Nitrogen

Article

Removal of Nitrogen, Phosphates, and Chemical Oxygen Demand from Community Wastewater by Using Treatment Wetlands Planted with Ornamental Plants in Different Mineral Filter Media

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Abstract: This study aimed to explore the impact of various ornamental plants (*Heliconia psittacorum*, *Etlingera elatior*, *Spatyphilum walisii*) grown in different filter media (porous river rock (PR) and tepezyl (TZ)) on the removal of pollutants in vertical-subsurface-microcosm treatment wetlands (TWs). This study also sought to assess the adaptability of these plant species to TW conditions. Twenty-four microcosm systems were utilized, with twelve containing PR and twelve containing TZ as the filter media. Each porous media type had three units planted with each species, and three were left unplanted. Rural community wastewater was treated in the TWs. The results showed no significant differences in the effects of the porous media on pollutant removal performance ($p > 0.05$). However, it was noted that while both porous media were efficient, TZ, a residue of construction materials, is recommended for sites facing economic constraints. Additionally, the removal efficiency was found to be independent of the type of ornamental plant used ($p > 0.05$); however, the measured parameters varied with plant spp. The adaptation of the plants varied depending on the species. *H. psittacorum* grew faster and produced a larger number of flowers compared to the other species (20–22 cm). *S. wallisii* typically produced 7–8 flowers. *E. elatior* did not produce flowers, and some plants showed signs of slight disease and pests, with the leaves turning yellow. In terms of plant biomass, the type of porous media used did not have a significant effect on the production of above ($p = 0.111$) or below-ground biomass ($p = 0.092$). The removal percentages for COD in the presence and absence of plants were in the ranges of 64–77% and 27–27.7%, respectively. For TN, the numbers were 52–65% and 30–31.8%, and for N-NO_3, they were 54–60% and 12–18%. N-NH_4 saw removal rates of 67–71% and 28–33%, while P-PO_4 saw removal rates of 60–72% and 22–25%. The difference in removal percentages between microcosms with and without plants ranged from 30 to 50%, underscoring the importance of plants in the bio-removal processes (phytoremediation). These results reveal that incorporating ornamental plants in TWs with TZ for wastewater in rural areas holds great promise for enhancing the visual appeal of these systems and ultimately gaining public approval. Our findings also enable us to offer recommendations for selecting suitable plants and substrates, as well as designing combinations for TWs.

Keywords: phytoremediation; treatment wetlands; ornamental plants; bioremediation

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1. Introduction

Treatment wetlands (TWs) have been extensively researched worldwide for treating industrial [1–3], emerging [4–6], and municipal wastewater [7–11]. They are known for their simple construction and operation. TWs are considered efficient and cost-effective solutions for wastewater treatment. They consist of cells filled with porous filter media such as river rock, tezontle, zeolite, and plastic residues [12,13]. The efficiency of TWs is related to its components, such as the filter medium (substrate) and vegetation [14]. The presence of plants in TWs helps to clean the water of pollutants (absorbing/adsorbing some elements), maintain the water temperature, and avoid the resuspension of nutrients, and their roots release carbon exudates and oxygen (mainly in the rizhosphere zone) [15,16]. Several studies have reported that the main natural wetland plant species also used in TWs include *Phragmites* spp., *Typha* spp., and *Scirpus* spp. [16,17]. In recent decades, terrestrial ornamental plants have been tested for their adaptability to TW conditions and their ability to remove pollutants, offering an economical alternative for developing countries and making the system a multipurpose treatment solution.

In some areas of Mexico, various ornamental plant species have demonstrated their potential for phytoremediation in both monoculture [7,18,19] and polyculture [17,20,21] settings, showing removal rates ranging from 40 to 90% for organic and inorganic pollutants. Additionally, a study by Zurita et al. [22] found that ornamental plants (*Zantedeschia aethiopica*) grown in horizontal-flow subsurface TWs exhibit healthier growth and less stress compared to those planted in vertical-flow systems. However, research on chlorophyll fluorescence and chlorophyll content index in the ornamental plants *L. japonica* and *C. laevis* grown in both horizontal and vertical TWs suggests that these species are well adapted and thrive in vertical wetland systems [23]. These findings underscore the need for comprehensive studies into both the pollutant removal capabilities and stress responses of ornamental plants in TW systems, with particular attention paid to the specific plant species involved.

Some studies have demonstrated the phytoremediation potential of typical natural wetland plants in TWs [10,17]. However, in recent decades, the plants used in TWs have comprised ornamental vegetation because they possess several benefits, such as their aesthetic appearance, biodiversity enhancement, commercial value, and the removal of contaminants to avoid health problems. One study on the use of ornamental plants (*Canna hybrids*, *Anturium* spp.) for rural wastewater with TWs showed removal rates of 88%, 82%, and 52% for COD, phosphorus, and TN with *Canna hybrids*. When using *Anturium* spp., the removal rates were 87%, 84%, and 50% [12]. Another study compared the use of ornamental plants from tropical regions (*Canna hybrid*, *Alpinia purpurata*, and *Hedychium coronarium*) in TWs for wastewater treatment, detecting the removal of 63%, 78%, and 60% of nitrogen for each species, respectively. For phosphorous, the removal rates were 78%, 69%, and 68%, respectively [14]. Such studies have highlighted the effectiveness of the use of ornamental plants for wastewater treatment. However, knowing that the removal effect or behavior is dependent on the species, it is important to evaluate new species of ornamental plants in improving water quality and for the other benefits mentioned.

On the other hand, in treatment wetland design, the choice of filter media is crucial. Some TWs use expensive or uncommon materials like zeolite [18], maerl [24], wallostonite [25], cobbles [26], or rough plastic residues [12,21] as a substrate. However, in economically challenged rural areas, it is important to consider using local or reused materials to make the cost more affordable.

Given the above, this study's aims were to evaluate the effect of removing pollutants (nitrogen compounds, phosphates, and COD) from rural community wastewater by using different ornamental species (*Heliconia psittacorum*, *Etlingera elatior*, *Spatyphilum walisii*) planted in two different reused filter media (porous river rock and tepezil) in subsurface-flow TW microcosms.

2. Materials and Methods

2.1. Study Site and Design and Operation of TWs

This study was conducted in San José Pastorías, Actopan, Veracruz, Mexico (−96°57′08″ N and 19°55′83″ S) (552 inhabitants; [27]), a site with a tropical climate (947.1 mm annual precipitation and a temperature of 24.5 °C). In the treatment wetlands, three different ornamental plants were utilized: *Heliconia psittacorum* (P1), *Etlingera elatior* (P2), *and Spatyphilum walisii* (P3). These plants, each with a height ranging from 0.35 to 0.50 m, were gathered from riparian and creek zones near the study area. Two different types of porous media were tested: porous river rocks (PR: 50% porosity) and tepezil (TZ: 40% porosity), this latter is a sandy-like inert mineral with a fine porous structure that facilitates aeration and capillarity. The PR was collected from the riverine area of the local river (Topiltepec), while the TZ material was collected from residues from building materials. A layer of 8 cm with PR 10 cm in diameter was added to each of the TWs from the bottom to the top of the microcosms to prevent clogging. Furthermore, a layer of 36 cm containing the porous medium with an average diameter of 1.2 cm was also added. The water level was adjusted to 10 cm below the surface.

The wastewater was collected in a septic tank and then pumped into a 1.1 m^3 plastic tank, and a plastic mesh was put at the end of the hose before the tank to trap large suspended solids (first filter). Twenty-four microcosms of TWs were constructed (cylindrical plastic containers). The dimensions of each of the TWs were 0.36 m high and 0.30 m in diameter (Figure 1). Twelve microcosms were filled with PR, while the remaining twelve were filled with TZ as the porous media. Each set of microcosms in the respective porous filter media were labeled as follows (Three plants per TW)*:* *Heliconia psittacorum* (P1) A, B, and C; *Etlingera elatior* (P2) A, B, and C; *Spathiphyllum wallisii* A, B, and C; and control (unplanted) A, B, and C. In all the microcosms, the flow rate was adjusted to achieve a three-day hydraulic retention time (HRT) and a hydraulic loading retention rate (HLR; 4 cm d^{-1}) (depth of water per unit time) under subsurface down-flow wetland conditions. The inflow rate was maintained, measuring the flow every two days.

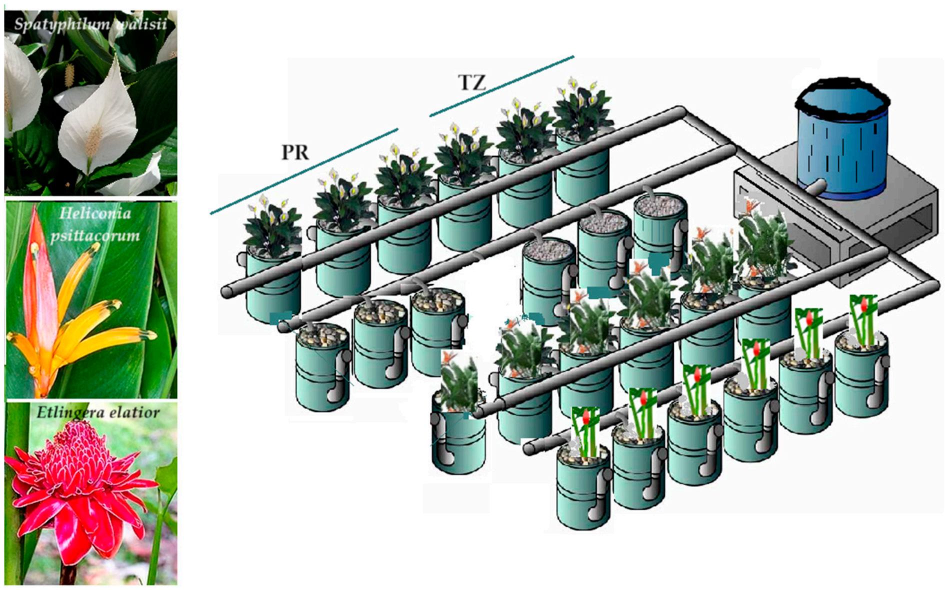

Figure 1. Scheme of the microcosm TWs under study. PR: TWs with porous river rock, TZ: TWs with tepezil.

2.2. Physical–Chemical Parameters and Plant Growth Measurement

The microcosms were analyzed over an 8-month period to assess their effectiveness in removing pollutants. The surveyed water quality parameters included chemical oxygen demand (COD), nitrates (NO_3-N), ammonium (NH_4-N), total nitrogen (TN), and phosphate (PO_4-P) levels. The analyses were conducted at 15-day intervals in accordance with the Standard Methods for COD [21], nitrogen compounds [28,29], and PO_4-P [30,31]. The removal of contaminants from the TWs was calculated according to Zhang et al. [28], with the formula: removal (%) = ((inflow concentration) − (outflow concentration)/inflow concentration) (100). For dissolved oxygen (DO), total solids (TS), electrical conductivity (EC), pH, and water temperature, these were analyzed with a YSI 550 multiparameter.

The height of each individual plant was measured every fifteen days using a tape measure. For the biomass production of the plants, three randomly selected plants of each species were harvested every 30 days. The plants were rinsed and separated (root and aerial biomass (stems and leaves)) and were dried at 40 °C to eliminate humidity until a constant weight was obtained [30].

For the growth characteristics of the stems and leaves, some criteria were reviewed every two weeks and labeled with "-, x, or xx": -, plant grew normally; x, upper leaves withered; xx, the leaves of the whole individual plant turned yellow. On the other hand, diseases and pests in the plants were also reviewed every two weeks: -, no diseases and pests; x, slightly diseased, with pests; xx, serious diseases and pests.

2.3. Statistical Analysis

All statistical analyses were conducted using SPSS 28 software for Windows. To analyze the significant differences in pollutants removal between plants and porous media, a two-factor factorial design in the statistical analysis section was used (two-way ANOVA) followed by LSD tests (at the $\alpha = 0.05$ level). The values are expressed as the mean ± standard error.

3. Results and Discussion

3.1. Physical and Chemical Characteristics of Water in the Influent and Effluent of the Microcosm Treatment Wetlands

The physical and chemical characteristics of the wastewater are presented in Tables 1 and 2. Observing Table 1, the pH in the influent and control samples fluctuated between 7.1 and 7.5. However, in the microcosms with plants, the pH levels decreased to a more neutral range of 6.5 to 7.2. Despite the inhibitory effect of influent pH on nitrification and partial denitrification, as noted by Msimbira and Smith [32], the presence of plants aids in lowering the pH through the release of certain substances from the roots. This environment-enabled biodegradation occurs across a wide pH spectrum. According to Cases and Lorenzo [33], the optimal pH range for biodegradation in most aquatic and terrestrial systems is between 6.5 and 8.5.

The dissolved oxygen (DO) levels here ranged from 1.3 to 4.6 mg L^{-1}. This parameter is crucial in influencing pollutant removal in TWs. Vegetation in the systems acts as a conduit for supplying oxygen to the wetland environment, thereby promoting the removal of contaminants [34].

In the microcosms, the water temperature ranged between 16.9 and 19.8 °C. Temperature stands out as the most crucial physical factor influencing the survival of microorganisms. Biological enzymes involved in the degradation process operate optimally at specific temperatures, leading to varying metabolic turnover rates at different temperature levels [35]. Akratos and Tsihrintzis [26] discovered that the ideal temperature range for the survival of microorganisms responsible for pollutant removal is between 15 and 30 °C, which aligns with the values observed in our study.

Electrical conductivity (EC) plays a significant role in the ability of plants and microbes to process waste material in TWs. In our research, the EC ranged from 1012.9 to 1233 µS/cm, which falls within the optimal range for a growth medium [26].

Table 1. Chemical and physical parameter concentrations in the influent and effluent of the microcosm wetlands in study.

Parameter	**Wetland Plants in Different Substrates**								
	Influent	***Heliconia psittacorum***		***Etlingera elatior***		***Spatyphilum wallisii***		**Control**	
		PR	**TZ**	**PR**	**TS**	**PR**	**TZ**	**PR**	**TZ**
pH (pH units)	7.5 ± 0.3	7.2 ± 0.4	7.1 ± 0.2	7.2 ± 0.1	7.2 ± 0.3	7.1 ± 0.6	6.5 ± 0.1	7.5 ± 0.3	7.4 ± 0.2
DO (mg L^{-1})	1.3 ± 0.4	4.1 ± 0.6	4.2 ± 0.9	3.9 ± 0.5	4.6 ± 0.3	4.2 ± 0.8	3.9 ± 0.7	1.7 ± 0.6	1.5 ± 0.4
Temperature (°C)	19.0 ± 0.6	19.2 ± 0.9	19.4 ± 1.2	18.9 ± 1.3	17.6 ± 0.9	16.9 ± 1.2	18.4 ± 0.3	19.1 ± 0.4	19.8 ± 0.7
EC (µS/cm)	1151 ± 143	1150 ± 099	1209 ± 102	1124 ± 161	1233 ± 52	1124.2 ± 98	1130.8 ± 110	1126 ± 130	1012.9 ± 64

Values are given as the average ± standard error (n = 72). PR: microcosms with porous river rock, TZ: microcosms with tepezil.

Table 2. Water quality parameters in the influent and effluent, and mean removal percentages in the microcosms.

Parameter	**Wetland Plants in Different Substrates**							
	Heliconia psittacorum		***Etlingera elatior***		***Spatyphilum wallisii***		**Control**	
	PR	**TZ**	**PR**	**TZ**	**PR**	**TZ**	**PR**	**TZ**
COD								
Influent concentration (mg L^{-1})	299.2 ± 35.6							
Effluent concentration (mg L^{-1})	83.6 ± 19.2	82.1 ± 18.1	83.1 ± 16.6	81.9 ± 11.4	96.7 ± 15.4	106.2 ± 24.6	218.3 ± 21.3	216.3 ± 21.1
Removal (%)	72.1 ± 21.1 ^{a}	72.3 ± 12.8 ^{a}	72.6 ± 14.3 ^{a}	72.6 ± 14.3 ^{a}	67.7 ± 11.9 ^{b}	64.5 ± 10.9 ^{b}	27.0 ± 11.1 ^{c}	27.7 ± 19.4 ^{c}
NT								
Influent concentration (mg L^{-1})	65.4 ± 14.3							
Effluent concentration (mg L^{-1})	30.9 ± 05.1	22.6 ± 14.3	23.6 ± 11.6	23.9 ± 11.4	29.5 ± 09.1	28.6 ± 11.7	44.6 ± 11.4	45.8 ± 13.2
Removal (%)	52.8 ± 16.3 ^{a}	65.4 ± 13.1 ^{a}	63.9 ± 16.3 ^{a}	63.5 ± 11.3 ^{a}	54.9 ± 17.3 ^{b}	56.3 ± 16.1 ^{b}	31.8 ± 11.7 ^{c}	30.0 ± 11.8 ^{c}
NO_3-N								
Influent concentration (mg L^{-1})	6.48 ± 1.36							
Effluent concentration (mg L^{-1})	2.96 ± 0.92	2.76 ± 0.14	2.26 ± 0.16	2.62 ± 0.99	2.36 ± 0.82	2.84 ± 0.99	5.65 ± 0.65	5.32 ± 0.19
Removal (%)	54.3 ± 13.2 ^{a}	57.4 ± 3.6 ^{a}	59.6 ± 13.1 ^{a}	59.6 ± 10.8 ^{a}	63.6 ± 11.2 ^{b}	56.2 ± 11.3 ^{b}	12.8 ± 3.9 ^{c}	17.9 ± 6.3 ^{c}
NH_4-N								
Influent concentration (mg L^{-1})	4.01 ± 0.82							
Effluent concentration (mg L^{-1})	1.14 ± 0.22	1.32 ± 0.62	1.3 ± 0.32	1.13 ± 0.42	1.32 ± 0.11	1.21 ± 0.16	2.86 ± 0.71	2.69 ± 0.45
Removal (%)	71.6 ± 13.6 ^{a}	67.1 ± 09.2 ^{a}	67.6 ± 14.2 ^{a}	71.8 ± 11.3 ^{a}	67.1 ± 16.6 ^{b}	69.8 ± 13.1 ^{b}	28.7 ± 2.9 ^{c}	32.9 ± 02.1 ^{c}
PO_4-P								
Influent concentration (mg L^{-1})	10.6 ± 1.3							
Effluent concentration (mg L^{-1})	4.20 ± 0.36	4.11 ± 0.14	3.01 ± 0.33	3.15 ± 0.72	4.01 ± 0.97	4.11 ± 0.32	8.26 ± 0.32	7.92 ± 0.36
Removal (%)	60.4 ± 3.9 ^{a}	61.2 ± 3.6 ^{a}	71.6 ± 3.2 ^{a}	70.3 ± 3.4 ^{a}	62.2 ± 3.6 ^{b}	61.2 ± 6.9 ^{b}	22.1 ± 3.8 ^{c}	25.3 ± 3.6 ^{c}

Values are average ± standard error; different letters indicate significant differences between the columns at a 5% significance level. PR: microcosms with porous river rock, TZ: microcosms with tepezil.

3.2. Pollutant Removal in Treatment Wetlands

Table 2 summarizes the influent and effluent concentrations, as well as the percentage removal for COD, TN, NO_3-N, NH_4-N, and PO_4-P. The average influent concentrations for the physical–chemical parameters were 299.2 ± 35.6 mg/L for COD, 65.4 ± 14.3 mg/L for TN, 6.48 ± 1.36 mg/L for NO_3-N, 4.01 ± 0.82 mg/L for NH_4-N, and 10.6 ± 1.3 mg/L for PO_4-P.

The removal percentages ranged from 64 to 77% and 27 to 27.7% for COD with and without vegetation, respectively. There were not significant differences in the COD removals between different filter media or plants ($p \geq 0.05$). However, significant differences were observed between plants and unplanted systems ($p \leq 0.05$). The range of decontamination detected was similar to that reported by Shukla et al. [36], where they performed a study using three setups of TWs (unplanted, planted in monoculture (*Typha latifolia*), and planted in polyculture (*Typha latifolia* + *Commelina benghalensis*)). The polyculture system was the best performer, removing 77%, while in the monoculture and unplanted TWs, the removals oscillated between 53 and 58%.

In a study from Portugal, in which *Phragmites australis* planted in TWs was used, the removal efficiencies of COD were 65–93% [37]. It is worth mentioning that in these studies, common plants from natural wetlands were used, while in our study, only ornamental vegetation was used, showing similar water cleaning effects and indicating the opportunity to use ornamental vegetation (*Heliconia psittacorum*, *Etlingera elatior*, *Spathiphyllum wallisii*) as phytoremediators. In these contexts, some authors have argued that the ornamental plants they used helped to improve the landscape and that these species are not intended for animal and human consumption. This avoids the introduction of pollutants into the food web in addition to improving the environment with their aesthetic value [38,39].

Similarly, the removal percentages for TN ranged from 52 to 65% and 30 to 31.8% in the presence and absence of vegetation, respectively. Notably, for NO_3-N, the removal percentages were between 54 and 60% in the presence of plants, while in their absence, the removal percentages were only between 12 and 18%. The results showed similar trends in removal rates for NH_4-N, with percentages ranging from 67 to 71% in microcosms with plants, and from 28 to 33% in systems without plants. There were not significant differences in the nitrogen removal between different filter media or plants ($p \geq 0.05$). However, significant differences were observed between plants and unplanted systems for all three of the nitrogen forms measured ($p \leq 0.05$). In TWs, the removal of nitrogen compounds via the denitrification process may remove from 60 to 70% of the total removal nitrogen and from 20 to 30% of that which is derived from plant uptake [40–42], which is similar to the values detected in this investigation. On the other hand, in TWs, it is common that nitrogen compounds are removed at lower levels than other parameters; however, the removals observed using ornamental plants showed a similar trend in systems using natural wetland plants. For example, in TWs planted with *Juncus effusus* in Germany, removals of 45–75% were observed for nitrogen compounds (NH_4-N, NO_3-N, TN) [43]. Further investigation into other nitrogen removal routes in TWs, such as partial nitrification–denitrification, anammox, dissimilatory nitrate reduction, and the Canon process, is necessary to fully understand the landscape of nitrogen removal, as described by Mitsch et al. [44].

As for PO_4-P, the removal rates ranged from 60 to 72% in plant-containing systems and from 22 to 25% in systems without plants. Significant differences were observed between plants and unplanted systems ($p \leq 0.05$). However, interestingly, porous media did not significantly affect pollutant removal ($p \geq 0.05$), indicating that both filter materials were equally effective. The PR materials were sourced from rivers, while the TZ materials were construction residues, demonstrating a sustainable and economically advantageous reuse of resources. The substrates typically used in TWs consist of gravel and sand, but these materials are costly, ranging from 10 to 35 USD/m^3 [9]. The materials analyzed in this study could be an alternative for sites facing economic challenges. According to Dell'Osbel [45], using a bibliometric analysis, porous media is an important component for phosphorous removal, and many advances have been observed using materials from natural or artificial origins such as construction waste, helping contribute to a circular economy and to the balanced use of natural resources. It is important to highlight that the observed phosphate removals are similar to those reported in studies that do not use ornamental plants [34,46], demonstrating the usefulness of these species, which have other social and economic added value [47].

The observed differences in pollutant removal between microcosms with and without plants ranged from 30% to 50%, underscoring the crucial role of plants in the bioremediation process (phytoremediation) in conjunction with microbial activity. Plants are essential for introducing the physical processes necessary to remove and retain pollutants and to facilitate nutrient cycling [48–50]. Given these findings, it is imperative to foster collaboration between scientists, governments, and local communities to promote the use of phytoremediation in TWs to address wastewater issues. The combined wetlands (TWs) containing different species did not exhibit statistically significant differences (p = 0.278) in terms of pollutant removal for any of the assessed parameters. These characteristics could be taken into consideration for the development of new TW designs.

The positive impact of pollutant removal by plants is consistent with the findings of Jethwa and Bajpai [51], who noted that planted TWs perform better than unplanted controls, mainly due to the rhizosphere's role as a zone for microbial community attachment; as a surface for bacteria, gas, and carbon release; and for the creation of aerobic niches, the prevention of nutrient re-suspension, and the promotion of aerobic degradation. Nitrogen and phosphorous compounds are essential macronutrients for plants and microorganisms. Therefore, a certain amount of N and P is expected to be utilized for biomass synthesis, leading to higher removal in microcosms with plants compared to unplanted systems. Excessive nitrogen compound presence poses a significant threat to water quality, with adverse impacts on ecosystems and human health [52,53]. Mesquita et al. [54] indicated that the removal efficiencies of phosphorus compounds in TWs are marked by seasonality. However, the TWs in this study showed significant removal of such parameters. In addition, TWs for wastewater treatment represent a technological alternative for treating wastewater in rural areas with a mediterranean climate, as highlighted by Vera-Puerto et al. [55] in Chile and as detected for tropical regions in this study.

3.3. Plant Height and Biomass Changes

Figure 2 illustrates the changes in the heights of individual plants. *H. psittacorum* exhibited greater growth compared to the other species in both types of filter media. Its maximum heights were 80 cm and 84 cm in the PR and TZ filters, respectively, with a growth of almost 1 m during the study period. *E. elatior* showed smaller height increments than *H. psittacorum* in both filters, reaching maximum heights of 51 cm and 66 cm in the PR and TZ substrates, respectively, almost tripling in size during the study period. On the other hand, the *S. wallisii* plants only grew 30–35 cm in both filter media. Overall, the adaptation of plants to TW conditions was positive, indicating that the wetland conditions did not negatively impact their survival.

This makes them suitable for use as ornamental plants in TWs, with variations in adaptability depending on the species.

Our physical observations of the vegetation during the study considered the wilting degree, growth of stems and leaves, presence of diseases and pests, and flower production (refer to Table 3). Among the plants observed, *H. psittacorum* and *S. wallisii* displayed no symptoms and were considered the healthiest, whereas *E. elatior* exhibited some yellow leaves and was affected by pests and diseases during the initial four-week period, impacting its flower production. The order of flower production among the species was as follows: *H. psittacorum* > *S. wallisii* > *E. elatior.* Additionally, the reduced flower production in *S. wallisii* was associated with direct sun exposure, as these species are better adapted to shaded areas [56]. It is worth noting that the adaptation of *S. wallisii* in TW conditions presents an opportunity to promote nature-based solutions for wastewater treatment. This could involve creating an attractive landscape using ornamental flowers in backyard TWs or in larger areas for plant production and sale as living specimens for interior design. In tropical regions with temperatures ranging between 20 and 32 °C, Conover [57] recommended *Spathiphyllum* production, and we are considering the use of shade mesh over the TWs for optimal growth. *E. elatior*, on the other hand, typically thrives in wet soils with ample space for development, with elongated leafy stems reaching heights of up to 5 m arising from underground rhizomes [58]. It is possible that the conditions in the microcosms did not allow for quick adaptation. Lastly, the abundant flower production and long vase life reported by [59,60] for *H. psittacorum*, along with the colors of their bracts, are important considerations for their use in TWs, providing an aesthetic advantage in the system.

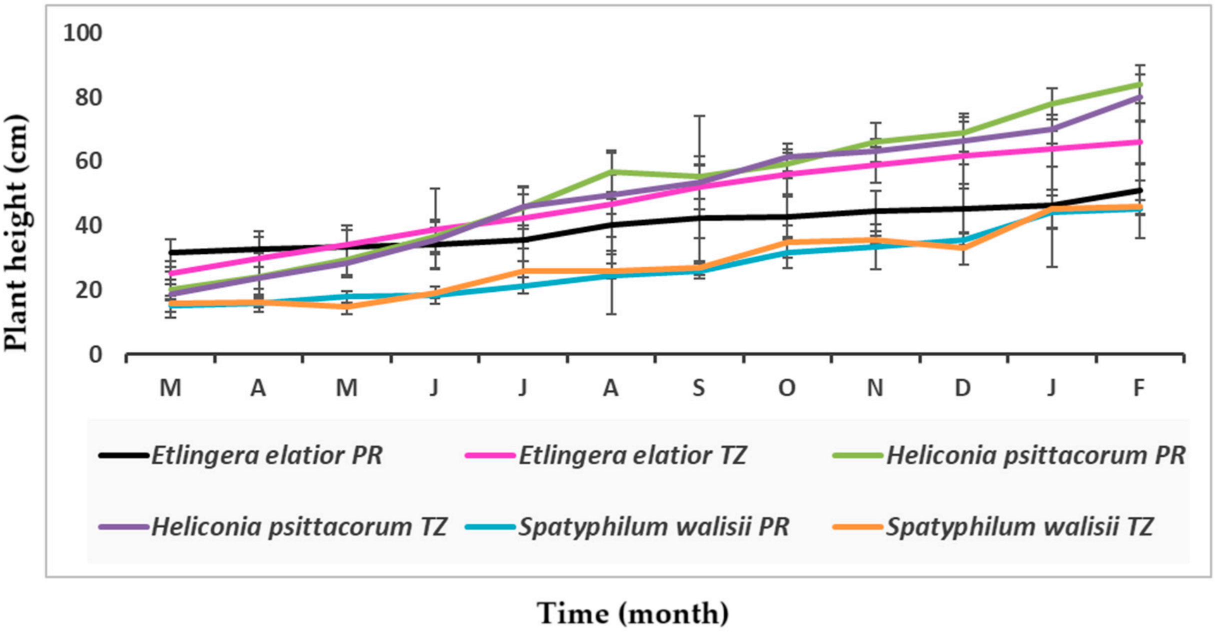

Figure 2. Individual plant height over time.

Table 3. Growth characteristics of plants.

Plant	Filter Media	Wilting Degree (Number of Plants)	Growth Characteristics Stems–Leaves–Flowers [a]	Diseases and Pests [b]	Number of Flowers during the Study
Heliconia psittacorum	PR	0	-	-	20
	TZ	0	-	-	22
Etlingera elatior	PR	2	XX	X	0
	TZ	2	XX	X	0
Spatiphylum wallisii	PR	0	-	-	8
	TZ	0	-	-	7

[a] Growth characteristics of stems and leaves: –, plant grew normally; x, upper leaves withered; xx, the leaves of the whole individual plant turned yellow. [b] Diseases and pests: –, no diseases or pests; X, slightly diseased, with pests; XX, serious diseases and pests.

In terms of plant biomass, the porous media material did not significantly affect the above or below-ground biomass production ($p = 0.111$, 0.092; Figure 3). However, there was a significant difference in biomass between different plants ($p = 0.018$). Specifically, *E. elatior* and *H. psittacorum* showed higher quantities of aerial and below-ground biomass productivity compared to *S. wallisii*, as seen in the plant height observations in Figure 2. These findings did not show implications for pollutant removal within the scope of this study. Both characteristics are important considerations when selecting plants for TWs [61,62]. In sum, incorporating various ornamental plants in TWs can enhance the aesthetic appeal of the system and offer an alternative for sustainable wastewater treatment gardens. The biomass vegetation used in this study was higher than biomass plants observed in a study with TWs treating swine wastewater using *Canna hybrids* (ornamental plant) and *Typha latifolia* (conventional wetland plant) [63].

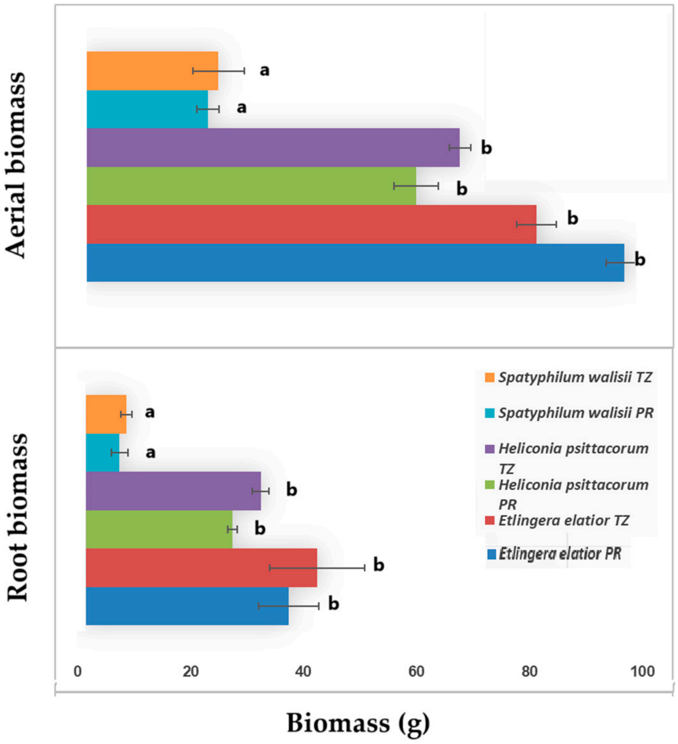

Figure 3. Effect of substrate media and plants on the biomass production of different ornamental vegetation. Values are average ± standard error. Different letters indicate significant differences ($p < 0.05$).

4. Conclusions

The findings of this study suggest that the use of *Heliconia psittacorum*, *Etlingera elatior*, and *Spatyphilum wallisii* should be implemented as vegetation in treatment wetlands in the two different filter media used (PR or TZ), with removal efficiencies of 54–60% for NO_3-N, 54–65% for TN, 61–72% for PO_4-P, 64–72% for COD, and 67–72% for NH_4-N, and removals of up to more than twice-higher than systems without plants (13–33%). Thus, this study revealed the phytoremediation process of the ornamental plants. It also highlighted the potential for producing ornamental flowers with commercial value, mainly *Heliconia psittacorum* and *Spatyphilum wallisii*; the use of these plants in TWs converts this technology into an alternative economically viable, aesthetically pleasing, and ecologically friendly option for the cleaning of wastewater in both urban and rural communities. Additionally, this study suggests that tepezil and porous river rock are both suitable materials for pollutant removal in treatment wetlands, as well as for supporting plant growth. However, TZ can be used as a reused substrate in these systems, making its eco-technology cheaper compared to other mineral materials. These economic considerations indicate that this is a more sustainable alternative for the treatment of wastewater. Thus, the use of TWs with TZ, *Heliconia psittacorum*, and *Spatyphilum wallisii* is suggested for the design of future treatment wetlands. Additionally, this study highlights the need for further research in tropical regions with ornamental plants in TWs on a large scale to validate their commercial use and removal efficiency in the long term. These results may have implications for wastewater issues in Mexico. They also provide a series of suggestions for plant and substrate selection, as well as a combination of designs for treatment wetlands.

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