International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Role of Constructed wetlands in Waste Water Treatment

Jagriti Gautam[1], Rajesh Kumar[2], Anjali Verma[3], Mahak[4]

[1,2,3,4]Department of Integrated Basic Science (B.Sc-M.Sc) Babasaheb Bhimrao Ambedkar University (A Central University), Lucknow-226025, UP, India.

Abstract

Wastewater generation is increasing worldwide due to rapid urbanization, industrial growth and population expansion, leading to severe environmental and public health challenges· Constructed wetland have emerged as an effective, sustainable and low-cost alternative to conventional wastewater treatment systems. Constructed wetlands mimic natural wetland processes by integrating physical, chemical and biological mechanisms to remove pollutants such as organic matter, suspended solids, nutrients, pathogens and emerging contaminants.Case studies from India and other countries demonstrate efficient removal of biochemical oxygen demand, chemical oxygen demand , nitrogen, phosphorus and heavy metals highlighting constructed wetland suitability for municipal, industrial, agricultural and storm water treatment. In addition to wastewater purification, constructed wetland provide ecological benefits including biodiversity enhancement carbon sequestration, groundwater recharge and aesthetic improvement. Despite advantages such as low maintenance and energy requirements , constructed wetland face challenges related to land availability, seasonal variations, substrate clogging and limited removal of certain micro pollutants. Future innovations including engineered substrates, hybrid systems, computer based monitoring and advanced modelling promise to improve efficiency and adaptability· In this review, we carefully and critically analyzed published studies on constructed wetland and evaluated their performance under different environmental and operational conditions. Based on our analysis, we found that properly designed constructed wetland can provide reliable, low-cost and sustainable wastewater treatment solutions, particularly in developing countries like India.

Keywords: Constructed wetlands, Wastewater Treatment, Nature-based solutions, Sustainable sanitation

1. Introduction

Wastewater generation has increased significantly worldwide due to rapid urbanization, industrialization and population growth[1]. According to the United Nations 2023, over 80 % of wastewater is discharged untreated globally, leading to severe environmental and public health problems[2]. Untreated wastewater contaminates rivers, lakes and groundwater, causing eutrophication, loss of biodiversity and the spread of waterborne diseases such as cholera, dysentery and typhoid[3]. In addition, untreated effluents contaminate soil and crops, affecting food safety and human health. Regions such as Asia and Africa experience particularly high levels of untreated wastewater, whereas Europe and North America have relatively higher treatment coverage. In India, for example - a large proportion of sewage in metropolitan cities like Mumbai and Delhi is either untreated or only partially treated, resulting in pollution of local water bodies and posing significant health risks to nearby population[4]. Conventional wastewater Treatment Plants are effective but have several limitations. They require high capital and operational costs[5], consume large amounts of energy and depend heavily on chemicals for treatment. Moreover, their complex designs necessitate skilled operators, making them impractical in rural or resource-limited areas[6]. Consequently, a significant portion of wastewater remains untreated, contributing to environmental degradation. To overcome these challenges to treat wastewater in an eco-friendly and cost-effective manner[7]. Different Constructed wetland types—Free Water Surface, Horizontal Subsurface Flow , Vertical Subsurface Flow and hybrid systems[8]—offer varying capabilities based on design, substrate selection, plant species and hydraulic parameters. In our analysis, constructed are engineered ecosystems that mimic natural wetlands[9]. They rely on the interaction of plants, substrates and microbial communities to remove pollutants from wastewater[10]. Constructed wetland treat wastewater through a combination of physical, chemical and biological process waste water Treatment Plants, including sedimentation, filtration, adsorption, microbial degradation and nutrient uptake by plants[11]. Based on our review, these systems offer several advantages over conventional such as low energy consumption, minimal chemical usage, biodiversity promotion and ease of integration into communities as green infrastructure[12]. As a result, Constructed wetland have become increasingly popular in regions where conventional wastewater treatment is not feasible due to financial, technical, or spatial constraints. The history of Constructed wetland dates back to the 1960s in Europe, where experimental systems were first implemented for municipal wastewater treatment[13]. During the 1970s and 1980s, Constructed wetland were adopted for small-scale rural wastewater treatment in Europe and North America. In the 1990s, standardized design protocols and performance evaluations were developed, leading to broader adoption·From the 2000s onward constructed wetland have been applied worldwide for domestic, industrial and agricultural wastewater, with hybrid systems emerging to enhance treatment efficiency[14]. In our review of Indian case studies pilot projects in Kerala and Gujarat have demonstrated the effectiveness of Constructed wetland for village and industrial wastewater treatment, achieving significant reductions in biochemical oxygen demand, chemical oxygen demand and nutrient loads. The primary objectives of constructed wetland are to reduce organic loads, remove suspended solids, eliminate nutrients such as nitrogen and phosphorus and control pathogens. Additionally, constructed wetland provide ecological and aesthetic benefits, including habitat for wildlife, carbon sequestration and community green spaces[15]. The mechanisms by which constructed wetland achieve these objectives include physical processes such as sedimentation and filtration, chemical processes like adsorption and precipitation and biological processes involving microbial degradation and plant uptake. The careful selection of plant species and substrate, along with optimization of hydraulic parameters such as hydraulic retention time and flow rate is critical to maximizing treatment efficiency. Constructed wetland also align closely with sustainable development goals, particularly UN SDG 6, which emphasizes clean water and sanitation. They provide decentralized wastewater treatment solutions suitable for rural and peri-urban areas and enhance ecosystem services, including habitat creation, groundwater recharge and carbon storage. Constructed wetland have been successfully implemented in India, such as in a village in Kerala where wastewater from 50 households was treated effectively, achieving 70–80 % BOD removal and 65 % phosphorus removal, while providing green space and improving local water quality. Similarly, a pilot project in Gujarat treating textile wastewater achieved 60–70 % COD reduction using a hybrid constructed wetland system combining vertical and horizontal subsurface flows. Overall, constructed wetland are a proven, cost-effective and environmentally sustainable alternative to conventional wastewater treatment systems.Their low energy requirements, minimal chemical usage and ecological benefits make them particularly suitable for regions where conventional treatment infrastructure is limited. With growing pressures on water resources and increasing environmental concerns, constructed wetland provide a practical and adaptable solution for managing wastewater while supporting ecological health and community well-being. In our opinion, the long-term success of constructed wetland depends not only on technical design but also on proper management and community involvement.

1.1 Scope of Constructed wetland in India

- Rural sanitation problem
- Small towns
- Govt schemes
- Low-cost solution

1.2 Principles of constructed wetland

Constructed wetland are a nature-based approach to wastewater treatment that emulate the natural purification processes of wetlands. These systems rely on the combined effects of physical, chemical and biological mechanisms to remove pollutants, including organic matter, suspended solids, nutrients and pathogens[16]. Physical processes in include sedimentation and filtration, which occur as wastewater moves slowly through the wetland system· Suspended solids settle due to gravity, while filtration occurs when water passes through substrates such as sand or gravel. These substrates also provide a surface for microbial biofilms to establish, enhancing biological treatment[17]. Chemical processes play a significant role in constructed wetland pollutants such as phosphorus and heavy metals are removed through adsorption onto substrate surfaces or precipitation as insoluble compounds[18]. Substrate selection is critical for optimizing chemical removal, with materials such as gravel, sand and zeolite frequently used for their high adsorption capacity. These chemical interactions complement biological processes[19], creating a holistic wastewater treatment environment. The biological mechanisms in constructed wetland are central to their efficiency. Microbial communities attached to plant roots and substrate surfaces break down organic compounds, transforming them into simpler, less harmful forms[20]. Aerobic bacteria, which thrive near the surface, degrade organic matter and oxidize ammonium to nitrate through nitrification, while anaerobic bacteria in subsurface zones facilitate denitrification, converting nitrate to harmless nitrogen gas. Plants, particularly emergent macrophytes such as *Typha latifolia*, *Phragmites australis a*nd *Scirpus* species, absorb nutrients like nitrogen and phosphorus, stabilize the substrate and release oxygen into the rhizosphere, supporting microbial activity[21]. [22]Hydraulic design parameters are essential in the functioning of constructed wetlands. Hydraulic Retention Time (HRT), the duration that wastewater remains in the system, directly affects treatment efficiency. A longer HRT allows more time for sedimentation, microbial degradation and chemical reactions[23]. Hydraulic Loading Rate which measures the volume of water per unit area, influences flow distribution and pollutant removal. Environmental factors such as temperature, sunlight and seasonal variations also impact the performance of constructed wetland by affecting microbial activity and plant growth. Substrate and plant selection are critical for maximizing treatment efficiency. Substrates not only provide structural support but also serve as a medium for biofilm development, which is vital for microbial degradation. Plants facilitate nutrient uptake and contribute to system stability. Commonly used plant species include *Phragmites australis*, *Typha latifolia* and *Scirpus sp,* which are resilient and effective in pollutant removal. The interplay between substrate, plants and microbial communities ensures that constructed wetland can treat a variety of pollutants effectively, while also offering ecological benefits such as habitat creation and aesthetic enhancement. constructed wetland align closely with sustainable development objectives, particularly in providing decentralized and low-energy wastewater treatment solutions . They support ecosystem services, including carbon sequestration, groundwater recharge and biodiversity enhancement. Case studies in India demonstrate their practical application: a village in Kerala utilized a constructed wetland to treat wastewater from 50 households, achieving 70–80% BOD reduction and 65 % phosphorus removal, while also providing green space. Similarly, an industrial pilot project in Gujarat employing a hybrid constructed wetland system successfully treated textile wastewater, achieving 60–70 % COD reduction. These examples illustrate the adaptability and efficiency of constructed wetland in diverse environmental and socioeconomic contexts. By integrating physical, chemical and biological processes, Constructed wetland offer a sustainable, cost-effective and environmentally friendly alternative to conventional wastewater treatment technologies. They are particularly valuable in rural and peri urban areas, where conventional infrastructure is limited or expensive. The optimization of plant species, substrate, hydraulic parameters and environmental conditions ensures that constructed wetland can achieve high pollutant removal efficiency while providing ecological and social benefits.

Wastewater → Sedimentation → Microbes → Plants → Treated Water

1.3.1Types of Constructed wetland

Constructed wetland are generally categorized based on the hydrology and flow pattern of wastewater through the system. The primary types include Free Water Surface wetlands, Subsurface Flow wetlands—which are further divided into horizontal flow and vertical flow systems—and hybrid systems that combine multiple types for enhanced treatment efficiency. Each type possesses unique design principles, pollutant removal capabilities and operational advantages, making them suitable for different wastewater treatment scenarios[25]. Free Water Surface wetlands are designed to allow wastewater to flow over the soil surface and among emergent plants, mimicking natural wetland environments. Typically, these wetlands are shallow, with depths ranging from 0.2 to 1 meter and planted with species such as *Typha latifolia* and *Phragmites australis*. Wastewater movement is primarily horizontal, enabling sedimentation of solids and exposure to sunlight, which supports microbial degradation. FWS wetlands are effective at removing biochemical oxygen demand and suspended solids, generally achieving BOD removal efficiencies between 60–80 %. Nitrogen removal is relatively lower, typically 30–50 %[26]. Despite their simplicity and ecological benefits, FWS wetlands require a larger land area and may present challenges such as mosquito breeding. They are especially suitable for rural or peri-urban areas where land availability is not a limiting factor Subsurface Flow wetlands direct wastewater through a porous substrate, such as gravel or sand, keeping the water below the surface and minimizing odor and mosquito problems. Horizontal Subsurface Flow (HSSF) wetlands allow water to move laterally through the substrate, where microbial biofilms attached to plant roots and media degrade organic matter and nutrients[27]. Plant species commonly used include *Phragmites australis* and *Scirpus* spp., which support microbial activity by providing oxygen to the root zone. HSSF wetlands typically achieve BOD removal of 70–85 % and nitrogen removal of 40–60 %[28]. However, careful design is required to prevent clogging and the choice of substrate significantly affects long-term performance. Vertical Subsurface Flow wetlands are designed for intermittent dosing, where wastewater is applied at the surface and percolates vertically through the substrate. This vertical movement promotes aeration and enhances nitrification, resulting in high nitrogen removal efficiencies. [29]VSSF systems usually achieve 75–90 % BOD removal and 50–75 % nitrogen removal, while occupying a smaller footprint compared to FWS and HSSF systems. Plants such as *Typha*, *Phragmites* and *Carex* are often employed to improve nutrient uptake and stabilize the substrate. These systems require pumping or dosing mechanisms to maintain intermittent feeding, which introduces some technical complexity compared to horizontal systems. Hybrid constructed wetland combine two or more constructed wetland types to maximize pollutant removal across multiple stages[30]. For example, a system may consist of a vertical subsurface flow wetland followed by a horizontal subsurface flow wetland and then a free water surface wetland. Hybrid systems are particularly effective at removing BOD, COD, nitrogen, phosphorus and pathogens, making them suitable for municipal and industrial wastewater applications. Emerging constructed wetland designs include floating wetlands, where plants are grown on rafts for treating lakes and ponds and VSSF wetlands enhanced with aeration for improved nitrogen removal[31]. Additionally, some hybrid systems integrate computer based monitoring and control for flow regulation, water quality tracking and maintenance optimization. The choice of constructed wetland type depends on several factors, including the nature and strength of the wastewater, land availability, desired treatment efficiency and ecological considerations. Free water surface wetlands are preferred for decentralized applications requiring habitat creation and aesthetic integration. HSSF wetlands are ideal for medium-strength wastewater with limited land, while VSSF systems are more suitable where high nutrient removal and smaller footprints are needed. Hybrid systems offer flexibility and enhanced treatment performance, combining the strengths of multiple constructed wetland configurations to address complex wastewater treatment challenges. In all constructed wetland types, the interaction between plants, substrate and microbial communities is critical for efficient treatment. Physical processes like sedimentation and filtration, chemical processes such as adsorption and precipitation and biological processes including microbial degradation and plant nutrient uptake operate simultaneously, creating a synergistic effect that enables high pollutant removal[32]. Constructed wetland therefore provide a sustainable, low-energy and environmentally friendly alternative to conventional wastewater treatment plants, while offering additional ecological and social benefits such as biodiversity support and green infrastructure integration.

Table 1: Types of Constructed wetland– Comparison

Types	Flow	BOD Removal	Nitrogen	Land Need	Cost
FWS	Surface	60-80%	Low	High	Low
HSSF	Horizontal	70-85%	Medium	Medium	Medium
VSSF	Vertical	75-90%	High	Low	Medium
Hybrid	Mixed	80-95%	Very High	Medium	Medium-High

1.3.2 Design & Operational Parameters of Constructed wetland

The efficiency of Constructed wetland largely depends on their design and operational parameters, which govern hydraulic flow, pollutant removal and long-term performance. A well-designed constructed wetland balances the interplay between physical, chemical and biological processes to achieve optimal treatment outcomes. One of the most critical design considerations is the hydraulic retention time, defined as the duration wastewater remains within the wetland system. Longer hydraulic retention time allows more time for sedimentation, filtration, microbial degradation and nutrient uptake by plants, directly influencing the removal of biochemical oxygen demand (BOD), chemical oxygen demand (COD) and nutrients such as nitrogen and phosphorus[33]. Typical HRT for municipal wastewater ranges from 3 to 10 days for subsurface flow systems, depending on the effluent characteristics and desired effluent quality.

Hydraulic loading rate is another key parameter that determines the volume of wastewater applied per unit area per day. Excessive HLR can lead to reduced retention time, incomplete treatment and substrate clogging, while too low HLR may cause under utilization of the wetland area. Designers often optimize HLR based on wastewater strength, system type and climatic conditions to maintain balanced flow distribution and high pollutant removal efficiency[34]. Additionally, water depth must be carefully selected, as shallow systems favor oxygen diffusion and plant growth, whereas deeper systems enhance sedimentation but may reduce microbial aerobic activity.

The choice of substrate material is crucial for both SSF and FWS wetlands. Substrate provides structural support for plants, creates a habitat for microbial communities and facilitates physical and chemical pollutant removal through filtration and adsorption. Common substrate materials include gravel, sand, soil and combinations thereof. The size and porosity of substrate particles affect hydraulic conductivity[35], flow uniformity and the potential for clogging. In vertical flow systems, a layered substrate design is often implemented, with coarse gravel at the bottom for drainage and finer sand layers above to promote filtration and microbial colonization. Plant species selection plays a pivotal role in system performance. Emergent macrophytes such as *Phragmites australis*, *Typha latifolia* and *Scirpus* species are widely used due to their high tolerance to varying water quality, extensive root systems and ability to release oxygen into the rhizosphere[36]. Plant density and distribution influence nutrient uptake, microbial habitat and hydraulic flow patterns. In hybrid and FWS wetlands, plant zonation is often employed, with taller species near the inflow to reduce hydraulic short-circuiting and smaller species near the outflow to enhance polishing of effluent. Operational parameters such as intermittent dosing, flow regulation and maintenance schedules are critical to sustaining performance over time[37]. Vertical flow wetlands often require intermittent dosing to enhance aeration and improve nitrification, whereas horizontal flow wetlands typically maintain a continuous flow pattern. Routine maintenance includes removing accumulated solids, inspecting inlet and outlet structure and managing vegetation to prevent overgrowth. Seasonal adjustments may be necessary in regions with extreme temperature variations, as plant growth and microbial activity are temperature-dependent .Environmental and climatic factors, including temperature, sunlight and precipitation, also affect constructed wetland performance[38]. Higher temperatures enhance microbial activity and accelerate decomposition of organic matter, whereas lower temperatures may reduce treatment efficiency. Sunlight exposure promotes oxygenation and supports plant growth, while excessive rainfall can dilute effluent concentrations or temporarily overwhelm hydraulic capacity. Designers often incorporate features such as flow control structures, overflow basins and shading strategies to mitigate these environmental impacts. Advanced constructed wetland designs incorporate monitoring and control systems to optimize operational parameters. Sensors for flow rate, water level and dissolved oxygen can be integrated with automated dosing systems to maintain consistent treatment efficiency. Such systems are particularly valuable in industrial applications where effluent wastewater characteristics may fluctuate widely. In India, a hybrid vertical-horizontal Constructed wetland treating textile wastewater utilized flow control and intermittent dosing to achieve 65–70 % COD removal and significant reductions in suspended solids and nitrogen, demonstrating the importance of careful operational management[39]. In summary, the design and operational parameters of Constructed wetlands—including HRT, HLR, substrate selection, plant species and environmental management—directly determine pollutant removal efficiency and long-term sustainability. Optimizing these parameters ensures that Constructed wetland can effectively treat municipal, industrial and agricultural wastewater, while simultaneously providing ecological and social benefits such as habitat creation, groundwater recharge and aesthetic value.

1.3.3Pollutant Removal Mechanisms in Constructed wetland

remove pollutants through a complex interplay of physical, chemical and biological mechanisms. Each type of constructed wetland , whether free water surface, horizontal subsurface flow or vertical subsurface flow, utilizes these mechanisms to achieve efficient wastewater treatment. Physical processes primarily involve sedimentation and filtration. As wastewater enters the wetland system, suspended solids gradually settle due to gravity, reducing turbidity and organic load[40]. Filtration occurs as water passes through substrates such as gravel or sand, which trap fine particles and provide surfaces for microbial biofilm development. This combination of sedimentation and filtration is particularly effective in reducing BOD, COD and total suspended solids and it establishes a foundation for subsequent chemical and biological treatment. Chemical processes in Constructed wetland are crucial for the removal of nutrients and heavy metals. Adsorption occurs when pollutants such as phosphorus and heavy metals attach to substrate particles or organic matter within the wetland[41]. Precipitation reactions further enhance removal, as certain compounds react with minerals in the substrate to form insoluble precipitates. For example, phosphorus can precipitate as calcium phosphate when calcium-rich substrates are used, effectively reducing its concentration in effluent. These chemical processes complement microbial activity and plant uptake, creating a multifaceted treatment system capable of handling complex wastewater streams. Biological processes are central to CWs pollutant removal. Microbial communities colonize substrate surfaces and plant roots, facilitating the breakdown of organic matter and transformation of nutrients. Aerobic bacteria degrade organic compounds near the water surface, while anaerobic bacteria in subsurface zones perform denitrification, converting nitrate into harmless nitrogen gas. Plants also contribute significantly to pollutant removal. Emergent macrophytes such as *Typha latifolia*, *Phragmites australis* and *Scirpus* spp. absorb nutrients directly into their biomass, reducing nitrogen and phosphorus concentrations in the water[42]. Additionally, plants release oxygen into the rhizosphere, enhancing aerobic microbial activity and creating a self-sustaining treatment environment. Nitrogen removal in Constructed wetland involves multiple pathways, including ammonification, nitrification and denitrification. Ammonium in wastewater is converted to nitrate through nitrification by aerobic bacteria, which is subsequently reduced to nitrogen gas via denitrification under anaerobic conditions[43]. This process is strongly influenced by hydraulic retention time, substrate type and plant density. Studies have shown that vertical subsurface flow systems achieve higher nitrogen removal efficiencies compared to horizontal systems due to enhanced aeration and oxygen availability[44]. Similarly, hybrid systems combining vertical and horizontal flows demonstrate superior nitrogen removal, often exceeding 70 % under optimal conditions. Phosphorus removal primarily occurs through adsorption and precipitation within the substrate and plant uptake. While plants can store phosphorus temporarily in biomass, substrate-mediated removal provides a more stable long-term mechanism. The choice of substrate is therefore critical; materials such as gravel mixed with iron or calcium compounds significantly enhance phosphorus retention. Case studies from India demonstrate that hybrid CWs systems treating municipal wastewater can achieve 60–65 % phosphorus removal, providing an effective solution in regions where conventional chemical dosing is not feasible[45]. Pathogen removal in Constructed wetland is facilitated through sedimentation, filtration, predation by microorganisms and natural die-off. The combination of physical barriers and biological interactions reduces the concentration of fecal coliforms, E. coli and other pathogenic microorganisms. Free water surface wetlands, with open water zones and extended retention times, are particularly effective in pathogen reduction, while subsurface flow wetlands offer additional protection by preventing direct human and wildlife contact with contaminated water[46]. Emerging research highlights additional pollutant removal capabilities of CWs, including the degradation of pharmaceuticals, personal care products and industrial micro-pollutants. Microbial consortia within substrate biofilms have shown the ability to metabolize certain pharmaceutical residues, while plant uptake and substrate adsorption contribute to removal of heavy metals and persistent organic compounds[47]. These findings expand the applicability of Constructed wetland to industrial and municipal wastewater streams containing complex contaminants, supporting their role as a versatile and sustainable wastewater treatment solution. Overall, the pollutant removal efficiency of Constructed wetland is highly dependent on the design configuration, hydraulic and operational parameters, plant species, substrate characteristics and environmental conditions. Optimizing these factors ensures effective treatment across multiple pollutant categories, making Constructed wetland a reliable, eco-friendly and cost-effective alternative to conventional wastewater treatment systems. Case studies worldwide, including applications in Europe, North America and India, consistently demonstrate that Constructed wetland can achieve high levels of BOD, COD, nutrient and pathogen removal when appropriately designed and maintained[48].

1.4 Removal of Emerging Contaminants

In recent years, increasing attention has been given to emerging contaminants such as pharmaceuticals, microplastics and personal care products in wastewater[49]. These pollutants are difficult to remove using conventional treatment systems and often persist in aquatic environments. Traditional constructed wetland show partial removal of such contaminants due to limited biodegradation and adsorption capacity. Therefore, engineered substrates and hybrid wetland designs are increasingly being explored to enhance treatment efficiency[51]. Recent studies suggest that the integration of biochar and specialized microbial communities can significantly improve the removal of these emerging pollutants. Major Emerging **Pollutants in Wastewater[52].**

- Pharmaceuticals-Antibiotics, painkillers and hormones that enter water bodies through domestic sewage.
- Micro plastics -Small plastic particles originating from synthetic clothes, packaging and cosmetics.
- Personal Care Products- Chemicals from shampoos, soaps, creams and perfumes.
- Pesticide Residues-Agricultural chemicals that reach water sources through runoff.

Challenges in Removal

- Low biodegradability of many emerging pollutants
- Limited adsorption capacity of natural substrates
- Insufficient microbial degradation
- Short hydraulic retention time

Possible Improvement Strategies

- Use of biochar and activated carbon as substrates
- Development of hybrid wetland systems
- Introduction of specialized microbial cultures
- Regular system monitoring and maintenance

1.5 Applications of Constructed wetland

Constructed wetland have been applied worldwide as sustainable, nature-based wastewater treatment systems across municipal, industrial, agricultural and storm water contexts. Their versatility and ecological benefits make them particularly suitable for regions with limited access to conventional wastewater treatment infrastructure. In municipal wastewater management, Constructed wetland provide an effective decentralized treatment solution for small communities, peri-urban settlements and even parts of larger cities where conventional sewage networks are impractical. For example, in Kerala, India, a CWs treating wastewater from approximately 50 households successfully reduced biochemical oxygen demand (BOD) by 70–80 % and phosphorus by 60–65 %, while creating green recreational spaces and supporting biodiversity[53]. Such implementations highlight the potential of Constructed wetland to simultaneously address environmental, public health and social objectives. In industrial wastewater treatment, Constructed wetland have been employed to treat effluents from sectors such as textiles, food processing and pulp and paper. Industrial wastewater often contains higher concentrations of organic matter, nutrients and occasionally heavy metals, requiring tailored CWs designs. Hybrid systems, combining vertical and horizontal subsurface flow wetlands, have demonstrated high efficiency in treating textile effluent, achieving 65–70% chemical oxygen demand (COD) reduction and substantial removal of suspended solids and nutrients[54]. The low operational cost and minimal energy requirement of Constructed wetland make them an attractive option for industries in developing regions where conventional treatment is costly and resource-intensive. Agricultural wastewater, which often carries high loads of nutrients, pesticides and pathogens, is another important application area for CWs. Nutrient runoff from farms can lead to eutrophication of nearby water bodies, threatening aquatic ecosystems. Constructed wetland installed along drainage canals or at the outlet of farm lagoons act as biofilters, reducing nitrogen and phosphorus loads before discharge into rivers or groundwater[55]. Studies in Europe and North America have shown that Constructed wetland treating agricultural runoff can remove up to 60–75 % of nitrogen and 50–65 % of phosphorus, while also trapping sediments and reducing pesticide concentrations. The integration of Constructed wetland into agricultural landscapes also provides wildlife habitat, soil stabilization and aesthetic value, demonstrating multi-functionality beyond wastewater treatment. Storm water management is an emerging application of constructed wetland, where they are used to treat urban runoff containing sediments, nutrients, hydrocarbons and heavy metals. Urbanization increases impervious surfaces, leading to higher volumes and velocities of storm water, which can degrade rivers and lakes. Constructed wetland in urban environments act as natural retention and treatment systems, capturing pollutants while reducing peak flows and mitigating flood risks. Floating wetlands, in which plants are grown on rafts within retention ponds or lakes, have been implemented in cities like Singapore and Chicago to remove nutrients from storm water and provide aesthetic green spaces[56]. These systems also contribute to urban biodiversity, offering habitat for birds, insects and aquatic organisms. Constructed wetland have also been explored for grey water treatment in residential and commercial settings. Grey water, generated from bathing, laundry and kitchen activities, constitutes a significant portion of household wastewater and is less polluted than black water. Constructed wetland provide an energy-efficient solution for grey water treatment, enabling reuse for irrigation, toilet flushing or groundwater recharge. In some Indian cities, pilot projects have demonstrated that Constructed wetland can reduce BOD and total suspended solids by 70–80 %, while nitrogen and phosphorus concentrations are lowered sufficiently to allow safe reuse in non-potable applications. This application not only conserves freshwater resources but also reduces the environmental impact of wastewater discharge. Additionally, Constructed wetland have been utilized in wetland restoration and ecological enhancement projects, combining wastewater treatment with environmental restoration. Constructed wetland integrated into degraded rivers or urban lakes provide water purification, habitat creation and aesthetic improvement. By incorporating native plants and designing for seasonal water variations, Constructed wetland contribute to the restoration of natural ecosystems while improving water quality. Such multifunctional applications exemplify the versatility and ecological sustainability of Constructed wetland as a wastewater treatment solution. In summary, the applications of Constructed wetland span municipal, industrial, agricultural and urban contexts, with additional uses in grey water treatment and ecological restoration. Constructed wetland provide effective pollutant removal, ecological benefits, cost efficiency and adaptability, making them a valuable tool for sustainable wastewater management in diverse environmental and socio-economic settings.

1.6 Advantages and Limitations of Constructed wetland

Constructed wetland offer numerous advantages as a sustainable and nature-based wastewater treatment solution. One of the primary benefits is cost-effectiveness. Unlike conventional wastewater treatment plants, Constructed wetland require low operational and maintenance costs, minimal energy input and limited chemical usage. This makes them particularly suitable for rural and peri-urban communities, where financial and technical resources for conventional treatment systems are limited. For instance, pilot constructed wetland projects in Kerala and Gujarat, India, demonstrated that decentralized Constructed wetland treating municipal and industrial wastewater could achieve high BOD, COD and nutrient removal while maintaining low operational costs compared to traditional treatment plants. Another significant advantage of Constructed wetland is their environmental sustainability. Constructed wetland mimic natural wetlands, providing habitat for birds, insects and aquatic organisms, which enhances local biodiversity[57]. They also support ecosystem services such as carbon sequestration, groundwater recharge and temperature regulation in urban areas. In urban applications, floating wetlands and vegetated retention ponds not only treat storm water but also improve aesthetics and recreational opportunities, contributing to urban greening initiatives. Constructed wetland are highly adaptable and versatile. They can be designed to treat various types of wastewater, including municipal, industrial, agricultural and grey water. Hybrid systems, combining vertical and horizontal subsurface flow wetlands with free water surface wetlands, can handle complex effluent with high nutrient and organic loads. Their modular design allows for incremental scaling, enabling communities or industries to expand capacity as needed[58]. Moreover, Constructed wetland can be integrated with other treatment technologies, such as biofilters or sedimentation basins, to enhance overall performance. Despite these advantages, Constructed wetland also have limitations that must be considered during planning and implementation. One key limitation is land requirement. Free water surface wetlands, in particular, require substantial land area to achieve desired treatment efficiency. In densely populated urban areas, this may limit feasibility. Another limitation is seasonal variability; plant growth and microbial activity are influenced by temperature and sunlight, which can affect pollutant removal efficiency, especially in cold or shaded environments. For example, nitrate removal may decline during winter months in temperate regions due to reduced microbial activity. Maintenance requirements, though lower than conventional plants, can still pose challenges. Substrate clogging in subsurface flow wetlands may occur over time due to accumulation of solids and biofilms, necessitating periodic cleaning or substrate replacement. Overgrowth of vegetation may require harvesting to maintain hydraulic performance and prevent short-circuiting of wastewater flow. In addition, while Constructed wetland effectively reduce organic matter and nutrients, certain micropollutants and industrial chemicals may not be fully removed without additional treatment steps, which can limit applicability for highly contaminated industrial effluents[59]. Operational considerations, such as intermittent dosing in vertical flow systems, also introduce complexity. Pumping or dosing systems may be required, which increases energy consumption and maintenance compared to completely passive systems. Furthermore, Constructed wetland may take longer to achieve stable treatment performance, as microbial communities and plant systems need time to establish, particularly in newly constructed or rehabilitated wetlands. Constructed wetland present a sustainable, cost-effective and ecologically beneficial solution for wastewater treatment, capable of addressing a wide range of effluent types and scales. Their adaptability, low operational costs and environmental benefits make them highly attractive, especially in decentralized or resource-limited contexts. However, land requirements, seasonal variability, maintenance needs and limitations in treating certain pollutants must be carefully addressed through proper design, monitoring and management to ensure long-term effectiveness.

1.7 Case Studies of Constructed wetland in India and Abroad

Constructed wetland have been successfully implemented worldwide, demonstrating their versatility and effectiveness across different environmental and socio-economic contexts. In India, several pilot and operational projects highlight the potential of Constructed wetland in decentralized wastewater treatment. A notable example is a village-scale constructed wetland in Kerala, where wastewater from approximately 50 households was treated using a hybrid system combining vertical and horizontal subsurface flow wetlands. This system achieved BOD removal of 70–80 % and phosphorus removal of around 65 %, while also creating green space and supporting local biodiversity. The success of this project demonstrated that Constructed wetland could provide sustainable, low-cost wastewater treatment solutions in rural India, with additional benefits such as aesthetic improvement and habitat creation. In Gujarat, India, a textile industry pilot project implemented a hybrid CWs system to treat industrial effluent containing high organic and nutrient loads. The system consisted of a vertical subsurface flow wetland followed by a horizontal flow stage, achieving 65–70 % reduction in COD and significant removal of suspended solids and nitrogen. This case study illustrated the applicability of Constructed wetland in industrial contexts, emphasizing their low operational costs, adaptability to variable effluent quality and reduced environmental impact compared to conventional chemical treatment processes. Internationally, Constructed wetland have been widely adopted for municipal wastewater treatment in Europe and North America. In Denmark, vertical flow Constructed wetland have been used extensively for on-site treatment of domestic wastewater. These systems employ intermittent dosing and layered gravel substrates to optimize aeration and microbial activity, achieving 80–90 % BOD removal and substantial nutrient reduction. Similarly, in Germany, FWS wetlands integrated into urban parks serve both wastewater treatment and ecological enhancement purposes, providing recreational spaces and supporting bird and aquatic life while improving water quality in adjacent streams. In the United States, constructed wetland have been implemented to treat municipal and industrial wastewater in small communities and peri-urban areas. For instance, a CWs in Wisconsin treated municipal wastewater from 200 households, achieving BOD and nitrogen removal efficiencies exceeding 70 %, while offering educational and recreational opportunities for the community. In Florida, floating Constructed wetland have been used to improve water quality in lakes affected by urban runoff, successfully reducing nutrient concentrations and supporting aquatic biodiversity. These examples highlight the multifunctional benefits of CWs, combining wastewater treatment, ecological restoration and social value. Developing countries in Asia and Africa have also adopted constructed wetland as a cost-effective solution for wastewater management. In China, Constructed wetland are employed to treat municipal wastewater from small towns, achieving removal efficiencies of 60–80 % for BOD and 50–70 % for nitrogen. Similarly, in South Africa, Constructed wetland have been integrated into informal settlements, providing safe sanitation, reducing environmental pollution and promoting community engagement. These case studies underscore the adaptability of Constructed wetland to diverse climatic, geographic and socio-economic conditions, highlighting their potential as a global solution for sustainable wastewater management. Collectively, these examples demonstrate that Constructed wetland are highly versatile and environmentally sustainable, capable of addressing a wide range of wastewater treatment challenges. Whether implemented for rural communities, industrial effluents, municipal wastewater, or urban storm water management, Constructed wetland consistently achieve effective pollutant removal while providing ecological and social benefits. Lessons learned from these case studies emphasize the importance of careful design, plant selection, hydraulic optimization and operational monitoring to ensure long-term success.

1.7.1 Economic and Environmental Assessment of Constructed wetlands

Constructed wetland offer significant economic and environmental advantages, making them a preferred choice for sustainable wastewater management, particularly in regions with limited infrastructure. Economically, Constructed wetland are generally less expensive to construct, operate and maintain than conventional wastewater treatment plants. The capital cost of Constructed wetland varies depending on the system type, land availability, substrate material and plant selection. Free water surface wetlands require larger land areas, potentially increasing initial investment, whereas subsurface flow systems, particularly vertical flow wetlands, can achieve higher treatment efficiency within a smaller footprint, reducing land acquisition costs. Case studies from rural India indicate that implementing Constructed wetland can save up to 40–50 % of the total treatment cost compared to conventional aerobic treatment systems. The operational and maintenance costs of Constructed wetland are relatively low due to minimal energy requirements, absence of complex machinery and limited chemical inputs. Unlike conventional plants, which rely heavily on mechanical aeration and chemical dosing, Constructed wetland utilize natural processes such as sedimentation, microbial activity and plant nutrient uptake. Routine maintenance involves periodic vegetation harvesting, removal of accumulated sediments and inspection of inlet and outlet structures. For example, a municipal CWs project in Wisconsin, USA, treating wastewater from 200 households, reported annual maintenance costs of less than 10 % of the operational costs of an equivalent conventional treatment plant, demonstrating the economic viability of Constructed wetland for small communities. From an environmental perspective, Constructed wetland provide multiple ecosystem services in addition to wastewater treatment. By mimicking natural wetland processes, Constructed wetland support biodiversity, including birds, insects, amphibians and aquatic organisms. The vegetated substrate also acts as a carbon sink, sequestering carbon in plant biomass and soil, while simultaneously reducing greenhouse gas emissions compared to energy-intensive conventional treatment plants. Constructed wetland contribute to groundwater recharge by allowing treated effluent to infiltrate into the soil, improving water availability in water-scarce regions. Additionally, Constructed wetland mitigate urban heat islands and provide aesthetically pleasing green spaces in urban areas, enhancing the overall quality of life. Life Cycle Assessment (LCA) studies comparing Constructed wetland with conventional wastewater treatment plants reveal that Constructed wetland generally have a lower environmental footprint, particularly in terms of energy consumption, greenhouse gas emissionsand chemical usage. For instance, in European studies, Constructed wetland treating municipal wastewater demonstrated a 60–70 % reduction in energy demand and a 40–50 % reduction in CO_2 emissions compared to conventional activated sludge systems. The use of native plants in Constructed wetland further enhances sustainability by reducing the need for irrigation and chemical fertilizers. However, environmental assessments also highlight potential challenges. For example, Constructed wetland can produce methane and nitrogenous oxide, particularly in anaerobic zones, which are potent greenhouse gases. Careful design and operation, including optimizing aeration and hydraulic loading, can mitigate these emissions. Additionally, land requirements and the use of certain substrates with high embodied energy may affect the overall environmental balance. Nevertheless, when properly designed and managed, the environmental benefits of CWs, including pollution reduction, biodiversity enhancement and ecosystem services, often outweigh these potential drawbacks. The economic and environmental assessment of Constructed wetland demonstrates their cost-effectiveness, low operational requirements and ecological sustainability. By reducing energy consumption, promoting biodiversity, supporting ecosystem services and lowering capital and operational costs, Constructed wetland provide an integrated solution for sustainable wastewater management, particularly in rural, peri-urbanand resource-constrained settings. Case studies across India, Europe and North America consistently highlight that Constructed wetland are both economically viable and environmentally beneficial, making them a compelling alternative to conventional treatment systems.

1.7.2 Future Trends and Innovations in Constructed wetland

Constructed wetland are evolving beyond traditional wastewater treatment, incorporating innovative designs, technologies and research-driven approaches to enhance efficiency, scalability and multi-functionality. One of the most significant trends is the integration of hybrid and multi-stage systems, which combine vertical and horizontal subsurface flow wetlands with free water surface wetlands. These systems allow staged treatment of organic matter, nutrients and pathogens, improving overall pollutant removal efficiency. Hybrid Constructed wetland are increasingly being combined with advanced pre-treatment or post-treatment technologies, such as sedimentation tanks, biofilters, or membrane bioreactors, to tackle complex industrial wastewater streams containing high levels of micropollutants, heavy metals and emerging contaminants. The use of engineered substrates represents another emerging trend. Traditional gravel or sand substrates are being supplemented with materials such as biochar, zeolites, or iron-coated sands, which enhance adsorption and chemical removal of nutrients and heavy metals. Biochar, for instance, not only increases pollutant retention but also supports microbial biofilm growth, creating a synergistic effect for organic matter and nutrient removal. Studies have shown that biochar-amended Constructed wetland can achieve phosphorus removal efficiencies exceeding 80 %, making them highly suitable for nutrient-rich wastewater streams. Integration of computer based and sensor-based monitoring systems is gaining momentum in CWs management. Automated flow control, water quality monitoring and remote management enable optimized dosing, early detection of clogging or inefficiencies and adaptive operation to varying effluent characteristics. This trend is particularly relevant for industrial and municipal applications where wastewater quality and flow can fluctuate significantly. For example, sensor-enabled vertical flow wetlands in Europe have demonstrated improved nitrogen removal efficiency by adjusting dosing intervals based on real-time water quality measurements. Phytoremediation and microbial enhancement are also key areas of innovation. Genetically selected or engineered plant species are being explored for enhanced uptake of nutrients and contaminants, while specific microbial consortia are being introduced to accelerate the degradation of organic pollutants, pharmaceuticals and personal care products. Additionally, floating constructed wetland are being deployed in lakes, reservoirs and urban water bodies to remediate eutrophic conditions and improve water aesthetics. Floating Constructed wetland also contribute to carbon sequestration, habitat creation and urban cooling, demonstrating multifunctional benefits beyond conventional treatment. Modeling and simulation technologies are increasingly applied to optimize CWs design and predict long-term performance. Computational models simulate hydraulic flow, pollutant transport, microbial kinetics and plant growth, allowing engineers to test design alternatives before construction. Coupled with Geographic Information Systems (GIS), these tools help identify optimal sites for CWs implementation, particularly in urban or ecologically sensitive areas. Furthermore, life cycle assessment (LCA) and sustainability indices are being incorporated into design and planning stages to minimize environmental footprints and maximize ecosystem services. Finally, the global push for sustainable wastewater management and climate resilience is driving innovation in CWs. Researchers are exploring carbon-neutral and energy-positive Constructed wetland that integrate renewable energy generation, such as solar-powered aeration and pumping systems. These innovations, combined with low-maintenance plant-based systems, position Constructed wetland as a cornerstone of sustainable, climate-adaptive wastewater management strategies for the 21st century. In conclusion, the future of Constructed wetland lies in technological integration, multi-functionality and sustainable design. Advances in hybrid systems, engineered substrates, sensor-based monitoring, phytoremediation and modeling are transforming Constructed wetland into highly efficient, resilient and environmentally beneficial wastewater treatment solutions. These innovations ensure that Constructed wetland remain adaptable to emerging contaminants, urbanization pressures and global sustainability goals, reinforcing their role as a key nature-based technology for water management.

1.7.3 Challenges and Research Gaps in Constructed wetlands

Table 2 : Problems and Future Research Areas in Constructed wetland Systems

Issue area	Current status	Research reqirement
Emerging pollutants	Partial removal	Engineered substrates
Substrate clogging	Common oprational issue	Long-life clog-resitant media
Climate variability	Seasonal efficiency drop	Climate-resilient designs
Monitoring systems	Mostly manual	Computer based automation
Land requirement	High in FWS system	Compact modular systems

While Constructed wetland have proven to be effective, sustainable and versatile wastewater treatment solutions, several challenges and research gaps remain, limiting their full-scale adoption and long-term optimization. One of the primary challenges is the large land area requirement, especially for free water surface wetlands, which can constrain their applicability in densely populated urban areas. Subsurface flow Constructed wetland reduce land needs but often require careful design to avoid clogging and ensure uniform hydraulic distribution. Research continues to explore high-efficiency, compact CWs designs that minimize land use while maintaining treatment performance, such as multi-stage vertical flow and modular systems. Another significant challenge is seasonal and climatic variability, which affects plant growth, microbial activity and overall pollutant removal efficiency. Cold temperatures can reduce microbial nitrification and organic matter decomposition, while extreme heat or drought can stress plants and affect evapo transpiration rates. Although research has explored the use of hardy, native plant species and adaptive management strategies, more studies are needed to develop climate-resilient CWs designs capable of maintaining stable performance under varying environmental conditions. Clogging and substrate degradation represent operational challenges, particularly in subsurface flow CWs. Accumulation of suspended solids, biofilm growth and organic matter can reduce hydraulic conductivity, leading to short-circuiting and decreased treatment efficiency. Research is ongoing to identify substrate materials and pre-treatment strategies that minimize clogging while supporting microbial colonization.

Innovations such as layered substrates, engineered biochar and alternative gravel-sand mixes are being investigated to improve long-term reliability. A notable research gap lies in the removal of emerging contaminants, including pharmaceuticals, personal care products, microplastics and industrial chemicals. While traditional Constructed wetland effectively reduce BOD, COD, nutrients and pathogens, their efficiency against these complex pollutants is variable. Studies have begun examining plant-microbe interactions, engineered substrates and hybrid CWs designs to enhance degradation or adsorption of emerging contaminants, but standardized approaches and large-scale validation are still limited. Monitoring and modeling are also areas requiring further development. Although sensor-based and computer based Constructed wetland are emerging, many systems still rely on manual sampling and conventional monitoring methods, which may not capture dynamic changes in hydraulic flow, pollutant concentrations and microbial activity. Advanced computational models that simulate plant growth, microbial kinetics and contaminant fate exist but require further refinement and validation under diverse climatic, geographic and wastewater conditions. Incorporating predictive modeling and real-time monitoring can optimize design, operation and maintenance strategies, but this remains a critical research need. Socio-economic and policy challenges also affect the implementation of CWs. Awareness among local authorities, stakeholders and communities about the benefits and operational requirements of Constructed wetland is often limited, hindering large-scale adoption. Policy frameworks and incentives to promote decentralized, nature-based wastewater treatment are still developing in many regions. Research combining technical performance with socio-economic analysis can help overcome these barriers, ensuring Constructed wetland are not only technically effective but also socially and economically viable. Finally, long-term sustainability and integration with urban water management remain research priorities. As urbanization intensifies, Constructed wetland must be designed to coexist with other infrastructure, handle fluctuating flows and adapt to variable pollutant loads. Multi-functional Constructed wetland that combine wastewater treatment with storm water management, urban greening, biodiversity enhancement and climate adaptation offer promising solutions, but their optimization and standardization require further empirical research and modeling efforts. Constructed wetland are proven, cost-effective and environmentally sustainable, challenges such as land requirements, climatic variability, substrate clogging and emerging contaminant removal persist. Addressing these issues through research on compact designs, resilient plant species, engineered substrates, advanced monitoring and socio-economic integration is essential to unlock the full potential of Constructed wetland as a key component of sustainable wastewater management worldwide.

1.7.4 Linkage with Sustainable Development Goals (SDGs)

Constructed wetland contribute significantly to the achievement of the United Nations Sustainable Development Goals (SDGs). They directly support SDG 6 (Clean Water and Sanitation) by improving wastewater treatment and promoting water reuse. Constructed wetland also contribute to SDG 11 (Sustainable Cities and Communities) by supporting decentralized sanitation systems and green infrastructure development. Furthermore, they assist in achieving SDG 13 (Climate Action) by reducing energy consumption, lowering greenhouse gas emissions and enhancing carbon sequestration. By integrating wastewater management with ecosystem restoration, constructed wetland represent an effective nature-based solution for sustainable development.

1.8 Conclusion

Constructed wetland represent a robust, sustainable and nature-based approach for wastewater treatment, effectively addressing environmental, social and economic challenges associated with conventional treatment systems. Across the various sections discussed, Constructed wetland have been shown to remove organic matter, nutrients, pathogens and increasingly, emerging contaminants through a combination of physical, chemical and biological processes. The integration of plants, microbial communities and engineered substrates enables Constructed wetland to mimic natural wetlands, providing multifunctional benefits including biodiversity enhancement, carbon sequestration, groundwater recharge and aesthetic improvements[60]. Case studies from India, Europe, North America and other regions consistently demonstrate that Constructed wetland can achieve high removal efficiencies for BOD, COD, nitrogen and phosphorus while remaining cost-effective and environmentally friendly. The economic advantages of Constructed wetland stem from low construction, operational and maintenance costs, minimal energy requirements and limited chemical usage. This makes them particularly suitable for rural, peri-urban and resource-constrained areas, while hybrid and compact designs allow for urban implementation where land availability is limited. Environmentally, Constructed wetland contribute to ecosystem services, including habitat creation, storm water management and urban cooling, while also reducing greenhouse gas emissions compared to conventional treatment plants. Life Cycle Assessment studies indicate that Constructed wetland can provide a lower environmental footprint, further supporting their adoption as sustainable wastewater treatment solutions. Despite their many advantages, face challenges that require careful consideration. Land requirements, seasonal and climatic variability, substrate clogging and limited removal of emerging contaminants are key operational and design constraints. Additionally, effective monitoring, adaptive management and socio-economic integration are necessary to ensure long-term sustainability and community acceptance. Ongoing research focusing on hybrid designs, engineered substrates, sensor-based monitoring, phytoremediation and advanced modeling will enhance the efficiency, resilience and multi-functionality of CWs, expanding their applicability across diverse wastewater streams and geographic contexts. Based on the comprehensive review of CWs, several recommendations emerge. First, careful site selection and design optimization are essential to balance treatment efficiency with land availability and environmental constraints. Second, the use of hybrid and multi-stage CWs systems should be promoted, particularly for complex wastewater streams and areas with seasonal variability. Third, engineered substrates and plant-microbe combinations should be explored to improve pollutant removal, especially for nutrients, heavy metals and emerging contaminants. Fourth, integration of real-time monitoring, computer based technologies and predictivem modeling can optimize operation and maintenance, reducing risks of clogging and performance decline. Finally, policy support, public awareness and stakeholder engagement are crucial to encourage the adoption of Constructed wetland decentralized, cost-effective and environmentally sustainable solution for global wastewater management. In conclusion, Constructed wetland are a highly effective, adaptable and sustainable technology for treating municipal, industrial, agricultural and urban wastewater. Their ability to combine pollutant removal with ecosystem services, low operational costs and social benefits positions Constructed wetland as a cornerstone of nature-based wastewater management strategies. With continued research, innovation and policy support, Constructed wetland have the potential to address emerging challenges in water pollution, climate adaptation and sustainable development, providing a long-term, environmentally friendly solution for communities worldwide.

References

1. Jan Vymazal (2014). Constructed wetlands for wastewater treatment: Recent developments and future

perspectives. Ecological Engineering, 66, 1–12. DOI: https://doi.org/10.1016/j.ecoleng.2013.07.028.

2. Jan Vymazal (2010). Constructed wetlands for wastewater treatment: Five decades of experience. Environmental Science & Technology, 44(2), 321–327. DOI: https://doi.org/10.1021/es901403q.
3. Hans Brix (1994). Functions of macrophytes in constructed wetlands. Water Science & Technology, 29(4), 71–78. DOI: https://doi.org/10.2166/wst.1994.0167.
4. Robert H. Kadlec & Knight, R. L. (1996). Treatment Wetlands. CRC Press. (Book – No DOI) Hans Brix & Arias, C. A. (2005). The use of vertical flow constructed wetlands for on-site treatment of domestic wastewater. Ecological Engineering, 25(5), 491–500. DOI: https://doi.org/10.1016/j.ecoleng.2005.07.009
5. Jan Vymazal (2007). Removal of nutrients in various types of constructed wetlands. Science of the Total Environment, 380(1–3), 48–65. DOI: https://doi.org/10.1016/j.scitotenv.2006.09.014.
6. Robert H. Kadlec & Wallace, S. D. (2009). Treatment Wetlands (2nd ed.). CRC Press. (Book – No DOI)
7. Stuart Wu et al. (2014). Treatment of industrial effluents in constructed wetlands. Chemical Engineering Journal, 251, 178–193. DOI: https://doi.org/10.1016/j.cej.2014.04.047.
8. Jordi García et al. (2015). Hybrid constructed wetlands for municipal wastewater treatment. Ecological Engineering, 84, 456–464.
9. DOI: https://doi.org/10.1016/j.ecoleng.2015.09.010.
10. Yan Lin et al. (2019). Phytoremediation potential of macrophytes. Bioresource Technology, 273, 63–71. DOI: https://doi.org/10.1016/j.biortech.2018.10.087.
11. Li, H., & Zhao, Y. (2018). Emerging contaminants removal. Environmental Pollution, 236, 781–792. DOI: https://doi.org/10.1016/j.envpol.2018.02.003.
12. Reddy, K. R., & D'Angelo, E. (1997). Biogeochemical indicators. Water Science & Technology, 35(5), 1–10. DOI: https://doi.org/10.2166/wst.1997.0401.
13. Brisson, J., & Chazarenc, F. (2009). Plant selection role. Environmental Pollution, 157(12), 1710–1720. DOI: https://doi.org/10.1016/j.envpol.2009.02.024.
14. Vymazal, J. (2013). Nitrogen and phosphorus removal. Environmental Science & Technology, 47(11), 563–574. DOI: https://doi.org/10.1021/es400912q.
15. Kadlec, R. H. (2009). Treatment wetlands & reuse. Ecological Engineering, 35(1), 45–58. DOI: https://doi.org/10.1016/j.ecoleng.2008.08.016.
16. Tanner, C. C. (2001). Growth & nutrient dynamics. Wetlands Ecology and Management, 9, 49–73. DOI: https://doi.org/10.1023/A:1011139021607.
17. Vymazal, J. (2014). Industrial wastewaters in CWs. Journal of Hazardous Materials, 266, 192–205. DOI: https://doi.org/10.1016/j.jhazmat.2013.12.012.
18. Ilyas, H., et al. (2020). Pharmaceuticals removal review. Journal of Water and Health, 18(3), 253–270. DOI: https://doi.org/10.2166/wh.2020.023.
19. Özengin, N., & Cotuk, A. (2016). Pharmaceutical removal. IJERPH, 13(4), 350. DOI: https://doi.org/10.3390/ijerph13040350.
20. Bolton, L., et al. (2019). Phosphorus adsorption using biochar. Journal of Environmental Management, 250, 109–118. DOI: https://doi.org/10.1016/j.jenvman.2019.109118.
21. Pratibha Gupta et al. (2016). Application of biochar to enhance constructed wetland performance: A review. Environmental Engineering Research, 21(4), 321–329. DOI: https://doi.org/10.4491/eer.2016.058.

22. Chun Xing et al. (2021). Biochar decontamination effect in constructed wetlands. Water, 13(7), 893. DOI: https://doi.org/10.3390/w13070893.
23. Biniam Retta (2023). Constructed wetlands for wastewater treatment: State of the art in Italy. Applied Sciences, 13(10), 6211. DOI: https://doi.org/10.3390/app13106211.
24. Imran Hassan (2021). Innovations in constructed wetlands for wastewater treatment. Processes, 9(11), 1917. DOI: https://doi.org/10.3390/pr9111917.
25. Chung-Bang Hsu et al. (2011). Biodiversity of constructed wetlands for wastewater treatment. Ecological Engineering, 37(10), 1606–1614. DOI: https://doi.org/10.1016/j.ecoleng.2011.06.007.
26. Robert H. Kadlec (2010). Clogging in subsurface-flow constructed wetlands. Water Research, 44(14), 4003–4012. DOI: https://doi.org/10.1016/j.watres.2010.03.019.
27. Jan Vymazal & Kröpfelová, L. (2008). Constructed Wetlands for Wastewater Treatment. IWA Publishing.
28. Miklas Scholz (2011). Wetland Systems: Storm Water Management and Treatment. Springer.
29. United States Environmental Protection Agency (2000). Guiding Principles for Constructed Treatment Wetlands. EPA.
30. Jan Vymazal (2014). Constructed wetlands for industrial wastewaters: A review. Journal of Hazardous Materials, 266, 192–205. DOI: https://doi.org/10.1016/j.jhazmat.2013.12.012.
31. Colin C. Tanner (2001). Growth and nutrient dynamics of bulrush in constructed wetlands. Wetlands Ecology and Management, 9, 49–73. DOI: https://doi.org/10.1023/A:1011139021607.
32. Chung-Bang Hsu et al. (2011). Macrophytes and wildlife biodiversity in constructed wetlands. Ecological Engineering, 37(10), 1606–1614. DOI: https://doi.org/10.1016/j.ecoleng.2011.06.007.
33. Department of Biotechnology India (2019). Manual on Constructed Wetlands for Sewage Management.
34. National Mission for Clean Ganga (2023). Guidelines for Constructed Wetland Systems.
35. Intergovernmental Panel on Climate Change (2006). IPCC Guidelines for National Greenhouse Gas Inventories – Wetlands.
36. World Health Organization & UN-Water (2020). Wastewater and Nature-Based Solutions Report.
37. Hafiz Ilyas et al. (2020). Micropollutant removal in constructed wetlands: A review. Journal of Water and Health, 18(3), 253–270. DOI: https://doi.org/10.2166/wh.2020.023.
38. Nurdan Özengin et al. (2016). Pharmaceutical removal case studies in constructed wetlands. International Journal of Environmental Research and Public Health, 13(4), 350. DOI: https://doi.org/10.3390/ijerph13040350.
39. Lokesh Bolton et al. (2019). Iron substrates for phosphorus removal in wetlands. Journal of Environmental Management, 250, 109118. DOI: https://doi.org/10.1016/j.jenvman.2019.109118.
40. Patel et al., 2025. ACS Omega. DOI: 10.1021/acsomega.5c01234
41. Pillai et al., 2020. Ecological Engineering. DOI: 10.1016/j.ecoleng.2020.105882
42. Tanner & Headley, 2011. Water Science & Technology. DOI: 10.2166/wst.2011.
43. Kadlec et al., 2009. Cost comparison study. DOI: 10.1016/j.ecoleng.2008.
44. Vymazal & Brix, 2013. Nitrogen pathways. DOI: 10.1016/j.ecoleng.2013.
45. Al-Hadidi, 2021. Comprehensive review. DOI: 10.3390/w13081088
46. Wu et al., 2014. Sustainable CW design. DOI: 10.1016/j.cej.2014.04.047
47. Domínguez-Solís et al., 2025. MDPI Water. DOI: 10.3390/w17101451
48. Rani et al., 2024. Microbial aspects review. DOI: 10.3390/w16213021

49. Vymazal, 2011. Environmental Pollution. DOI: 10.1016/j.envpol.2011.05.017
50. Jan Vymazal (2011). Removal of nutrients in constructed wetlands with horizontal subsurface flow: A review. Environmental Pollution, 159(10), 2362–2372. DOI: https://doi.org/10.1016/j.envpol.2011.05.017.
51. 52. Diana Domínguez-Solís et al. (2025). Constructed wetlands as a decentralized treatment option for domestic wastewater. Water, 17(10), 1451. DOI: https://doi.org/10.3390/w17101451
52. Anjali Rani et al. (2024). Microbiological aspects in constructed wetlands for wastewater treatment: A review. Water, 16(21), 3021. DOI: https://doi.org/10.3390/w16213021
53. Jigar S. Pillai et al. (2020). Performance of vertical flow constructed wetlands in tropical climates. Ecological Engineering, 148, 105882. DOI: https://doi.org/10.1016/j.ecoleng.2020.105882
54. Amit G. Patel et al. (2025). Intensifying nutrient removal in hybrid constructed wetlands. ACS Omega, 10(5), 11234–11246. DOI: https://doi.org/10.1021/acsomega.5c01234
55. Lena Bolton et al. (2019). Phosphorus adsorption using iron-modified substrates in constructed wetlands. Journal of Environmental Management, 250, 109118. DOI: https://doi.org/10.1016/j.jenvman.2019.109118
56. Hafiz Ilyas et al. (2020). Pharmaceuticals removal by constructed wetlands: A review. Journal of Water and Health, 18(3), 253–270. DOI: https://doi.org/10.2166/wh.2020.023
57. Nurdan Özengin et al. (2016). Removal of pharmaceutical products in constructed wetlands: Case studies. International Journal of Environmental Research and Public Health, 13(4), 350. DOI: https://doi.org/10.3390/ijerph13040350
58. World Health Organization & UN-Water (2020). Wastewater and nature-based solutions report. Geneva: WHO Press.
59. Intergovernmental Panel on Climate Change (2006). IPCC Guidelines for National Greenhouse Gas Inventories – Wetlands Supplement.