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Review

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Meryem Hdidou [1], Mohamed Chaker Necibi [1], Jérôme Labille [2], Souad El Hajjaji [1,3], Driss Dhiba [1], Abdelghani Chehbouni [1] and Nicolas Roche [1,2,*]

1 International Water Research Institute (IWRI), Mohammed VI Polytechnic University, Ben Guerir 43150, Morocco; Meryem.HDIDOU@um6p.ma (M.H.); Chaker.NECIBI@um6p.ma (M.C.N.); Souad.ELHAJJAJI@um6p.ma (S.E.H.); driss.dhiba@um6p.ma (D.D.); abdelghani.chehbouni@um6p.ma (A.C.)
2 Aix-Marseille University, CNRS, IRD, INRAE, Coll France, CEREGE, 13545 Aix en Provence, France; labille@cerege.fr
3 Centre Eau, Ressources Naturelles, Environnement et Développement Durable (CERNE2D), Mohammed V University, Rabat 10090, Morocco
* Correspondence: nicolas.roche@univ-amu.fr

Abstract: Located in a semi-arid to arid region, Morocco is confronting increasing water scarcity challenges. In the circular economy paradigm, the reuse of treated wastewater in agriculture is currently considered a possible solution to mitigate water shortage and pollution problems. In recent years, Morocco has made significative progress in urban wastewater treatment under the National Wastewater Program (PNA). However, rural sanitation has undergone significant delays. Therefore, an alternative technology for wastewater treatment and reuse in rural areas is investigated in this review, considering the region's economic, social, and regulatory characteristics. Constructed wetlands (CWs) are a simple, sustainable, and cost-effective technology that has yet to be fully explored in Morocco. CWs, indeed, appear to be suitable for the treatment and reuse of wastewater in remote rural areas if they can produce effluent that meets the standards of agricultural irrigation. In this review, 29 studies covering 16 countries and different types of wastewater were collected and studied to assess the treatment efficiency of different types of CWs under different design and operational parameters, as well as their potential application in agricultural reuse. The results demonstrated that the removal efficiency of conventional contamination such as organic matter and suspended solids is generally high. CWs also demonstrated a remarkable capacity to remove heavy metals and emerging contaminants such as pharmaceuticals, care products, etc. The removal of microbial contamination, on the other hand, is challenging, and does not satisfy the standards all the time. However, it can be improved using hybrid constructed wetlands or by adding polishing treatment. In addition, several studies reported that CWs managed to produce effluent that met the requirements of wastewater reuse in agriculture of different countries or organisations including Morocco.

Keywords: circular economy; constructed wetland; water–energy nexus; rural sanitation; wastewater reuse

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1. Introduction

Decades ago, water was perceived as an abundant natural resource since it was replenishable through seasons [1]. However, the planet is currently facing the rising issue of water scarcity [2], notably in arid and semi-arid regions where restricted water resources are being exhausted [3]. According to the Food and Agriculture Organization (FAO), water, food, and energy are interconnected and jeopardized by population growth, urbanisation, economic and industrial development, and climate change. Hence, the concept of the water–energy–food nexus aims to explain the complex interaction between them in order to enable the use of these limited resources in a sustainable way [4]. Indeed, Agriculture is considered the largest consumer of freshwater [5], with 69% of global water withdrawals, reaching 86% in Morocco [6,7]. Therefore, water shortages in agriculture may have significant consequences on food security and nutrition [8]. Furthermore, the available water resources appear insufficient to meet the water growing demands, resulting in a water demand–supply deficit [9]. In addition, pollution caused by human activities degrades water quality, rendering it unsuitable for many purposes [1].

To deal with this situation, the reuse of treated wastewater as a non-conventional water resource has recently gained substantial importance [7,10]. Wastewater is now perceived as a renewable, inexpensive non-conventional resource rather than a source of pollution [11–13]. Therefore, in areas suffering from water scarcity, these resources can be used to supplement or replace freshwater use for applications that do not require drinking water quality, most notably agricultural irrigation [1,2,8]. The reuse of treated wastewater represents an important opportunity to address the disparity between demand and water resources in Morocco since they could cover more than 13% of total water demand if properly treated and recycled [14]. Indeed, the National Water Plan (PNE) and the National Plan for Reuse (PNREU) promote this practice and aim to increase treated wastewater reuse to 325 million m^3/year by 2030 [15].

Aside from relieving pressure on freshwater resources, the reuse of treated wastewater in agriculture has some economic and environmental benefits, mainly providing nutrients (nitrogen and phosphorus) and organic matter, which helps increase agricultural productivity while reducing the use of chemical fertilisers and their costs, as well as preserving freshwater quality by reducing wastewater effluent discharge into water bodies [12]. However, even though wastewater reuse has several benefits, it might also engender public health hazards if appropriate management is not implemented [12,13,16]. In fact, wastewater reuse has several disadvantages related to the presence of undesirable contaminants, such as organic matter (chemical oxygen demand (COD) and biochemical oxygen demand (BOD)), total suspended solids (TSS), nutrients (Nitrogen, Phosphorus, etc), heavy metals (e.g., cadmium, chromium, nickel, lead, copper, and zinc), emerging pollutants (e.g., organic solvents, pesticides, and pharmaceuticals), toxic anions (sodium, chloride, etc), and pathogens (bacteria, viruses, protozoa, and nematodes) [11,17,18]. These contaminants may have a negative impact on soil, groundwater quality, and human health [12,16]. Hence, to overcome these drawbacks, appropriate treatment must be provided to comply with standards and regulations for the safe reuse of wastewater in agriculture.

Located in North Africa, with a façade on the Mediterranean basin, which is one of the most water-scarce regions in the world, Morocco is confronting increasing water shortage challenges [7]. Water stress is now a reality in Morocco, and it is expected to worsen because of population and economic activity growth, as well as the effects of climate change on its semi-arid climate. In fact, with a decrease in precipitation and a rise in temperature, the periods of drought will intensify [19]. As a result, the renewable internal freshwater supplies, which are currently below the essential water stress threshold of 1000 m^3 per year per capita, are expected to decrease further. The pressure on water resources is exacerbated by the high rate of wastewater discharge into the natural environment, despite efforts undertaken to enhance wastewater treatment in urban areas under the National Wastewater Programme (PNA). Indeed, the rate of depollution exceeded 45% through the implementation of 123 wastewater treatment plants using mainly natural and aerated ponds, activated sludge, and trickling filters as treatment technologies [14]. Nevertheless, the PNA has prioritized urban sanitation over rural sanitation, resulting in insufficient or non-existent treatment plants. Therefore, the choice of tailored treatment technologies in remote rural areas must take into consideration their technical and financial capacities.

Conventional wastewater treatment technologies, such as activated sludge, membrane processes, etc., have proven their efficiency. They are, however, very costly and require intensive energy, making them unsuitable for developing countries where the water–energy nexus must be considered [10,11,20,21]. In parallel, Nature-Based Solutions (NBSs) such as constructed wetlands (CWs) are gaining popularity, and could be considered as an ingenious treatment technology, especially for small communities and remote areas. However, CWs are not fully explored in Morocco.

CWs are a simple, sustainable, and cost-effective technology inspired by natural wetlands [22]. They are designed to eliminate pollutants from wastewater using a variety of natural removal processes involving substrates, plants, and microorganisms [23]. Several studies have reported that CWs are very effective in removing conventional substances (COD, BOD, TSS, etc.), as well as heavy metals, micropollutants, and microorganisms, resulting in a good quality effluent.

Effectively, CWs appear to be a promising technology in terms of providing decent sanitation for rural areas, in addition to recovering water and nutrients for reuse in agriculture within the circular economy context in Morocco [24]. In this context, this review paper aims to evaluate the performances of CWs while gaining a better understanding of the impact of the design and operational parameters as well as their components (substrate, vegetation, and microorganism) on the treatment efficiency of different types of wastewater. The review paper also investigates this technology as an alternative for wastewater treatment and reuse in agricultural irrigation in the Moroccan context.

2. Materials and Methods

The main objective of this literature review is to provide an overview of the treatment performances provided by different types of constructed wetlands, along with an investigation of the effect of the different components on their efficiency. This analysis aims to assess their potential for application in rural sanitation and wastewater reuse in agricultural irrigation in Morocco. For this purpose, data were collected by conducting searches on the scientific databases Science Direct and Web of Science, among other sources. Several combinations of key words were used, including the terms "constructed wetlands", "free water surface", "horizontal flow", "vertical flow", "hybrid", "substrates", "vegetation", "microorganisms", and "wastewater reuse". It is noteworthy that several papers were not considered because they lacked information about the treatment efficiency and did not correspond to the review objective. Eventually, 29 research articles were analysed covering 16 countries and different types of wastewater. A summary of the studies including the type of the CWs, design parameters (e.g., vegetation and substrate) and operational parameters (e.g., HLR, OLR, and HRT) is presented as well as the removal efficiencies of the different systems in Tables 1 and 2.

3. Constructed Wetlands Definition and Classification

Nature-based solutions (NBSs) are defined according to the International Union for Conservation of Nature, IUCN, as "Actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" [25]. These actions are, indeed, "inspired by, supported by or copied from nature" to tackle and solve societal and environmental hazards. Moreover, NBSs are energy and resource-efficient and resilient to change. However, they must be adapted to local conditions to fulfil these requirements [26].

In addition to conventional wastewater treatment technologies, NBSs could treat wastewater and improve its quality. Among these NBSs, constructed wetlands (CWs) are considered a cost-effective and sustainable wastewater treatment technology.

CWs are ecological systems that have been designed to exploit the purifying functions of natural wetlands for wastewater treatment. These systems tend to effectively mimic different processes that occur in wetlands under controlled conditions. Wastewater remediation in CWs involves a wide range of physical, chemical, and biological processes influenced by the synergistic effect of plants, soils, and microorganisms [27].

CWs can be designed in various configurations to enhance and optimise specific processes, allowing the removal mechanisms to target a wide range of pollutants [28]. The classification of constructed wetlands is based on various design parameters and specific characteristics of the system. Among these criteria, hydrology (free water surface and subsurface), type of vegetation (emergent, submerged, and free-floating), and flow direction (horizontal and vertical) are commonly considered in the classification of wetlands [28,29]. CWs are categorized into two broad types depending on their hydrology: free water surface flow CWs and subsurface flow CWs. Furthermore, subsurface flow CWs can be classified as horizontal subsurface flow CWs or vertical subsurface flow CWs according to the flow direction (Figure 1).

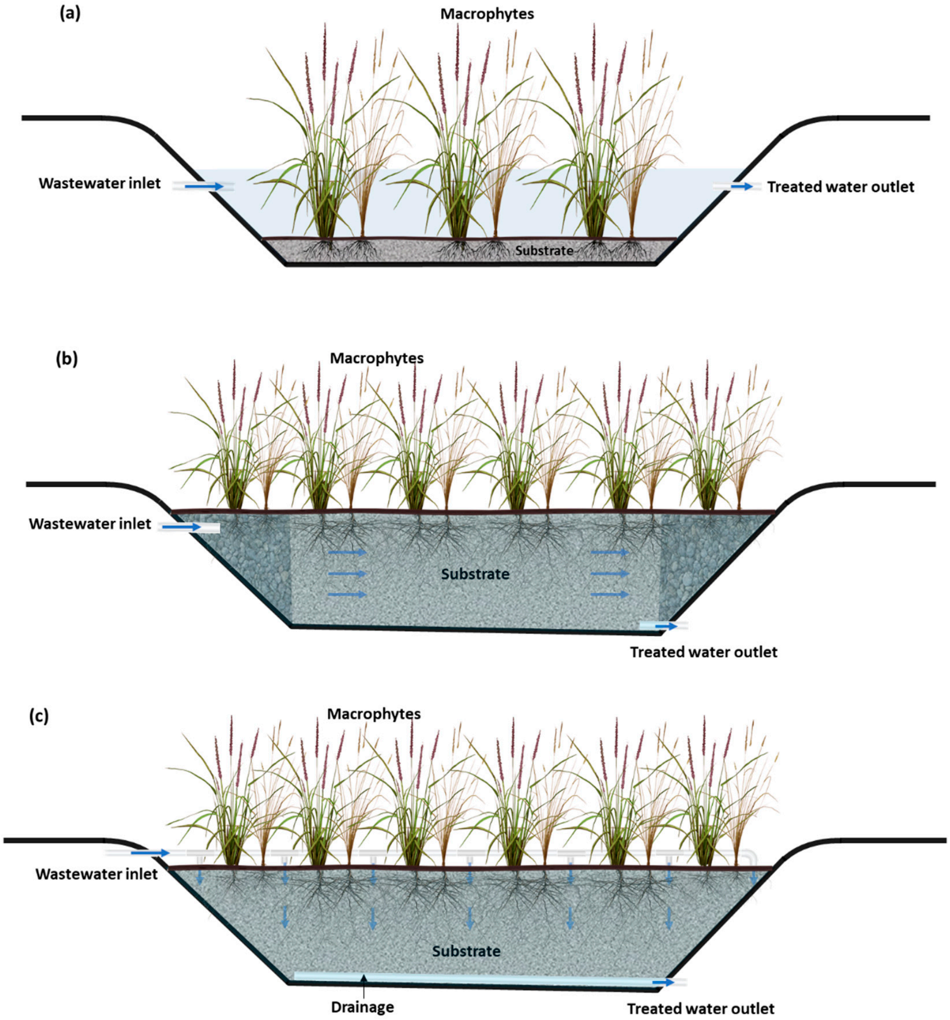

Figure 1. Free water surface CW (**a**); horizontal subsurface flow CW (**b**); vertical subsurface flow CW (**c**).

3.1. Free Water Surface Constructed Wetlands (FWS CWs)

Free water surface CWs consist of shallow lagoons with a sealed bottom that allows wastewater to flow over the surface while preventing leakage of wastewater to the aquifer [27]. Usually, they contain soil or a suitable medium to support the growth of rooted vegetation and a sealed bottom maintaining a shallow water depth of 20–40 cm [27,28,30–32]. Unlike the other types of CWs, the soil's main function in FWS CWs is to support root plants, so there are no particular soil quality requirements [30]. Plants play a major role in FWS CWs since they help to reduce wind speed, assist sedimentation, and provide attachment for bacteria, contaminant uptake, and oxygen release from roots [30]. A variety of plant types can be used in FWS CWs, such as emergent plants, submerged plants, freely floating plants, and floating leave plants. However, FWS CWs with emergent plants are the most used ones [11,31,33]. The commonly used plant species in these systems will be introduced in Section 3.2. In these systems, wastewater treatment involves physical (sedimentation, filtration, and UV exposure), chemical (precipitation, adsorption, and volatilisation), and biological (microbial degradation, microbial nutrient transformations, uptake from the water column and root zone, microbial competition, and bacterial die-off) processes [11,31,32,34].

For example, Gunes et al. [35] assessed a full-scale FWS CWs preceded by a septic system composed of three compartments for the treatment of high-strength domestic wastewater. Macrophytes and algae were used in the FWS CWs, and the retention time was 29.1 days for a daily flow of 462 m^3d^{-1}. The system achieved a removal efficiency of 86%, 92%, 56%, and 43% for TSS, BOD, Total Nitrogen (TN), and Total Phosphorus (TP), respectively. The septic tank helped remove 60% of TSS, while the removal of the other pollutants was poor. Thus, the total elimination of phosphorus was not sufficient and must be enhanced by integrating adsorbing materials as CW substrate. The study also reported that the treatment efficiency was affected by the hydraulic retention time (HRT). Consequently, the high HRT used resulted in good removal efficiency of organic matter and nitrogen.

Ezzat and Moustafa [36] also evaluated a system comprising a dynamic roughing filter (DRF) followed by three horizontal free water surface flow wetland mesocosms, arranged in parallel, treating wastewater supplied from a septic tank. The FWS CWs were planted with *Cyperus papyrus* using two different bed materials: soil or soil amended with zeolite. The pre-treatment unit aimed to reduce the organic load of the influent, and it effectively contributed to the treatment with a removal rate of 66.9%, 55.5%, 40.01%, and 30.02 % for BOD_5, TSS, NH_3^+, and Fe, respectively. The system using soil amended with zeolite was shown to be more efficient with a removal efficiency of 84.3%, 76.3%, 98.8%, and 94.6% for BOD_5, TSS, NH_3^+, and Fe, respectively, in summer. Hence, the effluent complied with the FAO guidelines for wastewater reuse in irrigation. The zeolite used in the CW bed enhanced the treatment efficiency by providing a higher specific area for the growth of the microbial biofilm and, therefore, the increase in biodegradation. Furthermore, the zeolite acted as a cation exchange agent, leading to better removal of NH_4^+, Total Phosphorus (TP), and heavy metals. This system also demonstrated its efficiency at removing faecal indicator bacteria with a removal rate of 99.7%, 99.4%, and 98.8% for total coliform (TC), faecal coliform (FC), and *E. coli*, respectively, in warm seasons. A decrease in these performances was observed during winter. The bacteriological quality respected the World Health Organisation's regulation for wastewater reuse in unrestricted irrigation. This study also concluded that the inhibition ability of *Cyperus papyrus* (L.) roots' extracts towards pathogenic bacteria is equivalent to that of the synthetic standard antibiotic amoxycillin/clavulanate. Furthermore, six antibacterial and antioxidant substances of medicinal interest were identified in plant root extracts, making the harvested plants a valuable economic resource to balance the operating costs [36].

Thus, the FWS CWs seem to be very effective in removing organic matter through microbial degradation and removing suspended solids through filtration and sedimentation. The removal of nitrogen is high, and it is performed by nitrification in aerobic zones followed by denitrification of nitrate in anaerobic zones at the bottom. The removal of pathogens and other pollutants (e.g., heavy metals, etc.) is high, while phosphorus (P) removal occurs slowly. Considering that phosphorus is usually removed by adsorption and precipitation, it is significant that in the FWS system, the contact between the water and the medium is restricted [27,30]. However, this type of CW has a large footprint and requires an extensive area, rendering it unsuitable for use as a wastewater treatment system for agricultural reuse. Furthermore, FWS CWs have a significant potential for human exposure to pathogens, and thus, they are rarely used for secondary wastewater treatments; however, they are used as advanced effluent treatments [11,34].

3.2. Horizontal Subsurface Constructed Wetlands (HSSF CWs)

Among the subsurface constructed wetlands, horizontal subsurface CWs are the most frequently used ones [37]. A HSSF CW usually consists of a rectangular bed filled with gravel or sand that is planted with emergent plants, where pre-treated wastewater flows steadily beneath the surface in a horizontal direction through porous media. As a result, there is no water surface exposed to the atmosphere, which reduces the occurrence of odour problems and health hazards related to pathogenic organisms [27,31,34]. A pre-treatment stage is required for the wastewater that feeds the HSSF CW to minimize the suspended solids and, consequently, avoid bed clogging [31].

Organic matters, suspended solids, microbial contamination, and heavy metals can all be removed very effectively using HSSF CWs [9,33]. However, the removal of nutrients is limited, especially the removal of ammonia, because of the lack of oxygen in the system. On the other hand, denitrification is enhanced. The elimination of phosphorus is restricted unless a reactive medium is used [29,38]. Several studies have confirmed these findings.

For example, Toscano et al. [39] evaluated the removal efficiency of HSSF CWs with different plantation conditions considering water balance and evapotranspiration. Vegetated HSSF CWs achieved a higher removal rate than unplanted HSSF CWs. The removal of COD was limited and varied from 59% to 63% for different plants. The HSSF CW achieved higher removal of TN in planted systems (59–61%) compared with unplanted systems (43%) due to plant uptake. However, the removal of TP was very restricted (19% to 29%). Evapotranspiration (ET) in vegetated beds tended to be higher than ET in unplanted beds, emphasizing the impact of vegetation and seasons on evapotranspiration and water balance. The ET also varied for the different plants and the average ET values were 15.6 mm d^{-1}, 10.2 mm d^{-1}, 7.1 mm d^{-1}, 6.8 mm d^{-1}, and 3.3 mm d^{-1} for *P. australis*, *A. donax*, *V. zizanoides*, *Mx giganteus*, and unplanted beds, respectively. Toscano et al. [39] concluded that warm temperatures are beneficial for wastewater treatment in constructed wetlands because they promote plant growth and microbial activity, thus improving the treatment quality; however, they could increase the evapotranspiration. Using a similar approach, Tuttolomondo et al. [40] investigated the impact of evapotranspiration on treatment performance in a pilot-scale HSSF CW treating secondary effluent from an activated sludge treatment plant. The system comprised three independent units filled with silica quartz river gravel and operating at a hydraulic loading (HLR) of 0.12 m/day. Three vegetation conditions were used: one unit was unplanted, one was planted with *Cyperus alternifolius*, and the third was planted with *Typha latifolia*. Compared to unplanted CW, the removal efficiencies of BOD and COD were higher in planted CWs (Table 2). Evapotranspiration in unplanted units, on the other hand, was lower than in planted units. The type of plant also had an effect on evapotranspiration, with *Typha latifolia* having a higher evapotranspiration cumulative (ETc). Therefore, evapotranspiration is an important parameter to consider when designing CWs because it affects water balance and causes water loss, which is considered unprofitable for wastewater reuse in agriculture, particularly in arid and semi-arid regions.

Witthayaphirom et al. [41] assessed HSSF CWs treating landfill leachate and using a mixture of sand, clay, and iron powder as substrate. The average removal rates of BOD, COD, TSS, and TN were 69.6%, 64.3%, 68.3%, and 61.8%, respectively, in the first year and improved to reach 93.2%, 91.9%, 85.5%, and 87.5% in the third year of the system's operation. During summer, higher organic matter removal was achieved due to enhanced microbial activity. The reactive substrate containing iron also improved the treatment efficiency through adsorption, precipitation, and complexation. Witthayaphirom et al. [41] also evaluated the ability of this system to remove organic micro-pollutants (i.e., DEP, DBP, 2,6-DTBP, BHT, and DEHP). The HSSF CW achieved a mass removal rate of 64.4–66.1% during the first year of operation and improved in the subsequent years to reach 73.3–91.4%. The prevailing removal mechanisms were adsorption and biodegradation, but their contribution to the overall removal differed according to the chemical properties of the organic micro-pollutants. The iron and clay present in the substrate favoured these two mechanisms by increasing the media's specific area, which improved both the adsorption and development of microbial biofilm, thereby promoting biodegradation [41,42].

Several studies have reported that HSSF CWs have some drawbacks in terms of organic matter and nutrient elimination. This is attributed to several factors, including the predominance of anaerobic conditions and the deficiency of dissolved oxygen since its primary source is plant roots, as well as the use of inappropriate substrate missing certain ions such as Ca, Mg, Fe, or Al [43]. Aerating HSSF CWs and, therefore, enhancing dissolved oxygen in the system could improve BOD_5, TSS, and TN elimination but had no effect on TP and faecal coliform elimination compared to non-aerated HSSF CWs [29]. Interestingly, Andreo-Martínez et al. [43] assessed the performances of a horizontal subsurface constructed wetland fed with artificially aerated domestic wastewater and filled with blast furnace slags and construction sand as a substrate. This HSSF CW was proven to have a high pollutant removal capacity with an average removal of 92.7%, 97.8%, 97.5%, 91.5%, and 96.9% for COD, BOD_5, TSS, TN, and TP, respectively. This system was also able to remove heavy metals from the wastewater, and the efficiency removal ranged from 100.0% for Cd and 52.7% for Co.

3.3. Vertical Subsurface Constructed Wetlands (VSSF CWs)

To overcome the drawbacks of HSSF CWs that consist of limited oxygen transfer capacity, VSSF CWs have become more widely used [11,27]. The VSSF CWs consist of a bed filled with layers of gravel or sand in which the wastewater is applied intermittently at the surface and flows vertically to be collected at the bottom of the system [27,29,31,33]. This allows air to fill pores as wastewater infiltrates through the bed, resulting in a high oxygen transfer rate in the system, which is favourable for nitrification and organic matter elimination. Consequently, these systems require less surface area than HSSF CWs [9,11], which is advantageous for wastewater reuse in agriculture [11].

The VSSF CWs are more efficient in the treatment of different contaminants. For example, Verma and Suthar [44] compared a horizontal subsurface flow and a vertical subsurface flow constructed wetland at the pilot scale for dairy wastewater treatment. Both systems were planted with *Typha angustifolia* and filled with layers of sand, gravel, and boulders. In general, the performances of the VSSF CW exceeded the performance of the HSSF CW and reached an average removal efficiency of 82.8%, 83.2%, 66.2%, and 59.7% for BOD_5, COD, and NH_4^+-N, respectively, due to higher oxygenation. However, the higher removal efficiency of NO_3 was obtained in HSSF CW (62.9%) compared to VSSF CW (47.5%). The lack of oxygen in HSSF CW promoted denitrification. Suspended solids were also removed more efficiently in HSSF CW, with an elimination rate of 72.6% in comparison with VSSF CW (55%), which demonstrated that HSSF CWs provide appropriate sedimentation, filtration, and adsorption in the bed substrate, allowing improved reductions in TSS. On the other hand, the rapid drainage in VSSF CW may lower the elimination efficiency of TSS. An average PO_4^{3-} removal rate of 49.4% and 59.7% in HSSF CW and VSSF CW, respectively, were obtained. Adsorption, precipitation, plant and microbial uptake, mineralisation, sedimentation, burial, and other processes related to phosphorus removal mechanisms occur in CWs. Vegetation can contribute significantly to the removal of heavy metals through complexation, chelation, precipitation, and filtration. The average removal of Cr, Fe, and Ni was 47.3%, 65.5%, and 64.8%, respectively, in the HSSF CW and 47.3%, 65.5%, and 64.8%, respectively, in the VSSF CW.

Zeng et al. [45] also assessed VSSF, HSSF, and FWS pilot-scale CWs using two types of plants (i.e., *Thalia dealbata* and *Canna indica*). VSSF CWs exhibited higher COD, NH_4^+-N, TN, and TP removal rates than the HSSF and FWS CWs (Table 2). Because of the presence of sufficient dissolved oxygen, the degradation of COD and the removal of TP were also enhanced in the VSSF CWs compared to the other configurations. However, NO_3^--N was not eliminated in this type of constructed wetland due to the aerobic conditions (3.6–5.8 mg/L DO) that promoted nitrification over denitrification. The removal of NO_3^--N was good in the FWS CWs and, to a lesser extent, in the HSSF CWs. The VSSF CWs had more functional bacteria such as nitrifiers, aerobic denitrifiers, methanotrophs, and phosphorus removal bacteria than FWS CWs and HSSF CWs, which are beneficial for achieving higher COD, NH_3^+-N, TN, and TP removal efficiency in this system.

A promising treatment system was designed by Nakamura et al. [46] to treat highly concentrated anaerobic digestates. The compact system consisted of a vertically constructed wetland with a multi-layer structure wherein four filtration layers were combined with three superficial subsurface spaces to optimise the required surface area. The superficial subsurface spaces allowed oxygen transfer to occur from both sides of the CWs' beds (upper and bottom surface), resulting in an enhancement of the oxygen transfer rate (OTR). Indeed, this design allowed the reducing of the land requirement by three quarters compared to conventional vertical CWs. The system comprised three stages with a total depth of 1.70 m. The system achieved an average COD, TN, TP, and NH_4^+-N removal of 99%, 62–76%, 96–97%, and 100%, respectively, due to this design's high OTR (102 g O_2/m^2d). These removal efficiencies are comparable or higher than those obtained with conventional CWs.

A pilot-scale VSSF CW operating under different conditions was evaluated by Abdelhakeem et al. [47]. The influence of vegetation condition (presence or absence of *Phragmites australis*), type of substrate (gravel or vermiculite), and feeding mode (continuous or batch) were assessed. The systems operated with a hydraulic loading rate of 0.15 $m.d^{-1}$ and a retention time of 0.5 days. The average removal efficiencies of different pollutants are shown in Table 2. The results showed that plants significantly influence the treatment with higher removal efficiency in planted CWs compared to unplanted ones, except phosphorus elimination. Substrate and feeding mode had no significant effect on COD and BOD elimination. However, the substrate (Vermiculite) enhanced the removal efficiency of NH_4^+ and TP. In comparison, the use of batch feeding mode helped to improve TSS removal.

3.4. Hybrid Constructed Wetlands

Hybrid constructed wetland consists of combining different types of CWs to exploit their different advantages. The overall objective is to achieve higher performances.

In Morocco, a study carried out by El Fanssi et al. [48] assessed the treatment performances of hybrid constructed wetlands installed in the rural village of Tidili Mesfioua near Marrakech and evaluated the impact of seasonal variation on the removal of different pollutants. COD, BOD_5, and TSS were highly removed with 91.4 %, 93.47%, and 94.83% removal efficiencies, respectively. Physical and microbiological mechanisms play an important role in these pollutants' removal in hybrid constructed wetlands. Due to the physical filtration mechanisms and low porosity of the gravel medium, solid organics could be percolated and captured in the substrate bed for a long period of time, resulting in greater biodegradation. In addition, sedimentation of suspended solids and rapid decomposition processes also led to high removal rates.

Furthermore, COD and BOD_5 removal appeared to be influenced by temperature since the highest organic matter removal rate coincided with the higher temperature observed during the warm season. Hybrid constructed wetlands were used to improve total nitrogen removal efficiency since VSSF and HSSF CWs provided different redox conditions that were suitable for nitrification and denitrification. A significant average removal efficiency of 67% was obtained, with a maximum of 73.89% recorded in summer. The high total nitrogen removal resulted from strong nitrification at the VSSF; nitrate generated in the effluent successfully decreased in the HSSF effluent through denitrification. A seasonal trend was observed for TN removal rate efficiency, which proves that temperature affects TN removal. The average abatement was of the order of 4.36 Log units for total coliforms (TC) and 4.27 Log units for faecal coliforms (FC), and the highest removal efficiency of bacterial indicators of faecal contamination was observed in summer.

Several studies have demonstrated that temperature greatly influences the removal of pollutants in constructed wetlands since low temperature directly affects microbial activity [11]. For this reason, Liang et al. [49] developed a newly constructed wetland design to overcome the limitations caused by low temperature and frozen soil. This system was composed of a VSSF CW, and two HSSF CWs used shallow geothermal energy to raise the temperature of wastewater. The constructed wetland showed improved performance, especially for the removal of NH_4^+-N and TN, since their elimination was performed through microbial degradation. An average removal of 54.8% was achieved, indicating that the removal effect was good. However, the average removal of TP was 77.7 %, indicating that it is unlikely to be affected by low temperatures since phosphorus is mainly eliminated by adsorption on the substrate used (zeolite, volcanic rock, and steel slag).

Ávila et al. [50] also demonstrated that hybrid constructed wetlands can achieve high performances in the elimination of conventional wastewater parameters as well as emerging contaminants. The used system comprised a vertical subsurface flow, a horizontal subsurface flow, and a free water surface CWs working in series. The average removal efficiencies of 89%, 99%, 98%, 94%, and 47% were obtained, respectively, for COD, BOD_5, TSS, TN, and TP. Several emerging contaminants were targeted, including analgesic-anti-inflammatory pharmaceuticals, personal care products, and endocrine-disrupting compounds. Their removal efficiencies were also interesting and exceeded 80%. The pre-treatment consisting of an Imhoff tank contributed to the removal of BOD_5 and TSS (61% and 46%, respectively), which helped to minimise the organic loading rate admitted in the constructed wetland system (6 g BOD_5/m^2d). The combination of the different constructed wetland configurations allowed various removal mechanisms to occur at various intensities in each one, including aerobic and anaerobic biodegradation, adsorption, photodegradation, volatilisation, etc. The disinfection in the hybrid constructed wetland appeared to be highly effective with a 99.999% *E. coli* removal rate.

In another study, Nguyen et al. [51] tested a hybrid CW comprising a VSSF CW followed by a FWS CW. The VSSF CW consisted of layers of expanded clay (ExC), sandy soil, sand, and gravel and was planted with *Colocasia esculenta*. The FWS CW was packed with sandy soil substrate and was planted with *Dracaena sanderiana*. The system was operated for 21 weeks with different hydraulic loading rates ranging from 0.02 m/d to 0.12 m/d. The dissolved oxygen increased from 0.22 mg/L in the inlet to 6.3 mg/L, indicating an improvement in the water quality. The system was efficient in the removal of TSS with an average efficiency of 76%. However, these performances decreased with the increasing of the HLR and, consequently, the higher velocity, which caused a disturbance in the system. A good BOD_5 removal rate was achieved (74%). The rising HLR affected the removal efficiency, which was reduced from 82–80% in phase II and III (corresponding to HLRs of 0.02 m/d and 0.04 m/d, respectively) to 59% in phase IV (corresponding to HLRs of 0.12 m/d) (Table 2). The system reduced the total coliforms noticeably with an overall efficiency of 84%. Several parameters can influence the removal of total coliforms from the effluent, including the Hydraulic Retention Time, vegetation, substrate materials, dissolved oxygen, pH, etc. Moreover, the effluent quality met the standards for agricultural irrigation established by Vietnam and other countries, confirming that constructed wetlands can be used to treat and reuse wastewater.

Torrens et al. [52] evaluated the performance of a full-scale pilot constructed wetland. The system consisted of a hybrid CW comprising two stages of vertical flow French Reed Bed (FRB) and a horizontal subsurface flow CW. A pre-treatment comprising settler tank with bar racks was envisaged. The different stages were filled with various materials, namely: Silex, Granite, River gravel, and River sand. All the systems were planted with *Phragmites*, except HSSF CW, which was planted with *Typha.* The treated influent was highly concentrated. The results showed an overall removal rate of 90.7%, 99.5%, 98.3%, 80.9% and 90.7% for COD, BOD_5, TSS, TN, and PO_4^{3-}, respectively. The pre-treatment managed to eliminate a considerable quantity of suspended solids. The three stages of VSSF CW were dotted with a good filtering capacity, especially in the first stage. High removal efficiency of organic matter compared to other studies with the same conditions was also reported [53]. This could be explained by the high temperatures in the region that enhance the microbiological activity, thereby improving organic matter biodegradation and nitrification. Significant removal efficiency of bacterial indicators was reported (5.6 ULog) due to high retention time.

Table 1. Constructed wetland systems and their characteristics in terms of type, substrate and vegetation used, and operational parameters.

Type of CW	Location	Experimental Scale	Type of Wastewater	Pre-Treatment	Surface (m^2)	Experimental Period (Months)	Plant Species	Substrate	HLR (m/d)	HRT (day)	OLR (g/m^2d)		Reference
											COD	BOD_5	
Multistage FWS CW	Turkey	Full-scale	High-strength domestic wastewater	Septic system	2840	12	2nd stage: Algae + Macrophyte 3rd stage: *Typha latifolia* L.	-	0.163	29.1	100.21	47.50	[35]
FWS CW	Egypt	Mesocosms	Domestic wastewater	Dynamic roughing filter	0.975	-	*Cyperus papyrus*	M1: Soil M2: Soil amended with zeolite	0.15	2.93	-	5.8	[36]
HSSF CW	Spain	Full-scale	Artificially aerated domestic wastewater	Decanter tank	8	12	*Phragmites australis*	Blast furnace slags (BFS) Construction sand	0.0262	8.70	-	-	[43]
HSSF CW	Italy	Pilot-scale	Treated wastewater	-	4.5	-	*Vetiveria zizanoides* *Miscanthus x giganteus* *Arundo donax* *Phragmites australis*	Volcanic gravel	0.36	0.54	40	-	[39]
HSSF CW	Mexico	Microcosms	Domestic wastewater	-	0.495	6	*Canna indica* *Cyperus papyrus* *Hedychium coronarium*	S-A: Porous stone + tepezil + soil S-B: Porous stone + Plastic residues+ tepezil + soil	0.08	3		-	[54]
HSSF CW	Thailand	Pilot-scale	Landfill leachate	-	2	36	*Typha* sp.	Mixture: sand-clay-iron powder	0.04	5.9–6.8	-	-	[41]
HSSF CW	Italy	Pilot-scale	Secondary treated wastewater	Secondary treated wastewater	33	6	*Cyperus alternifolius* L. *Typha latifolia* L.	Silica quartz river gravel	0.12	-	6.54	3.216	[40]
Four-layer VSSF CW	Japan	Full scale	Anaerobic digestate	-	100		Ornamental flowers	Granular calcium silicate Recycled granular glass sand Granular zeolite	0.01	-	135.4	-	[46]
Multistage VSSF CWs	China	Lab-scale	Synthetic wastewater	-	0.2	4	*Phragmites communis*	CW-Z: Cobblestone + Zeolite + Quartz sand + soil CW-M: Cobblestone + Mn ore + Quartz sand + soil CW-C: Cobblestone + Biochar + Quartz sand + soil	0.05	3	153.965	-	[55]

Table 1. *Cont.*

Type of CW	Location	Experimental Scale	Type of Wastewater	Pre-Treatment	Surface (m^2)	Experimental Period (Months)	Plant Species	Substrate	HLR (m/d)	HRT (day)	OLR (g/m^2d)		Reference
											COD	BOD_5	
VSSF CW	China	Lab-scale	Synthetic sewage	-		4	*Iris pseudacorus*	GG-CW: Gravel + Gravel+ sand WS-CW: Gravel+ Walnut shell group + sand MO-CW: Gravel+ Mn ore group + sand AA-CW: Gravel+ Activated alumina group + sand	-	3	-	-	[56]
VSSF CW	Egypt	Pilot-scale	Domestic wastewater	-	-	8	*Phragmites australis*	Gravel Vermiculite	0.15	0.5	-	-	[47]
Hybrid CW (VF-HF-HF Cws)	China	Pilot-scale	Domestic wastewater	-	16	3	-	Gravel Zeolite Volcanic rock Steel slag	0.2–0.3	06–10	-	-	[49]
Hybrid CW (VSSF-HSSF-FWS CWs)	Spain	Pilot-scale	Urban wastewater	Screening + sand and grease removal + Imhoff tank	786	1	SSF: *Phragmites australis* FWS: *Typha* spp. + *Scirpus* spp.+ *Iris pseudacorus* + *Carex flacca.* +*Cyperus rutundus.* +*Juncus* spp.	Sand Siliceous gravel Siliceous gravel Stones	0.044	>7.4	-	6	[50]
Hybrid CW (VSSF-HSSF CWs)	Morocco	Full-scale	Domestic wastewater	Screening + decanter tank	218	24	*Phragmites australis*	VSSF: Pebble + coarse gravel + fine gravel HSSF: Mixture of sand and gravel	0.17	-		-	[48]
Hybrid CW (Novel VSSF-FWS CWs)	Vietnam	Lab-scale	Domestic wastewater	-	-	-	*Colocasia esculenta* (Tree) *Dracaena sanderiana* (Lucky bamboo)	NVF: Expanded clay + sand+ gravel + sandy soil FWS: Sandy soil layer	I: 0.02 II: 0.04 III: 0.06 IV: 0.12	-	-	1.022 3.136 4.614 8.952	[51]
Hybrid CW (VSSF-VSSF-HSSF CWs)	Senegal	Full-scale	Municipal wastewater	Settler tank with bar racks	192	6	*Phragmites* and *Typha*	FV1a: Silex FV1b: Granite FV1c: River gravel + Silex FV2a: River sand FV2b: River sand FHa: Silex FHb: Silex	0.026	-	66–199	30–92	[52]
VSSF CWs FWS CWs HSSF CWs	China	Pilot-scale	Domestic wastewater	-	0.48	6	*Thalia dealbata* *Canna indica*	Gravel	0.25	-	55	-	[45]
HSSF CW VSSF CW	India	Pilot-scale	Dairy wastewater effluent	-		9	*Typha. angustifolia*	Sand + gravel + boulders	0.288–0.345	1	-	-	[44]

Table 2. Removal efficiency of different pollutants in FWS, HSSF, VSSF, and hybrid constructed wetlands.

Reference	Specification	Removal Efficiency (%)										
		Organic Matter		Suspended Solids	Nutrients					Pathogens Indicators		
		COD	BOD_5	TSS	NH_4^+-N	NO_3^--N	TN	TP	PO_4-P	FC	*E. coli*	TC
[35]	Multistage FWS CW	91.6	91.5	86			57.1	43.4				
[36]	FWS CW Soil amended with zeolite		84.3	76.3	98.8 (NH_3)					99.4	98.8	99.7
[43]	HSSF CW	92.7	97.8	97.5			91.5	96.9			Absence	
	With artificial aeration											
[39]	Unplanted HSSF CW	53		83	43		43		19		99.36	
	Planted HSSF CW											
	Vetiveria zizanoides	62		86	51		59		25		99.84	
	Miscanthus x giganteus	61		86	52		57		20		99.84	
	Arundo donax	59		89	53		56		28		99.84	
	Phragmites australis	63		88	57		61		29		99.92	
[54]	HSSF CW (PRR + tepezil + soil)											
	Canna indica	91.4		76.7	62.7	44			45.1			
	Cyperus papyrus	91.9		74.2	50.9	41.7			57.2			
	Hedychium coronarium	90.9		57.4	39.1	40.3			55			
	Unplanted	76.5		34.2	17.5	20.8			38.5			
	HSSF CW (PRR +PET+ tepezil + soil)											
	Canna indica	90.9		76.2	68.6	41			49.5			
	Cyperus papyrus	91.2		73.8	54.8	38.2			53.9			
	Hedychium coronarium	91.4		52.5	31.2	37.5			57.2			
	Unplanted	77.7		35.1	20.2	17.4			35.2			
[41]	HSSF CW	64.3–91.9	69.6–93.2	68.3–85.5								
[40]	Planted HSSF CW											
	Cyperus	63.6	60.5									
	Typha latifolia L.	69.3	65.5									
	Unplanted HSSF CW	48.7	35.3									
[46]	VSSF CW											
	Unsaturated	98.7			99.96		62.4	97.3				
	Saturated	98.9			99.77		76.5	96.1				
[55]	VSSF CW											
	Zeolite	80.89			85.98	87.21	58.23					
	Manganese	83.84			94.87	94.68	71.71					
	Biochar	86.64			93.93	93.28	62.98					
[56]	VSSF CW											
	Gravel group	71.6			31		22.3	8				
	Walnut shell group	69.7					38.1	11.1				
	Mn ore group	90.1			84.1		65.1	97.1				
	Activated alumina group	83.4					21.1	99				

Table 2. *Cont.*

Reference	Specification	Removal Efficiency (%)										
		Organic Matter		Suspended Solids	Nutrients					Pathogens Indicators		
		COD	BOD_5	TSS	NH_4^+-N	NO_3^--N	TN	TP	PO_4-P	FC	*E. coli*	TC
[47]	VSSF CW Gravel/Continuous	70	83	61	19	−18		19				
	Gravel/Batch	76	85	80	36	−22		16				
	Vermiculite/Continuous	76	83	78	26	−27		31				
	Vermiculite/Batch	78	87	81	48	−31		24				
[49]	Hybrid CW	-	-	-	44.5		54.8	77.7		-	-	-
[50]	Hybrid CW	89	99	98	98		94	47			99.99	
[48]	Hybrid CW	91.4	93.47	94.83			67	62		99.994		99.995
[51]	Hybrid CW											
	Phase I: HLR = 0.02 m/d		75	88	84							59
	Phase II: HLR = 0.04 m/d		82	85	92							74
	Phase III: HLR = 0.06 m/d		80	80	91							80
	Phase IV: HLR = 0.12 m/d		59	56	89							77
	Overall		74	76	90							84
[52]	Hybrid CW	90.7	99.5		95.6	−304.2	80.9		90.7	99.999		
[45]	VSSF CW											
	Unplanted	75			73	Ns	14	24				
	T. dealbata	76			81	Ns	18	37				
	C. indica	77			76	Ns	27	47				
	FWS CW											
	Unplanted	46			−2	68	6	11				
	T. dealbata	58			1	53	14	17				
	C. indica	50			−1	44	8	15				
	HSSF CW											
	Unplanted	50			3	36	3	13				
	T. dealbata	57			7	37	6	18				
	C. indica	59			7	42	6	22				
[44]	HSSF CW	73.9	73	72.6	53.1	62.9			49.4			
	VSSF CW	82.8	83.2	55	66.2	47.5			59.7			

4. Constructed Wetlands Components

A constructed wetland is a complex system that includes water, substrate, plants, and a variety of microorganisms. The interaction of these elements results in the treatment of wastewater through a variety of removal processes [57]. To ensure a sustainable CW system and to maintain a long-term treatment performance, several parameters must be taken into consideration, and the most important ones are substrate selection, plant selection, water depth, hydraulic loading rate (HLR), hydraulic retention time (HRT), and feeding mode [58].

4.1. Substrate

Substrates, also known as media or matrix, are a key element of CWs since they connect all the components [57]. Besides providing support to plant roots and attachment to biofilm growth [57,59], substrates play an important role in pollutants' elimination since most of the physical, chemical, and biological reactions occur in CWs beds [60]. The processes involved in wastewater treatment through substrates include physical sedimentation and filtration, adsorption, complexation and precipitation, ion exchange [11,57,58], microbial degradation, and uptake and metabolism by plant root in the substrate [60].

The substrate significantly affects the treatment performances and operation stability [61]. Furthermore, the adsorption ability of various materials toward pollutants varies, resulting in different removal efficiencies [62]. Consequently, an appropriate selection of substrate materials can improve purification efficiencies significantly [60], making it a critical step while designing CWs [57,58,61]. Several criteria must be taken into consideration while selecting substrate materials, mainly their local availability and cost. Other characteristics of the materials are also taken into account including physical properties that define hydraulic feasibility and clogging probability (e.g., particle size, porosity, specific surface area, hydraulic conductivities, and mechanical resistance), chemical properties controlling the safety of the substrates, and their capacity to remove pollutants (e.g., surface charge, toxicity, and chemical stability) and biological properties (e.g., electron donors/acceptors) [59,60].

A wide range of materials may be utilized as constructed wetlands filling including natural materials, which are the most common (e.g., gravel and sand), artificial materials (e.g., activated carbon and expanded clay), and agricultural/industrial wastes (e.g., slag and woodchip) [59]. Recycling wastes and treated wastewater represent an opportunity to integrate the CWs in resource recovery and circular economy [24,63,64].

Ten solid wastes (clay brick fragments, coal boiler slags, cork granulates, crushed eggshells, grape pomaces, rock limestone fragments, olive seeds, pine bark fragments, snail shells, and wood pellets) were evaluated as substrates for Constructed Wetlands by Mateus and Pinho [65]. For this reason, the authors performed physical characterisation, adsorption, and leaching tests. Accordingly, the study concluded that limestone fragments, clay brick fragments, coal slags, snail shells, and cork granulate could be used as substrates in CWs because they showed an interesting capacity of adsorption for phosphorus or organic compounds or both. Other materials were excluded because of their poor adsorption ability, and most importantly, because they released nutrients or other contaminants in water. The selected materials were tested by Mateus and Pinho [63] in five sets of lab-scale VSSF CWs. A stratified mixture was produced using limestone as the top and bottom layers, and brick fragments, limestone, coal slags, cork granulate, or snail shells in the sandwiched layer. These CWs were planted with *Phragmites australis*. The effect of substrate type on pollutants' removal was studied at different hydraulic retention times. All the systems showed an average removal efficiency of COD that was greater than 70%, with the highest removal achieved by coal slag (94%) and cork granulate (86%). Coal slag also showed the best removal efficiency of TP (86%) and TN (80%), unlike snail shells, which showed a lower removal rate of TP and TN (20% and 44%, respectively). In a similar approach, Bianchi et al. [66] reported that harvested *Phragmites australis* from constructed wetlands could be dried and tested as a bio-sorbent to optimize the treatment efficiency of a CW on landfill leachates. Effectively, this bio-sorbent showed an important adsorption capacity for Fe (70–100%), Zn (65–85%), and Cu (46–80%) in a column filtration system. Therefore, recycling *Phragmites australis* as a bio-sorbent in CWs can improve water quality while managing wastes within a circular economy.

Yuan et al. [55] evaluated the effects of different materials as substrates on the removal efficiency of nitrogen and antibiotics (e.g., ciprofloxacin hydrochloride (CIPH) and sulfamethazine (SMZ)) from synthetic wastewater. For this, three parallel lab-scale VSSF CWs were designed and filled with three different materials: zeolite, manganese ore, and fruit stone biochar. A layer of quartz sand and a layer of cobblestone were used as a top layer and as a support layer, respectively. The systems were planted with *Phragmites communis* and operated at a hydraulic retention time of three days. A good COD removal efficiency was obtained for the three CWs (>80%). The average removal efficiencies of TN were higher in the CW with Mn ore (71.71%) and the CW with biochar (62.98%) compared to the CW packed with zeolite (58.23%) treatment. These results confirm that materials with higher specific surfaces and more micropores achieve better treatment. For the antibiotics, CIPH was removed efficiently (>80%) compared to SMZ (<70%). The CIPH removal rates were higher in the CW containing Mn ore (93.70%), followed by CW filled with biochar (88.05 %) and CW with zeolite (83.71%). This can be explained by the presence of metal cations in the Mn ore that can enhance the adsorption of CIPH.

A study was carried out by Xu et al. [56] to investigate the impact of substrate type on pollutants' elimination in lab-scale VSSF CWs. Four materials were used as substrates: gravel (GG-CW), walnut shell (WS-CW), manganese ore (MO-CW), and activated alumina (AA-CW). All the units were planted with *Iris pseudacorus* and fed with synthetic water simulating rural wastewater. The removal rates of COD were MO-CW (90.1%) > AA-CW (83.4%) > GG-CW (71.6%) > WS-CW (69.7%). MO-CW achieved the highest removal efficiency of COD due to its strong oxidising property and high adsorption capacity. Activated alumina also achieved good removal efficiency because its porous surface enhances microbial growth and adsorption capacity. MO-CW showed better removal efficiency of NH_4^+-N and TN (84.1% and 65.1%, respectively) compared to the other substrates because Mn ore can supply electrons, thereby enhancing nitrification. MO-CW and AA-CW had the best removal efficiencies for TP removal (97.1% and 99.0%, respectively), indicating that adsorption is the predominant process in phosphor removal.

Clay-based materials are characterised by a high specific surface area, great cation exchange capacity, surface hydrophilicity, etc. These properties provide them with a great adsorption capacity toward contaminants. For this reason, they can be used as substrates in CWs to enhance their treatment efficiencies. Different forms of clay-based materials are used in CWs, including in artificial materials (e.g., expanded clays, Filtralite P, etc.) [51,59], in industrial waste (clay brick fragments) [63,65], or in mixtures with sand. Indeed, Witthayaphirom, Chiemchaisri, and Chiemchaisri [42] investigated the ability of a reactive media containing various fractions of sand (S), clay (C), and iron powder (Fe) to remove organic micro-pollutants (OMPs). Testing these three compounds separately indicated that iron powder and clay can significantly improve the removal efficiency of organic matter, nitrogen, and OMPs compared to sand. Therefore, incorporating iron powder and clay in an inert medium such as sand can considerably enhance the treatment efficiency of constructed wetlands by increasing the adsorption capacity of the substrate. Indeed, this can be supported by the high surface area of clay and the complexation and co-precipitation in presence of iron. Witthayaphirom, Chiemchaisri, and Chiemchaisri [42] concluded that a mixture composed of 60% sand, 30% clay, and 10% iron powder (w/w) was satisfying for the treatment, with a removal efficiency of 76.3%, 70.2%, 69.0%, for BOD, COD, and TKN, respectively. The micropollutants were also removed through biodegradation (67.5% DEP, DBP 65%, DTPB 62.2%, and BHT 66.0%) and adsorption (63.9% DEHP). Witthayaphirom, Chiemchaisri, Chiemchaisri, et al. [41] used this mixture of sand, clay, and iron in a HSSF CW treating landfill leachate and achieved good treatment performances, as shown above.

Clogging is a serious issue that occurs in CWs, which causes a deterioration of bed permeability, and thereby a decrease in the treatment efficiency. Clogging is mainly induced by the accumulation of particulate matter trapped in the substrate and the biological development [67]. Miranda et al. [68] investigated the effect of the substrate type on HSSF CWs' clogging. Gneiss gravel (coefficient of uniformity CU = D_{60}/D_{10} = 3.1 and initial porosity n = 0.398) and crushed PET bottles (n = 0.642) were used to fill six pilot-scale HSSF CWs. Two distinct types of plants were planted in each CW: *Pennisetum purpureum* and *Cynodon* spp. A flow rate of 0.18 m^3d^{-1} was applied to each bed, with a mean organic loading rate of 33.7 g $m^{-2}d^{-1}$ of BOD_5. A theoretical hydraulic retention time (HRT) of 3.0 and 1.9 days was maintained in CWs filled with Gneiss gravel and crushed PET bottles, respectively. The monitoring of the systems showed that after twenty months of operation, the HSSF CWs displayed a surface runoff, especially in the first centimetres from the inlet, indicating bed clogging, except the one that was unplanted and packed with crushed PET bottles.

Moreover, the clogging occurred more frequently at the HSSF CWs entrance because it underwent the highest organic load and served as the first filter of suspended solids. As a result, the planted systems presented more surface runoff compared to the unplanted systems. This can be explained by the fact that plants contribute to the substrate clogging through the depositing of organic matter.

4.2. Vegetation

The visible structure of the constructed wetlands, which is vegetation, is regarded as a crucial component of the treatment wetlands. Plants have several characteristics that contribute to the effectiveness of wastewater treatment in constructed wetlands [69]. Indeed, plants provide the necessary conditions that influence the system's performance [27]. Several studies reported that planted constructed wetlands outperformed unplanted ones [34]. This is due to the multiple effects that macrophytes may have in wastewater treatment, notably: promoting filtration and sedimentation; increasing the contact time between wastewater, substrate, and roots; improving hydraulic conductivity and preventing bed clogging; enhancing biofilm development, which influences microbial activity; transferring oxygen from the atmosphere to the substrate, ensuring enhanced aeration of the bed; and plant uptake of various pollutants, especially nutrients [27,69,70]. Thereby, the macrophytes used in constructed wetlands must: (1) be tolerant to high organic and nutrient loads; (2) have a good ability to absorb pollutants; (3) have developed roots and rhizomes that provides attachment for bacteria and enhance oxygenation, and (4) to have the capacity to adapt to extreme climates [58,71].

Plants usually used in constructed wetlands are classified into four categories: emergent plants, submerged plants, floating leaved plants, and free-floating plants [11]. Emergent plants are the most commonly used type in both free water surface and subsurface flow constructed wetlands [58]. *Phragmites australis* (Common reed), *Phalaris arundinacea* (Reed canarygrass), *Typha* spp. (Cattails), and *Scirpus* spp. (Bulrushes) are the frequently used plants. However, *P. australis* is the most commonly used macrophyte [71].

Several studies comparing the treatment efficiency of planted and unplanted CWs have been conducted, and the majority of them have shown that planted systems outperform unplanted systems. For example, Toscano et al. [39] showed that vegetated HSSF CWs achieved a higher removal rate of COD, TN, and PO_4-P than unplanted HSSF CWs (Table 2).

A study carried out by J. Wang et al. [72] explored the performances of a constructed wetland to remediate the contaminated storm/runoff water from the urban areas before its discharge into surface water. The constructed wetland included a large community of macrophytes, namely emergent, submerged, and floating plants as well as periphytons. The principal plant species were *Typha latifolia*, *Hydrilla verticillata*, *Eichhornia crassipes*, and some periphyton filamentous algae (Spirogyra). The phytoremediation in the system was effective and managed to remove nutrients (with an average removal rate of 42% and 35% for TP and TN, respectively) as well as heavy metals (23%). Faecal coliforms were effectively reduced with a removal efficiency that ranged from 59% to 81%. Indeed, plants can contribute to the removal of pathogens through retention by macrophytes' organs, root secretions that kill microorganisms, and the development of antibiotic-active bacteria in the rhizosphere. J. Wang et al. [72] also reported that regular plant harvesting help to enhance treatment efficiency.

Leto et al. [73] compared the performances of HSSF CWs planted with two types of emergent macrophytes, namely *Cyperus alternifolius* L. and *Typha latifolia* L. The systems were used for the phytoremediation of treated urban wastewater. This study showed that the plant species could influence the treatment efficiency under identical hydraulic and design conditions. Indeed, *T. Latifolia* achieved better performances (64.3%, 72.4%, 75.7%, 51.6%, and 47.9% for TSS, BOD_5, COD, TKN, and TP, respectively) compared to *C. Alternifolius* (47%, 64.8%, 66.6%, 36.1%, and 31.7% for TSS, BOD_5, COD, TKN, and TP, respectively). This could be attributed to *T. latifolia*'s ability to colonise the substrate and its capacity to adapt to harsh environmental conditions. On the other hand, the presence of vegetation accentuated the evapotranspiration with an average water loss of 2.02 and 1.77 m^3/month for *Typha* and *Cyperus*, respectively, compared to unplanted systems (1.48 m^3/month).

Maucieri et al. [74], on the other hand, investigated the contribution of five macrophytes (*Carex elata* All.; *Juncus effusus* L.; *Phalaris arundinacea* L. var. *picta*; *Phragmites australis* (Cav.) Trin.; *Typha latifolia* L.) in the elimination of phosphorus. For this, 24 microcosms subsurface flow constructed wetland systems were used, which were unplanted. This study demonstrated that the plant presence enhanced PO_4-P elimination by 5.4% (*P. arundinacea*) to 9.4% (*C. elata*) in comparison to unplanted systems. *T. latifolia* managed to remove the totality of the load while the removal rates for *P. arundinacea*, *C. elata*, *J. effusus*, and *P. australis* were 86.2%, 48.1%, 37.6%, and 36.0%, respectively. Hence, *T. latifolia* represents the most adapted plant species for the removal of PO_4-P from wastewater.

4.3. Microorganisms

Wetlands represent a favourable environment for the development and growth of microorganisms [34]. These microorganisms play an important role in wastewater treatment in constructed wetlands since they contribute to the elimination of different contaminants through the assimilation, transformation, and recycling of pollutants [11,34]. For example, aerobic degradation removes organic matter emitting carbon dioxide, whereas anaerobic degradation generates several gases (carbon dioxide, hydrogen sulfide, and methane). Nitrogen can be removed through various phases of the nitrogen cycle where microorganisms are involved (nitrification, ammonification, and denitrification). On the other hand, microbial activity influences the removal of phosphorus by plant uptake via the transformation of insoluble phosphorus into a soluble form [32].

$$\text{Nitrification: } 2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 2H^+ + H_2O$$

$$2NO_2^- + O_2 \rightarrow 2NO_3^-$$

$$\text{Denitrification: } 2NO_3^- + 10e^- + 12\,H^+ \rightarrow N_2 + 6\,H_2O$$

Meng et al. [75] enumerated the microbial communities involved in the removal of organic matter and nitrogen. Heterotrophic bacteria, autotrophic bacteria, fungi such as yeasts and basidiomycetes, and certain protozoa are all involved in the biodegradation of organics in CWs. On the other hand, Nitrogen exists in a variety of forms, which explains the diversity of phylogenetic groups responsible for nitrogen elimination. Ammonia-oxidizing microbial communities, denitrifying microbial communities, and anammox microbial communities are the most common microbial communities involved in nitrogen removal. Meng et al. [75] also pointed out the different factors that influence the microbial activity in CWs, including the availability of organic matter, the redox condition, temperature, pH, the presence of plants, and media characteristics.

Fu et al. [76] investigated the effect of substrate on microbial community and nitrogen removal using nine lab-scale CWs filled with different combinations of materials (ceramist, activated carbon, and sand). The study revealed considerable differences in the microbial communities of the different systems, which corresponded to differences in denitrification and COD removal efficiencies measured in the lab-scale CWs. Zeng et al. [45] also studied the bacterial N, P, and COD removal in different types of CWs (vertical flow, horizontal flow, and surface water flow CWs) under different planting conditions. The study reported that the CWs' configuration had a higher impact on microorganisms than planting conditions. In addition, functional bacteria such as nitrifiers, aerobic denitrifiers, methanotrophs, and phosphate removal bacteria were more abundant in VSSF CWs compared to HSSF and FWS CWs. This could explain why VSSF CWs have higher treatment efficiencies.

5. Discussion on CWs Performances under Different Design and Operational Parameters

In light of the different studies, CWs can be regarded as a promising system for wastewater treatment, regardless of the variability in performance that different designs have provided. Indeed, the FWS CWs showed high efficiencies in terms of organic matter removal, most notably when the hydraulic retention time was high [35]. However, the removal of nutrients and specifically phosphorus was limited, due to the restricted contact between the substrate and the wastewater. This can be improved by incorporating a reactive media such as zeolite [36]. However, FWS CWs require extensive area and present a significant risk of pathogen exposure, making them unsuitable for secondary treatment of wastewater and reuse in agriculture. Nevertheless, they can be used as an advanced effluent treatment [51], especially with their ability to achieve high elimination of microbiological contamination in warm seasons. HSSF CWs, on the other hand, can reach high performances for TSS removal, with a limited removal of organic matter and nitrogen due to the lack of dissolved oxygen [39,41,44]. Artificial aeration and the use of reactive media could significantly improve the performances of the CWs and make it possible to reach high removal efficiency (above 90%) for organic matters, suspended solids, and nutrients [43]. In comparison to HSSF and FWS CWs, VSSF CWs achieve higher removal rates of organic matter and nutrients because they provide higher oxygenation, which enhances aerobic degradation and nitrification [44,45]. An improved VSSF CWs configuration enables the achieving of high treatment efficiencies and optimisation of the required surface area by increasing the oxygen transfer rate in the system, which emphasizes the importance of a good aeration to reach higher treatment efficiencies in CWs [46]. The Hybrid constructed wetland demonstrated high performances in the removal of the different contaminants. This was due to the combination of different types of CWs, allowing various removal mechanisms to occur at various intensities (aerobic and anaerobic degradation, adsorption, filtration, volatilisation, photodegradation, etc.). The elimination of nitrogen can also be enhanced, since both nitrification and denitrification can take place [48,50,52].

Besides conventional contamination, CWs have proven their efficiency in the elimination of heavy metals and emerging contaminants and microorganisms. Indeed, CWs demonstrated their ability to remove heavy metals from wastewater, with up to 100% elimination of cadmium in a HSSF CW filled with blast furnace slag and planted with *Phragmites australis* [43]. Different removal mechanisms can be involved in their elimination including phytoremediation, filtration, sedimentation, precipitation, adsorption, ion exchange (with ions that could be present in the substrate such as Na^+, K^+, Ca^{2+}), microbial activity, etc. [36,44]. The removal of heavy metals in CWs is affected by several parameters including the pH, COD load, dissolved oxygen, temperature, and also the concentration of heavy metals, since high concentrations can inhibit plant activity [77]. The elimination of pathogens in CWs could be related to physical, chemical, and biological factors' processes. Filtration, sedimentation, and adsorption to the substrate are the significant physical mechanisms. The chemical mechanisms consist of oxidation and exposure to UV radiation, antibiotics, or biocides secreted by vegetation. Biological mechanisms include natural die-off, predation, retention in biofilms, the antimicrobial activity of root exudates, and competition for limited nutrients. The intensity of these different removal mechanisms varies according to the type of the CWs, water chemistry, retention time, seasonal variation, substrate, and vegetation [78,79]. Although several studies showed substantial elimination of microbial contamination reaching over 99% [36,39,50,52,80], other studies showed lower removal rates [51]. The removal of microbial contamination in CWs is still challenging, and the implementation of polishing step, such as disinfection using chemical agents or UV lights, is recommended if the treated wastewater is to be reused in agriculture [22,43]. Emerging pollutants such as pharmaceuticals, personal care products, and endocrine-disrupting compounds could also be removed in CWs, with a removal efficiency exceeding 80% for some compounds through different removal mechanisms (e.g., biodegradation, adsorption, volatilisation, hydrolysis, and photodegradation) [41,50,55].

The presence of vegetation in CWs is very beneficial for wastewater treatment, since it contributes to the elimination of different pollutants and the transfer of oxygen from the atmosphere to the beds [72,74]. However, the presence of vegetation associated with high temperature could accentuate the evapotranspiration [73]. Indeed, high temperatures and the presence of plants contribute in terms of enhancing the treatment efficiencies in CWs; however, they could increase the evapotranspiration, which affects water balance and causes water loss, and this is considered unprofitable for wastewater reuse in agriculture, particularly in arid and semi-arid regions [39,40,73].

Another factor that influences the treatment efficiency of CWs is temperature. Several studies demonstrated that seasonal variation has an impact on treatment performance, especially for the removal of organic matters, nutrients, and microbial contamination, since low temperatures directly impact the microbial activity, while higher removal rates were always observed in warm and hot seasons because higher temperatures promote plant growth and microbial activity [39,48,52]. For this reason, a new design was proposed to enhance the treatment efficiency of CW in cold regions using geothermal energy [49].

In addition, the selection of the substrate also plays an important role in the performance and sustainability of CWs. A compromise must be found between their purification and hydraulic conductivity in order to avoid clogging problems [42,68]. CWs filled with materials with high adsorption capacity, high porosity, and small particle size, containing ions (e.g., Ca, Mg, Fe, or Al) for ion exchange and complexation, could achieve higher performances [42,55,56,63,65].

6. Wastewater Reuse and Potential of Constructed Wetlands in the Moroccan Context

Wastewater reuse in Morocco is regarded as an alternative to help reduce the growing water deficit, an adaptation solution to climate change, and to mitigate the environmental impacts of wastewater discharges [81]. The reclamation of treated wastewater is implemented for various purposes, including aquifer recharge in the Gharb region, Eucalyptus trees forest irrigation in the Kenitra region, and mainly golf course irrigation in different cities (e.g., Marrakech and Bensliman) [82]. For example, the city of Ait Melloul (Morocco) saved 4 Mm^3/year by reusing treated wastewater for irrigation instead of depleting freshwater sources to irrigate a 400-hectare forest [2]. Moreover, the National Water Plan (PNE) and the National Plan for Reuse (PNREU) promote this practice and aim to increase treated wastewater reuse to 325 million m^3/year by 2030 [15]. In addition, a chapter focused on Wastewater reuse, and sewage sludge has been included in the Water Law enacted in 2016 (Law 36-15), where it is specified that the treated wastewater must comply with quality standards set by regulations [19].

Although wastewater reuse in agriculture has several benefits, it may generate a negative impact on soil, groundwater quality, and human health due to the presence of some contaminants [12,16]. Besides microorganisms and pathogens that could generate direct health risks in cases of exposure, treated wastewater contains chemical constituents such as salt, heavy metals, nutrients, and micro-pollutants that could accumulate in soil and plants with the risk of entering the trophic chain [3,12]. Therefore, water quality must be controlled and appropriate treatment must be considered in order to obtain effluents respecting standards and regulations on wastewater reuse for agriculture [9]. Organisations and countries have established different standards and guidelines for safe wastewater reuse in agriculture. The World Health Organization (WHO) guidelines are regarded as a reference for the other standards focusing on microbiological health hazards. The FAO's guidelines, on the other hand, are a reference for physico-chemical parameters [83]. The USEPA imposes stringent standards, making it hard for developing countries to adopt them because of the high cost and technology required [84]. Recently, standards on minimum requirements for wastewater reuse were issued by the European Commission [9]

In Morocco, the standards for water destined for irrigation are defined by the "Joint Decree of the Ministry of Equipment and of the Ministry in charge of Spatial Planning, Urbanism, Habitat and the Environment No. 1276-01 of 10 Chaabane 1423 (17 October 2002) laying down standards for the quality of water intended for irrigation". The parameters to control and sampling frequencies are shown in Table 3 [85].

Table 3. Moroccan guidelines for the quality of irrigation water.

Parameters	Legal Limits	Control Frequency
Biological Parameters		
Faecal coliform (CFU/100 mL)	1000	Fortnightly
Salmonella (U/51 mL)	Absence	Fortnightly
Choleric Vibrio (CFU/450 mL)	Absence	Fortnightly
Pathogenic parasites	Absence	Fortnightly
Intestinal nematode eggs	Absence	Fortnightly
Ankylostome larvae	Absence	Fortnightly
Metals and Metalloids		
Mercury (mg/L)	0.001	Quarterly
Cadmium (mg/L)	0.01	Quarterly
Arsenic (mg/L)	0.1	Quarterly
Chromium (mg/L)	0.1	Quarterly
Lead (mg/L)	5	Quarterly
Copper (mg/L)	0.2	Quarterly
Zinc (mg/L)	2	Quarterly
Selenium (mg/L)	0.02	Quarterly
Fluoride (mg/L)	1	Quarterly
Cyanide (mg/L)	1	Quarterly
Phenol (mg/L)	3	Quarterly
Aluminium (mg/L)	5	Quarterly
Beryllium (mg/L)	0.1	Quarterly
Cobalt (mg/L)	0.05	Quarterly
Iron (mg/L)	5	Quarterly
Lithium (mg/L)	2.5	Quarterly
Manganese (mg/L)	0.2	Quarterly
Molybdenum (mg/L)	0.01	Quarterly
Nickel (mg/L)	0.2	Quarterly
Vanadium (mg/L)	0.1	Quarterly
Physico-Chemical Parameters		
Total salinity (mg/L)	7680	fortnightly
Electrical conductivity (mS/cm)	12	Fortnightly
Sodium (mg/L)	9 (Surface irrigation)	Fortnightly
	69 (Sprinkler irrigation)	Fortnightly
Chloride (mg/L)	350 (Surface irrigation)	Fortnightly
	105 (Sprinkler irrigation)	Fortnightly
Boron (mg/L)	3	Fortnightly
pH	6.5–8.4	Fortnightly
TSS (mg/L)	100	Fortnightly
Nitrate(mg/L)	30	Fortnightly
Carbonate (mg/L)	518	Fortnightly
Sulphates (mg/L)	250	Fortnightly

Although conventional wastewater treatment plants can generate effluents that meet different levels of regulations and standards, they require intensive energy. They have higher operating and maintenance costs, making them unsuitable for developing countries. Therefore, cost-effective, and easy-to-handle technologies have to be developed. Constructed wetlands appear to be a good alternative since they can produce a good quality effluent, with a high removal efficiency of different contaminants, including heavy metal pathogens and micro-pollutants [11,78]. Several studies have been carried out in order to evaluate the performances of CWs and the potential reuse of their effluents in agriculture.

For example, Andreo-Martínez et al. [43] reported that the quality of the final effluent of an artificially aerated HSSF CW complied with the Spanish regulations for wastewater reuse, except for electrical conductivity and the sodium adsorption ratio, which increase in summer because of evapotranspiration. The hybrid CWs studied by Avila et al. [50] also produced an effluent that complies with the Spanish regulations for some water reuse applications such as the recharging of aquifers by percolation through the ground, silviculture, and irrigation of forests and other green areas that are non-accessible to the public. Nguyen et al. [51] stated that the constructed wetlands can effectively be used for reuse of their effluents in agricultural irrigation, since the quality of the effluents generated by hybrid CWs met the standards of several countries such as China, Italy, Turkey, and the USA, as well as the WHO guidelines. Some parameters, on the other hand, such as BOD_5 and NH_4-N, did not comply with Vietnam's standard limits for reuse, which are very stringent. Ezzat et al. [36] reported that the FWS CWs produced a good quality effluent characterised by 0.2 mg/L, 0.056 mg/L, 2.35 NTU, 5.93 mg/L, and 11.33 mg/L for NH_3, Fe, turbidity, BOD, and TSS, respectively. Hence, the effluent complied with the FAO guidelines for wastewater reuse in irrigation. The bacteriological contamination also met the WHO guidelines for unrestricted irrigation (1148, 820, 520, 480, 7, and 3 cfu/100mL for TC, FC, FS, *E. coli*, *P. aeruginosa*, and *S. aureus*, respectively). Torrens et al. [52] reported that a hybrid CW achieved a good removal efficiency, resulting in a quality that respects Senegalese discharge regulations and the WHO recommendations for reuse in unrestricted irrigation. On the other hand, a VSSF CW did not succeed in producing an effluent that respects the Egyptian guidelines for wastewater reuse in irrigation, with a COD concentration that exceeded the limits [47].

In Morocco, the use of CWs as a treatment technology has yet to be developed. For example, a hybrid constructed wetland was installed in the rural village of Tidili Mesfioua near Marrakech. The hybrid constructed wetland consisted of two stages: the first stage comprised three parallel VSSF CWs with a surface area of 130 m^2 each and 0.9 m depth, and the second stage comprised two parallel HSSF CWs with a surface area of 88 m^2 and 0.6m^2 depth. The VSSF CWs were packed with different layers of pebble, coarse gravel, and fine gravel, while the HSSF CWs were filled with coarse gravel and fine gravel. The CWs were planted with *Phragmites australis* [48]. A study carried out by the authors assessed the treatment performances of this wastewater treatment plant for two years and evaluated the impact of seasonal variation on the removal of different pollutants.

The CWs were fed with hydraulic loading rates of 0.5 and 0.75 $m^3/m^2/d$, for VSSF CWs and HSSF CWs, respectively, and organic loading rates of 194 g BOD/m^2/d and 28 g BOD/m^2/d for VSSF CWs and HSSF CWs, respectively. Indeed, COD, BOD_5, and TSS were highly removed with 91.4 %, 93.47%, and 94.83% removal efficiencies, respectively. The high removal rate observed in this study was promoted by the different physical and microbiological mechanisms involved in hybrid constructed wetlands. Furthermore, COD and BOD_5 removal appeared to be influenced by temperature since the highest organic matter removal rate coincided with the higher temperature observed during the warm season. A seasonal trend was also observed for the TN removal rate efficiency, which proves that temperature affects TN removal. In addition, a significant average removal efficiency of 67% was obtained with a maximum of 73.89% recorded in summer. This was due to different redox conditions being provided by the VSSF and HSSF CWs, which were suitable for both nitrification and denitrification. Indeed, the high total nitrogen removal resulted from strong nitrification at the VSSF; nitrate generated in the effluent successfully decreased in the HSSF effluent through denitrification. Hence, hybrid constructed wetlands could be used to improve the total nitrogen removal efficiency. The average abatement was of the order of 4.36 Log units for total coliforms (TC) and 4.27 Log units for faecal coliforms (FC), and the highest removal efficiency of bacterial indicators of faecal contamination was observed in summer. According to these results, the bacteriological quality of the effluent in term of faecal bacteria was in accordance with the Moroccan regulation for wastewater reuse in irrigation, which confirms that constructed wetlands should be considered as an alternative to conventional wastewater treatment methods for wastewater reuse in small communities.

Another CW was implemented in the village of Douar Ouled Ahmed near Casablanca for the treatment of wastewater generated by a Hammam (public bath). The treated wastewater is intended for reuse in agricultural irrigation in a solidary farm. Saidi et al. [86] evaluated the performances of this treatment plant. This unit includes a three-compartment septic tank, which ensures wastewater pre-treatment and helps in the removal of suspended solids. The water then flows through a HSSF CW with a surface area of 105 m^2 and a depth of 0.9 m, which is filled with gravel of different sizes and planted with *Phragmites australis*. Afterwards, the water is conveyed to a storage tank composed of three compartments. The first two compartments have a shallow depth (15 cm), which enables solar radiation to penetrate and eliminate pathogenic microorganisms, while the third compartment, which has an important volume, serves as a storage tank. The CW achieved a good removal rate for organic matter (67% and 85% for DOC and BOD_5, respectively). According to this study, the water loss caused by evapotranspiration ranges from 10 to 29 mm/d and increases as temperature rises and humidity decreases. These values are notably lower than those reported in another studies in Morocco, which reported an evapotranspiration of 57 mm/d for the same plant (*Phragmites australis*) [87]. The physico-chemical parameters, such as temperature, pH, conductivity, and N-NO concentration, comply with the Moroccan standards for water intended for irrigation. Furthermore, the CW significantly reduced the microbiologic contamination, with an absence of Salmonella and Choleric Vibrio, and all the other bacterial indicators were below the standard values for irrigation water. However, the water quality was deteriorated after storage due to the algal development in the presence of nutrients and sunlight. It must be noted that these two studies did not take into consideration the elimination of heavy metals, which represent an important aspect in the Moroccan standards for water intended for irrigation.

7. Conclusions

Constructed wetlands have gained popularity worldwide in recent years since their effectiveness has been proven in the treatment of different types of wastewater. As shown throughout the present review and the various studies conducted on the topic worldwide, the treatment performances of different types of constructed wetlands (FWS, HSSF, VSSF, and hybrid CWs) operating with different design and operational parameters (e.g., types of vegetation, substrates, temperatures, hydraulic retention times, organic loading rates, etc.) have been evaluated. According to these studies, CWs can achieve high treatment efficiencies that could be comparable, or even exceed, in some cases, the efficiencies of conventional treatment technologies. Indeed, all types of constructed wetlands are very effective in eliminating conventional pollution (TSS, COD, BOD, etc.), with VSSF CWs outperforming FWS and HSSF CWs due to their higher oxygen transfer rates. Moreover, CWs have demonstrated a good capacity for removing heaving metals and emerging pollutants. The removal of microbial contamination, on the other hand, is challenging and can be improved using multistage or hybrid CWs along with high hydraulic retention times and small media sizes. In addition, several studies reported that CWs produce high quality effluent that meets the standards and regulations for wastewater reuse in agriculture. Therefore, CWs are considered as a sustainable, inexpensive, and energy-saving solution that can be adopted as an alternative treatment technology for remote rural sanitation, with great potential in terms of providing effluents that are suitable for reuse in agriculture in the Moroccan context.

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