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Natural & Constructed Wetlands: A Review on Water Purification Functions and Ecosystem Services

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Abstract: Wetlands are the most effective ecosystems for purifying water. Wetlands serve importance as a home for a wide variety of species, act as natural filters, control floods, store carbon in plants and serve as cultural, and recreational importance. Despite their importance, 87% of the world's wetlands have been lost over the past 300 years due to land drainage for housing, industry, and agriculture. Additionally, 21% of global wastewater is released untreated, posing severe threats to the remaining wetlands. These ecosystems play a crucial role in addressing water pollution by acting as natural filtration systems. They can remove up to 60% of metals, trap up to 90% of sediment runoff, and eliminate up to 90% of nitrogen. Wetland purification processes involve complex interactions like sedimentation, adsorption, ion exchange, and biological uptake by plants and microorganisms. These mechanisms significantly reduce nutrient enrichment, organic contaminants, and heavy metal concentrations, safeguarding water quality. This review highlights wetlands' pivotal role in wastewater treatment and their effectiveness in recycling treated water within sustainable water management. The integration of Nature-Based Solutions (NBS) is emphasized, along with the importance of wetland restoration to maintain these services. Global and regional case studies demonstrate the success of wetlands in water purification and their critical value in ecosystem conservation and restoration efforts.

1. Introduction

Wetlands are ecosystems characterized by water saturation for part or all of the year, acting as transitional zones between upland and aquatic environments. They encompass various types, including marshes, swamps, bogs, and fens, each defined by unique vegetation, hydrology, and geographic features. Wetlands are commonly found in low-lying areas with poor drainage or steep slopes where water accumulates, serving essential ecological functions. It is estimated that wetlands cover approximately 6% of the Earth's surface, with marshes (20%), peatlands (30%), and floodplains (15%) being the predominant types (Kadlec *et al.*, 2008). However, their global extent remains challenging to measure, with estimates ranging from 748 million to over 4,000 million hectares (Ramsar Convention)

Despite their ecological significance, wetlands face considerable degradation due to urbanization, agricultural expansion, and pollution, resulting in the loss of 87% of global wetland areas over the past

300 years (Kadlec *et al.*, 2008). This destruction has led to declining water quality, reduced biodiversity, and diminished ecosystem services, including flood regulation, habitat support, and water purification. The role of wetlands in water purification has long been recognized, with these ecosystems serving as natural filtration systems that remove pollutants such as heavy metals, sediments, and nitrogen through processes like sedimentation, adsorption, ion exchange, and biodegradation (Ana Dorido *et al.*, 2008; Razzouki *et al.*, 2015; Errich *et al.*, 2021; Abouri *et al.*, 2024). Wetlands' ability to purify water is particularly important in mitigating pollution from both point and non-point sources, thereby improving water quality. In addition to water purification, wetlands provide critical services such as groundwater recharge, coastal protection, carbon sequestration, and biodiversity support (Ramsar Convention)

This review paper focuses on the multifaceted role of wetlands, with an emphasis on their capacity for wastewater treatment and water purification. The paper aims to explore the ecological, economic, ecosystem services, nature-based solution and cultural importance of wetlands, highlighting their vital contribution to environmental management and sustainability. By understanding these systems, we can advocate for enhanced conservation and restoration efforts, ensuring that wetlands continue to provide essential services to both humans and wildlife.

2. Methodology

2.1 Search Strategy

To identify relevant literature, a comprehensive search was conducted across multiple academic databases, including PubMed, Google Scholar, Litmaps, Connected Papers, and Science Space. These databases were selected for their broad coverage in environmental science and water purification. The search used a combination of keywords like "wetlands," "water purification," "nutrient removal," "heavy metal removal," "organic pollutant removal," "constructed wetlands," and "nature-based solutions," refined with Boolean operators (AND, OR) to capture relevant studies.

2.2 Inclusion and Exclusion Criteria

Inclusion criteria included:

- Peer-reviewed articles published between 1990 and 2024.
- Studies directly addressing wetlands' role in water purification, nutrient removal, or pollutant sequestration.
- Research on both natural and constructed wetlands.

Exclusion criteria included:

- Studies not focused on water purification or wetlands.
- Non-peer-reviewed sources, conference abstracts, and grey literature.
- Articles published in languages other than English.

2.3 Data Extraction and Synthesis

A standardized data extraction form was used to collect information on study objectives, methods, purification mechanisms, environmental contexts, and conclusions. A thematic analysis approach identified common patterns, trends, and themes across the studies. Quantitative data on purification rates were compiled and, where possible, a meta-analysis was considered to assess the effectiveness of wetlands in water purification.

2.4 Study Selection Process

Initial screening of titles and abstracts assessed relevance to the review objectives. Studies passing this step underwent full-text review based on predefined inclusion criteria. Only studies directly related to wetlands and water purification were included in the final synthesis.

2.5 Quality Assessment

Each study was evaluated for quality based on factors like study design, sample size, methodology, and clarity of outcomes. Studies were rated for reliability to ensure valid and consistent results, minimizing biases in the final review.

3. Wetlands

Wetlands are unique ecosystems characterized by their saturation with water, either seasonally or year-round, depending on their landscape position. Historically, various terms such as marshes, swamps, bogs, and fens have been used to describe wetlands based on their vegetation, water conditions, and geographic features. These areas act as transitional zones between upland ecosystems and aquatic environments, often located in topographic depressions or along steep slopes where low-permeability soils lead to water accumulation. They can also exist in flat regions with poor drainage, sometimes referred to as blanket bogs or pocosins in North America. A defining characteristic of wetlands is their persistent saturation, which limits the types of plant species that can thrive in such moist conditions. This saturation alters soil characteristics through chemical, physical, and biological changes during flooding. Wetlands are among the most biologically productive ecosystems on Earth, featuring dense vegetation and providing habitats for diverse wildlife, including mammals, birds, and amphibians (Kadlec *et al.*, 2008).

Wetlands have long been recognized as valuable natural resources. Their significance is evident in both natural environments—such as those inhabited by the Marsh Arabs at the confluence of the Tigris and Euphrates rivers in southern Iraq—and managed systems like rice paddies in Southeast Asia (Ana Dorido *et al.*, 2008). They offer numerous benefits, including:

- Water Supply and Management: Wetlands help regulate water flow and maintain water quality.
- Resource Extraction: They support fishing, hunting, and harvesting of plants.
- Plant Cultivation: Wetlands can be used for agriculture, particularly in rice cultivation.
- Wildlife Habitat: They provide essential habitats for a variety of species.
- Integrated Systems: Wetlands can support aquaculture and other integrated farming systems.
- Erosion Control: They help stabilize shorelines and prevent soil erosion.
- Education and Recreation: Wetlands serve as sites for education and recreational activities.
- Ecological Restoration: They play a role in restoring and maintaining ecological balance (Ana Dorido *et al.*, 2008).

One of the most important functions of wetlands is their ability to purify water. They act as "living filters" and "ecotones," effectively improving the quality of water that flows through them. Wetlands engage in various physical, chemical, and biological processes to break down pollutants from diverse sources, enhancing water quality. Historically, many regions have utilized wetlands as natural treatment systems for wastewater, effectively managing a wide range of contaminants, including toxic organic substances (Ana Dorido *et al.*, 2008). Constructed wetlands (CWS) are engineered systems designed to mimic the natural functions of wetlands, using biological and physical processes to treat water and remove pollutants. These systems replicate the natural movement of water and utilize soil, land, and microorganisms to filter contaminants from wastewater. Although constructed wetlands cover significant areas, they are typically smaller in scale and tailored to purify water from various sources (Robison *et al.*, 2008)

In summary, wetlands are crucial ecosystems that provide essential services for environmental health and human well-being, making their protection and restoration a priority in sustainable land and water management strategies.

Some of the plants used in Wetlands as Water Purification System: (Anthony Wong, 2017)

- Water Mimosa (*Neptunia oleracea)*
- Water Hyacinth (*Eichhornia crassipes)*
- Red Stem Flag (*Thalia Geniculata)*
- Water Spinach (*Ipomoea aquatic Forsskal)*
- Vertiver (*Veteveria zizaniodes)*
- Water Lily (*Nymphaea).*

While the ability of wetlands to treat water is well acknowledged, the full scope of their treatment potential is still not completely understood. Recent studies have shown that natural wetlands may absorb contaminants, which has led to the development of innovative water treatment technologies that mimic similar processes. However, there are concerns regarding the possible negative effects of toxic substances and pathogens present in many wastewater sources, as well as the long-term impact of added nutrients and alterations in hydrology on natural wetlands. These concerns have contributed to the increasing interest in utilizing constructed wetland systems (CWS) for wastewater treatment (Ana Dorido *et al.*, 2008).

4. Natural Wetlands

The U.S. Fish and Wildlife Service provides a comprehensive definition and categorization scheme for wetlands to facilitate scientific research and understanding of these critical ecosystems. Wetlands are established as areas where terrestrial and aquatic ecosystems intersect, and where water plays a crucial role in influencing both biological communities and soil characteristics (Ana Dorido *et al.*, 2008).

4.1 Anthropogenic Pressures and Degradation

Natural wetlands are facing significant threats from anthropogenic activities, leading to widespread degradation. Key factors include:

- Climate Change: Alters precipitation patterns, temperature, and hydrological cycles.
- Poor Land-Use Practices: Agriculture and urbanization encroach on wetland areas.
- Drainage: Wetland areas are drained for development, agriculture, or other uses.
- Freshwater Abstraction: Excessive extraction of freshwater resources impacts wetland hydrology.

As a result of these pressures, more than 50% of global wetlands have been lost in recent decades, with continuing trends that further endanger remaining wetlands (Gabriela *et al.*, 2023). Additionally, wetlands act as vital buffer zones between rivers and adjacent terrestrial systems, making them susceptible to the impacts of excessive nutrient inputs that cause eutrophication, thereby threatening their integrity and ecological functions (Gabriela *et al.*, 2023).

4.2 Water Purification Function

One of the most significant yet often underappreciated roles of wetlands is their capacity to improve water quality. Acting as "natural water purifiers," wetlands effectively mitigate various pollutants. They can significantly reduce or remove pollutants from both point and nonpoint sources, including:

- Point Sources: Such as municipal wastewater and certain industrial discharges.
- Nonpoint Sources: Such as runoff from agricultural, urban, and mining activities.

Wetlands have been shown to remove a range of contaminants, including organic matter, suspended solids, excess nutrients, pathogens, metals, and micropollutants (Ana Dorido *et al.,* 2008). This remarkable ability to filter and purify water underscores the ecological importance of wetlands and highlights the need for their protection and restoration in the face of ongoing environmental challenges.

In summary, the conservation of wetlands is crucial, not only for preserving biodiversity and ecosystem functions but also for maintaining water quality in aquatic systems globally. Given the significant pressures they face, comprehensive efforts are required to protect and restore these valuable ecosystems.

4.3 Factors Influencing Water Quality

The hydrological cycle plays a crucial role in shaping wetlands by influencing microbial activity, plant types, and the biogeochemical cycling of nutrients within these ecosystems. The relationship between hydrology and the biological health of wetlands is intricate, as hydrological parameters significantly impact physicochemical properties such as nutrient availability, soil and water pH, and anaerobic conditions in the soil. Conversely, biotic processes, including vegetation and microbial dynamics, can also influence the hydrological characteristics of wetlands (Ana Dorido *et al.*, 2008).

4.3.1 Role of Soil in Wetlands

Soil serves as a vital physical component of natural wetlands. Its physical and chemical characteristics directly influence the types of wetland plants and the microbial communities that thrive within. Key soil properties, such as sorption capacity, redox potential, and acid-base characteristics, are essential in regulating the physicochemical processes occurring in wetland water, which in turn are responsible for the removal of contaminants and significantly affect overall water quality (Ana Dorido *et al.,* 2008; Akartasse *et al.,* 2022; Shaheen *et al.,* 2025).

4.3.2 Vegetation in Wetlands

Wetland vegetation primarily consists of macrophytes, which are specialized plants adapted to saturated environments and capable of surviving in anaerobic soil conditions due to their high-water content. Wetland plants share certain characteristics with their counterparts in well-drained soils, such as a reliance on water and a capacity to withstand chemically challenging environments. As a result, many wetland plant species have evolved various adaptations to cope with environmental stressors (Ana Dorido *et al.,* 2008). One critical aspect of wetland plant adaptations is their intricate structural mechanisms to prevent root anoxia (lack of oxygen). The oxygenation of the rhizosphere (the soil region close to the roots) is vital for sustaining robust root activity, enabling these plants to mitigate the adverse effects of metals and sulfides—soluble phytotoxins that can accumulate in anoxic substrates (Ana Dorido *et al.,* 2008; Fan *et al.,* 2023).

4.3.3 Microbial Activity and Nutrient Cycling

Microorganisms play a fundamental role in the biogeochemical transformations of nutrients within wetland ecosystems. They are crucial for the metabolism of organic compounds, including certain xenobiotics, substances not commonly found in nature (Vymazal, 2020). The relationship between bacteria and plants is particularly significant: bacteria help mineralize complex organic materials, facilitating nutrient uptake for plants, while enzymes from root exudates enhance microbial activity.

The types of microbial communities and biochemical processes present within the rhizosphere are largely influenced by the aerobic conditions established by plants. This interplay between microbial activity and plant structures contributes to the unique capabilities of different wetland types in managing water contaminants. The cooperative dynamics between these biological components are vital for the overall health and functionality of wetland ecosystems (Ana Dorido *et al.*, 2008).

4.4 Purification Capacity

The effectiveness of wetlands as natural water purifiers is attributed to a variety of physical, chemical, and biological mechanisms that remove contaminants. These processes include:

- **Sedimentation:** Particles settle out of the water column as it flows through the wetland, reducing turbidity.
- **Filtration:** Wetland soils and vegetation filter out particulates and debris from the water.
- **Chemical Precipitation**: Certain dissolved substances react to form solid particles, which can then be removed from the water.
- **Sorption:** Pollutants adhere to soil particles or plant surfaces, effectively reducing their concentration in the water.
- **Biodegradation:** Microorganisms break down organic pollutants into less harmful substances.
- **Plant Absorption**: Wetland plants absorb nutrients and contaminants directly from the water, incorporating them into their biomass.

4.5 Interplay of Wetland Components

The efficiency of wetland types in addressing water pollutants is influenced by the interplay of these various factors. This collaboration among different components leads to varying capacities in mitigating non-point source pollution (runoff from diffuse sources rather than from a single point, such as a pipe). The characteristics of individual wetland types play a crucial role in determining their specific effectiveness against pollutants. Here's a summary **Table 1** of how various types of natural wetlands address different non-point pollution issues along with their distinct characteristics.

Understanding the capacity of different wetland types to engage with various non-point pollution issues underscores the importance of preserving and restoring these ecosystems. The specific mechanisms involved in pollutant removal vary based on the characteristics and hydrology of each wetland type. Ongoing research is essential to deepen our understanding of these relationships and enhance the management of wetland. (Ana Dorido *et al.*, 2008).

Natural wetlands serve as highly effective systems for purifying water by leveraging a combination of physical, chemical, and biological processes. These systems play a critical role in reducing pollutants, improving water quality, and maintaining ecological balance. This document summarizes key research findings on the purification abilities of wetlands, emphasizing their significance in environmental conservation and water management (Ana Dorido *et al.*, 2008).

Table 1: Wetlands Components that explains it's pollutant removal mechanism (Ana Dorido *et al.*, 2008).

WETLAND TYPES	CHARACTERISTICS	POLLUTANT REMOVAL MECHANISM
Marshes	Dominated by herbaceous plants and often occur in areas with abundant water	Sedimentation, filtration, plant absorption
Swamps	Characterized by woody vegetation; found in flood-prone areas	Biodegradation, sorption, chemical precipitation
Bogs	Highly acidic, low-nutrient environments dominated by sphagnum moss	Limited biological uptake; mainly physical processes (sedimentation, filtration)
Fens	Groundwater-fed wetlands with higher nutrient levels than bogs	Biodegradation, sorption, plant absorption
Floodplains	Areas adjacent to rivers that are periodically flooded	Sedimentation, filtration, chemical precipitation

4.5.1 Physical Process in Wetland Purification

Physical processes in wetlands involve the removal of pollutants through sedimentation and filtration. Suspended solids and particulate matter settle out as water flows slowly through the wetland. Vegetation and soil act as natural filters, trapping larger particles and facilitating the settling of smaller ones. This process is critical in reducing turbidity and removing heavy metals bonded to particulates **(**Nichols, D. S. 1983).

4.5.2 Chemical Process in Wetland Purification

Chemical processes are driven by interactions between water, soil, and plants that alter the chemical composition of pollutants. Processes such as adsorption, precipitation, and redox reactions play vital roles. For instance, phosphates can be adsorbed onto soil particles or precipitated as insoluble salts, reducing their availability in water. Similarly, redox reactions in anaerobic zones facilitate the transformation of nitrogen compounds, aiding in nitrogen removal (Verhoeven, J. T. A., & Meuleman, A. F. M. 1999).

4.5.3 Biological Processes in Wetland Purification

Biological processes are primarily mediated by microorganisms and plants. Microbial activity breaks down organic matter and degrades pollutants such as nitrogen and phosphorus. Plants contribute by uptaking nutrients for growth, thereby reducing their concentrations in water. Additionally, microbial biofilms on plant roots enhance nutrient cycling and pollutant degradation. These biological interactions are crucial for maintaining the ecological balance within wetlands **(**Halder & Ghosh, 2014).

5. Constructed Wetlands

Constructed wetlands are engineered systems designed to mimic the natural processes of wetlands for the treatment of wastewater. These systems leverage the inherent abilities of natural wetlands to transform and remove pollutants, but they do so under more controlled conditions, allowing for greater precision in design and operation (Vymazal, 2020).

5.1 Key Features of Constructed Wetlands

5.1.1 Tailored Design*:* Constructed wetlands can be specifically designed to meet treatment needs by selecting appropriate substrates, vegetation types, and flow patterns. This customization enhances their efficiency in pollutant removal (Vymazal, 2020).

5.1.2 ***Site Selection and Flexibility***: Unlike natural wetlands, constructed wetlands can be established in locations that are optimal for treatment, taking into account factors like land availability and proximity to pollution sources. They can also vary in size to accommodate different treatment capacities (Vymazal, 2020).

5.1.3 ***Factors Influencing the Selection of Constructed Wetlands:*** The choice of constructed wetland is influenced by several factors:

- Type of Pollutants: The specific contaminants targeted for removal.
- Substrate Material: The composition of the substrate (soil, sand, gravel) affects filtration and microbial activity.
- Local Vegetation: Availability of suitable plant species for effective treatment.
- Temperature: Affects biological activity and pollutant degradation rates.
- Hydraulic Retention Time (HRT): Calculated as HRT=Volume/Discharge (where Volume = Area × Water Depth × Porosity).
- Hydraulic Loading Rate (HLR): The rate at which water is applied to the wetland (Verhoeven, J. T. A., & Meuleman, A. F. M. 1999).

Control over Hydraulic Pathways: One of the significant advantages of constructed wetlands is the ability to control hydraulic pathways and retention times, which are critical for effective treatment. This allows for better management of water flow and pollutant exposure to treatment processes (Vymazal, 2020).

5.2 Role of Vegetation

While plants are integral to the functioning of constructed wetlands, their role in pollution removal is primarily indirect. Key contributions of wetland vegetation include:

- **Insulating Subsurface Flow Systems**: Plants can help maintain temperature and moisture levels in subsurface flow systems (Vymazal, 2020).
- **Oxygenation:** They provide oxygen to otherwise anoxic (oxygen-depleted) substrates, promoting aerobic microbial activity that is crucial for breaking down pollutants (Vymazal, 2020).
- **Surface for Bacterial Attachment:** Plant surfaces offer a habitat for bacteria that play a vital role in the biodegradation of contaminants (Vymazal, 2020).
- **Excretion of Antibacterial Compounds**: Some plants release antibacterial compounds from their roots, which can help suppress harmful pathogens (Vymazal, 2020).
- **Facilitating Sedimentation**: In surface flow constructed wetlands, vegetation reduces wind and water turbulence, promoting the sedimentation of suspended solids (Vymazal, 2020). The direct contribution of plants to pollutant removal is mainly through nutrient uptake, which occurs when biomass is harvested for maintenance (Vymazal, 2020).

5.3 Applications of Constructed Wetlands

Constructed wetlands can effectively treat wastewater from various sources, including:

- **Runoff from Hard Surfaces**: Such as parking lots and rooftops, which often carry pollutants like oils, heavy metals, and sediments (Robison *et al.*, 2008)

- **Agricultural Runoff**: Including nursery irrigation water, which may contain fertilizers and pesticides (Robison *et al.*, 2008)
- **Grey Water**: Wastewater from domestic sources such as washing machines, showers, and sinks (Robison *et al.*, 2008)
- **Black Water**: Wastewater containing fecal matter, requiring more intensive treatment (Robison *et al.*, 2008)
- **Combination of Wastewater Types**: Constructed wetlands can be designed to handle a mixture of the above sources, making them versatile in wastewater treatment applications (Robison *et al.*, 2008)

Constructed wetlands represent a sustainable approach to wastewater treatment, combining natural processes with engineered systems to effectively manage and reduce pollutants. Their ability to be customized for specific treatment needs, along with their ecological benefits, makes them a valuable tool in environmental management and pollution control. Continued research and development in this field can enhance their effectiveness and expand their applications in various settings (Robison *et al.*, 2008 & Vymazal 2020).

5.4 Classification of Constructed Wetlands

In order to replicate natural wetlands for human use and profit, **Constructed Wetland Systems (CWS)** are manmade complexes made up of water, emergent and/or submerged plants, animal life, and saturated substrates (Ana Dorido *et al.*, 2008). The primary classification of CWS is based on the type of water flow regime, with two main types commonly used in practice (Ana Dorido *et al.*, 2008):

Free Water Surface (FWS) Wetlands: Also known as aerobic wetlands or surface flow (SF) wetlands, these systems are very comparable to real wetlands as their aquatic plants are either free-floating or rooted in a soil layer at the bottom. In these systems, water moves horizontally through the above-substrate plant stems and leaves. The water at the top is often aerobic, whereas the substrate and lower levels are typically anaerobic (Ana Dorido *et al.*, 2008; Opitz *et al.*, 2021).

FWS wetlands can be further classified according to the predominant macrophyte type found in the system (Ana Dorido *et al.*, 2008):

- **Floating Macrophyte Systems**: These systems employ both free-floating species (like *Eichhornia crassipes* (water hyacinth), *Lemna spp.*, and *Spirodella spp.* (duckweed)) and rooted floating species (such as *Nymphae spp.* and *Nuphar spp.* (water lilies), *Potamogeton natans* (pondweed), and *Hydrocotyle vulgaris* (pennywort)).
- **Submerged Macrophyte Systems**: In these systems, the photosynthetic components of the plants are completely covered, yet the flowers are exposed to the atmosphere. Submerged aquatic plants can generally be divided into two groups: elodeid (like *Elodea spp.*, *Myriophyllum aquaticum* (parrot feather), and *Ceratophyllum spp.*) and isoetid (rosette) types (like *Isoetes*, *Littorella*, and *Lobelia*).
- **Rooted Emergent Macrophyte Systems**: In natural wetlands, plants are the most prevalent form of life. These plants grow well above the water's surface, generating aerial stems and developing extensive root and rhizome systems. Common species include mannagrasses (*Glyceria spp.*), duck potatoes (*Sagittaria latifolia*), cattails (*Typha spp.*), blue and yellow flags (*Iris spp.*), rush (*Juncus spp.*), spikerushes (*Eleocharis spp.*), reed canary grass (*Phalaris arundinacea*), and common reed (*Phragmites australis*).

However, since they lack standing water, **Subsurface Flow (SSF) Wetlands** differ from natural wetlands. Instead, they are built on a substrate covered in aquatic flora and are often composed of soil, sand, gravel, or small stones. This design allows wastewater to flow beneath the surface while reaching the roots of the plants (Ana Dorido *et al.*, 2008). SSF systems can be further classified based on water flow patterns, as they are required to have emergent macrophytes (Ana Dorido *et al.*, 2008):

- Vertical SSF Systems (which may exhibit upstream or downstream properties)
- Horizontal SSF Systems
- Hybrid Systems

In vertical SSF systems, wastewater is applied to maintain vertical flow through the substrate, either upward or downward. Various feeding and collecting methods can achieve this, such as sporadic application or the insertion of input pipes buried 60–100 cm deep in the substrate. These wetlands are also known as "infiltration wetlands," as the wastewater seeps through the substrate (Ana Dorido *et al.*, 2008).

Wastewater enters horizontal SSF systems at one end and travels through the porous medium below, moving slowly and primarily horizontally. The bed is gently sloped to facilitate the flow towards the outlet, where the effluent is collected before leaving through a level control system. During this process, the wastewater encounters a combination of anoxic, anaerobic, and aerobic zones; aerobic zones develop around the roots and rhizomes that release oxygen into the substrate (Ana Dorido *et al.*, 2008).

Hybrid systems integrate both horizontal-flow (horizontal SSF) and vertical-flow (vertical SSF) designs in a staged arrangement. However, since there are not many operational examples of these hybrid systems yet, it is premature to determine which configuration will be most effective.

Most experts agree that SSF wetlands offer several advantages over FWS systems (Ana Dorido *et al.*, 2008). When comparing SSF wetlands to FWS wetlands, the former typically exhibit better pollution removal efficiency per unit area. This improved efficiency is due to the increased surface area provided by the substrate, which supports the growth of microorganisms. Additionally, SSF wetlands often require less land area to achieve a specific level of treatment than FWS wetlands.

SSF systems also present reduced potential for odors and insect vectors, commonly found in standing wastewater systems like FWS systems, along with lower risks of exposure for humans and animals since the water surface in an SSF system is below the substrate surface (Ana Dorido *et al.*, 2008). Moreover, the accumulation of plant debris on the surface of SSF wetlands can provide some degree of thermal insulation in colder climates. Another advantage of wastewater percolating through the substrate in SSF systems is the accelerated treatment of organic pollutants and nutrients (Ana Dorido *et al.*, 2008).

5.5 Purification Capacity

In order to eliminate pollutants, both artificial and natural wetlands use a range of physical, chemical, and biological processes at the same time. Sedimentation, plant absorption, sorption, precipitation, microbial degradation, and volatilization are important processes. Either by being retained in the flora and substrate of the wetland or by being lost to the atmosphere, pollutants can be removed from water. To assess the possible uses, benefits, and drawbacks of artificial wetland systems, it is important to have a basic understanding of these processes (Ana Dorido *et al.*, 2008).

The removal of pollutants in constructed wetlands (CWS) involves a combination of physical, chemical, and biological processes, each playing a crucial role in ensuring effective wastewater treatment.

i. ***Physical Processes*:** The physical removal of contaminants in wetlands primarily occurs through sedimentation and filtration. The design of CWS promotes low flow velocities and laminar flow patterns, which facilitate the sedimentation of suspended particles. The presence of vegetation creates resistance that slows down wastewater circulation, allowing particles to settle effectively. Floating plants also play a significant role by acting as sediment traps, preventing resuspension of settled particles. The substrate medium serves as a filter bed, enhancing the physical removal of suspended materials through straining processes. Additionally, volatilization contributes to pollutant removal by allowing dissolved substances to escape into the atmosphere, although this can lead to air pollution if volatile organic compounds and inorganic substances, such as ammonia, are released (Ana Dorido *et al.*, 2008).

ii. ***Chemical Processes:*** Chemical removal mechanisms in wetlands include sorption and precipitation. Sorption involves the adsorption and absorption of pollutants onto the surfaces of plant roots and substrates, which can immobilize contaminants over time. The effectiveness of sorption is influenced by various factors, including the characteristics of the pollutants, the composition of the wastewater, and the properties of the substrate, such as pH and organic matter content. Complexation, hydrolysis, and redox reactions also facilitate the removal of contaminants by altering their chemical forms, making them more amenable to adsorption or precipitation. Precipitation is particularly important for long-term contaminant removal, as it transforms soluble pollutants into insoluble forms, often influenced by pH and redox conditions. Co-precipitation events can further enhance the removal of pollutants through sorption (Ana Dorido *et al.*, 2008).

iii. ***Biological Processes:*** Biological mechanisms are integral to pollutant removal in CWS. Wetland plants absorb inorganic contaminants, such as nitrates, ammonium, and phosphates, using them as essential nutrients. Some plant species can also accumulate toxic metals like lead and cadmium. The efficiency of this biological uptake is determined by the plants' growth rates and the concentration of pollutants in their tissues. As plants die and decompose, their accumulated nutrients and contaminants are released back into the substrate and water, where they can be leached or further processed by microorganisms. Microbial metabolism is vital for breaking down complex organic chemicals, effectively removing a variety of organic pollutants, especially from urban and industrial wastewater. Microbes also facilitate the nitrification and denitrification processes, contributing to the removal of inorganic nitrogen and the release of nitrogen gas (N_2) into the atmosphere (Ana Dorido *et al.*, 2008).

Understanding these interconnected physical, chemical, and biological processes is essential for enhancing the effectiveness of treatment wetlands. Additionally, insights into biogeochemical cycling—the movement and transformation of metals, organic compounds, and nutrients—provide valuable information regarding the functionality and integrity of both natural and restored wetlands, particularly in assessing their capacity for pollutant removal in response to human activities (Ana Dorido *et al.*, 2008).

5.6 Pollutant Removal Mechanisms

The removal of pollutants from wastewater and stormwater in constructed wetlands (CWs) primarily relies on three components : vegetated plants, microorganisms/biofilms in the root zone, and filter media/substrate (Biswal BK *et al.,* 2022). Pollutants are removed through various processes such as sedimentation, filtration, adsorption, and biological degradation (Biswal BK *et al.*, 2022).

5.6.1 Key Mechanism Include:

- **Rhizodegradation:** Microbial breakdown of contaminants in plant roots.
- **Phytostabilization:** Stabilizing heavy metals in the rhizosphere.
- **Phytodegradation:** Decomposition of pollutants by plant enzymes.
- **Phytoextraction:** Uptake of contaminants from soil and sediments by plants.
- **Phytovolatilization:** Release of contaminants into the atmosphere.

5.6.2 Specific Contaminant Removal:

- **BOD and organic contaminants:** Removed via biological degradation and adsorption.
- **Suspended solids:** Reduced through sedimentation and filtration.
- **Nitrogen:** Removed through plant uptake and microbial processes.
- **Phosphorus:** Eliminated via adsorption, sedimentation, and biological uptake.
- **Pathogens:** Die-off and filtration processes help reduce their presence.
- **Heavy metals:** Treated through adsorption, sedimentation, and plant uptake (Verhoeven *et al.*, 1999).

6. Wetland's Ecosystem Services

A wetland is defined as any area that temporarily or permanently retains water. These ecosystems, including sloughs, swamps, ponds, and marshes, support diverse plant and animal life and offer vital services, with an estimated global value in billions of dollars annually (Pascal Baidou, 2014).

Wetlands are among the most productive environments, ranging from boreal forest bogs to amphibian-rich marshes. They provide essential habitats for migratory birds and permanent homes for animals like insects, toads, turtles, and snakes (Pascal Baidou, 2014).

In addition to providing biodiversity, wetlands regulate water levels, helping prevent flooding during wet seasons and alleviating droughts by slowly releasing stored water during dry periods. They also stabilize soil, prevent erosion, and trap sediments that contribute to fertile ecosystems (Pascal Baidou, 2014).

Often called the "kidneys of the landscape," wetlands filter water through plants, bacteria, and animals, capturing nutrients like phosphorus that could contribute to harmful algal blooms. They also sequester carbon and greenhouse gases, playing a key role in mitigating climate change (Pascal Baidou, 2014).

The services wetlands provide can be categorized into population, ecosystem, and global values. Population values involve ecological functions like supporting endangered species, providing habitats for hunting or fishing, and offering resources like wood and peat. Ecosystem values refer to broader functions such as water purification, flood control, and aquifer recharge. Global values include contributions to global nitrogen, sulfur, and carbon cycles (William J Mitsch *et al.*, 2015).

The Millennium Ecosystem Assessment (2005) introduced a new framework for categorizing ecosystem services into four distinct types: provisioning, regulating, cultural, and supporting (William J Mitsch *et al.*, 2015).

i. **Provisioning ecosystem services** refer to the products obtained from ecosystems, such as food, water, timber, fiber, and genetic resources.
ii. **Regulating ecosystem services** encompass various functions, including air quality regulation, climate control, water purification, disease management, pest control, pollination, and natural hazard mitigation.

iii. **Cultural ecosystem services** are the benefits people derive from ecosystems that relate to spiritual enrichment, recreation, ecotourism, aesthetics, education (both formal and informal), inspiration, and cultural heritage.

iv. **Supporting ecosystem services** include fundamental ecosystem processes like nutrient cycling and primary productivity, which contribute to the other three categories.

Wetlands are unique and productive ecosystems where terrestrial and aquatic habitats converge, providing numerous vital functions:

i. **Ecosystem Services**:
   - Water Purification and Replenishment: Wetlands regulate water quantity, recharge groundwater, and enhance water quality. They help manage floods and storms, aid in erosion control, and improve water security while playing a key role in climate change adaptation (World Wetlands Day, 2015).
   - Biodiversity Support: Wetlands are highly productive habitats, supporting diverse species of plants and animals. They serve as crucial breeding and feeding grounds, especially for waterbirds and migratory species (World Wetlands Day, 2015).

ii. **Economic and Nutritional Value**:
   - Wetlands provide significant food sources, including rice and fish. Well-managed rice paddy systems yield high productivity and support biodiversity that enhances pest control. Inland capture fisheries, many coastal fisheries, and substantial aquaculture production depend on wetland ecosystems (World Wetlands Day, 2015).

iii. **Climate Change Mitigation**:
   - Wetlands are important carbon sinks, particularly in peatlands and mangroves, which help mitigate climate change impacts (World Wetlands Day, 2015).

iv. **Cultural and Recreational Significance**:
   - Wetlands hold historical, cultural, and recreational value, providing spaces for activities like hiking, fishing, bird watching, photography, and hunting (World Wetlands Day, 2015).

6.1 Consequences of Wetland Destruction

- **Hydrological Disruption:** The destruction of wetlands disrupts watershed hydrology, affecting the movement, distribution, and quality of water, and increasing runoff, which can lead to heightened flood peaks (Pascal Baidou, 2014).
- **Carbon Release:** Draining wetlands releases stored carbon back into the atmosphere, contributing to climate change (Pascal Baidou, 2014).
- **Loss of Biodiversity**: The loss of plant life and key habitats impacts species that rely on wetlands for food, breeding, and shelter (Pascal Baidou, 2014).

Research highlights the critical importance of protecting wetlands for environmental health, supporting dependent plants and animals, and benefiting human society (Pascal Baidou, 2014).

6.2 Aquaculture & Pisciculture

Wetlands are vital ecosystems providing resources like fish, rice, timber, and medicinal plants, supporting both local and urban populations. Fish, as a key protein source, is crucial for over a billion people, with many species depending on coastal wetlands like estuaries and mangroves at some point in their life cycles (Ramsar Convention)

The East Kolkata Wetlands, spanning 12,500 hectares, are a prime example of urban wastewater reuse through aquaculture. With 254 fisheries, this multifunctional ecosystem recycles nutrients from the city's wastewater, supporting both fish farming and agriculture, and benefiting around 60,000 people (UA Magazine, 2005).

The wetlands' fish ponds, or bheries, recover nutrients from 1,300 million liters of wastewater daily, and nearly all fish production is sold through wholesale markets. The sector provides direct employment for about 8,500 individuals, fostering specialized labor in roles such as harvesting, packing, and distribution. Many local residents engage in sewage-fed agriculture and pisciculture, contributing to both the local economy and sustainable practices (UA Magazine, 2005).

This innovative blend of aquaculture and wastewater treatment showcases the wetlands' ecological, social, and economic importance, highlighting their role as a sustainable resource recovery system and a model for other urban regions.

7. Wetlands as Nature-based Solutions

Nature-based solutions (NbS) encompass actions aimed at protecting, sustainably managing, or restoring natural ecosystems to effectively and adaptively address societal challenges, including climate change, human health, food and water security, and disaster risk reduction. These solutions provide benefits not only for human well-being but also for biodiversity (Cauley, 2023). The International Union for Conservation of Nature (IUCN) defines NbS as actions that protect, sustainably manage, and restore natural or modified ecosystems, tackling societal challenges while offering advantages for both human welfare and biodiversity.

Wetlands play a vital and irreplaceable role by providing a range of ecosystem services essential for biodiversity conservation, climate change mitigation, and human welfare. They support key economic activities such as tourism by providing food, water, and timber. Moreover, wetlands regulate hydrological cycles, manage floods and droughts, maintain soil moisture, recharge groundwater, purify water, regulate air quality, cycle nutrients, sequester carbon, and enhance local aesthetic and recreational values. The critical ecosystem services derived from multifunctional wetland landscapes—where multiple wetlands exist within a catchment area—result from the cumulative interactions of individual wetlands with their surrounding environments. It is estimated that wetland ecosystem services account for over 20% of the total global value of ecosystem services (William J Mitsch *et al.*, 2015).

Given their capacity to provide various ecosystem services, wetlands are particularly relevant as nature-based solutions. In recent decades, the significance of wetlands in water management has gained attention, especially due to irregular patterns of water availability exacerbated by more frequent and intense hydrometeorological extreme events. Additionally, issues like eutrophication and rising wastewater levels—driven by anthropogenic activities and climate change—make sustainable water management increasingly urgent (William J Mitsch *et al.*, 2015).

7.1 Disaster Risk Reduction

Wetlands are crucial for regulating water, reducing runoff, moderating peak flows, and slowing water velocity, which are essential for flood mitigation. They effectively manage flood risks for shorter return periods (up to five years), but their effectiveness diminishes for extreme floods (greater than 100 years). Wetlands, such as detention basins, help mitigate flood risks depending on factors like size, location, and soil properties (William J Mitsch *et al.*, 2015).

While small wetlands can handle low-return period floods, larger floods require combined strategies across multiple scales. The relationship between wetlands and flood risk mitigation is complex, and climate change further complicates this understanding. Current models that combine climate and hydrological data provide insights into future flood risks but lack spatiotemporal accuracy, especially in areas with fewer wetlands (William J Mitsch *et al.*, 2015).

Besides flood mitigation, wetlands also help alleviate drought by storing water, but their role in drought management is unclear due to evapotranspiration losses. There is a need to improve wetland protection and integrate their functions into climate change risk assessments for better water management (William J Mitsch *et al.*, 2015).

7.2 Water Quality Improvement

Wetlands serve as effective Nature-Based Solutions (NbS) by improving water quality and mitigating the adverse effects of soil erosion, runoff, and wastewater pollution. They achieve this through various natural processes, including: (William J Mitsch *et al.*, 2015).

- **i.** **Pollutant Retention**: Wetlands retain contaminants via mechanical processes like sedimentation and filtration, as well as through adsorption on substrates and biosorption. This helps to remove a range of organic and inorganic substances, including nutrients, heavy metals, pesticides, hydrocarbons, xenobiotics, and antibiotics from contaminated water.
- **ii.** **Disinfection**: The interaction between wetland plants and microorganisms contributes to disinfection, aided by UV radiation from sunlight. This natural process enhances the overall water purification capacity of wetlands.
- **iii.** **Sources of Pollution**: Wetlands effectively filter pollutants from stormwater runoff in agricultural areas, urban surfaces, municipal wastewater (especially in areas lacking proper treatment facilities), landfill leachate, aquaculture effluents, and specific industrial wastewaters.
- **iv.** **Limitations**: While natural wetlands can significantly improve water quality, they have limitations on the volume of pollution they can handle before their natural processes become overwhelmed. This results in a limited capacity for ongoing pollution management.
- **v.** **Constructed Wetlands**: These have become popular alternatives for secondary and tertiary wastewater treatment across various climatic regions, particularly in developing countries due to their cost-effectiveness. However, there is still limited knowledge regarding their overall contribution to global treated wastewater volumes.
- **vi.** **Water Recycling**: Wetlands also facilitate the recycling and reuse of water and wastewater for irrigation, which is particularly beneficial in water-scarce regions. Recent innovations, such as integrating constructed wetlands with microbial fuel cells, are creating new bioenergy-producing wastewater treatment technologies (William J Mitsch e al., 2015).
- **vii.** **Sediment Removal**: Wetlands can remove up to 90% of sediments from runoff or streamflow. Their efficiency in pollutant removal varies over time and is influenced by specific wetland characteristics (e.g., plant species, size), the types of contaminants, and local climatic conditions.
- **viii.** **Enhancing Efficiency**: The removal efficiency can be improved through the harvesting of wetland plants, which not only aids in pollutant removal but also provides biomass for composting or biogas production.
- **ix.** **Watershed Context**: The ability of wetlands to manage pollution depends on their location,

total area, and the types of pollution sources, whether they are current surface sources or legacy sources from past activities. Constructed wetlands, when designed and maintained effectively, can provide a cost-efficient approach to enhancing water quality.

x. **Knowledge Gaps**: There is a need for more understanding of the morphological, physiological, and biochemical characteristics of wetland plants that influence the efficiency of wetlands in pollutant removal.

Overall, wetlands represent fully developed NbS that support environmental health and human well-being. They should be prioritized in restoration and protection efforts. Their numerous ecosystem services include safeguarding coastlines, promoting biodiversity, sequestering carbon, mitigating flooding, and purifying water by retaining contaminants. These benefits contribute to community health through sustainable economic opportunities and food and water security (Hank Cauley, 2023).

8. Benefits & Challenges of Using the Wetlands as Purifier

8.1 Benefits

- Water conservation
- On-site recycling and reuse
- Costs less to construct than most traditional water-filtration systems
- Lower operating cost
- Non-technical personnel can operate and maintain
- Energy conservation by using gravity flow and/or solar pumps
- Protection of the environment by eliminating pollutant runoff water
- Provides natural habitat for plants and animals (Robison *et al.*, 2008)

Wetlands play a crucial role in the water cycle, acting as natural filters that capture surface pollutants and sediment carried by water systems. They are significant reservoirs of the world's freshwater, with just one acre of wetlands capable of holding up to 330,000 gallons of water (Hank Cauley, 2023).

In addition to improving water quality, healthy wetlands offer numerous benefits, including erosion control for shorelines and inland areas, which helps prevent flooding, maintain stream flows, and provide vital wildlife habitats through nutrient retention. Furthermore, wetlands support the livelihoods of nearly one billion people worldwide. One study estimated the value of wetlands in flood prevention alone to be between \$1.2 and \$2.9 trillion in the U.S. (Hank Cauley, 2023).

Beyond these benefits, wetlands serve an essential function in carbon storage. They sequester carbon from the atmosphere through plant photosynthesis and trap sediment from runoff. Carbon is stored in living vegetation as well as in litter, peat, organic soils, and sediments, some of which have accumulated over thousands of years (Hank Cauley, 2023).

Wetlands hold a disproportionate share of the planet's soil carbon, containing between 20% and 30% of the estimated 1,500 petagrams of global soil carbon, despite covering only 5% to 8% of the land surface. In simpler terms, this amounts to around 225 billion metric tons of carbon, equivalent to the annual carbon emissions from approximately 189 million cars—more than the total number of registered vehicles in the U.S. in 2015 (Hank Cauley, 2023).

8.2 Challenges

- Many local and state agencies lack an understanding of how constructed wetlands work, many times envisioning foul-smelling, standing surface water, especially if black water is comingled.
- When water is stored in open ponds after filtration there can be liability concerns.

- Some state and local regulation codes may prohibit or restrict the use of alternative onsite systems.
- This is becoming less of a problem and is most often related to black-water filtration systems. Check with the county zoning office.
- Fluctuation in seasonal plant growth (winter vs. summer).
- Higher evaporation loss in desert areas. (Robison *et al.*, 2008)

Wetlands play a vital role for humanity, providing essential water needs for over three billion people, nearly half of the global population. The United Nations has emphasized that "Access to safe water, sanitation, and hygiene is the most fundamental human requirement for health and well-being"

However, despite our understanding of the significance of wetlands, it is estimated that more than 85% of the world's wetlands have been lost due to human activities, primarily from large-scale modern agricultural practices. Additionally, wetlands are increasingly threatened by invasive species, pollution, dam construction, mining, and various forms of human development (Hank Cauley, 2023).

9. Future Trends & Innovation

From 2022 to 2024, notable trends and innovations have emerged in utilizing wetlands as natural water purifiers. These trends highlight advancements in both natural wetland ecosystems and the growing implementation of constructed wetlands, which replicate the filtration capabilities of their natural counterparts.

9.1 Constructed Wetlands as a Major Innovation

Constructed wetlands have become increasingly popular as an eco-friendly and cost-effective approach to wastewater treatment. They utilize natural processes involving plants, microbes, and soil to eliminate pollutants like nitrogen, phosphorus, heavy metals, and emerging contaminants. Recent research is aimed at optimizing these systems to manage more complex conditions, such as high pollution loads, low temperatures, and varying nutrient compositions (Jiang, W *et al.*, 2024 & Xiaofeng Li *et al.*, 2024). Innovations like the integration of microbial fuel cells into wetland systems enhance pollutant removal, increasing their efficiency and adaptability to challenging environments (Yuyang Liu *et al.*, 2024).

9.2 Focus on Cold-Climate Wetlands

A key challenge driving recent innovation is the performance of constructed wetlands in colder climates, where traditional wetlands have been less effective due to decreased microbial activity. New strategies are being developed, including the use of resilient submerged plants and benthic fauna systems to enhance nutrient removal during winter. Furthermore, integrating biological contactors with wetland systems has proven effective for pollutant removal in cold seasons (Xiaofeng Li *et al.*, 2024).

9.3 Emerging Technologies in Monitoring & Management

Advancements in remote sensing and data analytics are improving the management and monitoring of both natural and constructed wetlands. Tools like Google Earth Engine and machine learning algorithms (e.g., random forests) enhance the ability to map, classify, and monitor wetland changes across extensive areas over time. This capability is vital for understanding the dynamics of wetland ecosystems, particularly in regions affected by climate change and human activities (Zhang J *et al.*, 2024).

9.4 Sustainable Wetland Development

Sustainability in wetland management has emerged as a crucial focus during the 2022-2024 period. Innovations, such as integrating wetlands with other wastewater treatment methods (e.g., anaerobic treatment), aim to enhance the resilience and efficiency of these systems. Researchers are also investigating ways to prevent clogging and improve oxygen supply, which are essential for maintaining long-term functionality and reducing operational costs (Jiang, W *et al.*, 2024 & Yuyang Liu *et al.*, 2024).

9.5 Wetlands for Carbon Sequestration & Biodiversity

Wetlands are increasingly recognized for their dual role in carbon sequestration and supporting biodiversity. Beyond purifying water, they play a crucial role in climate regulation by capturing carbon and sustaining a diverse array of species. Innovations are focused on enhancing these ecosystem services through improved conservation practices, monitoring, and restoration efforts, aligning with global initiatives to achieve biodiversity targets and combat climate change (Zhang J *et al.*, 2024).

In summary, both natural and constructed wetlands are at the forefront of ecological innovation as natural purifiers. With advancements in microbial technologies, adaptations for cold climates, and data-driven management, wetlands are becoming more effective and resilient in tackling water pollution challenges in an evolving world.

10. Results and Discussion

Wetlands are exceptional natural systems for water purification, driven by intricate physical, chemical, and biological processes. However, their performance is influenced by diverse factors, and there remain gaps in understanding their full potential and challenges. This section discusses key findings, identifies gaps, and proposes solutions for optimizing wetland use in pollutant removal.

10.1 Effectiveness of Wetlands in Pollutant Removal

i. **Heavy Metals**
  - ***Current Understanding*: ** Wetlands remove heavy metals effectively through adsorption onto soil particles, precipitation in anaerobic conditions, and phytoremediation byplants like *Phragmites australis*. Reported removal efficiencies often exceed 70%, with up to 93% for specific metals like zinc in controlled settings.
  - ***Identified Gaps*: ** Long-term sustainability of heavy metal retention in wetlands remains uncertain. Accumulated metals could alter soil chemistry, potentially reducing efficiency over time. Additionally, mixed pollutant scenarios—combining heavy metals with organic pollutants—are understudied.
  - ***Proposed Solutions*: ** Regular harvesting of metal-accumulating plants can mitigate soil saturation. Further research should focus on developing hybrid systems integrating constructed wetlands with advanced filtration technologies to address complex pollutant mixtures.

ii. **Nutrient Management**
  - ***Current Understanding*: ** Wetlands efficiently remove nitrogen and phosphorus, with denitrification converting nitrates into nitrogen gas and phosphorus immobilized via adsorption and precipitation. Removal rates range from 60% to 90%.
  - ***Identified Gaps:*** Seasonal variations impact nutrient removal efficiency, and

phosphorus saturation in soils can lead to re-release into water systems. Constructed wetlands exhibit greater control but often lack ecological diversity.

- ***Proposed Solutions*****:** Implement adaptive management strategies, such as alternating wetland hydrology to reduce phosphorus buildup. Introducing phosphorus-absorbing substrates (e.g., modified clays) in constructed wetlands can enhance long-term retention.

iii. **Organic Pollutants**

- ***Current Understanding*****:** Wetlands degrade organic pollutants through microbial activity and plant uptake, with removal efficiencies reaching 80%. However, emerging contaminants like pharmaceuticals and microplastics pose significant challenges.
- ***Identified Gaps:*** There is limited knowledge on the degradation pathways of emerging contaminants. Microplastics, in particular, resist breakdown and can accumulate in wetland ecosystems, impacting fauna and flora.
- ***Proposed Solutions*****:** Research into bioengineered microbial strains and enzymes capable of breaking down resistant contaminants is essential. Integrating constructed wetlands with complementary technologies, such as biochar filters, can target microplastics more effectively.

10.2 Integrated Mechanisms

The interplay of physical, chemical, and biological processes in wetlands enhances their purification capacity. For instance, sedimentation reduces turbidity while supporting adsorption and microbial degradation. Plant roots provide oxygen, enabling aerobic microbial activity in localized zones.

- ***Identified Gaps*****:** While these interactions are well-documented, their responses to environmental stressors (e.g., climate change, pollution surges) remain poorly understood.
- ***Proposed Solutions*****:** Develop dynamic models that simulate wetland responses to varying conditions, enabling better predictive management. Additionally, pilot studies integrating real-time monitoring systems can inform adaptive strategies.

10.3 Comparison of Natural & Constructed Wetlands

Constructed wetlands (CWs) are designed to optimize pollutant removal, offering better control over flow patterns and substrate conditions. Natural wetlands, in contrast, provide extensive ecosystem services, such as biodiversity conservation and flood regulation.

- ***Identified Gaps:*** Limited research explores hybrid systems combining natural wetlands' ecological benefits with constructed wetlands' efficiency. Moreover, the scalability of constructed wetlands for industrial applications remains a challenge.
- ***Proposed Solutions:*** Encourage pilot projects that integrate natural and constructed wetlands to harness complementary strengths. For industrial use, explore modular designs for CWs, enabling scalability while maintaining pollutant removal efficiency.

10.4 Conclusion & Future Directions

Wetlands are invaluable for water purification and environmental sustainability. To maximize their potential :

- ***Bridge Knowledge Gaps:*** Long-term studies should evaluate pollutant accumulation impacts and mitigation strategies.
- ***Innovate Hybrid Systems:*** Combine natural and constructed wetlands to balance ecological and

functional goals.

- ***Address Emerging Contaminants:*** Develop advanced biological and material-based solutions for resistant pollutants like microplastics and pharmaceuticals.
- ***Embrace Adaptive Management*:** Incorporate real-time monitoring and dynamic modeling to enhance resilience under changing environmental conditions.

By addressing these challenges, wetlands can remain at the forefront of sustainable water management, providing both ecological and practical solutions to global water quality issues.

Conclusion

Wetlands are indispensable ecosystems, often termed the "kidneys of the Earth," due to their ability to filter and purify water through physical, chemical, and biological processes. This review highlights their role in removing pollutants such as heavy metals, organic contaminants, and nutrients, making them vital for improving water quality and mitigating environmental challenges. Key processes like sedimentation, adsorption, ion exchange, and microbial degradation enable wetlands to address point and non-point sources of pollution efficiently. Constructed wetlands replicate these natural functions, offering scalable and cost-effective solutions for wastewater treatment.

Natural wetlands, including marshes, bogs, swamps, and fens, support biodiversity, regulate water flows, sequester carbon, and provide essential ecosystem services. However, anthropogenic pressures such as urbanization, industrial activities, and climate change have led to the loss of over 85% of wetlands globally, compromising their functionality. This degradation not only impacts water quality but also reduces resilience to disasters like floods and droughts.

Constructed wetlands are increasingly integrated into wastewater management, demonstrating high efficiencies in pollutant removal under controlled conditions. However, they lack the ecological complexity and multifunctionality of natural wetlands. Emerging trends focus on integrating wetlands into Nature-Based Solutions (NBS) for sustainable water management, disaster risk reduction, and climate adaptation. Case studies illustrate their success in mitigating pollution, enhancing biodiversity, and improving ecosystem services.

Despite significant progress, gaps remain in understanding the thresholds for pollution in natural wetlands, the long-term impacts of heavy metals and emerging contaminants, and the scalability of hybrid systems that combine natural and constructed wetlands. Future efforts should emphasize innovation, dynamic modeling, and real-time monitoring to address these challenges.

Concluding that, wetlands are critical for achieving sustainable water management and ecological conservation. By protecting and restoring natural wetlands and optimizing constructed systems, we can ensure their continued contribution to water quality, biodiversity, and climate resilience, reinforcing their role as vital Nature-Based Solutions

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