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Impact of Ornamental Vegetation Type and Different Substrate Layers on Pollutant Removal in Constructed Wetland Mesocosms Treating Rural Community Wastewater

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Abstract: Improving water quality is a relevant environmental aspect, and using constructed wetlands (CWs) is a sustainable option for this; both porous material filled cells and plants that collectively remove contaminants must be readily available and inexpensive. This study evaluated CWs and their functionality by comparing two ornamental plants (*Spathiphyllum wallisii* and *Hedychium coronarium*) planted in experimental mesocosm units filled with layers of porous river rock, tepezil, and soil, or in mesocosms with layers of porous river rock, and tepezil, without the presence of soil. The findings during the experiments (180 days), showed that the removal of pollutants (chemical oxygen demand (COD), total solids suspended (TSS), nitrogen as ammonium (N-NH_4), as nitrate (N-NO_3), and phosphate (P-PO_4) was 20–50% higher in mesocosms with vegetation that in the absence of this, and those mesocosms with the soil layer between 33–45% favored removal of P-PO_4. Differences regarding of vegetation removal were only observed for N-NH_4, being 25–45% higher in CWs with *H. coronarium*, compared with *S. wallisii*. Both species are suitable for using in CWs, for its functionality as phytoremediation, and aesthetic advantages could generate interest for wastewater treatment in rural communities, parks, schools or in domiciliary levels like floral flower boxes in the backyard. The study also revealed that a soil layer in CWs is necessary to increase the removal of P-PO_4, an ion hardly eliminated in water treatment.

Keywords: constructed wetlands; phytoremediation; water cleaning; ornamental vegetation

1. Introduction

Population growth is an aspect that has contributed to the excessive use of water, and in addition to the lack of wastewater treatment systems, the degree of water quality is currently getting poorer. According to CONAGUA [1], of municipal collected wastewater in Mexico, only the 63% of this is treated, which shows the clear need for wastewater treatment plants; however, the implementation of this is not a common case due the high costs required for the construction and operation thereof. For example, in Xaltianguis, Guerrero, Mexico, a conventional treatment plant for sewage and activated sludge was installed for a water volume of 1080 m^3/day, of which the construction cost was $596,500.00 plus $38,880.00 monthly for operating expenses (Mexican Pesos) [2]. Such costs prevent the constant replication of this type of system, which leaves even more vulnerable rural communities (<2500 inhabitants), which due to their low population numbers and dispersion are less likely to be provided with such methods. Therefore, the use of ecologically viable or sustainable alternatives to solve these problems is needed; for this purpose constructed wetlands (CWs), or so-called artificial wetlands are examples of such an alternative [3–5]. These systems simulate the functionality of improving water detoxification of contaminants by physical, chemical, and biological processes that natural wetlands have, and which are also called planet kidneys [3,6]. CWs are cells with a substrate, and where vegetation is planted to suit saturation conditions of wastewater in the roots. These are surface flow CWs when there is only one layer of soil at the bottom of the cell and the wastewater is in contact with the atmosphere, a situation that allows the presence of emergent plants (planted in the ground and projecting from the water column), floating plants on the water column, and/or submerged plants (rooted to the soil but do not protrude from the water column). Subsurface-flow CWs are cells filled with a granular medium of certain porosity that allows the development of microbial films by the presence of the substrate, so they can only have emergent plants [7].

Some studies have shown that plants are one of the most important features of CWs [8,9], the macrophytes have several properties in relation to the treatment process that makes them an essential component of the design. In CWs saturated and unsaturated of water with *Typha* or *Juncus*, the removal of nitrogen compounds was 20–30% higher in the presence of vegetation compared to unplanted systems [10]. Similarly, in removal of pesticides (imazalil and tebuconazole), unplanted vs. planted mesocosms were evaluated, and the presence of plants showed 20–40% more removal efficiency than units without vegetation [11]. In a review about the importance of plants in CWs, the author described that the vegetation has mostly a positive effect, i.e., supports higher treatment efficiency, for organics and nutrients. *Phragmites*, *Typha*, and *Scirpus* spp. are the most frequently used plants around the globe [8]. However, in tropical and subtropical regions, ornamental plants are studied according to their ability of adaptation in CW conditions.

On the other hand, the treatment performance of CWs can strongly be affected by the media (substrate); gravel and sand have been used as the traditional media in CW designs [3,7]. The role of media was studied comparing different biochar-packed vertical flow constructed wetland columns (corn biochar, wood biochar, and gravel). It was demonstrated that corn and wood biochar provide significantly higher removal efficiencies for organic matter and phosphorous, compared with gravel, and the results are attributed to the higher adsorption ability and microbial cultivation in the porous biochar media [12]. Other investigations have looked at porous river rock or tepezil as media in CWs, showing important removal of pollutants [7,13]. Considering the effect of different substrates as filter media in CWs, the effect of multilayer substrate configuration was evaluated. It was demonstrated that the pollutant removal performance improved in the multilayer (units with three and six layers), compared to the monolayer CWs [14,15].

Between physical, chemical, and biological processes, contaminant removal is carried out within the system maintaining a hydraulic retention time therein. Although this environmental technology has widely been used in Europe and the United States [8,16,17], in Mexico, its use has not been extensive, and even different substrates and vegetation of the tropical zone need further study to improve the effects of removal, as conditions differ from those places where the systems have been extensively evaluated.

In this regard, the use of waste or local substrates to fill the cells subsurface-flow CWs, and the use of ornamental vegetation which is not typical of natural wetlands, but has physiological characteristics that could adapt to CWs and also generate an aesthetic landscape to produce flowers was investigated. In order to know the best design of CWs, and intensify the removal of pollutants by using ornamental plants with flower production, and different substrates, the main aim of this study was to evaluate the effect of removing pollutants from the community wastewater by using different layers of substrates (porous river rock PRR) + tepezil (TZ) vs. PRR + TZ + soil), and different ornamental vegetation (*Spathiphyllum wallisii* and *Hedychium coronarium*) in subsurface-flow CW mesocosms.

2. Materials and Methods

The study was conducted in the community of Pastorías (Actopan township), Veracruz, Mexico (19°33′47.96″ N and 96°34′18.99″ W), has 620 inhabitants and has had a sewer system since 2013 [11]. However, there is no system for the treatment of wastewater and this is only stored in a receiving tank of approximately 15 m^3, which is not enough, so waste water leaves the receiving tank, and gravity flows it into the Topiltepec River, Actopan River sub-basin, causing damage to the flora and fauna of the ecosystem. Furthermore, the use of the river as a recreational area is a common activity in the community, so the wastewater inlet river denotes a focus of infection. The climate of the coastal plain of the Gulf of Mexico—a region that includes the community where the mesocosms are—has three periods comprising of: rainy season from July to October; cold front with strong winds and rain between November until February; and dry periods between March until June [18,19]. Weather in the region is tropical with an annual precipitation of 947.1 mm, and annual average temperature of 24.5 °C (26.1, 26.6, 25.2, and 20.3 °C in spring, summer, autumn, and winter, respectively).

Design Features and Operating Criteria of Mesocosm

Twelve mesocosms of horizontal subsurface-flow CWs (1.1 m length × 0.45 m width × 0.54 m depth; free water surface flow column of 10 cm; 0.109 m^3 water volume) were established in a backyard with a transparent roof to avoid the influence of rainwater. Four units were planted with four seedlings of *H. coronarium*, and four with the same number of plants, but the species was *S. wallisii* (Figure 1); half-filled cells up and down with a PPR layer (0.22 m) followed by a layer of TZ (inert mineral such as sand, lightweight, used to make building blocks; 0.22 m). The other half had a PPR layer of 0.17 m, + a layer of 0.17 m of TZ, and 0.1 m layer of soil at the bottom, after the TZ layer (as shown in Figure 1). Duplicates of experimental units filled in the two different ways by using vegetation, but without the presence of plants, they were used as controls or white units. PRR (50% porosity) was collected from the Topiltepec river. It is noteworthy that the mesocosms with *S. wallisii* were covered with mesh shade to favor the development of the species, since it is not typical of sun-exposed sites [20]. TZ was collected as waste in a community building (40% porosity). Both substrates were approximately 2.5 cm in diameter. Another data about the material filter used is described in Figure 2. CWs were fed tap water for 30 days, and 10 days with wastewater mixed with 50% tap water for the process of vegetation adaptation. Subsequently the fed water was wastewater from a manifold of 1100 L, which was filled by pumping from the drainage system. Mesocosms were operated at a hydraulic retention time of three days, inflow rate: 0.04 m^3/day, and hydraulic loading rate = 8.0 cm/day. It is also worth mentioning that the two species of used plants were chosen because of their abundant presence in the region.

The parameters measured as indicators of water quality were chemical oxygen demand (COD), total solids suspended (TSS), nitrogen as nitrates ($N\text{-}NO_3$), and ammonium ($N\text{-}NH_4$), and phosphate ($P\text{-}PO_4$), dissolved oxygen (DO) (Table 1), measured according to standard methods [21]. The percentage of contaminant removals (Em) was determined with Equation (1) [22].

$$\mathrm{Em} = [(\mathrm{Ci} - \mathrm{Ce})/\mathrm{Ci}] \times 100\% \quad (1)$$

where Ci is the concentration of the pollutant in the influent (in milligrams per liter), and Ce is the concentration of the pollutant in the effluent (in milligrams per liter).

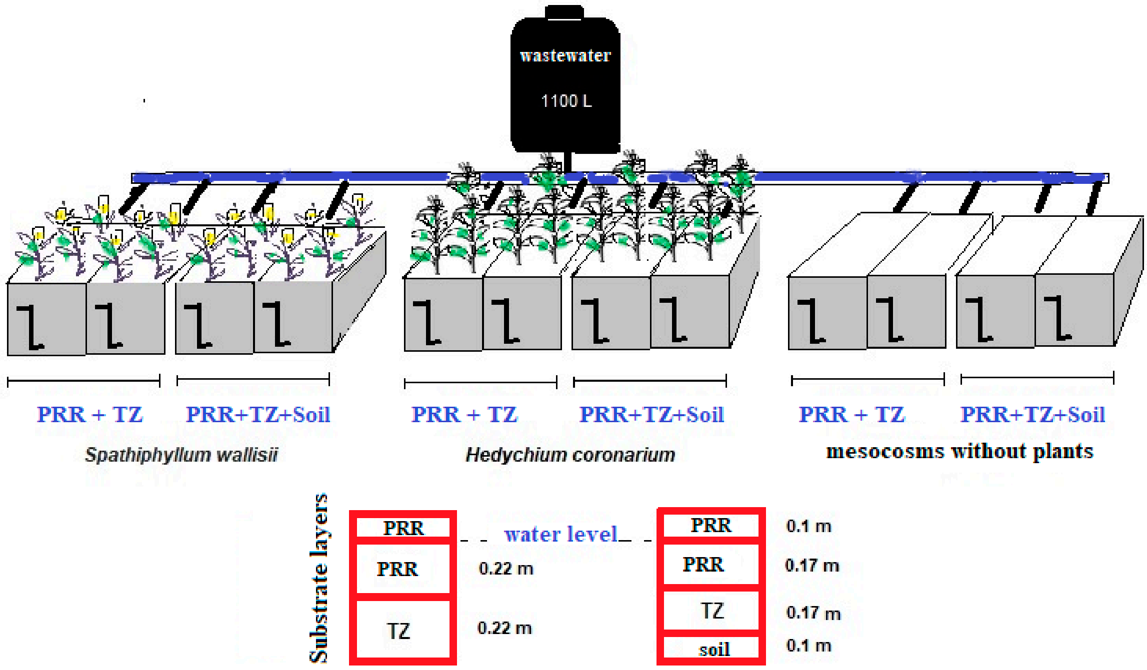

Figure 1. Schematic of the mesocosms wetland study.

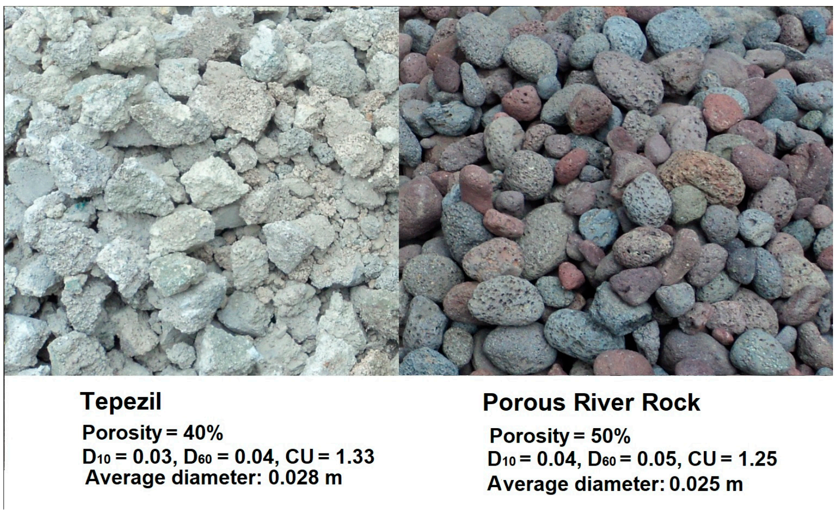

Figure 2. Materials used as filter media in the constructed wetlands (CWs) in this study.

Table 1. Measured parameters according to standard methods.

Parameter Type	Sampling Frequency	Measured Parameter
Physical/hydraulic	Weekly	pH, temperature, flow * DO
Chemicals	Fortnightly	COD, TSS, $N\text{-}NH_4$, $N\text{-}NO_3$, $P\text{-}PO_4$

* This parameter was measured to see if the flow changed by plugging and adjusting if necessary.

3. Results and Discussion

The characteristics of the wastewater before entering the mesocosms, and after the treatment period are described in Table 2. The pH in water ranged from 6.9 to 7.3 in the mesocosms, with an average value of 7.6 ± 0.3 at the entrance. The DO was 2.2 ± 0.3 mg L^{-1} at input, while the output, the concentrations were between 4.1 and 4.6 for systems with presence of vegetation, and between 2.6 and 2.7 mg L^{-1} in systems without presence of plants. The water temperature was similar in both, the input and the output of the experimental units (18–20 °C).

Table 2. pH, dissolved oxygen and water temperature. Mean values ± standard error (n = 156).

Parameter/ Experimental Units	Influent	*Spathiphyllum wallisii*		*Hedychium coronarium*		Control	
		PPR	TZ	PPR	TZ	PPR	TZ
pH (pH units)	7.6 ± 0.3	7.3 ± 0.3	7.2 ± 0.5	7.1 ± 0.9	6.9 ± 0.6	7.4 ± 0.2	7.3 ± 0.3
DO (mg L^{-1})	2.2 ± 0.3	4.6 ± 0.7	4.8 ± 0.6	4.7 ± 1.1	4.1 ± 0.4	2.6 ± 0.5	2.7 ± 0.3
Temperature (°C)	18.0 ± 0.9	19.6 ± 0.5	19.1 ± 1.9	17.8 ± 1.6	18.9 ± 0.9	20.0 ± 0.6	19.6 ± 0.5

Growth of the species evaluated (Figure 3) tended to be higher in *H. coronarium* (60–70 cm) which is derivative of nature of the species compared to *S. wallisii* (32–40 cm), since the former can reach up to 2.5 m height and grows well in waterlogged and frequent exposure sun sites. In addition, *H. coronarium*, also called matandrea, white or ginger butterfly, depending on the region, reproduction is important because several of its components such as rhizomes or leaves have been reported to be beneficial against infections and joint pain [23]. Showing adaptation to wastewater treatment systems of this species, leads to the consideration of it as an attractive option in this type of environmental technology due to its flowering, and the additional use of the flower for seedling production, or use of its components for medicinal aspects. In the case of *S. wallisii*, it is not a common wetland plant, but its adaptation was shown, therefore if this occurs over a larger area, its production would be important for those who manage the system, since it is an ornamental plant with market value per plant $70 to $150 (Mexican Pesos), depending on sizes and presence of flowers. Considering these advantages, plus the ability to function as phytoremediation, they are now a viable option in CWs systems.

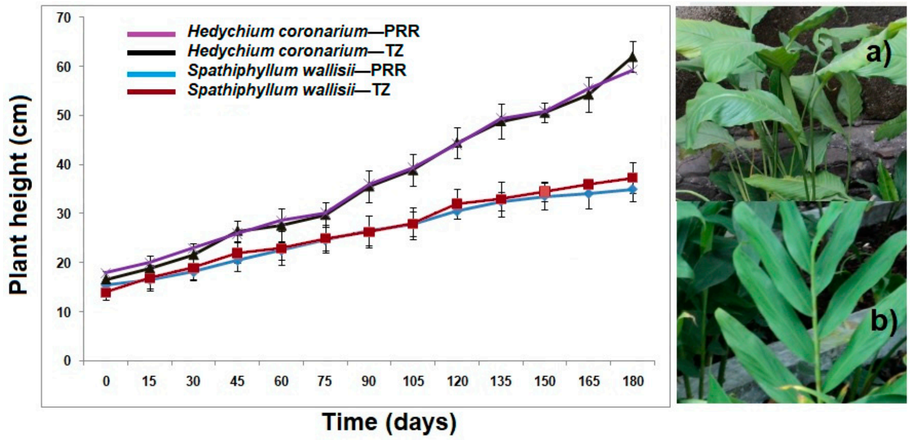

Figure 3. Vegetation growth in study. (**a**) *Spathiphyllum wallisii*, and (**b**) *Hedychium coronarium*.

Concentration and Removal of Contaminants in CW Mesocosms

In the system input, the average concentration of organic matter was measured as COD (398 ± 39 mg/L), while the outputs ranged from 31–96 mg/L. Low observed concentrations indicated removal of such as a parameter in a range of 75% to 77% in control systems, while in the mesocosms with plants, the removal fluctuated between 90% and 92%, regardless of the type of species (p = 0.061). COD reduction compared to controls alluded to the oxygen supply provided by plants through their parenchymal system, which favors the development of vital microbial community responsible for the process of removal of the organic matter [24]. Likewise, it has been reported that plant roots minimize water velocity, and thus promotes sedimentation of suspended organic matter [8,25]. According to CONAGUA, in Mexico, the water bodies monitors have established that an acceptable criterion of COD discharges in wastewater that is biologically treated, must not exceed 40 mg/L [1].

TSS was used to measure the amount of settleable solids and organic solids and/or colloids, a body of water with high amounts of TSS prevents healthy diversity of aquatic life. Russell [26] indicates that water with acceptable quality must be between 76 and 150 mg/L, good quality between 26 and

75 mg/L, and excellent quality with concentrations ≤25 mg/L. In this study, the inlet concentration was 780 ± 72 mg/L, which was reduced when passing through the CWs (426–618 mg/L), reflected in turn in the removals, noting that these were statistically higher ($p > 0.05$) in the presence of vegetation systems regardless of the difference in substrate layers (41–45%), compared to mesocosms with no plants (20–22%). The detected data indicates that the treated water still had high concentrations of TSS, despite removals of almost 50%, which is a significant level of removal within environmental ecotechnology.

The average concentration of N-NO_3 at the entrance was 14.4 ± 0.11 mg/L, while in the wetlands ranged from 9.0 to 11.1 mg/L, which meant removals of 17% to 21% in control systems, and 37% to 42% in units with plants (Table 3). Mesocosms with different vegetation and substrate showed no significant difference ($p = 0.234$). This indicated that the presence of vegetation favored the release of radial oxygen [27], and this allowed nitrification in the rhizosphere zone. After denitrification processes in the anaerobic area, this last process could only have been present in the mesocosms with no plants, and in minor proportions, since the presence of vegetation under anaerobic conditions also favors carbon exudation from the root, which intensifies the denitrification [28]. Based on data from the US Environmental Protection Agency (USEPA) [29], the maximum allowed limit of N-NO_3 to allow aquatic life in freshwater systems acutely should not exceed 3.0 mg/L and 10 mg/L for recreational and aesthetic bodies of water, respectively. Besides that, when it is used for recreational uses and obtaining fish for consumption, it is a priority to lower levels of the ion, which even with the treatment of wetlands higher than 3.0 mg/L could be mitigated by combining superficial wetland systems, and subsurface CWs of both horizontal and vertical flow.

Table 3. Concentrations and removals average contaminants removed in the mesocosms CWs.

Parameter	Wetland Vegetation in Different Substrates					
	Spathiphyllum wallisii		*Hedychium coronarium*		Control	
	PPR + TZ	PPR + TZ + Soil	PPR + TZ	PPR + TZ + Soil	PPR + TZ	PPR + TZ + Soil
COD						
EC				398 ± 39		
CS	31 ± 11	36 ± 9.2	37 ± 9.6	35 ± 11.2	96 ± 11	91 ± 7.4
Removal (%)	92.2 ± 6.8 ^{a}	90.9 ± 0.8 ^{a}	90.7 ± 12.3 ^{a}	91.2 ± 10.2 ^{a}	75.9 ± 14.4 ^{b}	77.1 ± 11.2 ^{b}
TSS						
EC				780 ± 72		
CS	444 ± 82	426 ± 85	428 ± 76	460 ± 69	609 ± 69	618 ± 74
Removal (%)	43.1 ± 11.2 ^{a}	45.4 ± 7.9 ^{a}	45.1 ± 6.5 ^{a}	41.0 ± 9.6 ^{a}	21.9 ± 6.4 ^{b}	20.8 ± 8.2 ^{b}
N-NO_3						
EC				14.4 ± 0.11		
CS	8.4 ± 0.72	8.9 ± 0.18	8.6 ± 0.95	9.0 ± 0.98	11.1 ± 0.13	11.9 ± 1.0
Removal (%)	41.7 ± 4.8 ^{a}	38.2 ± 1.6 ^{a}	40.3 ± 11.6 ^{a}	37.5 ± 5.0 ^{a}	20.8 ± 7.6 ^{b}	17.4 ± 4.3 ^{b}
P-PO_4						
EC				6.06 ± 0.64		
CS	3.9 ± 0.19	2.79 ± 0.37	4.04 ± 0.26	2.96 ± 0.19	5.4 ± 0.34	4.6 ± 0.28
Removal (%)	35.6 ± 1.2 ^{b}	54.0 ± 2.9 ^{a}	33.3 ± 3.1 ^{b}	51.2 ± 2.6 ^{a}	10.9 ± 0.8 ^{d}	24.1 ± 1.5 ^{c}
N-NH_4						
EC				4.11 ± 1.08		
CS	2.32 ± 0.19	2.12 ± 0.33	0.98 ± 0.12	1.06 ± 0.66	3.2 ± 1.08	3.6 ± 0.75
Removal (%)	43.6 ± 3.6 ^{b}	48.4 ± 5.6 ^{b}	76.1 ± 5.9 ^{a}	74.2 ± 8.1 ^{a}	22.1 ± 2.6 ^{c}	12.4 ± 1.8 ^{c}

Values are given as the average ± standard error. Different letters (superscript) indicate significant differences between the columns at the 5% significance level.

The average amount P-PO_4 present at the input of the mesocosms was 6.06 ± 0.64 mg/L, while in effluents varied with respect to the type of treatment, reflected in the different removals of the compound. Ion removals tended to be statistically higher ($p > 0.05$) in the mesocosms with soil substrate including (54.0 ± 2.9 for *S. wallisii* and 51.2 ± 9.6 for *H. coronarium* units). Regardless of the type of vegetation, this is because the clay content of the soil provided a significant area of ion adsorption [3,30,31]. Soils with high clay content (this case), tend to fix more phosphorous than sandy soils having low clay content [32]. Minor removals were detected in the mesocosms with the same species, except where the substrate did not contain soil (33–36%). This was followed by removals in control units, where the importance of soil was also observed as adsorption media of the ion, and the average clearance in controls was reduced to 24.1% ± 3.5%, and 10.9% ± 4.1% in its absence. It can be noted that the detected ion concentration exceeded the limits set by the USEPA [29], which establishes a maximum of 0.05 mg/L ion in water bodies to prevent eutrophication problems. Although removals in the presence of vegetation were above 50%, these waters still require more treatment to reduce the toxic effects if this wastewater was discharged to other bodies of water, which can be solved by adding the surface wetlands or stabilizing gaps for hybrid wetlands with higher rates of removal. Several environmental factors influence the phosphorous removal in CWs, added to the adsorption, plant uptake of phosphorous is another mechanism of removal, this is related with the higher removals of the ion compared with the mesocosms without plants [32,33].

In the case of ammonium, an average concentration of 4.11 ± 1.08 mg/L was observed, while a range of ion concentrations in the outputs of 1.06 to 3.6 was recorded. The N-NH_4 was most poorly removed in control systems (<23%) as expected, since this form of nitrogen is preferably absorbed by vegetation, and whereas in the mesocosms control with no plants, this was only used by the microbial presence for nitrification. In units with plants the removal was greater than the controls, and differences between systems with different species planted were observed ($p = 0.042$); in systems with *H. coronarium*, the removal was greater than 70%, both in presence or absence of soil in the material layers, whereas cells with the presence of *S. wallisii* ion removals did not exceed 50%. The above was also reflected in the height of species (Figure 3). To see if this ion is within permissible limits, since in Mexico this parameter is not regulated, it was compared with data from the Taiwan Environmental Protection Agency, where they report that only 0.5 mg/L of the ion are permissible for protection of aquatic life [34], so more polishing is still required of wastewater by using only the treatment system of this study.

4. Conclusions

Using constructed wetlands to remove contaminants from water is a viable option. The use of ornamental plants: *H. coronarium* and *S. wallisii* are a viable option as well; although not being a typical plant of water saturated with high pollutant loads environments, they have shown in both functionality and the ease of adaptation of growth in the presence of wastewater to remove contaminants. According to the study, it was also found that adding a layer of soil in mesocosms enhanced removal of phosphates, and so its use should be replicated. Having CWs systems with ornamental vegetation is an option that could favor their use at home, community level and address problems of water discharges in institutions or companies. CWs with flower production fosters an aesthetic landscape and cooler environment. Therefore, it is suggested to apply these ecological alternatives in sites with discharges of wastewater and to avoid public health problems.

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