

Review

Characterization of Constructed Wetlands: A Safe and Sustainable Solution for Water Resources Treatment—An Overview

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Abstract

Water scarcity and pollution from anthropogenic activities are major challenges, increasing the need for sustainable wastewater treatment solutions. Constructed wetlands mimic natural wetland ecosystems using macrophytes and substrates, representing a possible nature-based solution aligned with circular economy principles and the United Nations Sustainable Development Goals. So, this revision integrates recent literature, providing an overview of natural wetlands and examining the design and operation of constructed wetland systems. Also, incorporates a case study that focuses on a constructed wetland implemented at an eco-friendly dog shelter in Portugal—a unique example globally—demonstrating practical wastewater treatment and small-scale water reuse, and offering insights for sustainable management. Performance assessment based on previous work indicates that the system effectively reduces most water quality parameters to levels compliant with national and European irrigation standards. Removal efficiencies exceeded 97% for chemical oxygen demand, total suspended solids, and turbidity, while maintaining low energy consumption and minimal maintenance. Overall, constructed wetlands emerge as a sustainable alternative to conventional wastewater treatment systems; however, several challenges remain to be addressed. Future research should focus on improved aeration strategies, optimized substrate–macrophyte combinations, and long-term monitoring under climate variability, with floating wetlands offering promising opportunities to further enhance treatment efficiency.

Keywords: water stress; unconventional water resources; wastewater treatment; phytoremediation; circular economy; sustainability



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1. Introduction

Water is an essential resource for human life, particularly for drinking and irrigation purposes [1]. Its availability depends on fresh water, with the main sources of clean water being the surface and groundwater [2]. Water quality is closely influenced by both natural and anthropogenic factors. Among the latter, industrial growth plays a major role, as it supports the basic needs of populations but also contributes to increasing environmental pressure [3]. Consequently, effluents inevitably cause an increase in organic and inorganic waste, contributing to water contamination [4]. These events bring environmental problems, such as pharmaceuticals, antibiotics, and other contaminants [5]. Municipal wastewater is the primary source of freshwater and marine contaminants, but it is not the only one. This includes domestic wastewater from small communities, runoff or wastewater discharge

from animal feedlots, and rural sewage [6–8]. In most cases, these contaminants end up concentrating in rivers, lakes, and small watercourses, which can pose serious problems for the aquatic systems in which they are found and, consequently, for human health [1,3,9]. For example, groundwater contamination is very difficult to detect due to its vast extent and lack of visibility, thus complicating its treatment [4]. The quality of water resources is essential to promoting economic development and conserving ecosystems, thus fulfilling sustainability goals [10]. According to [11], about 50% of European countries face issues related to water stress (Figure 1). In the United States, water consumption in certain regions exceeds the replenishment capacity.

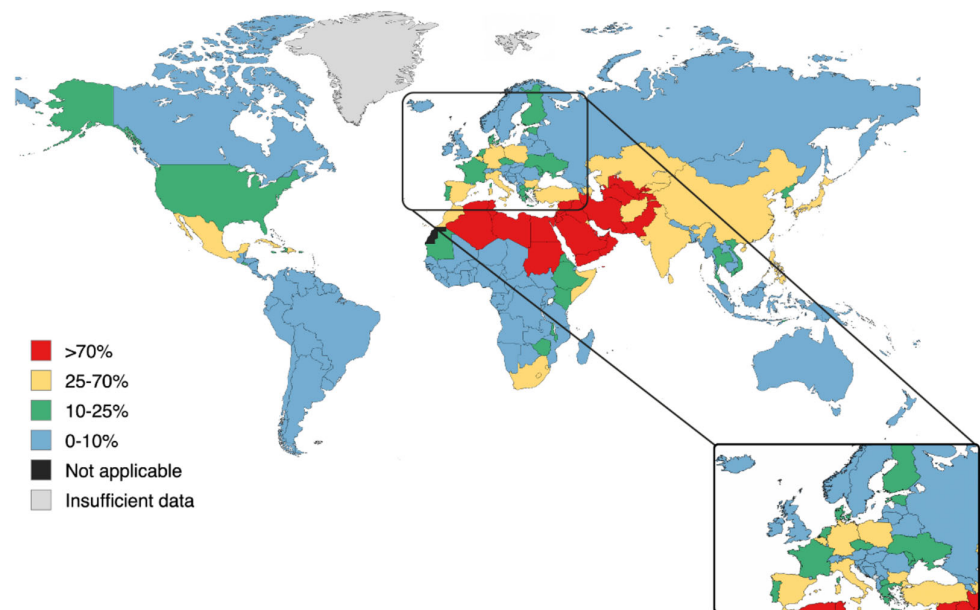


Figure 1. Water stress is represented as the ratio between the water withdrawn by major sectors, including environmental requirements, and the total amount of renewable freshwater resources, expressed as a percentage (adapted from [12]).

Additionally, climate change significantly influences groundwater levels due to irregular precipitation patterns, leading to fluctuations in groundwater recharge, especially in arid and semi-arid regions [13]. Climate variability alters the balance between water entering and leaving the subsurface, affecting both the quantity and quality of available water. Groundwater recharge depends on the amount of precipitation reaching the land surface and the water lost through evaporation and transpiration. During drier periods, declining precipitation combined with higher temperatures enhances evaporation, reducing percolation to aquifers and overall groundwater availability. Elevated temperatures and intensified evaporation also concentrate dissolved salts, increasing groundwater salinity and degrading water quality, particularly in shallow or coastal aquifers [14]. Furthermore, higher water-column temperatures can accelerate phosphorus release from sediments and stimulate cyanobacterial growth, intensifying eutrophication, especially in tropical semi-arid reservoirs [15]. Given these impacts, concern about water scarcity and availability has increased, highlighting the importance of adopting improved irrigation technologies to mitigate climate change effects [16]. According to the Water for Prosperity and Peace report, UNESCO [17], water management must consider the evolving economic and social realities, including climate change, geopolitical shifts, and their impacts on water resources. Therefore, in a country facing water scarcity, the concept of water reuse and recycling within a circular economy framework is particularly relevant, as it promotes resource efficiency, wastewater reuse, and nutrient recovery, thereby mitigating water shortages

and supporting sustainable management [18]. However, conventional treatment methods, such as chemical precipitation and adsorption, while widely used, face significant limitations. These include high operational costs, elevated energy consumption, and limited effectiveness in removing emerging contaminants like pharmaceuticals, pesticides, and other persistent organic pollutants [19,20]. As a result, there is an urgent need for more sustainable treatment solutions.

According to [21], innovative and sustainable technologies have been developed to reduce water consumption and avoid secondary environmental effects. Some of these technologies, such as phytoremediation, have low installation and maintenance costs [22]. Constructed wetlands (CWs) are an excellent example of this [23]. They currently represent an established technology capable of closely recreating a natural wetland and offering an alternative to conventional wastewater treatment systems [18,24]. According to the same authors, compared to conventional wastewater treatment systems, CW offer similar or enhanced pollutant removal, generally require lower energy and chemical inputs, and provide additional environmental benefits such as biodiversity enhancement and habitat creation. These systems replicate natural ecosystems that develop when water becomes the primary factor in environmental control, in conjunction with plants and animals [25]. This technique is based on a system of macrophytes in CWs, which exhibit efficient purifying capacities when applied to small population clusters, enhancing landscape integration, such as aesthetic and ecological [26]. Furthermore, these systems also use different types of substrates and microbial communities to help remove water pollutants, nutrients, and organic matter [27]. Ultimately, this study aims to critically evaluate and synthesize current knowledge on CWs, providing insights into their application as a sustainable technology for wastewater treatment. It focuses on the design and types of CWs, the role of phytoremediation, and the importance of selecting effective macrophyte species to enhance performance. To conduct this review, a systematic and comprehensive literature search on CWs was performed using major scientific databases, including Web of Science, Scopus, and Google Scholar. The search strategy was designed to identify peer-reviewed studies addressing the application of CWs for wastewater treatment, with particular emphasis on pollutant removal efficiency and their role as nature-based solutions. The keywords used in the search included “constructed wetlands,” “wastewater treatment,” “pollutant removal,” and “nature-based solutions,” along with relevant Boolean operators to refine the results.

Publications published between 2010 and 2025 were prioritized in order to capture recent scientific advances and technological developments in the field. In addition, seminal and highly cited earlier studies were included to provide historical background and contextualize the evolution of CW research. Additionally, a case study is presented, selected for hosting a fully operational CW that treats wastewater on-site. This provides a practical and representative example of CW-based water treatment implementation and potential water reuse under the specific environmental and climatic conditions of northern Portugal.

While numerous reviews discuss CWs, this manuscript uniquely combines a systematic synthesis of recent literature with a detailed case study of a fully operational CW treating wastewater at an eco-friendly dog shelter in northern Portugal. This approach not only provides a critical evaluation of CW design and performance but also illustrates practical implementation challenges and opportunities for resource recovery, contributing novel insights for both researchers and practitioners.

The CW is located in the municipality of Amares (Braga district), within a dog shelter recognized as the first eco-friendly shelter in northern Portugal and considered a national reference project. Beyond promoting animal adoption, the shelter incorporates circular economy practices, including water reuse, biomass recycling through composting, and the use of sustainable building materials. Opened in 2021, this CW system is the first

known globally to treat wastewater from animal enclosures using this nature-based technology. The CW is operated and maintained by the municipality to ensure consistent treatment performance.

By examining this case study, the research highlights the practical benefits of CWs and their potential contribution to achieving the United Nations Sustainable Development Goals (UN-SDGs), particularly SDG 6: Clean Water and Sanitation, through the application of circular economy principles. Moreover, the implementation of CWs aligns with regional and international initiatives promoting nature-based solutions for wastewater treatment, such as the European Union Green Deal and the UNEP guidelines on Nature-Based Solutions.

2. Wetlands

2.1. Natural Wetlands

Natural wetlands (NWs) are areas of land that remain consistently saturated with water, either permanently or seasonally, acting as transition zones between terrestrial and aquatic ecosystems [28]. According to the same authors, they encompass various ecosystems, including lakeshores, swamps, estuaries, floodplains, stagnant water zones, and temporary shallow water body zones. Despite covering only a small percentage of the Earth's surface, freshwater wetlands are home to a significant proportion of the world's flora and fauna, highlighting their importance to global biodiversity. These characteristics support the development of distinct plant species, which are ascribed to aquatic plants. In this way, wetlands play important ecological roles, such as filtering water pollutants, providing flood protection, conserving biodiversity, and storing carbon [24]. These functions contribute to environmental balance and support climate change mitigation. They also provide habitat functions, such as refuge and nursery; production functions, such as food, medicinal resources, ornamental resources, and raw materials; and informational functions, such as science and education, aesthetics, culture and art, spirituality, and history [28]. Indeed, according to a recent review investigation [29] (Wood et al., 2024), this was further reinforced. The study revealed that recreation/tourism was the most frequently reported cultural ecosystem service (40%), followed by cultural identity/heritage (16%) and education/learning/knowledge (13%). So, their value is divided into three major types: ecological, economic, and sociocultural [30]. Their interest has increased due to the high nutrient absorption efficiency of various macrophyte species in these systems, serving as phytoremediation agents [31]. According to the same authors, nutrient absorption in some of these plants is high, and they can accumulate elements in specific areas, such as roots, stems, or leaves, which are in water or soil. Nutrient transformation and accumulation in these systems depend on many variables, such as water-column nutrient concentrations, the hydrological regime (including water depth and hydraulic loading), sediment characteristics, the type of vegetation present at the site, and the surrounding biota [32,33]. The processes that occur are diverse and complex. Bacteria that grow in the submerged parts of plants' stems and roots are facilitators and are responsible for some of these processes, such as nitrification and denitrification [18]. Hydraulic flow in these locations is generally slow due to the existing vegetation, which promotes greater contact time between water and the various surfaces of natural wetlands.

2.2. Constructed Wetlands for Wastewater Treatment

CWs were initially developed in Europe in the early 1950s [34]. As stated by [35], they are efficient treatment systems that can be highly beneficial in developing countries due to their simplicity and low operational costs. These systems, designed for wastewater treatment, aim to mimic the ecological functions of NWs, while exploring and improving the biodegradation capacity of plants [36,37]. Despite the typical construction of large

wastewater treatment systems in many countries, which utilize technological methods and chemical products, the rising interest in CWs and their ease of implementation with ecological technologies—combined with their low maintenance requirements—are driving factors for their growing popularity and subsequent expansion [3]. This has led to a paradigm shift in wastewater treatment approaches, with increased adoption of CWs globally.

CWs are usually recommended as secondary or tertiary treatment due to their high efficacy levels [2]. They have different types of configurations and can be classified based on the following characteristics [38–40]:

- Type of dominant macrophytes (submerged, emergent, or floating);
- Bed configuration (hybrid, single-pass, or recirculation systems);
- Type of effluent (domestic, industrial, agricultural, and leachate from landfills or mining activities);
- Required treatment (secondary, tertiary, or tuning);
- Filling medium (gravel, sand, pebbles, expanded clay, or synthetic material);
- Type of load (continuous or discontinuous).

Each of these characteristics influences the overall treatment performance; for example, the type of filling medium affects hydraulic conductivity, pollutant adsorption, and microbial activity.

There are two types of flow systems: surface flow systems (SF) and sub-surface flow systems (SSF), which can be either horizontal (HSSF) or vertical (VSSF) [41]. Figure 2 presents a general classification of different CW systems, highlighting the type of substrate, the vegetation employed, and the associated flow regime [23].

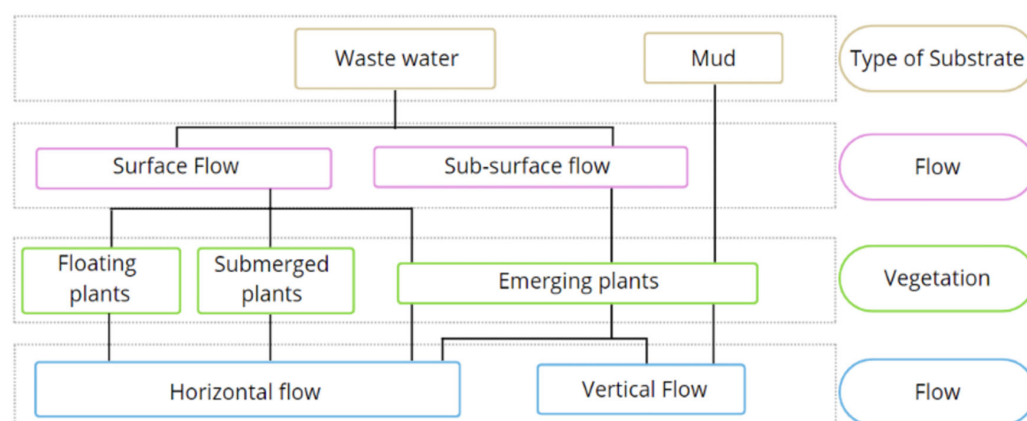


Figure 2. General classification of constructed wetlands.

The classification of the different CW systems is further discussed in detail in the subsequent section.

2.2.1. Surface Flow

This type of system (Figure 3a), which is more common in the United States than in Europe, is characterized by a water level maintained above the surface of the bed or filling medium [34], creating favorable conditions for biofilm development. Pollutant removal can occur under anaerobic, aerobic, or anoxic conditions, depending on factors such as bed configuration, water depth, effluent characteristics, macrophyte species, temperature, and other operational parameters.

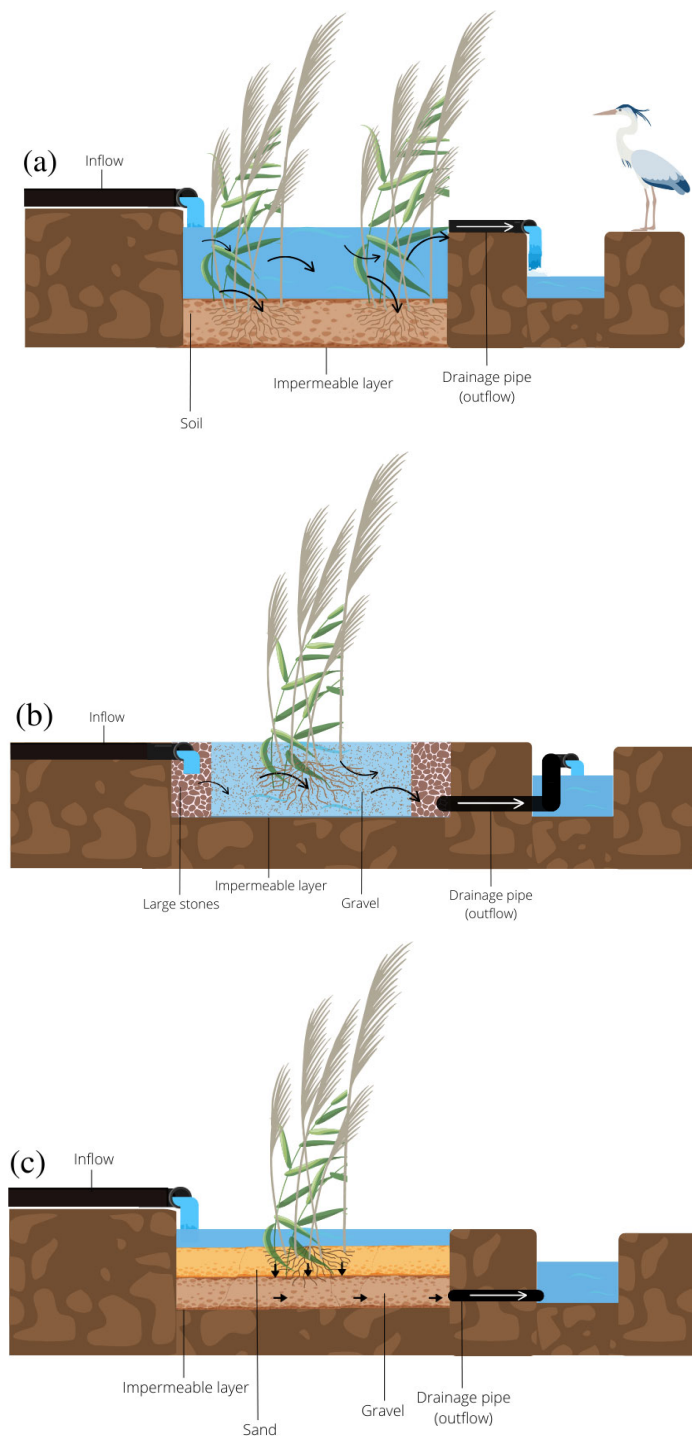


Figure 3. Classification of different flow systems. (a) Surface flow system; (b) Horizontal sub-surface flow system; (c) Vertical sub-surface flow system.

Surface flow (SF) systems employ floating, submerged, or emergent macrophytes. The supporting medium typically has a depth of 0.3–1.0 m, with bottom slopes between 0.5% and 1.5%. The gravel- or sand-based layer is relatively thin (0.10–0.20 m), while the overlying water column is generally shallow, ranging from 0.5 to 1.0 m. SF systems are widely applied for the treatment of domestic, agricultural, and industrial wastewater [2].

In addition to their treatment efficiency, SF systems offer several advantages, including a lower risk of clogging and the potential to support diverse wildlife. However, their open-water configuration can lead to insect proliferation and unpleasant odors due to direct exposure of the effluent to the atmosphere [18,24].

2.2.2. Sub-Surface Flow

This system is characterized by a water level maintained below the surface of the media bed. Typical bed depths range from 0.3 to 1.5 m, with approximately 0.6 m being the most commonly adopted depth. One of the main advantages of this configuration is the reduction of odors, insect proliferation, and direct human contact with wastewater, as the water remains confined beneath the bed surface [34,42,43]. Depending on the configuration of the inflow and outflow, subsurface flow systems can be classified into horizontal subsurface flow systems (HSSF) and vertical subsurface flow systems (VSSF) (Figure 3b,c) [44]. The HSSF system is the most used in European countries [45]. The influent, defined as the wastewater found at the entrance of the macrophyte beds to be purified, is distributed at the entrance of the bed, moving horizontally through the porous medium and the rhizosphere, resulting in the absence of surface runoff. As the inflow slowly moves through the rhizosphere, the place where the soil and plant roots meet, adsorption, precipitation, and microbial degradation mechanisms occur [5,46]. The purified effluent is then collected at the outlet located at the end opposite the inlet. Also, most CW systems with horizontal flow can reliably treat biochemical oxygen demand (BOD) and total suspended solids (TSS) [47]. However, they are often less effective for nitrogen removal unless a longer hydraulic retention time and sufficient oxygenation are provided [34,48]. The VSSF system can have two flow directions: upward or downward, the latter being more common [40]. Vertical upward flow is achieved through mechanical systems, capillary action, and counter-current mechanisms.

In the downward system, the influent flows vertically over the surface of the bed, leading to faster infiltration at the base of the bed, where it will later be collected. This intermittent flooding and draining allow air to refill the substrate pores within the bed, improving the oxygen transfer from the atmosphere to the system [2,49]. The efficiency of this system in pollutant removal also depends on the soil aeration capacity and the properties of the filling material [50–52]. Several studies have demonstrated that vertical flow has high efficiency in the removal of BOD, TSS, and nitrification [48,53,54]. As demonstrated by [55], these systems can substantially reduce organic matter and suspended solids and promote the transformation of ammonium to nitrate via microbial nitrification processes mediated, for example, by *Nitrosomonas* and *Nitrobacter* species.

CWs are heterogeneous systems, exhibiting a range of oxidation–reduction conditions as well as aerobic and anaerobic phases. They are also dynamic systems, with fluctuations in both intrinsic process parameters and extrinsic environmental factors—such as precipitation, sunlight exposure, and wind—which are generally more pronounced in the upper layer of the bed and occur over both short and long temporal scales [24]. Vegetation further contributes to spatial and temporal variability in environmental conditions [56]. In this context, Table 1 summarizes some of the key removal mechanisms in CWs.

Table 1. Example of removal mechanisms in a constructed wetland system [57] Removal efficiencies based on [58–61].

Parameters	Physical Mechanisms	Chemical Mechanisms	Biological Mechanisms	Removal Efficiencies
Suspended Solids	Sedimentation	—	Microbial degradation	60 to 98%
BOD ₅ (Biochemical Oxygen Demand)	Sedimentation	—	Microbial degradation	70 and 95%
COD (Chemical Oxygen Demand)	Sedimentation	—	Microbial degradation	82 to 88%

Table 1. Cont.

Parameters	Physical Mechanisms	Chemical Mechanisms	Biological Mechanisms	Removal Efficiencies
Metals	Sedimentation	Precipitation; Adsorption; Ion exchange	Uptake by microorganisms; Uptake by plants	33 to 99%
Petroleum Hydrocarbons	Volatilization	Adsorption	Uptake by microorganisms; Uptake by plants	78 to 91%
Synthetic Hydrocarbons	Sedimentation; Volatilization	Adsorption; Volatilization (NH ₄)	Uptake by microorganisms; Uptake by plants	55 to 90%
Nitrogen Compounds	Sedimentation	Precipitation; Adsorption	Uptake and transformation by microorganisms; Uptake by plants	24 to 70%
Organic and Inorganic Phosphorus	Sedimentation	—	Uptake by microorganisms; Uptake by plants	15 to 68%
Pathogenic Organisms	Sedimentation	—	Natural mortality; Microbial predation.	63 to 99%

2.2.3. Macrophyte Bed Classification

The term macrophyte (*macro*: large + *phyton*: plant) is used for macroscopic plants; however, it is frequently applied to aquatic plants. Aquatic plants are those that present their life cycle, or at least part of it, linked to water or humid environments. These types of plants are considered among the most effective species for tolerating and removing potential toxic elements from aquatic environments [62]. According to several studies, three fundamental types of macrophyte beds are considered (Figure 4) [63]:

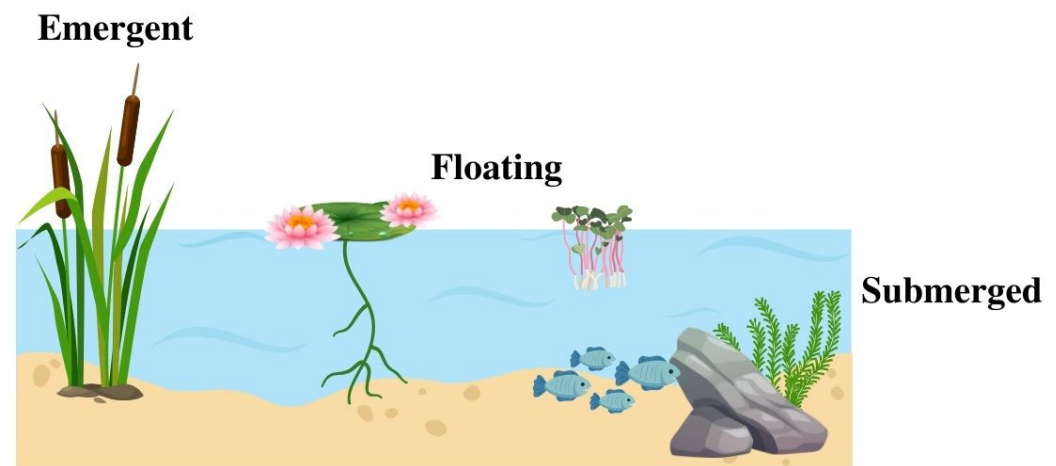


Figure 4. Representative image of the three fundamental types of macrophyte beds: floating, submerged, and emergent.

2.2.4. Emergent Plants

Systems based on emergent macrophytes are the most widely used, as they allow both vertical and horizontal flow configurations, previously mentioned. These plants are rooted in the soil with their leaves and the majority of stems extending above the water surface [3]. According to [4,64], this contributes to pollutant removal from both water and sediment compartments. They are typically found along flooded banks and within shallow water bodies. Due to their strong adaptation, growth, and development capabilities, emergent plants such as *Phragmites*, *Typha*, and *Juncus* are the most commonly used species in phytoremediation, particularly for wastewater treatment in constructed wetlands [24].

2.2.5. Floating Plants (Rooted or Free)

This group includes plants that float on the water's surface. Some are rooted, with the roots attached to the sediment, but their leaves are on the water surface, like *Nymphaea* sp. Others may be free, not rooted in the bed, like *Lemna* spp. and *Azolla filiculoides*.

2.2.6. Submerged Plants

Plants anchored to the ground or suspended in water grow completely submerged, although the reproductive organs are often at or above the surface. This is the case of the species *Potamogeton pectinatus* and *Elodea canadensis*.

Plants play a critical role in this type of system, contributing to several mechanisms that enhance wastewater treatment. These include preventing channelized flow, uptake of nutrients and potential toxic elements, forming symbiotic relationships that support the growth of attached bacteria, and increasing oxygen concentrations in the water by diffusion from roots to the rhizosphere [24,34,65,66]. This last one is due to the fact that these plants have a type of conductive and aeriferous parenchyma, known as aerenchyma, which allows them to develop better in waterlogged soils where common plants would die from root asphyxia.

These species with aerenchyma and hollow stems, such as *Phragmites australis*, can create high internal oxygen concentrations, which consequently enhance the oxygen levels around their roots in the external environment, known as the rhizosphere. These oxygen-rich environments foster favorable conditions for oxidation-reduction, which stimulates the aerobic decomposition of organic matter and the growth of bacteria. Nevertheless, the benefits extend beyond this. The careful selection of species capable of forming dense root systems and high biomass, preferably indigenous and well-adapted to the local climate, tends to enhance biodiversity in these areas [18,24]. Furthermore, it improves the aesthetics of wetlands [22] and can serve educational purposes.

Species with well-developed root systems and rhizomes adapted to the site should be preferred, as they can withstand short periods of drought and different residual loads [63]. Also, the root bioactivation mechanisms are commonly employed by most species to enhance absorption efficiency, including rhizosphere acidification, organic acid exudation, metal chelation, and enzymatic processes that increase nutrient availability [64]. These mechanisms also enable plants to regulate the uptake of potentially toxic elements, maintaining tolerable internal concentrations [31].

Although several studies indicate that contaminant removal is largely driven by phytoremediation, that is, by plant–contaminant interactions alone, accounting for more than 60% of overall removal efficiency [64], other biotic and abiotic factors should not be overlooked. So, it is important to consider the substrate in which the roots of plants are placed, as this significantly affects the efficacy of the systems in question [56]. Substrates containing varying levels of clays and organic matter play a crucial role in the removal of contaminants, largely due to their cation exchange capabilities [67]. Hydrological conditions are a defining factor of humid areas, characterized by the frequency, timing, and duration of flooding/rain and water level fluctuations [68]. Any alteration in water volume poses a potential threat to the overall ecosystem and its integrity [69,70]. As previously mentioned, substrate type, root-associated microorganisms, and the plants themselves are key components of this integrated system, and should consist of locally adapted species, carefully selected based on the characteristics of the water to be treated and the climatic conditions of the deployment site.

2.3. Plant Maintenance

Maintaining plants in a CW makes this process so attractive, as it does not require much maintenance, resulting in low costs. Depending on the macrophyte implemented, the type of maintenance required may vary. For example, *Lemna* spp. has a very low biomass but a very high growth rate, so more frequent collection is necessary. Its main role is to remove nutrients from a thin layer of water. Common water hyacinth, used in some countries, also needs frequent collection but has better potential for removing nutrients and reducing suspended particles. On the other hand, larger plants such as *Typha latifolia* and *Phragmites australis* only need to be harvested once a year.

According to [18], the maintenance of vegetation also involves controlling the water level so that good plant growth can be ensured. However, most macrophytes tolerate short periods of increased depth up to 50 cm, as well as the absence of water during drier weather [71]. However, there may be additional expenses due to the accumulation of sludge in the filling material or eutrophication, which may lead to future problems in flow distribution and effluent output [72].

2.4. Constructed Wetlands: Advantages and Disadvantages

CWs have been recognized for their ability to treat various types of effluents with minimal energy requirements and low operational and maintenance costs [73]. These systems, based on natural processes observed in wetland ecosystems, but in a controlled environment, consist of beds filled with appropriate substrates such as gravel, sand, or clay, and planted with vegetation that supports microbial communities, all working together to remove contaminants [2]. CWs are highly efficient at treating wastewater, and their low energy demands make them a sustainable choice compared to conventional treatment technologies [74]. They are designed not only to treat effluents but also to offer additional benefits, such as carbon sequestration, conservation of wildlife habitats, and flood control [75–77].

Despite conventional wastewater treatment systems, such as activated sludge, trickling filters, or biological discs, addressing pollution control in large population centers, they rely on energy from non-renewable resources, such as fossil fuels. These systems also require continuous monitoring and skilled workers to ensure the proper functioning of the processes and equipment used, such as aerators, clarifiers, and sludge recirculation units.

Furthermore, pathogens, nutrients, and both organic and inorganic contaminants can be effectively removed, thereby contributing to the protection of public health, for example, by reducing the risk of waterborne disease transmission [78,79]. Table 2 summarizes the main advantages and disadvantages of CWs compared to conventional wastewater treatment systems.

Table 2. Advantages and disadvantages of constructed wetlands compared to conventional systems [22,80–82].

Advantages	Disadvantages
Low operating and maintenance costs	Different species have different pollutant removal rates
Treated water can be used for recreational and gardening purposes	Treatment process in construct wetlands is slower compared to other treatment processes, with higher removal efficiency in summer than in winter.
High efficiency in removing BOD, COD and TDS	Risk of introduced plants becoming invasive due to their vigorous growth stimulated by nutrient-rich effluents.

Table 2. Cont.

Advantages	Disadvantages
Effective in removing nitrogen and phosphorus	Poor management can lead to bad odors and the proliferation of pathogenic organisms and insects
Contributes to drainage and flood management	High pollutant concentrations may become toxic to plants
Odor minimization	Larger land area required compared to conventional systems
Aesthetically pleasing	Risk of bed clogging in sub-surface flow systems due to high organic matter concentrations
Increases biodiversity and provides habitats for wildlife	
Biomass can be used for different application;	
Relies on natural processes	
No need for qualified personnel for system maintenance	
Low sludge production	

Eutrophication is a process that can interfere with the functioning of CW systems. It is characterized by excessive plant growth resulting from high organic loads in the beds. By increasing the concentrations of biogenic elements—mainly phosphorus and nitrogen, in both inorganic and organic dissolved forms—eutrophication can ultimately limit the biodiversity within the system. Therefore, the selection of the most suitable species for purification in CWs should consider several key aspects [23,24,64]:

- Show rapid growth, which enhances pollutant uptake efficiency and promotes faster biomass generation;
- In the case of beds with heights greater than 0.6 m, *Phragmites* should be chosen, as its roots can reach 1 m deep;
- If the tributaries have high sodium content, as occurs in wastewater in coastal towns, where brackish water intrusion can occur, *Phragmites australis* or *Phragmites vulgaris* should be used;
- Rapid development of the roots;
- High performance in wastewater purification, including the removal of nutrients (nitrogen and phosphorus), organic matter, and potentially toxic elements;
- Having a use after purification, such as incorporation into composting;
- Easy control;
- High resistance to salinity (up to 1500 mg NaCl/L) and other contaminants;
- Preference always for native species.

Figure 5 exemplifies the preparation of the species *Phragmites* sp., produced in a specific greenhouse, with the aim of placing it in this type of system due to its high purifying capacity.

It is worth noting that these systems support a variety of species, recreating the natural environment. In this way, by increasing biodiversity and providing habitats for terrestrial and aquatic fauna, they significantly promote wildlife development, which represents an additional advantage in the implementation of such systems [18,24]. Throughout the work period, numerous species were observed, both in these CWs as well as in their surrounding areas (Figure 6).

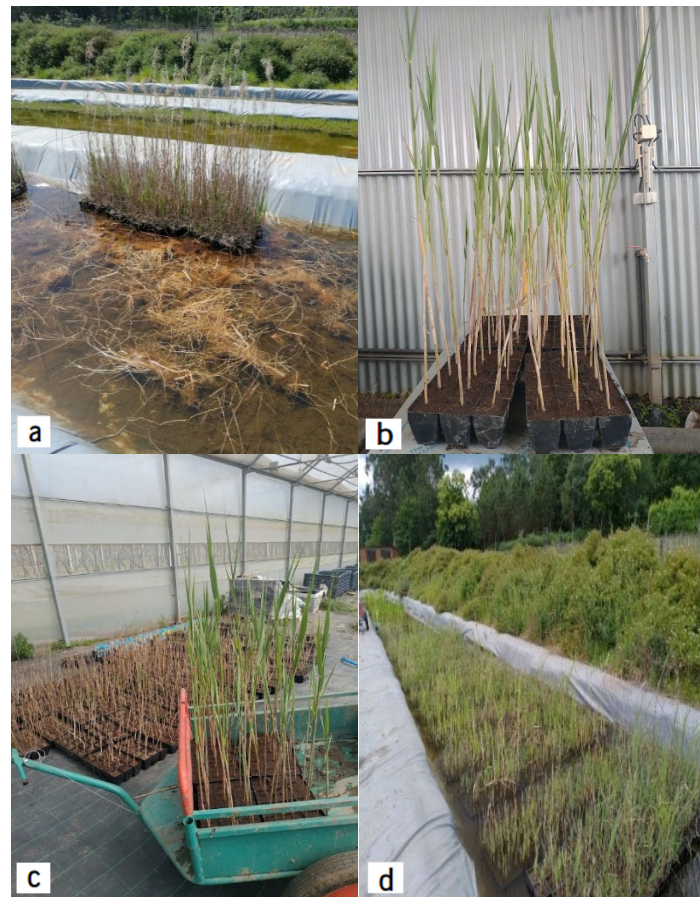


Figure 5. Vegetative multiplication of *Phragmites australis*. (a) *Phragmites australis* inside the pond before its multiplication; (b) *Phragmites australis* in the planting trays; (c) *Phragmites australis* after vegetative multiplication; (d) *Phragmites australis* inside the pond after vegetative multiplication.



Figure 6. Biodiversity observed in the PhytoClean constructed wetland.

Here, it is worth emphasizing the importance of incorporating native species into the system, as the increase in biodiversity would not be as significant if exotic species were used. Moreover, the introduction of non-native species could pose the risk of promoting organisms with greater competitive advantages over native flora, potentially leading to ecological imbalance. Therefore, a thorough understanding is required for the proper handling, management, and implementation of these systems.

3. Applied Study Case

The case study focuses on a CW integrated into a dog shelter recognized as Portugal's first eco-friendly facility and regarded as a national benchmark. In addition to promoting animal adoption, the project supports circular economy practices, including water reuse, biomass recycling through composting, and the construction of animal enclosures using sustainable methods.

Figure 7 illustrates the water circulation within the CW, from initial wastewater input to its final point of reuse. Generally, three groups of dominant macrophytes have been implemented in effluent treatment: emergent plants, which are rooted in the sediment with leaves extending above the water surface; floating plants, whose leaves rest on or just below the water surface; and submerged species, which remain mostly underwater [83]. Specifically, in the CW, only one emergent macrophyte is present, the native species *Phragmites australis*, commonly known as reed. This species is one of the most commonly used in CWs in Europe [84,85]. It has a high capacity to adapt to changing environmental conditions. A previous study by [86] reported that this species can reach up to 6 m in height and produce high biomass, supported by an extensive rhizome system. In the first lagoon, various species coexist, including *Typha latifolia*, *Iris pseudacorus*, *Juncus effusus*, *Lythrum salicaria*, *Mentha aquatica*, *Nymphaea alba*, and *Myriophyllum spicatum*.

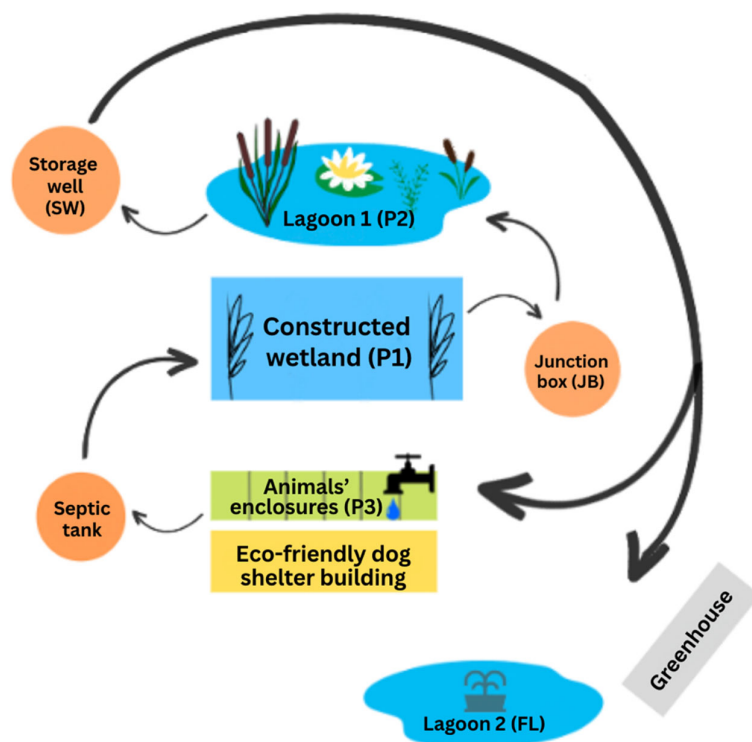


Figure 7. Schematic layout of the eco-friendly dog shelter. P1 inlet—Constructed wetland; P2—Lagoon 1; P3—Water outlet. Adapted from [23].

The treatment process starts when the effluent—the wastewater generated from cleaning the animals' enclosures of the shelter—flows into the septic tank. Here, the first phase of

purification occurs, with solids being decanted. The effluent then enters the CW (P1—inlet), where it is treated by the *Phragmites australis* species in contact with a sandy substrate. After this, the effluent proceeds to the CW junction box (JB) before entering the first lagoon (P2). This lagoon contains the remaining plant species used for water treatment. Furthermore, this lagoon was included, as it not only facilitates treatment through phytoremediation but also aids in eliminating harmful elements such as viruses and bacteria through sunlight (UV). As noted by [87], UV radiation is highly effective for treating effluents, especially for eliminating contaminants that are not adequately removed by standard treatment methods. This highlights the importance of UV treatment in maintaining water quality, particularly for water reuse applications. However, it should be noted that turbid water and, therefore, the presence of suspended particulate matter can interfere with UV treatment, as particles may shield microorganisms from exposure to the radiation and, thus, limit the overall effectiveness of the UV treatment [88].

At the end of the treatment process, the water that flows from Lagoon 1 is collected in a storage well (SW), where it remains until needed for its reuse through a manually operated water outlet (P3—outlet) installed for this purpose. This treated water is used to clean the animal enclosures, serve the sanitary facilities, and irrigate the trees of the greenhouse. The second lagoon (FL) has an ornamental purpose and receives some of this treated water and collects rainwater (Figure 7).

Figure 8 illustrates the various stages of wetland construction. The process began with excavation over one meter deep and the installation of a waterproof liner. Next, sand and gravel were placed as substrates, inlet and outlet pipes were installed, and *Phragmites australis* was planted.

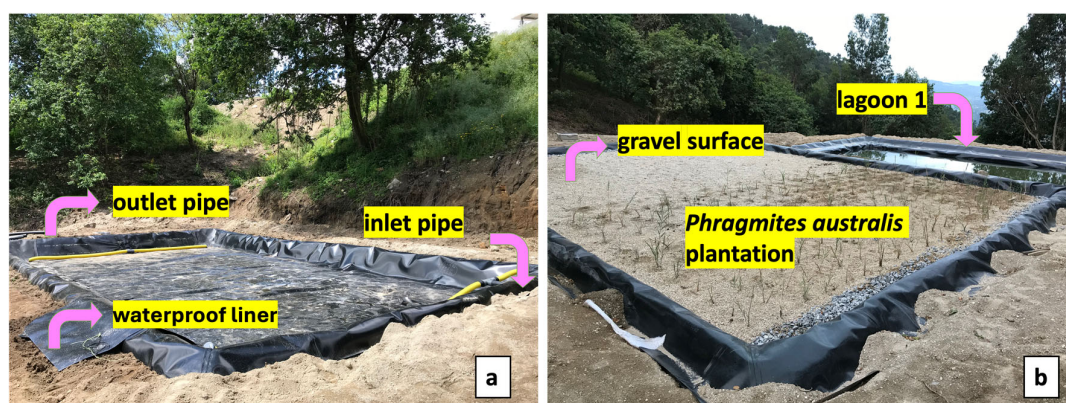


Figure 8. Stages of the horizontal subsurface flow system CW: (a) Excavation to a depth of over one meter, installation of a waterproof liner, and placement of sand and gravel as substrate; (b) addition of inlet and outlet pipes for the effluent and planting *Phragmites australis* in the CW.

Since its launch in 2021, the CW has required regular operation and maintenance—including sludge removal, vegetation harvesting, inspection of inlet and outlet structures, and monitoring of water quality—to ensure consistent water treatment performance, a responsibility managed by the Municipality. Figure 9 shows the evolution of the CW following the opening of the shelter and the beginning of the CW operation.

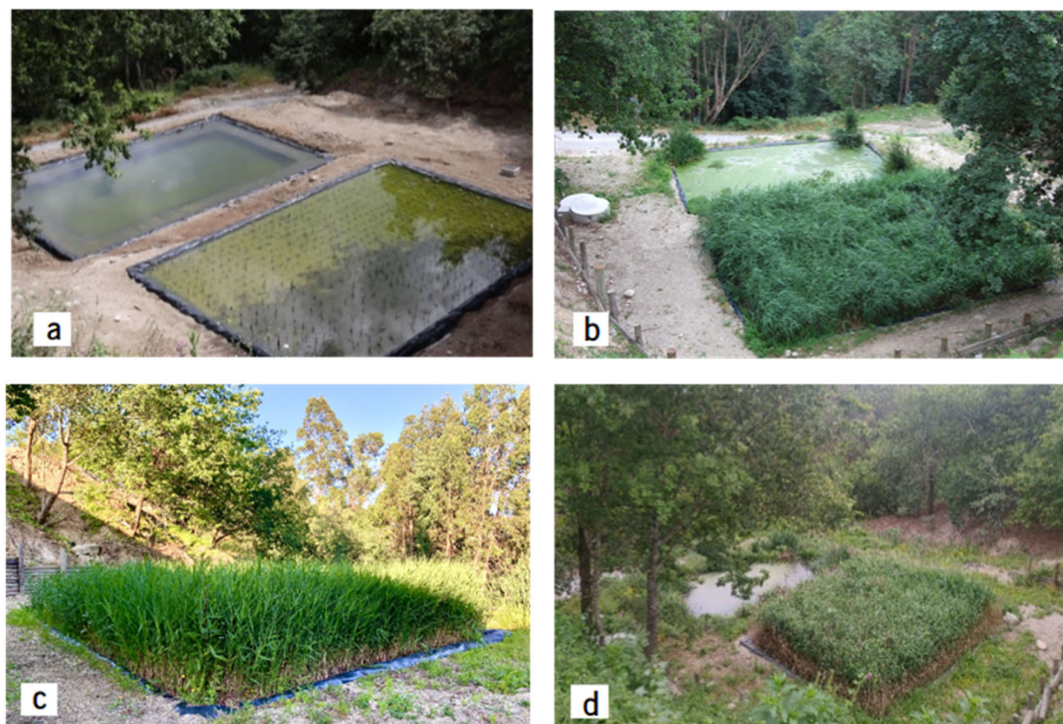


Figure 9. Constructed wetland (CW) of the shelter: (a) First stage of the CW, with the injection of clean water into the system; (b,c) Operational stage; (d) Current state of the CW.

The vegetation, particularly *Phragmites australis* in the CW, shows substantial growth, likely attributable to the high nutrient concentrations in the effluents from the dog shelter, classified as domestic wastewater [18].

Table 3 presents the average values of the parameters analyzed in situ and in the laboratory at the inlet (P1) and outlet (P3) sampling points over a five-month monitoring period (March–July 2022).

Table 3. Average values of the parameters analyzed in situ and in the laboratory at the inlet and outlet sampling points over a five-month monitoring period (March–July 2022). The maximum recommended value (MRV) and the maximum permissible value (MPV) correspond to Decree-Law No. 236/98 regarding the quality of water intended for irrigation, and to the emission limit value (MPV) for wastewater discharge, and DL No. 119/2019, for water reuse. All results are expressed in mg L^{-1} , except turbidity, which is presented in NTU, and redox potential, expressed in mV. (Chemical Oxygen Demand—COD; Total Suspended Solids—TSS; Redox potential—Eh) [18].

Parameters	Inlet (n = 5)	Outlet (n = 5)	MRV	MPV	MPV
COD	633.8	47.5	-	-	150.0
TSS	864.7	63.6	60.0	35 *	-
Turbidity	324.2	8.9	-	-	-
O ₂	1.2	0.8			
Eh	−103.6	−68.0			
F [−]	0.2	0.4			
F [−]	2.8	0.2	1 (2) *	15.0	-
PO ₄ ^{3−}	54.1	47.6	-	-	-
SO ₄ ^{2−}	4.1	3.1	575.0	-	2000.0
NH ₄ ⁺	90.2	87.5	-	-	10.0

* Value corresponding to DL No. 119/2019, Class D.

The ongoing monitoring revealed high removal efficiencies for parameters such as chemical oxygen demand (COD), total suspended solids (TSS), and turbidity, with maxi-

mum removal rates exceeding 97%. Anions and potentially harmful elements were detected at very low concentrations. However, ammonium (NH_4^+) concentrations did not comply with the required standards during any of the sampling periods.

This may be attributed to limited oxygen availability in the first lagoon (P1—inlet), which constrains nitrification and, consequently, the conversion of ammonium to nitrate. In the absence of a vertical-flow stage, implementing intermittent recirculation of water from the second lagoon (P2) back to P1 could enhance oxygenation, promote ammonium removal, and improve overall hydraulic performance. This limitation may also be related to inadequate water circulation due to infrequent system use, resulting in prolonged retention times. As reported above, previous studies have shown that horizontal-flow CW systems—such as the one implemented in this case study—can reliably treat parameters such as TSS; however, they are often less effective for nitrogen removal unless longer hydraulic retention times and sufficient oxygenation are provided [34].

The results meet both national and European water quality standards for irrigation, specifically Decree-Law No. 119/2019 [89] and the Decree-Law 236/98 [90], which sets criteria and quality standards, with pollutant removal exceeding 97% for COD, TSS, and turbidity.

According to [29], wetlands play a crucial role in motivating their future creation and restoration, emphasizing the strong link between wetlands and human culture.

4. Conclusions and Future Perspectives

Water scarcity, exacerbated by climate change and anthropogenic activities, poses a significant threat to global sustainability by severely impacting water security, ecosystem integrity, public health, and economic stability. The increasing discharge of municipal wastewater introduces a wide range of contaminants into freshwater resources, affecting both ecosystem health and human well-being. These challenges highlight the urgent need for innovative and sustainable water management strategies, particularly in water-stressed regions.

This review highlights the viability of constructed wetlands as a sustainable solution for addressing water contamination and promoting water reuse, in line with the United Nations Sustainable Development Goals. By examining the characteristics, design principles, and functionality of constructed wetlands, this study provides evidence of their capacity to replicate natural wetland processes in wastewater treatment, reinforcing their relevance as a nature-based and sustainable management strategy.

The case study of a constructed wetland integrated into an eco-friendly dog shelter further demonstrates the practical applicability of these systems, showcasing their ability to effectively treat wastewater and facilitate water reuse. Horizontal flow showed high removal efficiencies for chemical oxygen demand, total suspended solids, and turbidity, with removal rates exceeding 97%, meeting both national and European quality standards for irrigation reuse.

Despite the demonstrated technical feasibility and treatment efficiency of the implemented system, future research should explore optimized hydraulic regimes, such as increased circulation frequency, to mitigate ammonium accumulation and enhance nitrogen removal. Additional improvements in constructed wetlands design—including substrate composition, flow distribution, and passive aeration strategies—are also required to improve pollutant-specific treatment performance. Furthermore, comprehensive techno-economic assessments, incorporating capital and operational costs as well as life-cycle costing and comparisons with conventional treatment technologies, are essential to support long-term sustainability evaluations and promote broader implementation. Long-term monitoring is equally important to assess system stability, seasonal variability, and resilience under fluctuating pollutant loads, thereby supporting reliable full-scale applications.

Overall, constructed wetlands represent a viable and environmentally friendly alternative to conventional mechanical treatment systems, requiring substantially less energy and chemical input, resulting in a lower carbon footprint and reduced operational costs. In addition to mitigating water scarcity, constructed wetlands contribute to biodiversity enhancement and habitat creation, as evidenced by the presence of diverse plant and invertebrate communities. Their potential for resource recovery, including biomass production, further reinforces their role as multifunctional and sustainable nature-based solutions.

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