International Journal of Chemical and Biochemical Sciences
(ISSN 2226-9614)

Journal Home page: www.iscientific.org/Journal.html

Improved constructed wetlands for treating water

Rida Zahra*[1], Muhammad Idrees Jilani[2]

[1]*Department of Chemistry, University of Agriculture, Faisalabad-38040-Pakistan.*

[2]*Department of Chemistry, The University of Lahore, Lahore, Pakistan.*

Abstract

Constructed wetlands treatment systems have been designed and constructed to utilize the natural processes. Artificial wetlands use natural microbiological, biological, physical, and chemical processes to treat wastewater. The main types of constructed wetlands are free-water-surface and subsurface-flow. This is crucial for choosing the suitable type of constructed wetland and enhancing its design, construction, and maintenance. The objective of this article to provide a comprehensive review of constructed wetlands technology to enhance its sustainability and design. Treatment performance decreases in colder climates, researchers have sought ways to increase it. This review suggests that cold-area constructed wetlands can benefit from better operation. Numerous studies on constructed wetlands (CWs) have been prompted by the growing interest in low-cost, effective methods of treating wastewater and dirty water. Various plant species have the ability to mitigate environmental pollutants. Constructed wetlands designed to improve water quality. The design parameters and operational conditions of CWs including plant species, substrate types, water depth, hydraulic load, hydraulic retention time. Effective policies and governance structures are vital for the widespread adoption and continued success of CWs. Lastly, future research on improving the stability and sustainability of CWs were highlighted.

Keywords: constructed wetlands, natural processes, sustainability, wastewater treatment, design parameters, future research

Full length review article
**Corresponding Author*, e-mail: ridazahraa110@gmail.com

1. Introduction

Wetland is a particular kind of ecosystem that are submerged by water, either constantly or periodically, where oxygen-deprived procedures be resolved. The main distinction of wetlands from other landscapes or lakes is the presence of flexible vegetation of aquatic species, which are characteristic of the unique hydric soil. The improved version of a wetland is known as a "constructed wetland." Wetlands created for the treatment of water are intricate, interconnected systems of water, plants, animals, microorganisms, and the natural world. Wetlands serve a variety of services, including water purification, water storage, carbon processing and recycling, shoreline stabilization, and plant and animal support. While wetlands are often reliable, self-adapting systems, recognizing how natural wetlands are organized and operate considerably enhances the possibility of effectively constructing a wetland treatment system [1]. The use of technologies has become a viable and efficient method for treating wastewater and protecting the environment [2-4]. Researchers and environmental engineers have been working to improve the functionality and suitability of artificial wetlands for a long time. The developments and breakthroughs that have influenced the field of artificial wetlands, emphasizing the incorporation of innovative design strategies, cutting edge technologies, and ecological principles. The advancement of artificial wetlands offers an amazing array of opportunities, ranging from cutting-edge materials and intelligent monitoring systems to hybrid designs that combine technical and natural components [5].

The amalgamation of scientific discoveries, technological advancements, and ecological deliberations positions these enhanced artificial wetlands as a crucial component of sustainable water governance. An effective and robust wastewater treatment system is essential as worries about pollution and water scarcity grow on a worldwide scale. Drain water is no longer appropriate for reuse due to this violation of water quality requirements. The most common source of pollution for wastewater effluents from homes and businesses is degradable organic matter. As a result, the release of this kind of garbage into watercourses depletes the oxygen in the water body and causes major degradation. The quantity of garbage that is dumped into receiving water bodies far outweighs the bodies' inherent capacity to lessen the pollutants. The drainage water's present quality limits its potential for reuse in various applications. Egypt's drainage water quality is severely contaminated, particularly in the lower Nile Delta region [6]. Farmers and other individuals who eat the contaminated produce face health risks and even death as a result of this particularly in the last 20 years, simple treatment techniques like wetlands have emerged that can lower treatment costs and operational complexity without compromising the level of pollution management. These techniques simply require modest financial resources and are dependable and suitable for the local environment. Numerous studies on built wetlands (CWs) have been prompted by the growing interest in low-cost, effective methods of treating wastewater and dirty water. The physical, biological, and chemical associations amongst wetland components allow for treatment performance in CWs. Constructed wetlands are manmade ecosystems that assist manage wastewater by harnessing the biological processes that occur in wetland plants, soils, and related microbial populations. [7].

2.Constructed Wetlands

Constructed wetlands (CWs) are built systems created to help treat wastewater by leveraging the natural processes found in wetland plants, soils, and associated microbial communities. Many of the same processes that occur in natural wetlands are intended to be utilized by them, but in a more controlled setting. Depending on the dominant macrophyte's life form, CWs for wastewater treatment can be divided into systems with free-floating, floating-leaved, rooted emergent, and submerged macrophytes. While manmade wetlands are occasionally called 'reedbeds', the term reedbed strictly denotes constructed wetlands where reeds are the dominating plant species [8]. This is critical for determining the best form of manmade wetland and improving its design, construction, and upkeep. The types of built wetlands used are determined by the current ecological circumstances and their suitability for residential wastewater, farm wastewater, coal mine drainage, and stormwater. There are two types of constructed wetlands for wastewater regulation: surface flow wetlands and subsurface flow wetlands. Constructed wetlands can be integrated with traditional treatment techniques to increase treatment efficiency. The costs involved with constructed wetlands for wastewater management, followed by a review of the potential benefits of constructed wetlands in urban areas [9]. Constructed wetlands can be classified according to a variety of construction parameters. The three most essential criteria are hydrological (open water surface flow and subsurface flow); macrophytic vegetation form (emergent, submerged, floating-leaved, and free-floating); and flow path in subsurface wetlands (horizontal and vertical). It is feasible to mix various kinds of CWs, resulting in hybrid systems that take benefit of the unique characteristics of each. Many scholars recommend combining multiple kinds of wetland habitats in a certain method to create hybrid built wetlands. Common types include VF-HF systems, HF-VF systems, and VF-VF systems (Table 1) [10].

Wetlands constructed by surface flow are classified as free water surface (FWS) (Figures 1-4). Water runs in shallow channels over the wetland's surface, encouraging interaction between the water and the flora. It is appropriate for removing different kinds of contaminants. Water moves through the zones of wetland vegetation in a horizontal fashion while passing through a porous media layer made of soil or gravel in horizontal subsurface flow (HSSF). This process encourages biological treatment. In vertical flow wetlands, effective nutrient removal and aeration are achieved through water percolating vertically through a planted filter bed [11].

Mixed-use built wetlands are a combination of surface and subsurface flow wetlands. These are used to optimize treatment effectiveness, combining surface and subsurface flow elements. Integrated ponding systems are utilized for improved treatment and storage capacity. Pond systems are combined with artificial wetlands. Treatment wetlands that float (FTWs) like floating vegetable mats to provide extra treatment, vegetation is arranged on platforms that float with the water's surface. Floating reed beds are vegetable islands that float and improve the absorption of contaminants and nutrients. Cutting-edge treatment systems are adding aeration systems to constructed wetlands can improve their oxygen content, microbial activity, and treatment effectiveness. Planted Filters are the systems that make use of particular plant species that have superior capacity to remove pollutants. Upgraded nutrient elimination systems are Algal Turf Scrubber (ATS), including algae culture to improve the removal of nutrients. The introduction of particular microbial cultures to promote pollutant breakdown is known as bio augmentation [12].

2.1. Importance of wastewater treatment:

Wastewater treatment protects the environment by removing harmful chemicals and pollutants. It ensures safe drinking water by eliminating bacteria and contaminants and also prevents disease spread by removing harmful pathogens. The treatment preserves aquatic life by cleaning wastewater. There are different methods to promote sustainable water use through treated water reuse. Wastewater treatment ensures regulatory compliance and encourages responsible water management. It also contributes to community well-being by preventing waterborne illnesses and supporting a healthy environment [13].

2.2 Cost and benefits analysis of CWs for wastewater treatment:

Standards-based environmental regulation is a conventional policy tool that enforces compliance by establishing precise goals for non-compliant activities. Environmental regulation serves as a crucial tool for governments to stimulate technological advancement and enhance the economic and environmental efficiency of businesses. Although legislators continuously update regulations to improve sustainability, severe environmental requirements can impose significant costs on corporations and impede subsequent environmental preservation measures [14]. This exemplifies the escalating strictness of China's wastewater treatment plant (WWTP) emissions requirements and the imperative to enforce a highly rigorous emissions regulation. In 2012, Beijing issued the discharge level of water contaminants for local wastewater treatment plants, classifying the quality of water into four categories (Class AA, Class AB, Class BA, and Class BB), with Class AA being stricter than the Sustainable Diversion Limit (SDL). Adhering to more stringent regulations usually necessitates a greater quantity of energy and resources, resulting in increased expenses and elevated environmental consequences. The implementation of more stringent standards and regulations in China has resulted in a requirement for increased wastewater treatment capacity in Chinese wastewater treatment plants [15].

Constructed wetlands offer a more cost-effective and efficient alternative to conventional wastewater treatment methods, with the added benefit of delivering ecosystem services. Constructed wetlands are employed in more than 50 nations for the sustainable treatment of wastewater. They are extensively utilized in the treatment of tail water in wastewater treatment plants (WWTP) and are increasingly recognized as an engineered system that is more ecologically sound. There were around 150 CWs operating in China in 2020, with each having a treatment capacity of at least 30,000 m3·day−1 [16].

Constructed wetlands are artificial wetland systems that incorporate pollution-resistant wetland flora, substrate, and microorganisms. These components work together to effectively remove nutrients and harmful substances from residual water hybrid constructed wetlands integrate the beneficial aspects of both horizontal flow (HF) and vertical flow (VF) systems for the purification of urban wastewater. The primary objective of the HF component is to eliminate organic materials and facilitate denitrification, whereas the VF component is designed to promote wastewater nitrification by decreasing organic matter levels. The presence of the HF component can function as a buffer to avoid blockage of the VF component, thereby enhancing its ability to undertake nitrification [17]. Constructed wetlands for wastewater treatment involves conducting a thorough assessment of the expenses and advantages to determine the economic feasibility of these environmentally benign systems. The main factor to be taken into account is the initial capital investment, which includes costs for excavation, infrastructure construction, planting, and lining. The size, geographical position, and complex details of the wetland impact the extent of these initial expenses. Maintaining the functionality of CWs involves continuous operating and maintenance costs. Skilled staff are required for monitoring, vegetation maintenance, periodic cleaning, and infrastructure repairs, which increases the operational budget. The price of land suitable for building wetlands is of great importance. The feasibility of CW projects may be affected by the problems posed by land expenses, which can vary according on the region. Energy expenses are another aspect. Certain closed-loop configurations may necessitate energy for tasks like as water circulation or pumping, hence adding to the total operational expenses [18]. Constructed wetlands have advantages that boost like they improve water quality, ecosystems, and biodiversity and naturally filter toxins and promote ecological balance. CWs are often cost-effective in the long run despite upfront investments. Less energy-intensive procedures and lower operational costs can boost long-term profits. In addition to their utilitarian purpose, artificial wetlands are attractive and can be used for enjoyment. These traits can make a location more attractive and improve population welfare. Surface and subsurface flow CWs help industry and municipalities meet environmental standards by providing efficient, sustainable, and compliant wastewater treatment. Water conservation constructed wetlands purify wastewater and reuse it for non-potable uses, reducing freshwater use [19].

2.3 Natural wetlands vs Constructed Wetlands

Wetlands are often defined as regions where the soil remains saturated with water for an extended period of time, allowing particular plants to thrive. In the natural, these areas are like teeming centers of life, with greater biological activity than other sorts of settings. Because of all of this activity, wetlands have an incredible potential to convert contaminants present in wastewater into either innocuous compounds or nutrients that may help feed even more life. These ecosystems often emerge over time as part of the natural flow of things, sort of arranging themselves into this crucial aspect of the environment [20]. The primary distinction between constructed and natural wetlands is the hydrological system. In natural wetlands, the flow inside and outside is determined by seasonal weather conditions and groundwater dynamics. In contrast, in engineered wetlands, the hydraulic state is tightly regulated by inflow transmission headings, outlet collection networks, water level control equipment, and separators. Furthermore, engineered wetlands are designed to eliminate certain contaminants, such as silt, organic debris, and fertilizers. Constructed wetlands are artificial ecosystems that mimic the ability of natural wetlands to filter contaminants from the water. They have been planned and developed to take leverage of many of the procedures involving wetland vegetation, soils, and the related microbial communities to help treat wastewaters produced in natural wetlands [21]. Constructed wetland systems are engineered to use various natural wetland processes, while operating in a highly regulated setting. Constructed wetland also named as manmade, engineered or artificial wetlands. Constructed wetlands offer a higher level of control compared to natural systems, enabling the creation of experimental treatment facilities with precise specifications for substrate composition, vegetation type, and flow pattern. Furthermore, manmade wetlands possess various extra benefits in comparison to natural wetlands, such as the ability to choose the location, adaptability in determining the size, and, most significantly, the capacity to regulate the hydraulic pathways and retention time [22].

Subsurface Flow Constructed Wetlands: In contrast to surface flow wetlands, subsurface flow wetlands direct water from a layer of gravel or soil located below the surface. This stimulates and enhances biological processes, facilitating the decomposition of pollutants. An illustrative instance involves the utilization of gravel beds for the purpose of purifying wastewater [23].

Hybrid Constructed Wetlands: Hybrid built wetlands integrate many forms of created wetlands to produce a greater therapeutic impact. These are generally used to improve nitrogen removal and remediate a variety of commercial and rural wastewaters. Hybrid systems integrate components from both surface and subterranean flow wetlands. These adaptable configurations optimize the advantages of each type to provide effective water treatment. For example, a mixture of exposed water areas and sunken gravel beds can be utilized [24].

***Free water surface constructed wetlands**:* are designed to replicate the characteristics of natural ponds or marshes, enabling unrestricted water flow across the surface. Aquatic plants are quite beneficial in these locations because they remove excess nutrients and purify the water. Consider a typical setup: you have a free water surface constructed wetland (FWSCW), which consists of a shallow basin filled with around 20-30 cm of soil for the plants to root into, and the water above it is only about 20-40 cm deep. There's no need of soil here; it's mostly there to give the plants something to cling onto. As wastewater flows through the wetland, natural processes such as sedimentation, filtration, and chemical reactions help cleanse the water [25].

Integrated Constructed Wetlands (ICWs): An untreated free surface flow artificial wetland with rising vegetation regions and native soil material is called an integrated constructed wetland. In addition to treating wastewater from agricultural land and other resources, its goals include improving the biological richness of the wetland and integrating it into the natural environment. These are designed to include treatment stages such as cleansing and managing within a single wetland region. These stages may encompass several categories as marshes, swamps, bogs, and fens. of wetlands or supplementary technologies. An illustration of this concept is the implementation of a system in which water is directed via a series of surface and subterranean channels to improve its purifying process [26].

Vegetated ditches: are a straightforward and economical method that utilizes plant growth in shallow channels for water treatment. These ditches are useful in agricultural contexts since they aid in the control of runoff and the elimination of pollutants. Wastewater treatment ponds are artificial systems that imitate natural ecosystems and are frequently employed in both municipal and industrial environments. These systems utilize ponds or lagoons where wastewater undergoes natural processes aided by aquatic plants and microbes [27].

3. Sustainable design and operation in constructed wetlands

For decades, constructed wetlands (CWs) have been employed as a green wastewater treatment solution. CWs provide a land-intensive, low-energy, and low-operational-requirement alternative to traditional treatment systems, particularly in small populations and isolated areas. However, long-term viability and effective implementation of these systems still a difficulty. Currently, there is increasing concern about the water environment, including issues such as water scarcity, pollution of water, and the degradation of water resources on a worldwide scale [28]. Furthermore, the scenario is escalating in severity as a result of the compounding impacts of deteriorating environmentally harmful behavior and a substantial population, particularly in developing nations. In the past, conventional centralized sewage treatment systems have been effectively employed for the purpose of water pollution management in the majority of countries. Nevertheless, the implementation of wastewater treatment technologies such as the activated sludge process, membrane bioreactors, and membrane separation is obstructed by their increasing cost and limited practicality for extensive use in rural regions [29]. Sustainable developed wetland design and operation prioritizes ecologically friendly wastewater treatment. Optimization of natural processes, integration of indigenous flora, and biodiversity enhancement are design priorities. Operating sustainability involves optimizing water usage, minimizing energy consumption, and monitoring for long-term efficacy. In addition, they are constrained and inadequate when confronted with increasingly rigorous water and wastewater treatment regulation. However, it is crucial to select cost-effective and highly efficient conventional methods for wastewater treatment, particularly in developing regions. Constructed wetlands are attaining significant attention as a cost-effective and low-maintenance solution for wastewater treatment [30]. Constructed wetlands balance environmental benefits with financial effectiveness, making them a sustainable wastewater treatment option. Water shortages, pollution, and degradation are global water challenges. Due to increasing ecologically unfriendly activities and population growth, especially in developing nations, the situation is worsening. Most countries have successfully controlled water pollution with centralized sewage treatment systems. Activated sludge, membrane bioreactors, and membrane separation are expensive and unsuitable for rural locations. They also fall short of stricter water and wastewater treatment criteria. Choosing low-cost and efficient wastewater treatment technology is important, especially in developing regions. Constructed wetlands are a promising wastewater treatment alternative due to their low cost, operation, and maintenance [31].

4. Plant Selection in constructed wetlands:

Plants in artificial wetlands aid in the removal of nutrients by engaging in processes such as uptake, transformation, and microbial interactions. Choosing plants with strong nutrient uptake ability, such as specific types of *typha* and *phragmites*, can greatly enhance the effectiveness of removing nitrogen and phosphorus. Selection of plant species should be dependent on the site-specific conditions of the created wetland, such as soil type, climate, and hydrology. Indigenous plant species are frequently favoured due to their capacity to adapt and withstand local environmental circumstances [32].

Rhizosphere Processes: The rhizosphere, which refers to the soil surrounding plant roots, plays a crucial role in microbial activities. Rhizosphere microorganisms and their relationships with plants in wetlands are currently attracting a lot of interest due to their role in improving plant environmental adaption, eliminating wetland contaminants, and mitigating the effects of climate change. However, the shifting hydrological environment of wetlands causes additional processes in the rhizosphere habitat. Vetiver grass (*Chrysopogon zizanioides*), a plant with a robust root structure, improves the breakdown of organic pollutants by microorganisms and so enhances the overall effectiveness of treatment [33].

Biodiversity and Habitat Enhancement: The inclusion of a wide variety of plant species fosters biodiversity, resulting in a more robust ecosystem. This not only increases the ecological significance of the wetland, but also aids in the establishment of habitats for diverse species. When selecting plants for urban or public settings, it is important to take into account their aesthetic and recreational value. An aesthetically pleasing and varied plant community has the potential to enhance public image and foster community involvement [34].

Important Factors to Consider when Choosing Plants:

Firstly, choose plants that possess inherent adaptations for survival in aquatic situations. The wetland indicator status can be utilized to identify hydrophytic species that are well suited for waterlogged environments. Secondly, to achieve an optimal coverage of surface area and maintain a balance between open water and vegetated zones, it is important to take into account the growth form (emergent, submerged, or floating) and density of plant species. Thirdly, select plants with life cycles that align with the wetland's operational time and possess the ability to endure variable water levels and seasonal fluctuations [35].

4.1 Plants used in constructed wetlands

Several plant species like *Cyperus papyrus*, *Phragmites australis*, *Typha* and *Scirpus spp* enhance the process of treating wastewater in manmade wetlands. Utilized are cattails, bulrushes, and reeds. These plants aid in the process of purification by absorbing nutrients, filtering silt, and promoting the growth of bacteria. Their broad root systems provide a favorable environment for beneficial microorganisms that decompose organic substances. Aquatic vegetation improves the aesthetic appeal of the wetland and facilitates the harmonization of natural processes with objectives related to wastewater treatment. Contaminant clearance in constructed wetlands is dependent on the interplay between vegetation and microorganisms. Choosing appropriate plant species is essential for optimising system efficiency and ensuring long-term sustainability Physiological adaptations of plants in constructed wetlands (CWs) include the development of aerenchyma and the ability to tolerate anaerobic conditions [36].

4.2 *Plants tolerance to wastewater*

Plants have exceptional resilience to wastewater, highlighting their capacity for phytoremediation, an environmentally friendly method for purifying water. Multiple studies underscore the aptitude of different plant species to flourish in polluted environments, emphasizing their capability to absorb, accumulate, and convert toxins. In a study conducted it was shown that water hyacinth (*Eichhornia crassipes*) is effective in treating wastewater by efficiently eliminating heavy metals and organic pollutants. In addition, Mishra and Malik (2018) highlighted the significance of Vetiver grass (*Chrysopogon zizanioides*) in the process of wastewater treatment, emphasizing that its effectiveness is due to the root system's capacity to store pollutants. In addition, the study conducted by offers valuable information on the molecular mechanisms that contribute to plants' ability to withstand contaminants. It sheds light on the crucial genetic and physiological adaptations involved in this process. Having a comprehensive understanding of the molecular aspects aids in the process of choosing and modifying plants to improve the effectiveness of wastewater treatment [37].

4.3 Capacity of plants in pollution removal

Various plant species have the ability to mitigate environmental pollutants. Wastewater and air cleaning rely on the ability of plants to absorb and metabolize pollutants. Phytoremediation and green infrastructure efforts employ plants as filters to enhance ecological equilibrium and mitigate pollutants. Different plant species exhibit efficacy in absorbing nutrients, accumulating heavy metals, and degrading organic pollutants, hence aiding in the elimination of pollutants in constructed wetlands. Phytoremediation is the process of cleaning up polluted surroundings with plants. Plants can assist clean up a wide range of toxins, such as metals, pesticides, explosives, and oil. But they are most effective when contamination levels are inadequate, as large amounts might impede the development of plants and require a long time to get cleared up. Plant communities in constructed wetlands (CWs) make significant contributions to biodiversity, habitat enhancement, and the overall health of the ecosystem. It is of utmost importance to tackle challenges such as invasive species and climate impacts in order to improve the long-term viability of constructed wetlands [38].

5. Substrate selection in constructed wetlands

Constructed wetlands (CWs) are increasingly recognized as efficient and environmentally-friendly techniques for treating wastewater. The selection of the substrate is vital in maximizing the functioning of these wetlands. The selection of substrate has a significant impact on parameters such as nutrient removal, hydraulic conductivity, and microbial activity. Kadlec and Knight (1996) state that the hydraulic features of constructed wetlands are greatly influenced by the physical parameters of the substrate, such as particle size and porosity. Substrates with a high level of detail generate circumstances without oxygen, which support the removal of nutrients through microbial activities [39]. Substrate selection is an essential concern in CWs for wastewater treatment, and appropriate substrates may efficiently eliminate different contaminants, prevent obstruction, and enhance operating cycle. Challenges to consider when selecting substrate supplies include their origin and expenses, the hydraulic and technology potential, capacity to eliminate pollutants, assistance with development of plants and microbial attachment, security (secondary pollution), substrate obstruction, substrate existence, and reconstruction and elimination of exhausted substrate, among others (Fig). Because there are so many issues to take into account, selecting a substrate has turned into a complicated subject for engineers and researchers [40]. Furthermore, the composition of the substrate has an impact on both plant growth and root development. Using coarse substrates can improve plant establishment and nutrient uptake. In addition, the organic content of the substrate has an impact on the growth of microbial communities, which in turn helps break down organic matter in wastewater. Substrates play a vital role in sewage treatment in artificial wetlands, making up the majority of the volume. They offer structural support and serve as a medium for plants and microorganisms, exerting an impact on the variety and composition of microbial populations [41]. Microorganisms adhere to surfaces and create biofilms by multiplying. Substrates promote the presence of oxygen, enable the release of oxygen by plant roots, and serve as electron donors in denitrification. Pollutant removal is achieved through physical and chemical processes such as filtration, adsorption, and cation exchange. Soluble phosphides undergo interactions with metal cations, resulting in the formation of insoluble phosphates. On the other hand, negatively charged phosphates participate in anion exchange processes. Substrates, which can be obtained from natural sources, industrial or agricultural by-products, or synthesized materials, exhibit different methods of removal. Therefore, it is crucial to choose substrates carefully based on their ability to remove contaminants and the properties of the sewage [42].

5.1 Sorption capacity of substrate

The sorption capacity is a critical quantity in substrate research, since it indicates the substrate's capacity to adsorb and retain chemicals. This feature is indispensable in diverse domains, such as environmental science, agriculture, and material science. The term "sorption" includes both adsorption, which occurs on the surface, and absorption, which occurs within the bulk. The sorption capacity of a material is related to a material's surface chemistry, surface area, and, if applicable, its pore size distribution. The sorption properties of a material can inform on all these properties, as well as develop a key understanding of a material's performance, lifespan, and activity [43]. Activated carbon is a substrate commonly used in environmental applications due to its ability to effectively absorb contaminants. Due to their ability to eliminate impurities through both physical and chemical interactions, they are highly efficient in water and air purification procedures. Soil substrates are crucial in agriculture as they are responsible for retaining nutrients necessary for plant growth. The nutrient availability in soils is impacted by the sorption capacity, which can be modified by various factors, including the organic matter concentration. Material science investigates the sorption abilities of different materials, such as polymers used in drug delivery systems and zeolites used in gas separation applications [44].

6. Water Depth

The depth of water is a crucial component that significantly affects the ecological dynamics of wetlands. It plays a fundamental role in determining their richness and overall functioning. The characteristic in question is a variable one that changes both seasonally and regionally. This characteristic has an impact on the suitability of the habitat for different types of plants and animals. Researchers from several fields have thoroughly explored the complex correlation between water depth and wetland habitats [45].

The significance of water depth in wetland hydrology and its impact on nitrogen cycling. The authors emphasize that different water depths in wetlands give rise to specific zones, which in turn support a wide range of ecological niches. Mitsch and Gosselink emphasize the importance of changes in water depth for maintaining wetland plant populations. Brinson (1993) states that water depth is a crucial component that determines wetland classification and delineation. Brinson's extensive research underscores the importance of using water depth parameters to ensure precise wetland classification [46]. In addition, Mitsch and Wilson (1996) explore the ecological ramifications of modified water depths, examining how human actions such as drainage and water diversion might disturb the intricate equilibrium within wetland ecosystems. Their observations emphasize the necessity of implementing sustainable water management strategies in order to protect the ecological soundness of wetlands. The acknowledgment of water depth as a crucial factor has practical consequences for the management and preservation of wetlands [47].

7. Hydraulic load and retention time

The increasing prevalence of constructed wetlands (CWs) designed to enhance water quality globally, it is evident that this technology has become firmly established. An analysis of studies conducted since the early 1950s reveals that wetlands have been widely utilized as a means to enhance water quality by treating various types of domestic, agricultural, and industrial wastewater, including secondary treated effluents The systems are meant to replicate natural wetlands with a high level of control, using ecological engineering techniques. This enables the creation of treatment facilities in the field that have a certain composition of substrate, vegetation species, and flow pattern. The primary mechanisms responsible for removing or altering a significant portion of the nutrient and waste content in water flowing through constructed wetlands are microbial decomposition and adsorption by plants. [48]. The effectiveness and efficiency of treatment in a constructed wetland (CW) system are determined by a variety of variables, such as plant species or combinations, hydrology, landscape sequence, location-specific designs (system shape, size, and depth), substrate features, and operating methods. An effective design for a manmade wetland should be able to control the hydraulics, namely the hydraulic loading rates (HLR) and hydraulic retention time (HRT). These variables have a direct effect on the wetland's treatment effectiveness [49]. The hydraulic retention time (HRT) is calculated based on the average surface area of the wetland system (A), the depth of flow (y), and the porosity of the substrate (p), which represents the available space for water to pass through the media, roots, and other matters in the constructed wetland Research indicates that reducing the hydraulic loading in a CW system typically enhances the effectiveness of pollution treatment. Furthermore, a longer hydraulic retention time (HRT) leads to increased removal of nutrients. The optimal duration of hormone replacement therapy (HRT) is documented to vary between 4 and 15 days. A brief hormone replacement therapy (HRT) lasting 3-6 days successfully eliminated pathogenic germs and viruses [50].

A significant limitation for field-scale constructed wetland (CW) systems is the need for a somewhat expansive land area that is not easily approachable. However, there are no established criteria for building a constructed wetland (CW) system, unlike conventional biological treatment systems. The evaluation of various design parameters for different climatic zones has not been conducted for factors of a constructed wetland (CW), such as the selection of plant species based on their treatment efficiency with respect to the type of wastewater, or the variations in hydraulic loading and hydraulic retention time. Reducing the duration of HRTs results in a decreased need for land, which improves the likelihood of CW systems being accepted in developing nations such as India. Consequently, research has been undertaken to identify the most suitable design variables for the subtropical monsoonal environment of India [48]. The CW technique is widely recognized as a better alternative to conventional wastewater treatment procedures; nonetheless, there has been limited adoption of this technique in India. The majority of India's CW system expertise has been gained through small-scale experimentation, with an emphasis on wastewater treatment. This entails treating the secondary effluents from a Delhi milk processing business using a vertical subsurface flow (VSSF) designed wetland system. An investigation contrasting the effectiveness of three frequently used wetland plants (*Typha angustata, Phragmites karka, and Scirpus littoralis)* at a constant Hydraulic Retention Time (HRT) of 3 days revealed notable variations. The results indicated that T. angustata was more effective in treatment compared to the other two plants [51].

8. Use of best soil for constructed Wetlands

Selecting the appropriate soil for constructed wetlands is crucial for their effectiveness. Wetland soils now utilized for reclaimed wastewater disposal were subjected to laboratory trials to ascertain their potential for removing (reducing) nitrate ions. Soil samples from the surface were gathered and placed in a controlled environment without oxygen. Two different quantities of nitrate ions were added to the samples, and the release of nitrous oxide gas was monitored over a period of time. The denitrification rates varied between 0.06 and 0.92 grams of nitrogen per square meter per day, when 10 milligrams of nitrate-nitrogen per kilogram of oil was introduced [52]. The soils obtained from two built wetlands (mineral soils) and one natural wetland (organic soil) underwent complete conversion of NO_3 to N_2. Nevertheless, the ultimate reduction process was impeded in the soils obtained from two wetlands with organic soils. The inhibition is likely due to the reduced acidity (pH) of these soils. The findings indicate that the inclusion of wastewater increases the capacity for denitrification in these soils. More accessible aluminum in the soil may be used to remove more phosphorus from the soil than organic soils can, which makes them more suitable for wastewater treatment wetland, particularly organic soils might be better suited for an acid drainage treatment wetland to enhance sulfate reduction and ionic adsorption [20].

9. Future consideration on the sustainability of CWs

In contemplating the future sustainability of constructed wetlands, several critical conditions emerge. CWs must adapt to changing climate conditions. There is need for resilient design and management strategies to address the possible effects of climate change on the effectiveness of CW Developing plans for ongoing maintenance and management to prevent degradation of wetland functions over time, including sedimentation management, invasive species control, and infrastructure upkeep. Incorporating innovative technologies can enhance CW efficiency. According to Vymazal (2018), ongoing research on novel substrates, vegetation, and monitoring techniques can significantly improve treatment performance and longevity [53]. Continuous monitoring also enables adaptive management strategies, allowing intervention to be implemented promptly in response to change conditions. As pollution levels and the diversity of contaminants in wastewater evolve, constructed wetlands must be capable of treating a wide range of pollutants effectively. Continuous monitoring and adaptive management strategies are essential to ensure that wetlands remain effective in maintaining water quality. Recognizing and optimizing the multiple ecosystem services provided by CWs is crucial. Highlight the importance of maintaining biodiversity within CWs to maximize their ecological functions and overall sustainability [54]. Effective policies and governance structures are vital for the widespread adoption and continued success of CWs. Insights from stress the need for supportive regulations, incentives, and public awareness to foster CW sustainability. Applying life cycle assessment (LCA) to CW projects aids in identifying and mitigating environmental impacts. The importance of LCA in evaluating the overall sustainability of CWs from construction to decommissioning. Biodiversity Conservation: Constructed wetlands provide important habitats for a forms of plant and animal species. Maintaining and enhancing biodiversity within wetland ecosystems is crucial for their long-term sustainability. This may involve planting native vegetation, controlling invasive species, and creating diverse microhabitats. Resource Management: Constructed wetlands require careful managing resources such as water, energy, and nutrients. Implementing water conservation measures, utilizing renewable energy sources, and optimizing nutrient cycling can enhance the sustainability of wetland systems [55].

10. Challenges and Future Scope

Constructed wetlands show great potential for wastewater treatment, however they face challenges and present opportunities for future advancements. The effectiveness of manmade wetlands can fluctuate due to factors such as climate, substrate composition, and hydraulic loading. These factors cause variability in their performance. In contrast to temperate and humid regions, CW activities may be different under the current climate, which may have an impact on the services provided by ecosystems that can be predicted. The primary behavioral shift is a result of increased evapotranspiration during wind and air movement, which can reach 40% and upset the equilibrium of water in these systems, potentially leading to greater saline levels. In hot and arid areas, transpiration is said to cause greater water losses in wetland systems than open water evaporation. This indicates that water losses through evapotranspiration should be kept to a minimum if treated wastewater reuse is taken into consideration [56]. Constructed wetlands require sufficient land area for construction and operation. Finding suitable sites for wetland development, especially in densely populated or urban areas, can be a significant challenge.

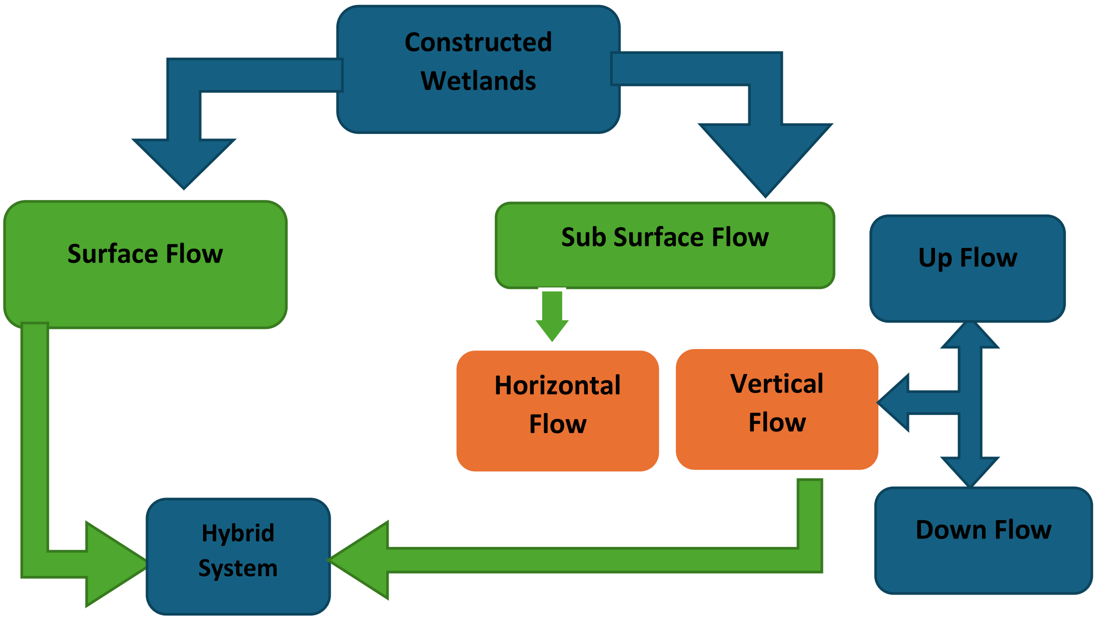
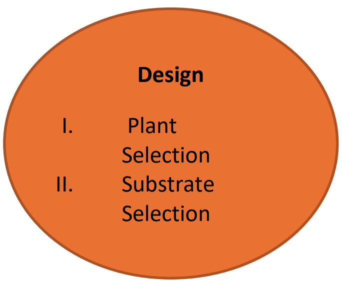


Figure 1: Types of constructed wetlands

Table 1: Classification of constructed wetlands and their removal efficiency

Wetland Type	**Removal Efficiency %**						
	COD	**BOD**	**TSS**	**TW**	**NH_4 N**	**NO_3N**	**TP**
Vertical Flow	-	98	95	46	83	-	61
Horizontal Flow	87	78	85	45	47	33	42
Free wetland surface	-	-	-	43	57	60	48
Vertical Flow - Horizontal Flow	81- 90	85 - 96	79 - 99	64	77 - 87	-	64 -88
Horizontal Flow - Vertical Flow	77 -95	88 -97	81 - 98	60 -85	79 -98	-	69 98
Vertical Flow - Vertical Flow	72 -94.8	96.5 -97.5	92.5	45 -86	66 - 98.7	75	76 - 92.8
Horizontal Flow - Free Wetland Surface	85	95	71	82	85	-	99
Free Wetland surface - Horizontal Flow	24 - 54	26 - 56	48 - 87	96 -99	58 -95	69 - 95	33 - 72
Horizontal Flow - Vertical Flow - Horizontal Flow	68	67	-	84	-	84	62
Vertical Flow - Horizontal Flow - Vertical Flow	99	99	-	-	87	51	88
Horizontal Flow - Free Wetland Surface – Horizontal Flow	86	-	90	-	84	-	65
Vertical Flow - Horizontal Flow – Free Wetland Surface	99	98	90	83	-	-	73



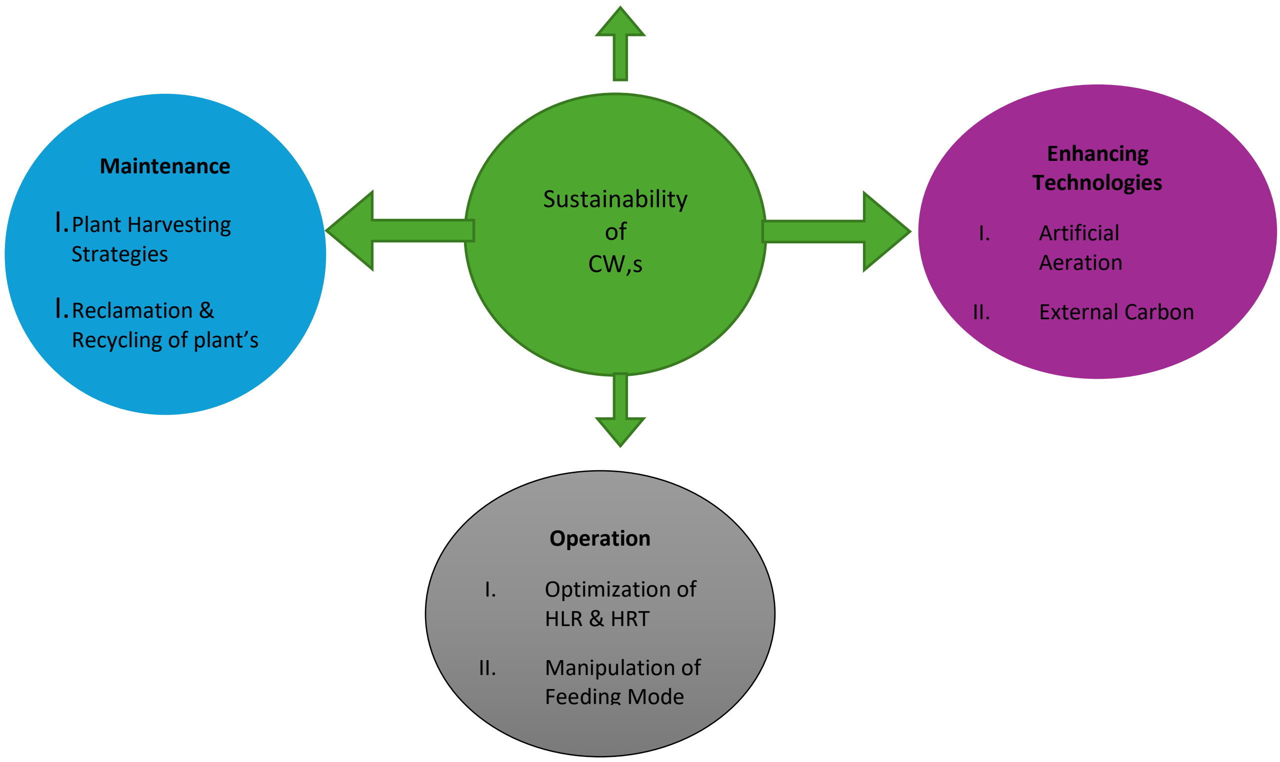


Figure 2: Sustainability of constructed wetlands

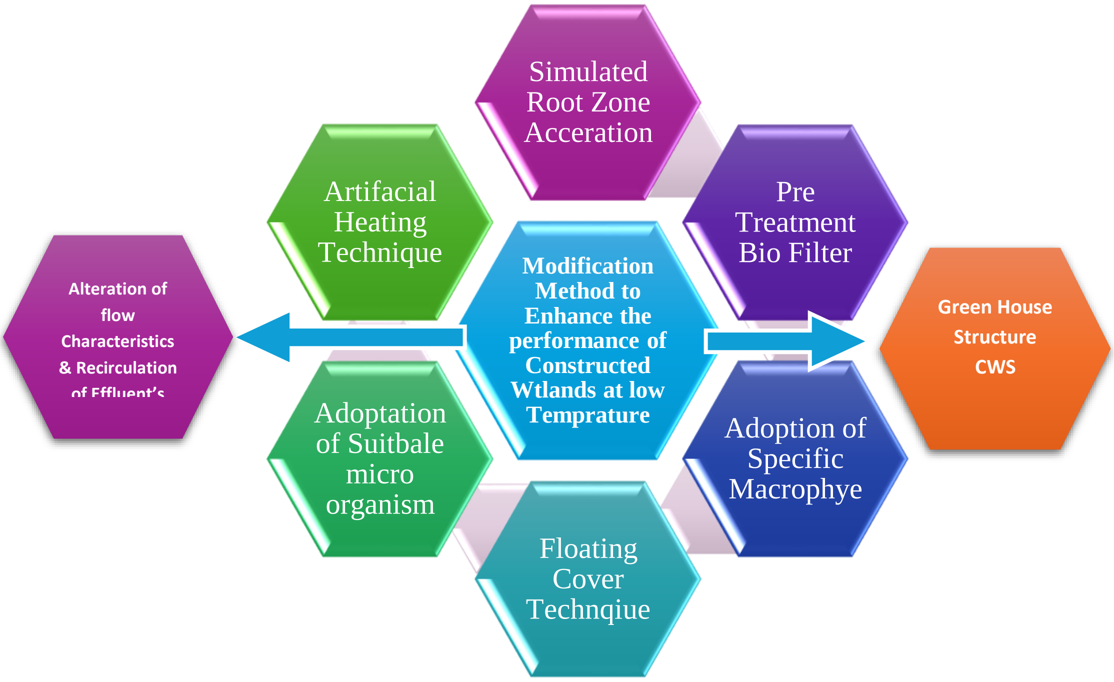


Figure 3: Modification methods to enhance the performance of constructed wetlands at low temperature

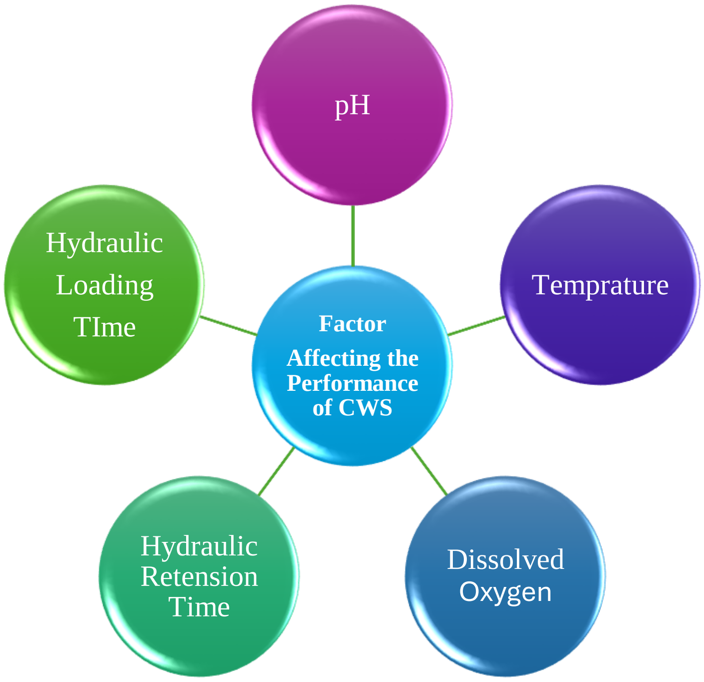


Figure 4: Factors Effecting the performance of constructed wetlands

Traditional engineered wetland designs may not successfully remove certain contaminants, such as medicines and heavy metals. Urbanization and the scarcity of land provide difficulties in implementing large-scale built wetlands. This requires the development of creative designs to incorporate them into urban environments. Long-term sustainability necessitates careful evaluation of maintenance requirements and the possibility for long-term performance degradation caused by variables such as blockage and plant die-off [7]. Exploring innovative substrate materials that provide superior adsorption and filtration capabilities has the potential to boost the effectiveness of removing contaminants. Integrating manmade wetlands with green infrastructure elements such as rain gardens can enhance the use of space in municipal environments. The integration of sensor technologies and real-time monitoring can improve control and optimize performance in engineered wetland systems. Genetic modification of wetland plants can enhance their ability to absorb pollutants and make them more resilient, hence expanding the range of toxins that can be efficiently remediated. Future advancements should incorporate policy frameworks that promote the extensive implementation of artificial wetlands for the purpose of sustainable water management [57].

11. Modification to enhance constructed wetlands at low temperature

Low temperatures can significantly impact constructed wetlands performance by slowing down microbial activity, reducing the efficiency of biological processes, and limiting the breakdown of contaminants. The decreased metabolic rates of microorganisms at lower temperatures result in a slower removal of pollutants, potentially leading to decreased treatment efficiency and longer retention times. Additionally, cold temperatures can affect plant growth and root development, which are essential for stabilizing the wetland structure and enhancing nutrient uptake. In some cases, ice formation may occur, causing physical damage to the wetland components and further impeding treatment processes. Overall, the impact of low temperatures underscores the importance of considering climate conditions and implementing appropriate design modifications to maintain optimal performance in constructed wetland systems [58]. To increase constructed wetlands performance at low temperatures, several modifications and strategies can be implemented such as increasing the surface area of the wetland can help maximize exposure to sunlight, which in turn can raise the temperature within the wetland and stimulate microbial activity. Providing insulation around the wetland components, such as the substrate and pipes, can help minimize heat loss and maintain warmer temperatures within the system. Install solar heating systems to supplement warmth during colder periods. Solar panels can absorb sunlight and convert it into heat energy, which can be used to warm the water within the wetland cells, thereby supporting microbial activity and treatment processes [59]. Choose plant species that are resilient to low temperatures and can continue to grow and contribute to the treatment process even in colder climates. Species like hardy grasses, rushes, and sedges are often more tolerant of cold temperatures and can thrive in such conditions. Introduce aeration and mixing mechanisms to enhance oxygen transfer and circulation within the wetland cells. Aeration systems can prevent the development of anaerobic conditions, which can inhibit microbial activity and treatment efficiency in cold climates [60]. Monitor and regulate pH levels within the constructed wetland system. Cold temperatures can influence pH levels, potentially affecting microbial activity and nutrient availability. Adding buffering agents or alkalinity supplements can help stabilize pH levels and maintain optimal conditions for treatment processes. Conduct regular maintenance activities to keep the constructed wetland system in optimal condition. This includes removing debris, sediment, and ice buildup that may obstruct flow or impede treatment processes. Regular inspections and monitoring of water quality parameters can also help identify and address any issues promptly [61].

12. Wetlands improve quality of water

Wetlands are essential for improving water quality by using a variety of physical, chemical, and biological mechanisms. These distinct ecosystems function as natural filters, enhancing water quality in diverse manners. Wetlands function as innate absorbers, capturing sediments and suspended particles from water as it traverses through. This procedure facilitates the reduction of cloudiness and the elimination of contaminants such as toxic metals and essential nutrients. Wetlands exhibit high efficiency in the elimination of surplus nutrients, such as nitrogen and phosphorus, from water. The microbial activity occurring in wetland soils converts and incorporates these nutrients, so avoiding their discharge into water bodies downstream [62]. Wetland-dwelling aquatic plants enhance water quality by absorbing and incorporating contaminants through a process known as biological uptake. Phytoremediation is a method that aids in the elimination of toxins, such as pesticides and organic pollutants. Microbial transformation refers to the important function that microorganisms in wetland soils have in breaking down and detoxifying different contaminants. This is achieved through processes including denitrification and biodegradation transformation refers to the important function that microorganisms in wetland soils have in breaking down and detoxifying different contaminants. Ultimately, wetlands function as natural water filters, employing a blend of physical, chemical, and biological processes to intensify the quality of water. Comprehending and conserving these ecosystems are crucial for the sustainable management of water [63].

12. Application of CWs for wastewater treatment

Wastewater treatment filters contaminants naturally via artificial wetlands (CWs). Planting appropriate plants reduces contaminants in wastewater treatment systems biologically, physically, and chemically. CWs improve water quality, habitat, and environmental compliance sustainably and cheaply. They clean storm water, industrial, and municipal wastewater. Wetlands have many benefits, including flood mitigation, habitat restoration and the treatment of both wastewater and stormwater to within National Pollutant Discharge Elimination System (NPDES) limits. They are a form of green infrastructure that is both effective and ecologically friendly. Wetlands have many ecological benefits. Full of natural vegetation and rich soil, wetlands provide habitat for birds, amphibians, fish, insects and more. Their natural sedimentation, filtration and biological activity treat the water within the wetland. In addition to these treatment capabilities, they serve as temporary storage to reduce flooding on downstream creeks, streams, rivers and properties during wet weather events [64].

13. Limitations of Constructed Wetlands

The effectiveness of constructed wetlands is influenced by climate conditions. Extreme temperatures, prolonged droughts, or heavy rainfall can impact the treatment efficiency, potentially leading to system overload or underperformance. Constructed wetlands necessitate significant land areas for optimal functioning. In urban settings where land is limited and expensive, this can be a critical drawback. Constructed wetlands may take several years to reach their full treatment potential due to the time required for microbial and plant communities to establish and stabilize [65]. The efficiency of nutrient removal, a key function of constructed wetlands, can vary depending on components such as vegetation form, hydraulic loading rates, and influent nutrient concentrations. While constructed wetlands excel at removing organic matter and nutrients, they may be less effective for certain contaminants like heavy metals or pathogens. Regular maintenance is crucial for sustained performance. Issues such as clogging, invasive species encroachment, and sediment accumulation can undermine the efficiency of the system. Constructed wetlands may not be suitable for large-scale industrial applications or densely populated areas with high wastewater volumes, limiting their applicability in certain contexts [66].

14. Constructed wetlands merits and demerits

Constructed wetlands have gained recognition as an environmentally friendly approach for wastewater treatment. This method mimics the natural processes that take place in wetlands, utilizing vegetation, soil, and microbes to purify water. While constructed wetlands offer several merits, they also present certain demerits that warrant consideration. Constructed wetlands excel in removing pollutants like nutrients, suspended matter, and various pollutants from wastewater, providing an efficient treatment option. Compared to traditional wastewater treatment plants, constructed wetlands generally have lower operational and maintenance costs, making them a cost-effective solution. These systems foster biodiversity by creating habitats for diverse plant and animal species, contributing to ecological restoration and conservation [67]. An innovative and environmentally friendly replacement for the existing methods of treating wastewater is the construction of artificial wetlands. However, there are still a lot of issues and restrictions because these systems are still relatively new to be used and the technology surrounding them is still in its infancy. Because constructed wetlands require large tracts of land, they are not practical in highly populated or metropolitan locations where property is expensive and in short supply. Performance may be influenced by climatic conditions, with extreme temperatures affecting microbial activity and consequently treatment efficiency. Constructed wetlands often require an extended start-up period for microbial communities to establish, delaying the full functionality of the system [68].

15. Conclusions

Ultimately, constructed wetlands employ natural mechanisms to enhance the quality of water and serve as environmentally benign and economically efficient alternatives for treating wastewater. Surface flow, subsurface flow, and hybrid constructed wetlands are suitable for different treatment requirements. Wetlands enhance the environment, promote water conservation, ensure regulatory compliance, and support sustainable design. For the economic feasibility of constructed wetlands, it is important to take into account the initial capital investment, operational expenses, land expenses, and energy requirements. Constructed wetland systems are attractive because of their enduring advantages and reduced operational expenses. They enhance biodiversity, visual appeal, and community welfare while effectively managing wastewater. Constructed wetland play a critical role in addressing water and sanitation challenges in undeveloped nations, where access to clean water is a critical public health concern. CW's ability to supply cost-effective and efficient wastewater treatment technology for sustainable water management is made possible by their resilient facilities and optimized design and operation. To achieve optimal removal of CW pollutants, it is essential to carefully choose the plants, substrates, and design parameters. Optimal performance relies on key factors such as plant adaptability, substrate sorption capacity, water depth, hydraulic load, and retention period. Manmade wetlands face challenges despite their inherent potential. In order to achieve widespread application, it is crucial to address factors such as land availability, treatment capacity, maintenance, and climate sensitivity. To overcome these restrictions and boost the usage of CW in different situations, the implementation of improvements, advanced monitoring systems, and strategies that are resilient to climate conditions may be beneficial. Constructed wetlands come up with a natural and effective method for treating wastewater, which enhances environmental sustainability and presents an alternative to current procedures. Conservation workers can further enhance water quality, mitigate pollution, and advocate for sustainable water management by tackling pertinent challenges and embracing forthcoming advancements.

References:

[1] J. Vymazal. (2011). Constructed wetlands for wastewater treatment: five decades of experience. Environmental science & technology. 45(1): 61-69.

[2] R. Shaheen, M.A. Hanif, S. Ali, R.W.K. Qadri. (2023). Screening of various hybrid composite materials for removal of extremely toxic acid yellow dye from wastewater. Desalination and Water Treatment. 312: 218-233.

[3] R. Shaheen, M.A. Hanif. (2024). Nanocomposite materials for decontamination of highly toxic acid dye from aqueous streams. International Journal of Environmental Analytical Chemistry. 1-15.

[4] R. Shaheen, M.A. Hanif. (2024). High speed removal of toxic acid red dye using photocatalytic-hybrid composite material. Desalination and Water Treatment. 100153.

[5] S. Wu, P. Kuschk, H. Brix, J. Vymazal, R. Dong. (2014). Development of constructed wetlands in performance intensifications for wastewater treatment: a nitrogen and organic matter targeted review. Water research. 57: 40-55.

[6] A. El Hawary, M. Shaban. (2018). Improving drainage water quality: Constructed wetlands-performance assessment using multivariate and cost analysis. Water Science. 32(2): 301-317.

[7] J. Vymazal, Y. Zhao, Ü. Mander. (2021). Recent research challenges in constructed wetlands for wastewater treatment: A review. Ecological Engineering. 169: 106318.

[8] J. Vymazal, Constructed Wetlands for Wastewater Treatment. In 2018.

[9] D. Parde, A. Patwa, A. Shukla, R. Vijay, D.J. Killedar, R. Kumar. (2021). A review of constructed wetland on type, treatment and technology of wastewater. Environmental Technology & Innovation. 21: 101261.

[10] J. Nivala, T. Headley, S. Wallace, K. Bernhard, H. Brix, M. van Afferden, R.A. Müller. (2013). Comparative analysis of constructed wetlands: The design and construction of the ecotechnology research facility in Langenreichenbach, Germany. Ecological Engineering. 61: 527-543.

[11] S.G. Abdelhakeem, S.A. Aboulroos, M.M. Kamel. (2016). Performance of a vertical subsurface flow constructed wetland under different operational conditions. Journal of Advanced Research. 7(5): 803-814.

[12] H. Ilyas, E.D. van Hullebusch. (2020). Performance comparison of different types of constructed wetlands for the removal of pharmaceuticals and their transformation products: a review. Environmental Science and Pollution Research. 27(13): 14342-14364.

[13] J.A. Silva. (2023). Wastewater Treatment and Reuse for Sustainable Water Resources Management: A Systematic Literature Review. Sustainability. 15(14): 10940.

[14] J.D. Resende, M.A. Nolasco, S.A. Pacca. (2019). Life cycle assessment and costing of wastewater treatment systems coupled to constructed wetlands. Resources, Conservation and Recycling. 148: 170-177.

[15] J. Qu, H. Wang, K. Wang, G. Yu, B. Ke, H.-Q. Yu, H. Ren, X. Zheng, J. Li, W.-W. Li. (2019). Municipal wastewater treatment in China: Development history and future perspectives. Frontiers of Environmental Science & Engineering. 13: 1-7.

[16] Q. Zhang, W. Yang, H. Ngo, W. Guo, P. Jin, M. Dzakpasu, S. Yang, Q. Wang, X. Wang, D. Ao. (2016). Current status of urban wastewater treatment plants in China. Environment international. 92: 11-22.

[17] C.-B. Hsu, H.-L. Hsieh, L. Yang, S.-H. Wu, J.-S. Chang, S.-C. Hsiao, H.-C. Su, C.-H. Yeh, Y.-S. Ho, H.-J. Lin. (2011). Biodiversity of constructed wetlands for wastewater treatment. Ecological Engineering. 37(10): 1533-1545.

[18] S.A.A.A.N. Almuktar, S.N. Abed, M. Scholz. (2018). Wetlands for wastewater treatment and subsequent recycling of treated effluent: a review. Environmental Science and Pollution Research. 25(24): 23595-23623.

[19] A. Stefanakis, Constructed Wetlands: Description and Benefits of an Eco-Tech Water Treatment System. In 2016; pp 281-303.

[20] G. Ansola, P. Arroyo, L.E.S. de Miera. (2014). Characterisation of the soil bacterial community structure and composition of natural and constructed wetlands. Science of the Total Environment. 473: 63-71.

[21] B. Adrados, O. Sánchez, C.A. Arias, E. Becares, L. Garrido, J. Mas, H. Brix, J. Morató. (2014). Microbial communities from different types of natural wastewater treatment systems: vertical and horizontal flow constructed wetlands and biofilters. Water research. 55: 304-312.

[22] J. Vymazal. (2010). Constructed wetlands for wastewater treatment. Water. 2(3): 530-549.

[23] M.M.P. Villar, E.R. Domínguez, F. Tack, J.M.H. Ruiz, R.S. Morales, L.E. Arteaga. (2012). Vertical Subsurface Wetlands for Wastewater Purification. Procedia Engineering. 42: 1960-1968.

[24] J. Vymazal. (2013). The use of hybrid constructed wetlands for wastewater treatment with special attention to nitrogen removal: A review of a recent development. Water research. 47.

[25] Ü. Mander, J. Tournebize, K. Kasak, W.J. Mitsch. (2014). Climate regulation by free water surface constructed wetlands for wastewater treatment and created riverine wetlands. Ecological Engineering. 72: 103-115.

[26] O. Donde Oscar, N. Atalitsa Caren, Constructed Wetlands in Wastewater Treatment and Challenges of Emerging Resistant Genes Filtration and Reloading. In *Inland Waters*, Adam, D.,Jiayi, P.,Mohammad Manjur, S., Eds. IntechOpen: Rijeka, 2020; p Ch. 6.

[27] S. Zhang, F. Liu, Z. Huang, R. Xiao, H. Zhu, J. Wu. (2020). Are vegetated drainage ditches effective for nitrogen removal under cold temperatures? Bioresource technology. 301: 122744.

[28] N. Pavlineri, N.T. Skoulikidis, V.A. Tsihrintzis. (2017). Constructed floating wetlands: a review of research, design, operation and management aspects, and data meta-analysis. Chemical Engineering Journal. 308: 1120-1132.
[29] S. Gupta, Y. Mittal, R. Panja, K.B. Prajapati, A.K. Yadav. (2021). Conventional wastewater treatment technologies. Current Developments in Biotechnology and Bioengineering. 47-75.
[30] H. Wu, J. Zhang, H.H. Ngo, W. Guo, Z. Hu, S. Liang, J. Fan, H. Liu. (2015). A review on the sustainability of constructed wetlands for wastewater treatment: design and operation. Bioresource technology. 175: 594-601.
[31] J.T. Watson, J.A. Hobson, Hydraulic design considerations and control structures for constructed wetlands for wastewater treatment. In *Constructed wetlands for wastewater treatment*, CRC Press: 2020; pp 379-391.
[32] M. Sanjrani, B. Zhou, H. Zhao, Y. Zheng, Y. Wang, S. Xia. (2020). TREATMENT OF WASTEWATER WITH CONSTRUCTED WETLANDS SYSTEMS AND PLANTS USED IN THIS TECHNOLOGY-A REVIEW. Applied Ecology & Environmental Research. 18(1).
[33] F. Rehman, A. Pervez, B.N. Khattak, R. Ahmad. (2017). Constructed wetlands: perspectives of the oxygen released in the rhizosphere of macrophytes. CLEAN–Soil, Air, Water. 45(1).
[34] R. Delahay, D. Sherman, B. Soyalan, K. Gaston. (2023). Biodiversity in residential gardens: a review of the evidence base. Biodiversity and Conservation. 32: 1-25.
[35] R. Temmink, M. Dorenbosch, L. Lamers, A. Smolders, W. Rip, W. Lengkeek, K. Didderen, G. Fivash, T. Bouma, T. Heide. (2021). Growth forms and life-history strategies predict the occurrence of aquatic macrophytes in relation to environmental factors in a shallow peat lake complex. Hydrobiologia. 848.
[36] J. Vymazal. (2011). Plants used in constructed wetlands with horizontal subsurface flow: a review. Hydrobiologia. 674(1): 133-156.
[37] P. Sharma, H.H. Ngo, S. Khanal, C. Larroche, S.-H. Kim, A. Pandey. (2021). Efficiency of transporter genes and proteins in hyperaccumulator plants for metals tolerance in wastewater treatment: Sustainable technique for metal detoxification. Environmental Technology & Innovation. 23: 101725.
[38] C. Macci, E. Peruzzi, S. Doni, R. Iannelli, G. Masciandaro. (2015). Ornamental plants for micropollutant removal in wetland systems. Environmental Science and Pollution Research. 22: 2406-2415.
[39] C. Yang, X. Zhang, Y. Tang, Y. Jiang, S. Xie, Y. Zhang, Y. Qin. (2022). Selection and optimization of the substrate in constructed wetland: A review. Journal of Water Process Engineering. 49: 103140.
[40] Y. Wang, Z. Cai, S. Sheng, F. Pan, F. Chen, J. Fu. (2020). Comprehensive evaluation of substrate materials for contaminants removal in constructed wetlands. Science of the Total Environment. 701: 134736.
[41] N. Ortiz-Delvasto, P. Garcia-Ibañez, R. Olmos-Ruiz, G. Bárzana, M. Carvajal. (2023). Substrate composition affects growth and physiological parameters of blueberry. Scientia Horticulturae. 308: 111528.
[42] M.J. Shahid, A.A. AL-surhanee, F. Kouadri, S. Ali, N. Nawaz, M. Afzal, M. Rizwan, B. Ali, M.H. Soliman. (2020). Role of Microorganisms in the Remediation of Wastewater in Floating Treatment Wetlands: A Review. Sustainability. 12(14): 5559.
[43] X. Wang, Y. Tian, X. Zhao, C. Peng. (2017). Hydrological performance of dual-substrate-layer green roofs using porous inert substrates with high sorption capacities. Water Science and Technology. 75(12): 2829-2840.
[44] S. De Gisi, G. Lofrano, M. Grassi, M. Notarnicola. (2016). Characteristics and adsorption capacities of low-cost sorbents for wastewater treatment: A review. Sustainable Materials and Technologies. 9: 10-40.
[45] S. Alikhani, P. Nummi, A. Ojala. (2021). Urban Wetlands: A Review on Ecological and Cultural Values. Water. 13(22): 3301.
[46] M. Brinson, Classification of Wetlands. In 2011; pp 95-113.
[47] R.H. Kadlec. (2016). Large constructed wetlands for phosphorus control: A review. Water. 8(6): 243.
[48] Y. Zhao, B. Ji, R. Liu, B. Ren, T. Wei. (2020). Constructed treatment wetland: Glance of development and future perspectives. Water Cycle. 1: 104-112.
[49] H. Ejhed, J. Fång, K. Hansen, L. Graae, M. Rahmberg, J. Magnér, E. Dorgeloh, G. Plaza. (2018). The effect of hydraulic retention time in onsite wastewater treatment and removal of pharmaceuticals, hormones and phenolic utility substances. Science of the Total Environment. 618: 250-261.
[50] M. Hickey, J. Elliott, S.L. Davison. (2012). Hormone replacement therapy. Bmj. 344.
[51] S. Aslanzadeh, K. Rajendran, M.J. Taherzadeh. (2014). A comparative study between single- and two-stage anaerobic digestion processes:

Effects of organic loading rate and hydraulic retention time. International Biodeterioration & Biodegradation. 95: 181-188.
[52] J. Li, B. Zheng, X. Chen, Z. Li, Q. Xia, H. Wang, Y. Yang, Y. Zhou, H. Yang. (2021). The Use of Constructed Wetland for Mitigating Nitrogen and Phosphorus from Agricultural Runoff: A Review. Water. 13(4): 476.
[53] V.K. Gupta, I. Ali, T.A. Saleh, A. Nayak, S. Agarwal. (2012). Chemical treatment technologies for waste-water recycling—an overview. Rsc Advances. 2(16): 6380-6388.
[54] A.I. Stefanakis. (2019). The role of constructed wetlands as green infrastructure for sustainable urban water management. Sustainability. 11(24): 6981.
[55] M. Garfí, L. Flores, I. Ferrer. (2017). Life cycle assessment of wastewater treatment systems for small communities: activated sludge, constructed wetlands and high rate algal ponds. Journal of Cleaner Production. 161: 211-219.
[56] D.A. Beebe, J.W. Castle, F. Molz, J.H. Rodgers Jr. (2014). Effects of evapotranspiration on treatment performance in constructed wetlands: Experimental studies and modeling. Ecological Engineering. 71: 394-400.
[57] D. Meyer, F. Chazarenc, D. Claveau-Mallet, U. Dittmer, N. Forquet, P. Molle, A. Morvannou, T. Pálfy, A. Petitjean, A. Rizzo. (2015). Modelling constructed wetlands: Scopes and aims–a comparative review. Ecological Engineering. 80: 205-213.
[58] M. Varma, A.K. Gupta, P.S. Ghosal, A. Majumder. (2021). A review on performance of constructed wetlands in tropical and cold climate: Insights of mechanism, role of influencing factors, and system modification in low temperature. Science of the Total Environment. 755: 142540.
[59] M.J. Osland, N.M. Enwright, R.H. Day, C.A. Gabler, C.L. Stagg, J.B. Grace. (2016). Beyond just sea-level rise: Considering macroclimatic drivers within coastal wetland vulnerability assessments to climate change. Global Change Biology. 22(1): 1-11.
[60] C.A. Gabler, M.J. Osland, J.B. Grace, C.L. Stagg, R.H. Day, S.B. Hartley, N.M. Enwright, A.S. From, M.L. McCoy, J.L. McLeod. (2017). Macroclimatic change expected to transform coastal wetland ecosystems this century. Nature Climate Change. 7(2): 142-147.
[61] M. Garfí, A. Pedescoll, E. Bécares, M. Hijosa-Valsero, R. Sidrach-Cardona, J. García. (2012). Effect of climatic conditions, season and wastewater quality on contaminant removal efficiency of two experimental constructed wetlands in different regions of Spain. Science of the Total Environment. 437: 61-67.
[62] N.K. Singh, J.D. Gourevitch, B.C. Wemple, K.B. Watson, D.M. Rizzo, S. Polasky, T.H. Ricketts. (2019). Optimizing wetland restoration to improve water quality at a regional scale. Environmental Research Letters. 14(6): 064006.
[63] A.J. Horne, Phytoremediation by constructed wetlands. In *Phytoremediation of contaminated soil and water*, CRC Press: 2020; pp 13-39.
[64] D.Q. Zhang, K. Jinadasa, R.M. Gersberg, Y. Liu, W.J. Ng, S.K. Tan. (2014). Application of constructed wetlands for wastewater treatment in developing countries–a review of recent developments (2000–2013). Journal of environmental management. 141: 116-131.
[65] F.J. Díaz, T. Anthony, R.A. Dahlgren. (2012). Agricultural pollutant removal by constructed wetlands: Implications for water management and design. Agricultural Water Management. 104: 171-183.
[66] S. Wu, S. Wallace, H. Brix, P. Kuschk, W.K. Kirui, F. Masi, R. Dong. (2015). Treatment of industrial effluents in constructed wetlands: challenges, operational strategies and overall performance. Environmental Pollution. 201: 107-120.
[67] A. Shukla, D. Parde, V. Gupta, R. Vijay, R. Kumar. (2022). A review on effective design processes of constructed wetlands. International Journal of Environmental Science and Technology. 19(12): 12749-12774.
[68] H.P. Raju, M.V. Kumar, P. Partheeban In *Wastewater Treatment in Constructed Wetlands by Phytoremediation Technique*, E3S Web of Conferences, 2023; EDP Sciences: 2023; p 03023.