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# A MINI-REVIEW ON CONSTRUCTED WETLANDS FOR REMOVING EMERGING CONTAMINANTS: A SUSTAINABLE SOLUTION FOR DEVELOPING COUNTRIES

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**Abstract**. Constructed wetlands (CWs) represent an innovative, cost-effective, and sustainable solution for wastewater treatment, particularly in addressing emerging contaminants (ECs) that evade conventional treatment methods. These engineered ecosystems leverage natural processes involving macrophytes, microbial communities, and filtration media to enhance pollutant removal. This review explores various CW configurations, including surface flow (SF), subsurface flow (SSF), and hybrid systems, highlighting their efficiency in removing ECs such as pharmaceuticals, heavy metals, microplastics, and synthetic organic compounds. Key design parameters, including hydraulic retention time (HRT), hydraulic loading rate (HLR), substrate selection, and plant species, play a crucial role in optimizing treatment performance. Removal mechanisms such as adsorption, microbial degradation, phytoremediation, and photodegradation are extensively analyzed to elucidate their contribution to pollutant reduction. Studies indicate that CWs achieve significant removal efficiencies, with some systems eliminating over 90% of ECs through synergistic biogeochemical processes. The integration of biochar and advanced substrate materials further enhances contaminant adsorption and microbial activity. Despite their effectiveness, challenges remain in optimizing CWs for varying wastewater compositions and environmental conditions. As global concerns over water pollution intensify, CWs offer an adaptable and environmentally friendly alternative to conventional treatment technologies, particularly in resource-limited regions. This review underscores the necessity for continued research into optimizing CW performance through innovative design modifications, enhanced microbial consortia, and hybrid wetland systems tailored to specific contaminant profiles. By bridging ecological engineering principles with sustainable wastewater treatment, CWs hold great potential for mitigating EC pollution and promoting environmental resilience.
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**Keywords**: Wetlands, Filtration, Remediation, Treatment, Pollutants

## 1. Introduction

Developing countries can use Constructed Wetlands (CWs) as an attractive sustainable wastewater treatment solution because of their potential to handle environmental issues. This review assesses the implementation of constructed wetlands that removes emerging pollutants which standard wastewater systems neglect to manage properly. The research examines CW operational efficiency together with design specifications and environmental advantages essential for sustainable resource management in limited resource environments [1].

The environment contains various unmonitored pollutants that belong to the category of emerging contaminants which include pharmaceuticals and personal care products alongside heavy metals and synthetic chemicals. Water bodies contain these contaminants mainly because of industrial effluents and domestic wastewater and agricultural runoff and urban surface runoff [2], [3]. Traditional pollutants differ from ECs because these compounds maintain their presence in aquatic environments which creates widespread environmental and health threats. The bioactivity of many pharmaceutical substances at low doses creates environmental damage to aquatic ecosystems and human hormonal systems [4].

ECs together with pharmaceuticals and industrial chemicals create substantial threats to both ecosystems and human health which requires new innovative treatment methods [5]. [6]. The review examines published research about CW effectiveness against pollutants through assessments of different configurations and operational parameters and plant species selection for optimal treatment results [7]. [8]. Constructed wetlands demonstrate their worth by providing affordable sustainable water treatment alternatives to traditional waste management systems since they enable growing regions to achieve effective wastewater management sustainably [1]. [9].

## 2. Types and Design of Constructed Wetlands for EC Removal

Constructed wetlands (CWs) are engineered systems designed to utilize natural processes for the treatment of wastewater. They are classified based on their design and operational characteristics into three primary types: surface flow (SF) wetlands, subsurface flow (SSF) wetlands (which may be further divided into horizontal and vertical flow), and hybrid systems that combine elements of both SF and SSF wetlands.

### *2.1 Surface Flow Wetlands (SF)*

Surface Flow Wetlands replicate natural wetlands through their design which enables wastewater to flow across vegetation-bearing substrates. Open water surfaces define these wetlands which serve as habitats for aquatic plants and animals. SF wetlands use vegetation to facilitate three main treatment processes which include sedimentation followed by filtration and biological processes [10]. The research indicates that SF wetlands effectively decrease emerging contaminants (ECs) through adsorption and microbial degradation processes (Dong et al., 2017). The operational efficiency of SF wetlands depends on hydraulic loading rates alongside the selected vegetation types [11] which creates additional challenges for operational and design strategies

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### *2.2 Subsurface Flow Wetlands (SSF)*

The wastewater treatment process using subsurface flow systems allows the water to pass beneath the ground surface which blocks atmospheric contact and minimizes odor emissions. The two main types of subsurface flow wetlands are horizontal flow constructed wetlands (HFCW) and vertical flow constructed wetlands (VFCW). The horizontal flow system distributes wastewater across the substrate to enable microbial contact with the bed material. Vertical flow systems allow wastewater to move downward through the substrate to create sequential aerobic and anaerobic conditions that improve nitrogen treatment along with other contaminant removal [12]. Vertical flow systems demonstrate superior nitrogen removal capabilities because their oxygen-rich environment supports nitrification processes according to [13].

### *2.3 Hybrid Systems*

The combination of SF and SSF designs in hybrid systems enables improved treatment performance through their unified benefits. The combination of these systems enables staged sequencing that improves the removal rates of nitrogen and organic matter contaminants [14]. Hybrid systems demonstrate strong capabilities in managing fluctuating wastewater inflow rates and changing pollutant loads which enables them to serve different applications throughout diverse climatic regions and geographical locations [15].

### *2.4 The removal efficiency of constructed wetlands*

This depends on two main design parameters. Multiple essential design elements determine how well constructed wetlands treat wastewater and eliminate emerging contaminants. The design parameters that influence CW performance consist of hydraulic retention time (HRT) and hydraulic loading rate (HLR) as well as macrophyte selection and substrate utilization.

#### *2.4.1 Hydraulic Retention Time (HRT) and Hydraulic Loading Rate (HLR)*
Hydraulic retention time and hydraulic loading rate serve as essential hydrological factors which determine how long wastewater stays in wetland systems. The average water stay duration in wetlands is known as HRT and longer retention times lead to better pollutant removal because they support extended microbial activity and improved biogeochemical processes [16]. Research demonstrates that achieving the best possible HRT conditions leads to successful denitrification and nutrient removal processes [17]. The water volume entering the wetland per unit area per time period is known as HLR which determines how water flows and distributes throughout the system. The performance of pollutant removal improves with longer retention times achieved through low hydraulic loading rates but excessive loading rates can cause short-circuiting and ineffective treatment [18], [19]. Improving CW efficiency for complex waste treatment requires proper optimization of both HRT and HLR.

#### *2.4.2 Choice of Macrophytes*
Constructing wetlands depends heavily on selecting appropriate macrophytes as this directly impacts their operational performance. The pollutant removal process of constructed wetlands depends on three macrophytes including Phragmites australis, Typha latifolia, and Limnocharis flava which remove pollutants through uptake mechanisms and rhizodeposition and by hosting beneficial microorganisms [20]. A wetland's selected plant species influence both its microbial and nutrient cycle operations and establish the ecosystem's total makeup. The plant species Typha latifolia demonstrates strong growth potential and environmental adaptability which makes it applicable for multiple CW applications [21]. The removal performance of particular macrophyte species depends on both environmental factors and the target contaminants in the treatment system.

#### *2.4.3 Substrate Materials*
Constructed wetlands depend heavily on substrate materials for achieving optimal removal efficiency. The selection of gravel alongside sand and biochar and activated carbon as substrate types determines hydraulic behavior and microbial growth and nutrient capture abilities [22]. Gravel maintains a stable support structure alongside perfect oxygen accessibility yet biochar serves for efficient carbon storage alongside nutrient trap capability through its open structure [16]. The treatment potential of activated carbon is enhanced because it effectively adsorbs various pollutants including some ECs. Soil features and chemical elements form microbial communities which in turn define pollutant removal power and influence treatment results.

## 3. Removal Mechanisms of Emerging Contaminants in Constructed Wetlands
Several physical and biological functions along with chemical processes drive the complex removal procedure of emerging contaminants within constructed wetlands. These mechanisms fall into four different categories: adsorption and filtration alongside microbial degradation as well as phytoremediation and volatilization and photodegradation.

### *3.1 Adsorption and Filtration*
The elimination of ECs depends heavily on the combined power of Adsorption and Filtration processes. The physical adsorption and filtration processes occur through substrates such as gravel, sand and biochar which function as effective trapping mechanisms in constructed wetlands. The large surface area of granular materials enables wastewater to adhere pollutants thus lowering their concentration during the flow process [23]. Biochar shows exceptional performance in adsorption processes because its porous nature enables strong retention of organic pollutants and heavy metals. Wetland systems achieve higher overall effectiveness when different substrate types are used together to capture a wide range of contaminants [12].

### *3.2 Microbial Degradation*
Constructued wetlands use Microbial Degradation as an essential process to degrade pharmaceuticals and organic pollutants. Different microbial communities in CWs' anaerobic and aerobic zones use enzymatic activity to break down various ECs [24]. Research indicates that particular bacterial strains transform multiple contaminants into less dangerous substances [23]. The stabilizing biological decomposition

processes depend heavily on microbial populations which display performance changes based on temperature conditions and pH levels and substrate availability [25]. The degradation system enables pollutant removal and stimulates nutrient circulation throughout the wetland ecosystem [26].

### *3.3 Phytoremediation*

Wetland plants act as active pollutant and metal concentrators through their root systems to directly take up organic substances and metals by means of phytoremediation. The water pollutant reduction process is supported by Phragmites australis and Typha latifolia which exhibit strong contaminant uptake abilities according to[27]. Through rhizodeposition macrophytes enhance microbial degradation by supplying organic compounds that stimulate microbial activity [26]. Plants use their physiological mechanisms to transform dangerous substances which enhances the total treatment performance of constructed wetlands [28].

### *3.4 Volatilization and Photodegradation*

Two essential degradation methods for constructed wetlands exist through Volatilization and Photodegradation. The photolytic reactions triggered by sunlight transform specific ECs with lower molecular weights into non-harmful byproducts [29]. The volatility of particular contaminants depends on environmental conditions including temperature and moisture levels [30]. Light and moisture work together to boost pollutant degradation in surface flow constructed wetlands because these systems allow maximum sunlight penetration.

## 4. Effectiveness of Constructed Wetlands in Removing Specific Emerging Contaminants

Constructed wetlands (CWs) serve as efficient wastewater processing facilities which successfully eliminate emerging contaminants (ECs) which comprises pharmaceuticals and personal care products (PPCPs), heavy metals, microplastics, synthetic organic compounds and nutrients. The review examines how constructed wetlands operate in these specific domains.

### *4.1 Removal of Pharmaceuticals and Personal Care Products (PPCPs)*

The degradation of pharmaceuticals and personal care products (PPCPs) occurs extensively in CWs alongside various antibiotic substances and painkillers and hormone disruptors. The wetland substrate's diverse microbial communities enable microbial degradation which drives most of the removal efficiency. Research demonstrates that CWs possess the ability to break down significant amounts of widespread pharmaceutical substances including carbamazepine and ibuprofen [31], [20]. The effective removal of these pollutants reaches above 90% through such advanced treatment practices that incorporate nutrient management and optimized wetland designs [15]. Plant species enhance biotransformation rates by releasing root exudates that stimulate microbial growth [32].

### *4.2 Removal of Heavy Metals*

Heavy metals removal occurs in CWs by means of plant uptake and substrate adsorption as well as other removal mechanisms. Wetlands utilizing hydroponic conditions enable Typha latifolia and other emergent plants to accumulate heavy metals such as lead (Pb), copper (Cu), and zinc (Zn) [33]. Research demonstrates that heavy metals adsorption occurs on substrate materials such as gravel and biochar because these materials create surfaces which allow contaminants to accumulate through ionic exchange and precipitation processes [34]. Biochar demonstrates exceptional characteristics for metal ion adsorption because it possesses both a large surface area and strong metal ion attraction properties [19].

### *4.3 Removal of Microplastics and Synthetic Organic Compounds*

The filtering function in constructed wetlands enables substantial elimination of microplastics along with synthetic organic compounds. The physical filtration process of CWs depends on vegetation and substrate which capture microplastics within the spaces between gravel and organic matter [35]. Biofilm development on substrate surfaces boosts biodegradation rates because microorganisms attached to the biofilms break down synthetic chemicals present in wastewater [31]. The initial research shows CWs effectively capture 90% of microplastic pollutants thus establishing them as a promising sustainable method for addressing this widespread environmental problem [36]. The integration of particular plant species which enhance retention and degradation processes enables constructed wetlands to reach maximum efficiency in solving this problem.

### *4.4 Removal of Nutrients*

Constructed wetlands serve as effective tools to reduce water body pollution by removing phosphates and nitrates which cause eutrophication risks. Plant life within wetlands helps transform nutrients while absorbing them which results in decreased environmental release of nitrogen compounds and phosphorus [37]. The scientific literature demonstrates that CWs maintain greater than 70% efficiency in nutrient reduction through biological processes including denitrification and plant tissue bioaccumulation [38]. The continual microbial activities within constructed wetlands help convert dangerous nitrates into nitrogen gas to support water quality enhancements and ecosystem health improvement [39].

## 5. The Role of Biochar in Enhancing Pollutant Removal in Constructed Wetlands

Biochar has emerged as an important tool to boost the wastewater treatment capacity of constructed wetlands (CWs) by removing multiple contaminants. Biochar derived from biomass using pyrolysis emerges as an exceptional environmental remediation tool because it retains nutrients well and benefits microbial communities positively while showing strong adsorptive behavior.

### *5.1 Adsorptive Properties of Biochar*

Biochar possesses outstanding adsorptive properties toward pharmaceuticals and heavy metals and organic contaminants because of its physical and chemical characteristics. Biochar demonstrates effective pharmaceutical compound adsorption properties that minimize their availability in constructed wetlands [40]. The porosity of biochar structures along with its extensive surface area extends its capability to absorb toxic heavy metals such as Pb, Cd, and Cu that leads to reduced pollutant concentrations in wastewater [41], [42]. Biochar demonstrates its effectiveness as a pollutant remover through two mechanisms: its strong absorption capabilities combined with its capability to transform CW substrate characteristics and boost the entire wetland system functionality.

### *5.2 Impact on Microbial Activity and Nutrient Retention*

Biochar acts as a vital factor that shapes microbial communities which exist in constructed wetlands. Biochar creates an environment that allows microorganisms to build biofilms which enhances biochemical processes and pollutant breakdown [43]. The incorporation of biochar enables microbial populations to grow more substantial and increases their enzymatic functioning which strengthens system nutrient cycling [44]. The improved microbial cell density accelerates organic pollutant decomposition and enables two valuable microbial transformations to occur simultaneously namely denitrification which removes wastewater nitrogen [45].

## 6. Challenges and Limitations of Constructed Wetlands for Emerging Contaminant Removal

Constructive wetland installations have demonstrated potential as an effective wastewater treatment system to eliminate emerging contaminants. Various obstacles alongside attractive properties prevent constructed wetlands from becoming a pervasive solution for operational efficiency. The following analysis examines the main obstacles faced by constructed wetlands which include variable removal performance because of environmental and seasonal changes and accumulation risks of pollutants in plant matter and sediment as well as space and land requirements and operational and maintenance difficulties.

### *6.1 Variability in Removal Efficiency Due to Climate and Seasonal Changes*

The removal efficiency of constructed wetlands shows significant variability because climate along with seasonal patterns play a dominant role in these systems. [46] established that temperature conditions and precipitation patterns and seasonal shifts control the hydraulic loading rates together with retention times in these systems. Constructed wetlands deliver inconsistent performance based on climatic patterns that control drainage conditions and loading patterns as colder temperatures slow necessary microbial denitrification processes needed for nitrogen removal in winter periods [47]. Unpredictable loading rate patterns decrease the capability of utilizing constructed wetlands as sustainable permanent wastewater solutions,

### *6.2 Risk of Contaminant Accumulation in Plant Biomass and Sediments*

Built wetlands face an important challenge because contaminants tend to build up inside plant matter and sediment deposits. Plant absorption work as efficient pollutants and nutrients processors despite running the risk of harmful substance accumulation such as heavy metals and persistent organic pollutants [48]. Plant material containing accumulated contaminants would represent a danger if it were used improperly for example as fodder or agricultural compost. Wetland sediments tend to accumulate pollutants which becomes a concern for sediment control and later could potentially release contaminants into the water column when disturbance happens through flooding or drought events [49]. The challenge requires constant monitoring and proper management practices to stop potential risks from contaminant accumulation.

### *6.3 Land and Space Requirements*

Constructed wetlands need extensive land areas and space to reach high pollutant removal goals. Constructed wetlands need significant property space which creates a major inconvenience in densely inhabited city areas along with regions having expensive and scarce land availability. Constructed wetlands tend to occupy more space than standard treatment methods such as activated sludge systems or membrane bioreactors because they provide comparable or better treatment results [50]. The physical size of constructed wetlands presents challenges for their implementation when land use conflicts with alternative development plans such as housing or commercial projects [51].

### *6.4 Maintenance and Operational Challenges*

The practicality and effectiveness of constructed wetlands depend heavily on operational challenges that need to be addressed. The operation of CWs demands continuous maintenance work which includes plant management alongside substrate renewal and water quality parameter assessment [52]. Invasive plant species create obstacles for maintenance operations which negatively affects the operational functionality of the system. The successful management of microbial communities in wetland systems depends on controlling external factors that affect water quality because it determines optimal pollutant removal [53]. Environmental variations create complications for microbial populations and their operational functions which reduces the reliability of maintenance operations.

## 7. Future Perspectives and Research Gaps

CWs function as promising wastewater treatment solutions while managing the presence of new environmental contaminants. The growing appreciation of wetlands' environmental merits leads research to concentrate on improvements in wetland structure together with performance tracking and decentralized implementations and policy standards. The effectiveness of CWs in wastewater management will improve through proper attention to these critical areas.

### *7.1 Innovations in Wetland Design*

Research developers have started implementing hybrid technologies along with biochar-integrated systems to boost constructed wetlands' operational performance. Several treatment types can be combined into hybrid wetlands because this arrangement permits their individual strengths to boost complete purification outcomes [54]. Biochar integration with CWs improves their adsorption capacity for heavy metals and organic compounds which leads to higher pollutant removal rates [55]. Additional studies about biochar's chemical reactions with different pollutants will help scientists determine which plants to combine with biochar for enhanced wastewater treatment results. The creation of tailored flow systems would improve wastewater treatment results when dealing with wastewater from agricultural runoff or industrial sources [56].

### *7.2 Long-term Performance Monitoring and Modeling*

Constructed wetlands require strong monitoring alongside proper modeling systems which capture variations displayed by removal processes during different seasonal periods. Long-term performance monitoring of CWs requires continuous evaluation which serves to track their temporal evolution and their response to climate changes and their lasting effects on biological cycles and pollutant breakdown [57]. Remote sensing-based numerical models assist CWs design optimization through performance prediction based on environment factor. The implementation of innovative approaches stands as a vital factor for CWs' effective operation which makes them reliable wastewater management solutions.

### *7.3 Potential for Decentralized Wastewater Treatment Applications*

Decentralized installation of CWs functions successfully as an option that surpasses large wastewater treatment plants for both rural and developing regions. Communities can use Constructed Wetlands to lower their expenses for central systems while simultaneously improving water quality in their area [52]. CWs offer an attractive solution for decentralized wastewater treatment because they 8the scalability of constructed wetlands according to different community demographics and wastewater characteristics combined with investigations into community reception as well as regulatory support for decentralized wastewater treatment projects.

### *7.4 Policy Recommendations for Integrating CWs in Wastewater Management*

The adoption of constructed wetlands as wastewater management standards requires supportive policies and regulations to establish their position in wastewater management frameworks. Governments together with environmental agencies need to support CW research efforts and create financial benefits for urban planning and infrastructure development to use CWs [58]. Established standards for CW design and performance would create uniform and reliable treatment results [59]. Public education campaigns must be implemented to educate people about constructed wetlands advantages and dispel incorrect beliefs regarding their performance. The backing from the public helps communities accept CWs better and enables their integration into regional environmental management plans.

## 8. Conclusion

CWs serve today as sustainable wastewater treatment facilities that effectively remove emerging contaminants (ECs) although these facilities represent an alternative to standard wastewater processing systems. The combined use of macrophytes with microbial degradation combined with adsorption processes and engineered substrates leads to effective treatment results for pharmaceuticals alongside heavy metals microplastics and various other ECs. CW systems serve different wastewater needs through their Surface Flow model and Subsurface Flow model and Hybrid designs which adapt to multiple water conditions. The performance of CW systems increases dramatically through proper adjustments of hydraulic retention time and hydraulic loading rate and selection of optimal substrates. Biochar and advanced filtration media act as performance enhancers for CW systems because they enhance the absorption of contaminants and improve microbial functions.

CWs succeed at treating pollutants effectively yet their extensive land use footprint along with changes in performance throughout the year creates operational obstacles. The advancement of constructed wetlands should aim to add new design elements that combine aerated wetlands and bio-augmented microbial communities to improve contaminant breakdown. The long-term evaluation of treatment sites together with optimized operations must receive continuous monitoring to optimize treatment results. CWs emerge as a promising nature-based solution to address sustainable wastewater management because they provide effective water quality improvement in areas with limited economic resources and insufficient infrastructure. The farther development of such systems will ensure protection of water resources and ecological health.

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