]. The SSF CW system should be further researched and implemented for heavily polluted lakes. The SSF CWs direct wastewater through a filter medium, combined with aquatic vegetation, to remove contaminants. The advantages of this technology include its high efficiency in removing organic compounds and heavy metals and its odor-free operation, which helps maintain a clean environment in surrounding residential areas [26]. The choice of substrate material is essential for enhancing treatment performance, preventing clogging, and ensuring system stability [9, 11]. Additionally, depending on climatic conditions and environmental applications, aquatic plants significantly affect treatment efficiency [8]. Therefore, comprehensive assessments are required to ensure species adaptability and optimize pollutant removal efficiency.

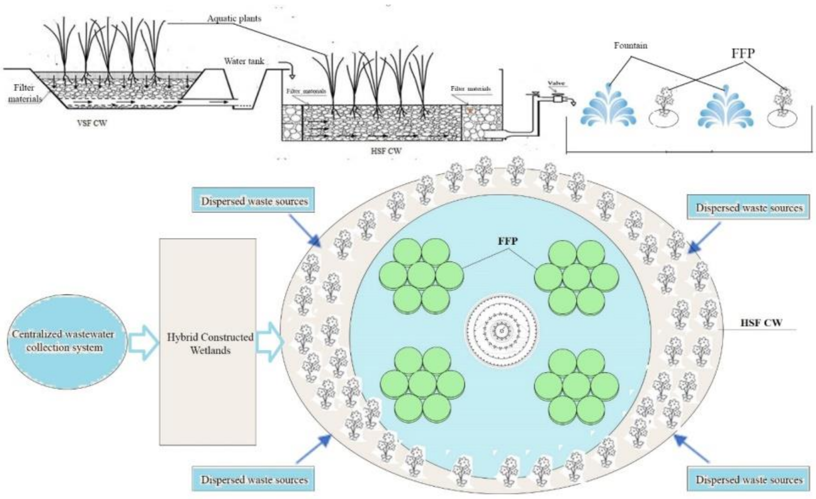


Figure 3. Simulation of a hybrid constructed wetland system for treating heavily polluted lakes in Ha Noi.

To further enhance treatment efficiency, a hybrid CW system can be implemented (Figure 3), integrating both FFP and SSF CW models. This system is particularly suitable for highly polluted lakes, providing comprehensive treatment for various contaminants, including organic matter, nutrients, pathogenic microorganisms, and heavy metals. Compared to standalone CW systems, the hybrid model offers superior treatment efficiency, improving water quality more effectively and allowing for flexible application across different lakes and ponds. In this design, the SSF CWs are the primary treatment stage, with filtration units placed along the shoreline. The partially treated effluent is then discharged into the lake, where floating plant rafts regulate pollutant levels through controlled plant density.

To maximize the effectiveness of CW technology, the study proposes a phased approach to optimize pollution control in Ha Noi’s lakes and ponds, as follows:

Phase 1: Assessment and design

Figure 4. Steps in the assessment and design phase for applying constructed wetland technology in Ha Noi’s lake and pond treatment.

Before implementing the CW-based water treatment models, a comprehensive assessment of pollution levels in each lake must be conducted. This involves analyzing key parameters such as organic matter concentration, nutrient levels, heavy metals, microorganisms, and other pollutants. Based on the assessment results, each lake’s most suitable CW model is selected to ensure optimal treatment efficiency (Figure 4).

Phase 2: Pilot implementation

Following the design phase, CW systems will be piloted in selected lakes with relatively high pollution levels, such as West Lake, Giang Vo Lake, and Linh Dam Lake. The most suitable CW type will be selected based on the analytical data from Phase 1, followed by the finalization of system design and trial operation. During this phase, the CW system will be installed and operated for approximately 6 - 12 months or longer, with continuous water quality monitoring to assess treatment efficiency. Additionally, factors influencing system performance, such as environmental conditions, socio-economic dynamics, and variations in pollution sources, will be analyzed to refine and optimize the technology.

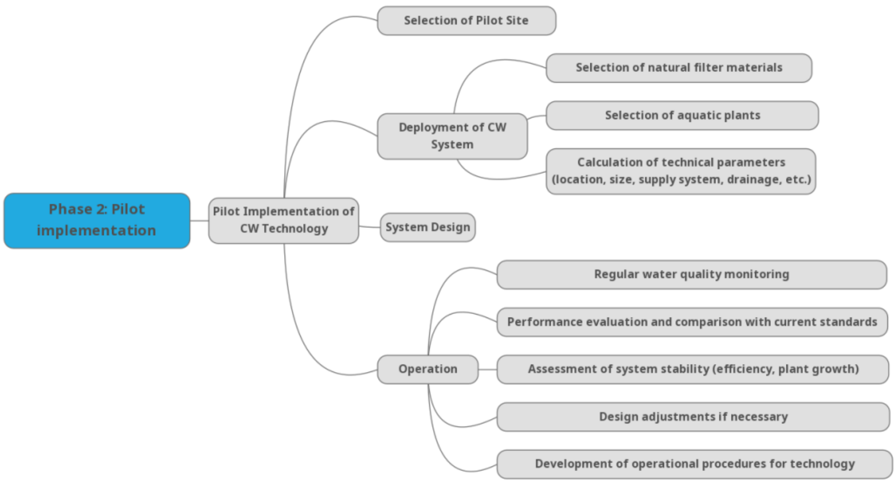


Figure 5. Steps in the pilot implementation phase for applying constructed wetland technology in Ha Noi's lake and pond treatment.

Phase 3: Scaling up

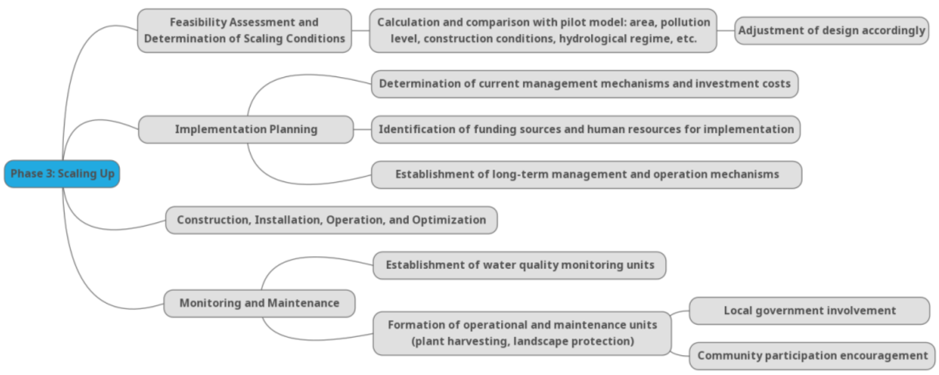


Figure 6. Steps in the scaling-up phase for constructed wetland technology application in Ha Noi's lake and pond treatment.

Based on the pilot phase results and the current environmental assessment data, the CW model will be expanded to lakes with similar characteristics. It is also essential to integrate measures for reducing discharge sources from residential areas and nearby industrial activities, including effluent discharge control, enhancement of public awareness of environmental protection, and the development of wastewater treatment systems before effluents are discharged into the lakes.

Although the CW technology operates on a simple principle, regular monitoring and periodic maintenance are essential to ensure system stability and optimal treatment performance. Furthermore, the widespread implementation of this technology requires coordinated and long-term policies to support its sustainable application in water quality management for Ha Noi's lakes and ponds.

5. CONCLUSIONS

Constructed wetland technology is an environmentally friendly and effective solution for treating pollution in Ha Noi's lakes and ponds while also enhancing urban landscapes. The most suitable CW types for Ha Noi's lakes include free-floating plants, subsurface flow, and hybrid CW systems. Appropriate CW systems should be selected based on pollution levels, hydrological conditions, and the potential for integration with source control measures. However, the current application of CWs remains limited due to a lack of large-scale pilot studies and practical assessments. To expand implementation, it is necessary to optimize system design, integrate complementary treatment methods, conduct large-scale trials, and develop supportive policies to promote urban environmental protection.

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

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