

Review Article

Designing of a Wetland System for the Treatments of Different Types of Wastewater: A Review

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Abstract

Wastewater pollution is a critical global challenge, particularly from diverse and potent sources like textile manufacturing, service stations, and clinical facilities. These effluents, laden with an array of harmful substances from vibrant dyes, heavy metals, and processing chemicals in textile wastewater, to oil, grease, hydrocarbons, and detergents from service stations, and the complex cocktail of pharmaceutical residues, pathogens, and disinfectant byproducts from clinical settings pose significant threats to aquatic ecosystems and human health. Traditionally, treating such variegated and persistent pollutants demands energy-intensive and chemical-heavy conventional methods. However, a promising and sustainable approach lies in the ingenious design of constructed wetland systems. Mimicking nature's own filtration and purification processes, these engineered ecosystems leverage the combined power of specific plants (macrophytes), a diverse microbial community, and a porous substrate (like gravel and sand) to effectively treat complex wastewater streams. Within these systems, plants absorb and accumulate pollutants (phytoremediation), microorganisms break down organic matter and transform contaminants, while the substrate physically filters solids and provides an anaerobic environment for specific biochemical reactions. It's a multi-faceted, low-energy, and environmentally benign process. The brilliance of designing a single, integrated wetland system for multiple wastewater streams textile, service station, and clinical lies in its potential for efficiency and resource optimization. Such a system offers a cost-effective, low-maintenance alternative that requires minimal chemical input. Beyond purification, these constructed wetlands can enhance local biodiversity, create valuable green spaces, and even support the reuse of treated water for non-potable purposes. Crucially, the system must be meticulously designed, considering the specific pollutant load, flow rates, and characteristics of each wastewater type to ensure optimal performance and compliance with stringent discharge standards. This holistic approach represents a beacon of sustainable wastewater management, demonstrating how ecological engineering can harness natural purification power to mitigate pollution, protect our planet, and foster healthier.

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Keywords

Wastewater Treatment, Wetland, Nitrogen Cycle, Microbial Activities, Non Edible Plants

1. Introduction

The escalating global population, rapid industrialization, and intensifying agricultural practices have placed immense pressure on finite freshwater resources, leading to a significant increase in wastewater generation. Conventional wastewater treatment plants (WWTPs), while effective, are often characterized by high energy consumption, substantial operational and maintenance (O&M) costs, and the generation of large volumes of sludge, posing environmental and economic challenges [1, 2]. In response to these limitations, there has been a global paradigm shift towards more sustainable, environmentally friendly, and economically viable nature-based solutions (NBS) for water purification [3]. Among these, constructed wetland (CW) systems have gained considerable prominence as a robust and adaptable technology for treating a wide spectrum of wastewaters [4].

Constructed wetlands are engineered systems designed to mimic the pollutant removal processes observed in natural wetlands. They typically consist of a shallow basin, a substrate (such as gravel, sand, or soil), and emergent or submerged aquatic vegetation, all interacting with a diverse microbial community to facilitate water purification [5]. Their appeal lies in their low energy requirements, minimal operational complexity, aesthetic value, potential for biodiversity enhancement, and capacity to treat various contaminants simultaneously [4, 6].

However, the effective design of a CW system is paramount to its long-term performance and sustainability [7]. A "one-size-fits-all" approach is rarely successful, as the characteristics of different wastewaters can vary dramatically in terms of pollutant type, concentration, flow rate, and temporal variability [8]. For instance, domestic wastewater primarily contains biodegradable organics, nutrients, and pathogens, while industrial effluents might be laden with heavy metals, recalcitrant organic compounds, or extreme pH levels [9, 10]. Agricultural runoff often carries high nutrient loads and pesticides, and stormwater presents challenges due to its intermittent,

high-volume nature and diverse urban pollutants [11, 12]. Landfill leachate, on the other hand, is characterized by its high strength, complex organic matrix, and high ammonia concentrations [13].

Nitrogen is an element which is having various oxidation numbers and also found as different compounds in various systems foremost of the wastewater, although nitrogen is considered as a nutrient that is present especially in the form of nitrate in the streams of water [14]. But the excess nitrogen in the water may cause some adverse impacts such as health issues and eutrophication [15]. Therefore, the removal of excess nitrogen is an essential process for water treatment, especially in the treatments of drinking water. When considering the methodologies for the removal of nutrients from water, the wetland system is a predominantly used method across most treatment plants [15]. Basically, the nitrogen removing process is classified as a biological treatment process because this is linked with the important chemical reactions of the nitrogen cycle [14]. The importance of the nitrogen cycle in the construction of wetlands is detailed further below.

Usually, it is an element that represents most oxidation numbers that are feasible for a non-metallic element. Nitrogen is found in high amounts in most wastewater streams because of the relatively higher nitrogen in agricultural wastes and sewage wastes, and excess nitrogen may adversely affect human health and cause eutrophication [15].

A wetland is a land area that percolates water from some particular inlet or more inlets and discharges from one or more outlets [16]. Usually, naturally occurring wetlands such as marshlands can be found alongside constructed wetlands as well [17]. When considering the parts of a typical wetland, it consists of a few natural components, and those components play major roles in the purification of water flowing through the wetland [5]. The components of the wetland and their functions are outlined in Table 1.

Table 1. The components of wetland and their functions.

Component	Materials	Functions
Vegetation	Canary grass, wild rice	Produce oxygen, sedimentation of the suspended solids in the flowing water, uptake excess nutrients from the flowing water
Soil/substrate	Soil, sand,	Provide large area for chemical and biological processes, adjust the hydraulic retention time of the

Component	Materials	Functions
	gravel, rocks	flow, removal of suspended solids and pollutants
Living organisms	Bacteria, fungi, protozoa	Help in the biochemical reactions
Water column	Water	Media for the biochemical reactions

Usually in the wetlands there can be categorized the purification of waste water by removing a few of contaminants as given in the below.

- 1) Organic matters
- 2) Suspended solids
- 3) Pathogens

4) Toxic compounds

5) Excess nutrients

The removal of such pollutants in the wetland systems it can be categorized in to various treatments according to the conditions of required and removals as given in the [Table 2](#).

Table 2. The processes of the removals of pollutants from the wastewater.

Process	Removals	Reactions/ actions
Physical process	Suspended solids	Sedimentation, precipitation
Chemical process	Heavy metals	Precipitation and photochemical reactions
Biochemical process	Pollutants and nutrition	Photosynthesis, respiration, nitrification, de-nitrification

The biochemical processes of the removal of nutrients from the waste water in the wetland system can be explained with

the possible processes of the nitrogen cycle as explained in the below.

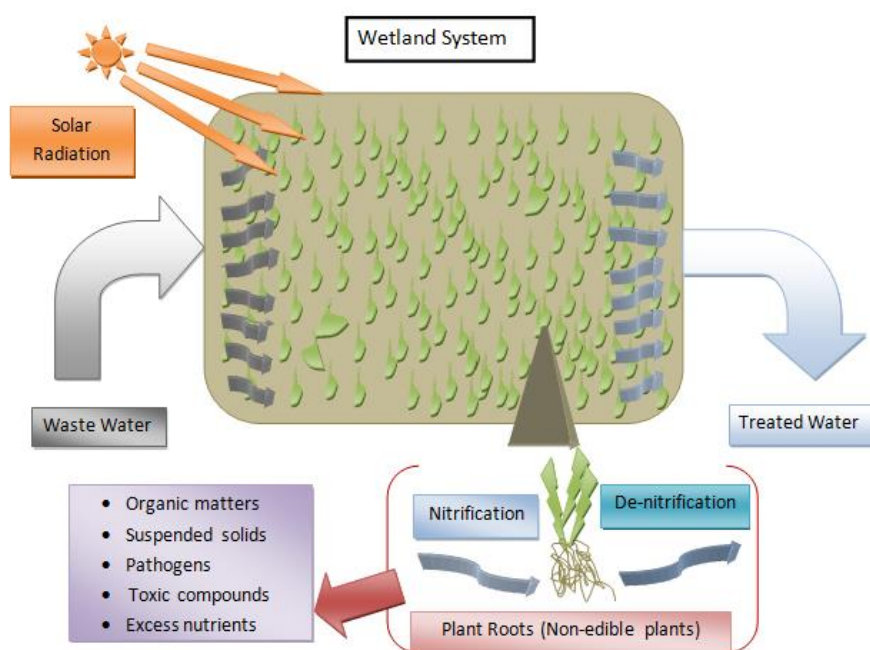


Figure 1. A systematic diagram of a typical wetland system for wastewater treatments.

This review aims to synthesize the current understanding of designing CW systems specifically tailored for the treatment of these diverse types of wastewaters [7]. It will explore the fundamental classifications of CWs, detail the underlying treatment mechanisms, and critically examine the key design parameters and considerations that must be adapted to each wastewater type. By highlighting the intricacies of design, operation, and future outlook, this paper seeks to provide a comprehensive resource for researchers, engineers, and policy-makers involved in implementing sustainable wastewater management solutions.

2. Classification of Constructed Wetland Systems

Constructed wetlands are broadly categorized based on the hydrologic regime and the flow path of water through the system [5, 17]. The selection of a particular type is often influenced by factors such as available land area, target pollutants, desired effluent quality, climate, and cost [4].

2.1. Free Water Surface (FWS) Wetlands

FWS wetlands, also known as surface flow wetlands, closely resemble natural marshes [17]. They consist of a shallow basin (typically 0.1-0.6 m deep) with a relatively impermeable base, filled with a shallow layer of water flowing over a substrate (often soil) in which emergent vegetation (e.g., reeds, cattails) is rooted. The water surface is exposed to the atmosphere, allowing for direct interaction with solar radiation and atmospheric oxygen.

2.1.1. Characteristics

Large surface area, visible water, relatively simple construction, aesthetic appeal, good for habitat creation [16].

2.1.2. Treatment Mechanisms

Primary removal processes include sedimentation, filtration by plant stems and roots, adsorption, anaerobic degradation in the substrate, and aerobic degradation in the water column and rhizosphere (root zone) [17]. Plant uptake also contributes to nutrient removal.

2.1.3. Advantages

Low construction cost, easy maintenance, habitat provision, good for general BOD and TSS removal, effective for large flow volumes with lower pollutant concentrations [18].

2.1.4. Disadvantages

Require large land area, potential for odor and mosquito breeding, less efficient for nutrient removal (especially nitrogen and phosphorus) compared to subsurface flow systems,

sensitive to cold climates due to exposed water surface [15, 19].

2.2. Subsurface Flow (SSF) Wetlands

SSF wetlands are designed such that the water flows horizontally or vertically through a porous media (e.g., gravel, sand, crushed rock) beneath the surface, ensuring that the water surface is not exposed to the atmosphere [5]. This design mitigates issues like odor, mosquito breeding, and provides better insulation against temperature fluctuations [19]. SSF wetlands are further divided into Horizontal Subsurface Flow (HSSF) and Vertical Subsurface Flow (VSSF) systems.

2.2.1. Horizontal Subsurface Flow (HSSF) Wetlands

In HSSF wetlands, wastewater enters at one end, flows horizontally through the porous medium, and is collected at the opposite end [17]. The wetland bed is typically saturated, creating predominantly anaerobic or anoxic conditions, except for the oxygenated rhizosphere around plant roots [20].

Characteristics

Water level is maintained below the surface, eliminating odor and mosquito issues [4].

Treatment Mechanisms

Rely heavily on microbial activity within the biofilm attached to the media and plant roots [14]. This method is excellent for BOD, TSS, and nitrification. The anoxic conditions facilitate denitrification if nitrate is present [15]. Phosphorus removal is primarily by adsorption to the media and plant uptake [21].

Advantages

No odor or mosquito problems, efficient for carbonaceous BOD and TSS removal, less sensitive to temperature fluctuations, smaller footprint than FWS for similar treatment levels [18].

Disadvantages

Prone to clogging if pre-treatment is inadequate, limited oxygen transfer restricts nitrification efficiency, less effective for pathogen removal without additional treatment [7].

2.2.2. Vertical Subsurface Flow (VSSF) Wetlands

VSSF wetlands involve intermittent dosing of wastewater onto the surface of the filtered bed, allowing it to percolate vertically through the media before being collected at the bottom [9, 22]. This intermittent loading creates alternating aerobic and anaerobic conditions within the bed.

Characteristics

Intermittent loading, typically unsaturated conditions for a period, promoting aeration [9].

Treatment Mechanisms

The alternating wet/dry cycles and vertical flow promote excellent oxygen transfer, leading to highly efficient nitrification [22]. Subsequent denitrification can occur in anaerobic zones, or in a coupled HSSF unit [23]. It is much suitable for

pathogen removal due to filtration and desiccation [24].

Advantages

High nitrification rates, better oxygen transfer, smaller footprint than HSSF for similar nitrogen removal, good for pathogen removal [9, 24].

Disadvantages

More complex operation due to pumping and intermittent dosing, higher energy consumption, susceptible to clogging if not properly designed and operated [7, 22].

2.3. Hybrid Wetland Systems

Hybrid wetland systems combine two or more different types of CWs in series or parallel to capitalize on the advantages of each system and overcome their individual limitations [15]. The most common configuration involves combining VSSF and HSSF units to achieve comprehensive nutrient removal. For example, a VSSF unit can be used for efficient nitrification, followed by an HSSF unit for denitrification, taking advantage of the oxygen-rich environment in the VSSF and the anoxic conditions in the HSSF [15, 23].

2.3.1. Characteristics

Sequential arrangement of different wetland types [18].

2.3.2. Treatment Mechanisms

Synergistic effects are combining the strengths of individual units such as VSSF for nitrification and HSSF for denitrification, leading to high overall nitrogen removal [15]. Enhanced phosphorus removal can also be achieved by selecting specific media in one of the stages [25].

2.3.3. Advantages

Superior contaminant removal efficiency, especially for nitrogen and phosphorus, greater operational flexibility, ability to treat complex wastewaters [18].

2.3.4. Disadvantages

Higher construction and O&M costs due to increased complexity, larger land area compared to single SSF units [7].

3. Understanding Different Wastewater Characteristics

The design of a CW system must be inherently linked to the specific characteristics of the wastewater it is intended to treat [7]. A thorough understanding of pollutant types, concentrations, variability, and potential toxicities is crucial for selecting the appropriate wetland type, sizing, media, and vegetation [8].

3.1. Domestic/Municipal Wastewater

Domestic wastewater, also known as municipal wastewater or sewage, primarily originates from residential, commercial, and institutional establishments.

3.1.1. Characteristics

Typically characterized by moderate concentrations of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), nitrogen (N) (primarily as ammonia), phosphorus (P), and a variety of pathogenic microorganisms (bacteria, viruses, protozoa) [9, 24]. It generally has a relatively stable flow rate and composition over time, though diurnal variations exist.

3.1.2. Treatment Goals

The primary goals for domestic wastewater treatment are the removal of organic matter (BOD/COD), suspended solids, nutrients (N and P to prevent eutrophication), and pathogens to meet discharge standards and protect public health [26].

3.1.3. Suitability for CWs

Domestic wastewater is one of the most common applications for CWs [4]. HSSF and VSSF systems, often in hybrid configurations, are highly effective for BOD, TSS, and nutrient removal, respectively [9]. Pre-treatment (e.g., septic tank, primary clarifier) is essential to remove large solids and protect the wetland from clogging [7].

3.2. Industrial Wastewater

Industrial wastewaters are highly diverse, their characteristics depending entirely on the specific industrial processes from which they originate. Examples include food processing, textile, pharmaceutical, chemical, metallurgical, and pulp and paper industries.

3.2.1. Characteristics

They can vary significantly in terms of pH (extremely acidic or alkaline), temperature, BOD/COD strength (often much higher than domestic wastewater), presence of specific heavy metals, toxic organic compounds (e.g., phenols, dyes, pesticides), salts, and recalcitrant compounds that are difficult to biodegrade [10]. Flow rates can also be highly variable and intermittent.

3.2.2. Challenges for CWs

High concentrations of specific pollutants, toxicity to plants and microorganisms, extreme pH, and shock loads can severely impair wetland performance or even lead to system failure [10, 27].

3.2.3. Design Implications

Industrial wastewater typically requires extensive pre-treatment (e.g., equalization tanks, pH neutralization, heavy metal precipitation, primary sedimentation, even advanced oxidation processes for refractory compounds) before entering the wetland [10]. Specialized media (e.g., reactive media for heavy metals or phosphorus) and tolerant plant species are often necessary [25, 28]. Hybrid systems with longer HRTs are usually preferred due to the complexity and concentration of pollutants [18].

3.3. Agricultural Wastewater

Agricultural wastewater includes runoff from agricultural fields (containing pesticides, herbicides, nutrients from fertilizers) and wastewater from livestock operations (manure, urine, bedding material).

3.3.1. Characteristics

High concentrations of nutrients (N and P), high BOD/COD (especially livestock wastewater), suspended solids, pathogens (e.g., *E. coli* from animal feces), and potentially antibiotics or hormones [11, 29]. Flow can be highly seasonal (e.g., surface runoff during rainy seasons) or intermittent for livestock operations.

3.3.2. Challenges for CWs

Diffuse pollution sources make collection challenging for runoff. High nutrient loads can overwhelm removal capacities, and high organic loads from livestock waste require robust treatment [29].

3.3.3. Design Implications

FWS wetlands are often used for agricultural runoff due to their large area and ability to handle variable flows, focusing on TSS and nutrient removal [11]. For livestock wastewater, robust SSF or hybrid systems are needed after significant pre-treatment (e.g., anaerobic digestion, solid-liquid separation) to reduce high organic and solid loads [29]. Vegetation selection focusing on high nutrient uptake capacity is crucial [20].

3.4. Stormwater Runoff

Stormwater runoff originates from precipitation events and flows over impervious surfaces (roads, rooftops, parking lots) in urban and suburban areas.

3.4.1. Characteristics

Highly intermittent flow, significant variability in volume and pollutant concentration. Pollutants include suspended solids, heavy metals (from vehicle wear, industrial activities), oil and grease, nutrients (from fertilizers), pathogens, and various organic compounds [30, 31]. The "first flush" often contains the highest pollutant load.

3.4.2. Challenges for CWs

Managing peak flows and large volumes, addressing shock loads of pollutants, and designing for highly variable hydrological conditions [12].

3.4.3. Design Implications

Wetlands designed for stormwater are often referred to as "stormwater wetlands" or "bioretention systems" [30]. They typically incorporate forebays for sedimentation of coarse solids, large storage volumes to attenuate peak flows, and specific zones for filtration and pollutant removal [31]. FWS wetlands with varying depths and extended detention times are common to allow for settling and biological degradation [12]. Focus is on TSS, heavy metals, and nutrient removal.

3.5. Landfill Leachate

Landfill leachate is a highly contaminated liquid generated when precipitation percolates through solid waste in a landfill, dissolving and entraining various soluble and suspended compounds.

3.5.1. Characteristics

High strength, often characterized by very high COD/BOD, high ammonia-nitrogen, heavy metals, chlorides, and a complex matrix of refractory organic compounds [13]. pH can be highly variable depending on the landfill's age and waste composition. Leachate characteristics evolve over the landfill's lifespan (e.g., young leachate is high in BOD, old leachate is high in ammonia and humic substances).

3.5.2. Challenges for CWs

High toxicity, recalcitrant compounds, high and variable concentrations of ammonia, and potential for clogging due to high suspended solids, if not pre-treated [13].

3.5.3. Design Implications

Leachate treatment using CWs usually requires extensive pre-treatment (e.g., equalization, aeration, coagulation/flocculation, physical-chemical processes) to reduce pollutant loads and toxicity [13]. Hybrid wetland systems, often with specialized media for heavy metal adsorption and enhanced aeration (e.g., VSSF or aerated wetlands) for nitrogen removal, are typically employed [18]. Longer HRTs are necessary to allow for the degradation of complex compounds.

4. Core Treatment Mechanisms in Constructed Wetlands

The efficacy of constructed wetlands in wastewater treatment stems from a complex interplay of physical, chemical, and biological processes occurring within the water column,

substrate, and root zone [5, 17]. Understanding these mechanisms is fundamental to effective wetland design.

4.1. Physical Processes

4.1.1. Sedimentation

This is a primary removal mechanism, particularly for total suspended solids (TSS) and particulate organic matter. As water flows through the wetland, its velocity decreases, allowing heavier particles to settle out primarily in the forebays and initial sections of the wetland bed [17]. FWS wetlands are particularly effective for sedimentation due to their open water surface and lower flow velocities.

4.1.2. Filtration

The porous media (sand, gravel) in SSF wetlands acts as a physical filter, trapping suspended solids as wastewater percolates through it [5]. Plant roots and stems also contribute to filtration by increasing the tortuosity of the flow path and providing surfaces for particle interception [20].

4.1.3. Adsorption

Pollutants can be adsorbed onto the surfaces of the substrate particles (e.g., sand, gravel, clay), organic matter within the bed, and root surfaces. This is a significant mechanism for the removal of heavy metals, phosphorus, and some organic compounds, especially in SSF systems where specific media are chosen for their adsorptive properties [21, 25].

4.1.4. Volatilization

Some volatile organic compounds (VOCs) and gases (e.g., ammonia from high pH wastewater, methane from anaerobic zones) can be transferred from the water column to the atmosphere. This process is more pronounced in FWS wetlands due to their exposed water surface [16].

4.2. Chemical Processes

4.2.1. Precipitation

Insoluble compounds can precipitate out of the water column and deposit onto the substrate. This is a crucial mechanism for phosphorus removal (e.g., formation of calcium, iron, or aluminum phosphates) and heavy metal removal (e.g., formation of metal hydroxides or sulfides under specific pH and redox conditions) [21, 25].

4.2.2. Redox Reactions

The varying oxygen levels and redox potentials within a wetland (aerobic zones in the water column and rhizosphere, anoxic zones, and anaerobic zones in saturated media) drive numerous chemical transformations [14]. These include the oxidation of organic matter, nitrification (oxidation of ammo-

nia to nitrate), and reduction processes like denitrification (reduction of nitrate to nitrogen gas) and sulfate reduction (leading to sulfide formation) [15].

4.2.3. Complexation

Metal ions can form complexes with organic ligands present in the water or released by plants and microorganisms. These complexes can either enhance or inhibit the mobility and bioavailability of metals [28].

4.2.4. Photodegradation

In FWS wetlands, sunlight can directly degrade certain organic pollutants (e.g., dyes, pesticides) through photochemical reactions (Sun and Huang, 2005). However, this is generally a minor removal pathway compared to biological processes.

4.3. Biological Processes

Biological processes, primarily driven by microbial communities and rooted vegetation, are the cornerstone of contaminant removal in CWs [14, 17].

4.3.1. Microbial Degradation

Microorganisms (bacteria, fungi, archaea) form biofilms on the surfaces of the substrate particles and plant roots, where they carry out the vast majority of pollutant transformations [5].

4.3.2. Organic Matter Degradation (BOD/COD)

Aerobic, anoxic, and anaerobic bacteria metabolize organic compounds for energy and growth. In aerobic zones, organic matter is oxidized to carbon dioxide and water. In anoxic/anaerobic zones, fermentative and methanogenic bacteria break down complex organics into simpler compounds and ultimately methane and carbon dioxide [14].

4.3.3. Nitrogen Removal

This is a two-step process as described in the below.

Nitrification

Under aerobic conditions (e.g., in VSSF wetlands or the rhizosphere of SSF wetlands), ammonia-nitrogen (NH_4^+) is oxidized to nitrite (NO_2^-) and then to nitrate (NO_3^-) by nitrifying bacteria (e.g., *Nitrosomonas* and *Nitrobacter*) [9].

Denitrification

Under anoxic conditions (low oxygen, high organic carbon, e.g., in HSSF wetlands or deeper zones of FWS wetlands), nitrate is reduced to nitrogen gas (N_2) by denitrifying bacteria, which then escapes to the atmosphere [15]. Efficient nitrogen removal often requires a hybrid system to provide both aerobic and anoxic conditions [18].

4.3.4. Phosphorus Removal

Microorganisms can assimilate phosphorus into their biomass. However, this is typically a minor pathway compared to

chemical precipitation and adsorption to media due to the relatively low P content in microbial biomass [25].

Microbial processes contribute to pathogen inactivation or removal through predation by protozoa, antibiotic production, competition for nutrients, and natural decay [24].

4.3.5. Plant Uptake and Transformation (Phytoremediation)

Wetland plants play multiple crucial roles beyond providing a surface for microbial growth [20, 32].

4.3.6. Oxygen Transport

Emergent macrophytes (e.g., Phragmites, Typha) transport oxygen from their leaves to their roots through aerenchyma tissue. This oxygen leaks into the rhizosphere, creating aerobic microsites within an otherwise anaerobic substrate, which is vital for aerobic microbial processes like nitrification [20].

4.3.7. Nutrient Uptake

Plants directly take up nutrients (N, P, K, micronutrients) from the wastewater for their growth. While plant uptake is a significant removal mechanism, especially for nitrogen and phosphorus, it is often limited by the plant's growth rate and biomass harvesting frequency [15, 20]. Regular harvesting can remove accumulated nutrients from the system.

4.3.8. Rhizofiltration, Phytostabilization, Phytoextraction and Rhizodegradation

Roots act as a physical filter, trapping suspended particles and associated pollutants is the rhizofiltration [20].

In phytostabilization process, plants can stabilize contaminants (e.g., heavy metals) in the soil/substrate by reducing their mobility and bioavailability, preventing their leaching into groundwater [20, 32].

In phytoextraction process, certain hyper-accumulating plant species can actively take up and accumulate heavy metals or other contaminants in their biomass [32, 33]. Subsequent harvesting of these plants removes the contaminants from the system.

In rhizodegradation, plants release root exudates (organic compounds) that stimulate the growth and activity of rhizosphere microorganisms, enhancing the microbial degradation of pollutants [32].

4.3.9. Transpiration and Hydraulic Control

Plants transpire water, which can significantly reduce the volume of water leaving the wetland, especially in arid climates. This also influences hydraulic residence time [20].

The integrated nature of these physical, chemical, and biological processes within the wetland ecosystem allows for robust and multifaceted treatment of various wastewater constituents. The challenge in design is to optimize these interactions for specific pollutant removal goals.

5. Designing Wetland Systems for Different Wastewaters

Effective wetland design is an intricate process that integrates engineering principles with ecological understanding [7]. It must consider the specific characteristics of the incoming wastewater, desired effluent quality, site conditions, and economic viability.

5.1. General Design Principles

Regardless of the wastewater type, several fundamental design principles apply to all constructed wetland systems [17].

5.1.1. Site Selection

Crucial factors include topography (flat or gently sloping land is ideal for gravity flow), soil permeability (low permeability soils minimize seepage; otherwise, an impermeable liner is required), climate (temperature, precipitation, evaporation influence HRT), and land availability (CWs are land-intensive) [16].

5.1.2. Hydraulic Loading Rate (HLR) and Hydraulic Retention Time (HRT)

These are perhaps the most critical design parameters [7]. HLR (m/day or cm/day) is the volume of wastewater applied per unit area per day. A lower HLR generally leads to higher removal efficiency. HRT (days) is the theoretical time wastewater spends within the wetland system. A longer HRT allows more time for pollutant degradation and removal. HLR and HRT are interdependent; for a given flow rate, increasing the wetland area increases HRT and decreases HLR. Typical HRTs range from 3-10 days for BOD removal, but can extend to 20-30 days for complex industrial wastewaters or cold climates [10, 19]. Empirical equations (e.g., first-order plug flow model) are often used to relate surface area, flow, and removal efficiency.

5.1.3. Aspect Ratio (Length: Width)

For HSSF wetlands, an aspect ratio of 2: 1 to 4: 1 (length to width) is common, promoting plug flow conditions and minimizing short-circuiting [4]. FWS wetlands can have higher aspect ratios or incorporate baffling to ensure uniform flow distribution.

5.1.4. Liner Design

An impermeable liner (e.g., geomembrane, compacted clay) is essential to prevent groundwater contamination, especially when treating industrial wastewater or landfill leachate, or when soil permeability is high [10].

5.1.5. Inlet and Outlet Structures

Must ensure uniform distribution of wastewater across the

wetland bed to prevent short-circuiting and dead zones. Inlet structures often include diffusers or perforated pipes. Adjustable outlet structures allow for water level control. Sampling points should be integrated for performance monitoring.

5.1.6. Pre-treatment

Almost always required to protect the wetland from clogging and shock loads [7].

5.2. Specific Design Considerations by Wetland Type

5.2.1. Free Water Surface (FWS) Wetlands

Table 3. Design considerations for FWS wetlands.

Character	Designs Aspects
Depth	Typically 0.1-0.6 m. Deeper sections can be incorporated for sedimentation (forebays) or to create open water zones for wildlife. Shallower areas promote emergent vegetation [16, 17].
Baffling	May be used to increase tortuosity and improve hydraulic efficiency, especially in larger systems.

5.2.2. Horizontal Subsurface Flow (HSSF) Wetlands

Table 4. Design considerations for HSSF wetlands.

Character	Designs Aspects
Media Type and Size	Crucial for hydraulic conductivity, surface area for biofilm growth, and pollutant adsorption. Common media include gravel (10-30 mm), sand, or crushed rock. Uniformity coefficient and effective size are important for preventing clogging [4].
Bed Depth	Typically 0.6-1.0 m. Too shallow limits treatment capacity; too deep can lead to excessive anaerobic conditions.
Slope	A slight slope (0.5-2%) is needed to ensure gravity flow and facilitate drainage.

5.2.3. Vertical Subsurface Flow (VSSF) Wetlands

Table 5. Design considerations for VSSF wetlands.

Character	Designs Aspects
Media Type and Size	Finer media (sand, fine gravel) are often used in the upper layers to promote filtration and aeration, while coarser media may be at the bottom for drainage [9].
Bed Depth	Typically 1.0-1.5 m for optimal aeration and nitrification
Dosing System	Intermittent dosing (e.g., 4-8 times per day) is critical to create alternating aerobic and anoxic conditions. This requires pumps, dosing tanks, and distribution networks (perforated pipes) [9].

5.3. Media Selection

The choice of substrate media is a critical design parameter, influencing hydraulic conductivity, surface area for microbial growth, and chemical adsorption properties [21, 25].

5.3.1. Conventional Media

Gravel (various sizes), sand, crushed stone, and soil are common.

5.3.2. Reactive Media

For enhanced removal of specific pollutants (especially phosphorus and heavy metals), specialized media can be incorporated. Examples include the followings.

Phosphorus Removal

Laterite, bauxite, blast furnace slag, fly ash, iron-rich sands, zeolite. These media have a high capacity for chemical adsorption and precipitation of phosphorus [21, 25].

Heavy Metal Removal

Zeolites, activated carbon, biochar, iron/manganese oxides, and certain industrial by-products can enhance metal adsorption and precipitation [28].

Denitrification

Carbon-rich media like wood chips or biochar can serve as an external carbon source for denitrifying bacteria in anoxic zones [23].

5.4. Vegetation Selection

Plant species selection is not merely aesthetic; it profoundly impacts the wetland's performance. Plants provide surfaces for microbial growth, oxygen transport, nutrient uptake, and hydraulic control [20].

Table 6. Key characteristics in vegetation selection.

Key Characteristics	Description
Tolerance	Ability to withstand anoxic conditions, high nutrient concentrations, specific toxins (e.g., heavy metals), and fluctuating water levels
Productivity	High biomass production is desirable for nutrient uptake and subsequent harvesting
Root System	Extensive and deep root systems enhance oxygen penetration and provide large surface areas for microbial attachment
Local Availability and Climate Adaptability	Use of native or locally adapted species reduces establishment costs and ensures resilience

Table 7. Common Species of plants.

Species	Applications
Phragmites australis (Common Reed)	Widely used due to its high tolerance, extensive root system, and high productivity
Typhalatifolia (Cattail)	Also very common, tolerant of diverse conditions
Scirpus spp. (Bulrushes), Carex spp. (Sedges), Iris pseudacorus (Yellow Flag Iris)	Other tolerant and effective species

For specific industrial wastewaters, hyperaccumulating species might be selected for phytoextraction of heavy metals [33]. Sufficient planting density is needed for effective root development and pollutant removal, but too high can lead to competition.

5.5. Pre-treatment Needs for Different Wastewaters

Pre-treatment is arguably the most critical design consideration, particularly for non-domestic wastewaters, as it protects the wetland from clogging, toxicity, and shock loads, thereby ensuring its longevity and performance [7].

5.5.1. Domestic Wastewater

A septic tank (for decentralized systems), Imhoff tank, or primary clarifier is needed to remove large solids, grit, and significant BOD/TSS for the sake of preventing the clogging of the wetland bed, reducing organic loading, and enhancing performance [7, 9].

5.5.2. Industrial Wastewater

The requirements in pre-treatments are highly variable. Depending on the specific industry, pre-treatment may include the following.

Table 8. *Types of pre-treatments for industrial waste water.*

Pre-treatment	Purpose
Equalization Basins	To buffer flow and concentration variations, protecting the wetland from shock loads
pH Neutralization	Essential for extreme pH wastewaters that can harm plants and microbes
Coagulation/Flocculation	For removal of fine suspended solids and some dissolved pollutants
Chemical addition or specialized filters	Heavy Metal Precipitation/Adsorption
Skimming tanks or dissolved air flotation units	Oil and grease removal
Biological Reactors (Anaerobic/Aerobic)	For high-strength organic wastes or specific recalcitrant compounds (e.g., UASB, activated sludge)
Advanced Oxidation Processes (AOPs)	For highly toxic or non-biodegradable compounds

Reduce toxicity, stabilize pH, lower pollutant concentrations to levels tolerable by wetland plants and microorganisms are expected through the above pre-treatments.

5.5.3. Agricultural Wastewater

Table 9. *Types of pre-treatments for agricultural wastewater.*

Pre-treatment	Purpose
Livestock Waste	Solid-liquid separation, anaerobic digesters (for high BOD/COD), settling ponds to reduce solids and high organic loads
Agricultural Run-off	Vegetated filter strips, sediment ponds, and grassed swales upstream of the wetland to capture solids and some nutrients

Prevent clogging, reduce excessive nutrient and organic loads are the expectations of those pre-treatments.

5.5.4. Stormwater Runoff

Table 10. *Types of pre-treatments for stormwater runoff.*

Pre-treatment	Purpose
Forebays	Essential for capturing coarse sediments, grit, and debris from the initial flush
Gross Pollutant Traps (GPTs)	To remove litter, leaves, and other large debris

Protect the main wetland from physical clogging and reduce maintenance are the expectations of those pre-treatments.

5.5.5. Landfill Leachate

Table 11. Types of pre-treatments for landfill leachate.

Pre-treatment	Purpose
Equalization	To manage highly variable flow and concentration
Aeration	To reduce BOD and assist in ammonia stripping (at high pH)
Coagulation/Flocculation, Chemical Precipitation	For heavy metals and some organics
Biological Reactors (e.g., membrane bioreactors, activated sludge)	Often used to pre-treat highly concentrated and complex organics and ammonia before wetland polishing

Mitigate extreme toxicity, reduce high strength pollutants are the expectations of those pre-treatments.

5.6. Addressing Specific Wastewater Challenges Through Design

The "designing" aspect truly comes into play when tailoring the wetland system to the specific challenges posed by different wastewaters [7].

5.6.1. High BOD/TSS Loads

Requires larger surface area, longer HRT, and robust pre-treatment (e.g., primary sedimentation). HSSF wetlands are generally very effective for BOD/TSS removal, but VSSF can also handle high organic loads with proper intermittent dosing [4, 9]. Hybrid systems can optimize removal by separating functions.

5.6.2. Nutrient Removal (Nitrogen and Phosphorus)

Nitrogen removal requires alternating aerobic (for nitrification) and anoxic (for denitrification) conditions [15]. Hybrid systems (e.g., VSSF followed by HSSF, or recirculating configurations) are most effective [18, 23]. Deeper beds in SSF systems can create localized anoxic zones.

Phosphorus (P) is primarily removed through adsorption and precipitation with media [25]. Design involves selecting P-adsorbing media (e.g., blast furnace slag, laterite) and ensuring adequate contact time [21]. Plant uptake contributes but is limited; harvesting P-rich biomass enhances long-term removal [17].

5.6.3. Heavy Metals

Involves selection of specific media with high cation exchange capacity or high content of iron/manganese oxides (e.g., zeolites, biochar) to enhance adsorption and precipitation [28]. Maintaining a slightly alkaline pH can promote metal precipitation. Specific plant species (hyperaccumulators) can be used for phytoextraction, requiring biomass harvesting

and safe disposal [33].

5.6.4. Refractory Organics and Toxic Compounds

Longer HRTs are crucial to allow for microbial degradation of complex compounds [10]. Enhancing aeration (e.g., VSSF, aerated wetlands) promotes the breakdown of some resistant organics [22]. For highly toxic wastewaters, significant pre-treatment is indispensable to reduce pollutant concentrations to levels that are not harmful to wetland biota.

5.6.5. Pathogens

Longer HRTs, higher bed depths, and finer media in SSF wetlands enhance filtration and provide more time for natural decay and predation [24]. VSSF wetlands are generally more effective than HSSF or FWS for pathogen removal due to their aerobic conditions and filtration capacity. Post-treatment disinfection (e.g., UV, chlorination) may be required for reuse.

5.6.6. Flow Variability (e.g., Stormwater)

Incorporation of large forebays or detention zones handles peak flows and acts as sedimentation basins. Bypass systems can divert extreme flows around the wetland to prevent wash-out, while beds are designed for varying water levels to accommodate fluctuating volumes [12].

6. Operation, Maintenance, and Performance Evaluation

Even the most meticulously designed wetland system requires proper operation and maintenance (O&M) to ensure its long-term performance and sustainability [7].

6.1. Operation and Maintenance (O&M)

6.1.1. Flow Management

Regular monitoring and adjustment of influent flow rates maintain design HRT and HLR. For VSSF systems, precise

timing and volume of intermittent dosing are crucial [9].

6.1.2. Water Level Control

Maintaining appropriate water levels within FWS and HSSF systems is vital for optimal hydraulic performance and plant health [17].

6.1.4. Vegetation Management

6.1.3. Clogging Prevention and Mitigation

This is a major O&M concern, particularly for SSF wetlands [7]. Effective pre-treatment is the primary defense. Routine inspection of inlet zones for accumulated solids is required. If clogging occurs, strategies may include resting the bed, flushing, or in severe cases, media replacement.

Table 12. Important stages in vegetation management.

Stage	Implementation
Establishment	Ensuring successful initial plant establishment is critical
Harvesting	Periodic harvesting of plant biomass can remove accumulated nutrients (especially P) and metals, prevent excessive growth, and maintain hydraulic capacity
Weeding	Removal of undesirable or invasive plant species
Pest and Disease Control	Addressing issues that might harm plant health
Mosquito Control	Primarily relevant for FWS wetlands. Strategies include maintaining appropriate water levels, promoting natural predators (fish, dragonflies), and biological larvicides. SSF wetlands inherently minimize mosquito breeding
Routine Inspection	Regular checks of liners for leaks, integrity of banks, and overall system health
Sludge/Sediment Removal	Forebays and initial sections of FWS wetlands will accumulate sludge and sediment over time, requiring periodic removal

6.2. Performance Evaluation

Performance evaluation is essential to verify that the wetland is meeting its design objectives and discharge standards [26].

6.2.1. Monitoring Parameters

Regular sampling and analysis of influent and effluent for key parameters are performed as follows.

Table 13. Key parameters in performance evaluation.

Category	Parameters
Organic Matter	BOD ₅ , COD
Solids	TSS
Nutrients	Total N, Ammonia-N, Nitrate-N, Total P, Orthophosphate
Pathogens	E. coli, Fecal Coliforms
Specific Pollutants	Heavy metals, specific organic compounds (for industrial/leachate treatment)
Physical Parameters	pH, temperature, dissolved oxygen (DO)

6.2.2. Performance Metrics

The mathematical formula for the performance calculation is given in the below [9, 27].

$$R = [(I - E) / I] * 100\%$$

Where,

R= Removal Efficiency (%)

I= Influent Concentration

E= Effluent Concentration

Effluent concentrations are directly compared with discharge limits.

Mass removal rate is known as the amount of pollutant removed per unit area per day (g/m²/day).

6.2.3. Challenges in Performance

Table 14. Challenges in the variations of performances/ efficiency.

Factor	Impacts
Seasonal Variability	Performance can be decreased in colder climates due to reduced microbial activity and plant dormancy
Shock Loads	It can temporarily impair performance, especially for sensitive microbial communities
Long-term Stability	Performance can be declined over very long periods due to media saturation, especially for phosphorus and metals

7. Future Perspectives and Research Gaps

Despite their proven efficacy, research and development in constructed wetlands continue to evolve, driven by new environmental challenges and technological advancements [7].

7.1. Enhanced Nutrient Recovery and Removal

While N and P removal are good, there is a growing interest in pushing removal efficiencies higher, particularly for phosphorus. Research focuses on novel reactive media with higher P adsorption capacities and regeneration potential, as well as optimizing plant harvesting strategies for nutrient recovery [21, 25].

7.2. Treatment of Emerging Contaminants (ECs)

Pharmaceuticals, personal care products (PPCPs), endocrine-disrupting chemicals (EDCs), and microplastics are increasingly detected in wastewaters. Research is needed to understand their fate and removal mechanisms in CWs, and to design systems specifically targeting these recalcitrant compounds, which may require specific microbial consortia or integrated setups [34, 35].

7.3. Resource Recovery

Beyond water purification, CWs offer potential for resource recovery. Biomass harvested from wetlands can be converted

into biofuels (biogas, bioethanol), compost, or used for other applications [35, 36]. Nutrient recovery from the effluent or accumulated in biomass remains an active area of research.

7.4. Integration with Other Technologies

Hybridization with advanced treatment processes, such as biofilters, membrane bioreactors, electrochemical systems, or even algal ponds, could lead to more robust systems capable of treating more complex wastewaters and meeting stringent discharge standards [18, 36, 37].

7.5. Clogging Mitigation and Management

Clogging remains a persistent challenge, especially for SSF systems. Research into novel media, pre-treatment techniques, and in-situ rejuvenation methods is crucial for extending wetland lifespan [7, 38].

7.6. Climate Change Resilience

Designing wetlands to be resilient to extreme weather events (e.g., prolonged droughts, intense rainfall, temperature variations) is essential, requiring adaptive management strategies and larger storage capacities or robust plant species [26, 39].

7.7. Smart Wetlands and Automation

The integration of sensors, real-time monitoring, and automation (e.g., intelligent dosing systems, remote control of flow) can optimize wetland performance, reduce O&M costs, and provide early warning of operational issues.

7.8. Life Cycle Assessment (LCA)

More comprehensive LCA studies are needed to fully evaluate the environmental footprint and sustainability of CW systems compared to conventional technologies, considering all stages from construction to decommissioning [7, 40].

8. Conclusion

Constructed wetland systems offer a compelling, sustainable, and eco-friendly approach to wastewater treatment, addressing the limitations of conventional methods while providing ecological co-benefits. The success of a wetland system, however, hinges critically on its design, which must be meticulously tailored to the specific characteristics of the wastewater being treated.

This review has underscored that the design choices ranging from the fundamental wetland type (FWS, SSF, Hybrid) to the selection of media, vegetation, and the indispensable pre-treatment units are not arbitrary. They are dictated by the pollutant profile, concentration, and flow variability of domestic, industrial, agricultural, stormwater, and landfill leachate wastewaters. Understanding the intricate physical, chemical, and biological removal mechanisms is paramount to optimizing these design parameters for targeted pollutant removal (BOD, TSS, nutrients, heavy metals, etc.).

While CWs offer robust treatment capabilities, continuous research is vital to enhance their performance, particularly for emerging contaminants, and to explore their potential for resource recovery. As global water challenges intensify, well-designed and thoughtfully managed constructed wetlands will undoubtedly play an increasingly pivotal role in achieving sustainable water management, safeguarding public health, and preserving our invaluable aquatic ecosystems.

Abbreviations

WWTP	Wastewater Treatment Plants
NBS	Nature-Based Solutions
CW	Constructed Wetland
FWS	Free Water Surface
SSF	Subsurface Flow
HSSF	Horizontal Subsurface Flow
VSSF	Vertical Subsurface Flow
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
TSS	Total Suspended Solids
VOCs	Volatile Organic Compounds
HLR	Hydraulic Loading Rate
HRT	Hydraulic Retention Time
AOPs	Advanced Oxidation Processes
GPTs	Gross Pollutant Traps
DO	Dissolved Oxygen
Ecs	Emerging Contaminants

EDCs	Endocrine-Disrupting Chemicals
PPCPs	Personal Care Products
LCA	Life Cycle Assessment

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Conflicts of Interest

The authors declare no conflicts of interest.

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