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Effect of Different Biomass Levels of *Eichhornia crassipes* and *Pistia stratiotes* on Nutrients, Organics, and Heavy Metals Removal from Wastewater

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ABSTRACT: This study investigates the impact of varying biomass levels of *Eichhornia crassipes* (water hyacinth) and *Pistia stratiotes* (water lettuce) on the removal efficiency of nutrients, organic matter, and selected heavy metals from paint industry wastewater. The experiment was conducted using different biomass quantities of the aquatic plants to evaluate their phytoremediation capabilities. Changes in physicochemical parameters, nutrients, organic pollutants, and selected heavy metals were monitored over a 14-day period. At the end of week 1, water lettuce (WL) achieved removal efficiencies of 37.16%, 62.94%, and 38.47% for NO_3^-, PO_4^{3-}, and NH_3, respectively. Water hyacinth (WH) achieved removal efficiencies of 45.18%, 61.07%, and 45.86% for NO_3^-, PO_4^{3-}, and NH_3, respectively. Similarly, both plants significantly removed heavy metals, with WH achieving average removal efficiencies of 95.91%, 90.88%, and 67.68% for Cr, Pb, and Cu, respectively. WL achieved the highest average removal efficiencies of 90% and 88.9% for Zn and Cu, respectively. A statistically significant difference was observed among the biomass level treatments and heavy metal removal efficiencies ($p < 0.05$). The results indicate that both species effectively reduced nutrient, organic pollutant, and heavy metal concentrations, with higher biomass levels showing greater removal efficiencies. WH exhibited slightly better performance in removing all evaluated parameters in the wastewater treatment compared to WL. This study highlights the potential of these aquatic plants for phytoremediation applications in wastewater treatment systems. Optimization of biomass levels and operational conditions could enhance removal efficiencies and make the process more sustainable.

KEYWORDS: Water hyacinth; water lettuce; biomass quantities; paint industry; phytoremediation

1. Introduction

Water pollution is a growing concern worldwide, an environmental issue that significantly affects the health and well-being of both humans and ecosystems. In developing countries like

Nigeria, industrialization has continued to increase pollution levels. Pollution in water bodies indicates the presence of chemical substances, organisms, and pathogens. These pollutants are introduced into surface water or groundwater through natural or anthropogenic activities, influencing the physical, chemical, and biological composition [1]. A common practice is the discharge of industrial effluents, both treated and untreated, into water bodies and lands. Untreated effluents discharged into the environment negatively impact ecosystems due to the presence of pollutants, whether organic or inorganic. The type of pollutant, its properties and chemical composition, and the level of contamination depend on the source of the industrial wastewater [2].

Manufacturing industries, such as textile, pharmaceutical, and paint industries, which use large volumes of water and chemical reagents, produce heavily polluted effluents. The paint industry is one of many industries that generate wastewater laden with heavy metals due to the components of paint [3]. Additionally, this industry is known to produce a large volume of effluent containing various pollutants, including residual acids, toxic chemicals, high chemical oxygen demand, and turbidity [4, 5]. Volatile organic compounds, pigments, resins, surfactants, and solvents are all organic components present in wastewater from the paint industry [6]. Releasing untreated paint effluent into the environment poses significant threats to ecosystems.

In developing and under-developed countries, paint industries often discharge their wastewater directly into streams and onto land [3]. Direct discharge into water bodies depletes oxygen levels, causes eutrophication, and results in the accumulation of toxic pollutants in aquatic organisms [7]. In Nigeria, the growing demand for paint is driven by an increasing population, urban expansion, and heightened construction activity, which collectively contribute to a rise in wastewater from the paint industry. While data on the annual volume of wastewater generated by the paint industry in the country remain limited, many paint factories release their wastewater into water bodies untreated or only partially treated. Consequently, treating wastewater before its release into the environment becomes essential.

Various wastewater treatment technologies have been developed to mitigate the impact of effluent discharge from paint industries on the environment. These treatments include physical, chemical, and biological methods, tailored to address different contaminants in the effluents. However, limitations such as high costs, low efficiency, and hazardous by-products characterize these treatment methods [8, 9]. Hazardous by-products, such as heavy metals, trace chemicals, and other inorganic solids, can be further treated using an eco-friendly and cost-effective method known as phytoremediation. This method can also be adopted for the cleanup of moderately contaminated media, providing an effective and low-cost solution.

Phytoremediation is a green technology that uses plants to remove pollutants from water, providing a sustainable and cost-effective solution for wastewater treatment [10]. It is a viable method that takes advantage of the natural ability of some plants to remove, accumulate, contain, and degrade organic and inorganic pollutants from contaminated media [11, 12]. Among the plants commonly used for phytoremediation are *Eichhornia crassipes* (Water hyacinth) and *Pistia stratiotes* (Water lettuce). These plants have been proven to be effective in the phytoremediation of polluted media because of their high nutrient uptake efficiency [13, 14, 15, 16]. The plants behave differently in various industries' wastewaters depending on the wastewater's physical and chemical composition.

WH and WL are floating aquatic plants characterized by rapid growth, the ability to reproduce vegetatively, and the capacity to multiply quickly [17]. Their high affinity for heavy metals (cations) and nutrients (anions), combined with rapid growth, high biomass production, and adaptability to polluted environments, makes both plants excellent choices over other phytoremediation plants. While other phytoremediation plants can only survive in less-contaminated environments, the tolerance levels of these two macrophytes allow them to thrive and perform effectively in highly contaminated water [17].

Several academic researchers have studied the phytoremediation potential of WH and WL for removing contaminants from wastewater. Their performances and efficiencies have also been compared with those of other aquatic plants. For example, phytoremediation of emulsion paint wastewater was carried out using *Azolla pinnata*, *Eichhornia crassipes*, and *Lemna minor* [18]. The results showed that the three plants effectively reduced total dissolved solids, dissolved oxygen, chemical oxygen demand, biological oxygen demand, and heavy metals. *A. pinnata* was reported to perform better than *E. crassipes* and *L. minor*. Similarly, *E. crassipes*, *L. minor*, and *P. stratiotes* were used to reduce phosphorus and COD within 15 days. Among them, *P. stratiotes* performed better than *E. crassipes* and *S. molesta* [19]. Furthermore, *P. stratiotes* was employed to eliminate physicochemical pollutants from paper mill effluent [20].

While *E. crassipes* and *P. stratiotes* have proven to be effective in treating wastewaters, the comparative assessment of their performance for nutrient and heavy metal removal from paint industry effluent under varying mass levels has not been reported. In this study, phytoremediation conditions were optimized by varying the mass of plants immersed in the paint industry wastewater using a two-way factorial design. This study aimed to further advance the field of phytoremediation by understanding how plant mass impacts pollutant removal. It provides insights into more effective and scalable system designs for industries with complex pollutant effluents, such as paint manufacturing.

However, the differences in the chemical properties of the plants within each mass group were not considered during the experiment. Pollutant concentrations in the effluent and the overall mass of the plants were prioritized over plant-specific characteristics or chemical properties. The assumption of homogeneity in the chemical characteristics of plants of similar size and age formed the basis for plant selection and mass grouping. Each plant group consisted of plants with similar size, age, and mass.

2. Materials and Methods

2.1. Sampling.

Wastewater was obtained from a paint industry (name withheld) located at Orita Obele, Akure, in Akure South Local Government Area of Ondo State, Nigeria. The wastewater was collected in two thoroughly washed 28-liter high-density polyethylene plastic containers. The containers were tightly sealed to prevent leakage and transported to the laboratory for chemical and heavy metal analyses prior to the experiment. The short distance between the effluent collection point and the experimental site helped prevent exposure to external contaminants. A portable multiparameter water analyzer was used to measure the physicochemical parameters of the wastewater both at the point of collection and at the experimental site. No significant changes were observed between the two measurements. WH and WL were collected from Igbokoda, in

Ilaje Local Government Area of Ondo State, Nigeria (latitude 6.350828 and longitude 4.806531). The plants were transported in pre-cleaned plastic bowls along with their underlay water to the experimental site. Before the experiment, the plants were acclimatized to new environmental conditions by storing them in a concrete pond with well-water for seven days. After acclimatization, WH and WL of similar maturity and size range were collected from the pond. The collected macrophytes were rinsed thoroughly with tap water to remove aggregate particles, allowed to drip off, weighed, and cultured in the wastewater..

2.2. Experiment set-up.

The experiment was conducted in an open shade at the Department of Civil and Environmental Engineering, Federal University of Technology Akure, Nigeria, under naturally controlled environmental conditions. Rainfall, pests, and other human activities were completely avoided. No artificial modifications were made to natural factors such as ambient temperature, humidity, and light; direct sunlight was only reduced by the shade. A completely randomized design was adopted for the experiment, utilizing a hydroponic system of phytoremediation to ensure controlled water quality and consistent contaminant exposure across plant samples. Paint effluent was batched into plastic containers, with 3.5 liters of wastewater per container. The experiment was conducted in replicates, using three biomass levels: 100 g (small), 120 g (medium), and 150 g (large) of WH and WL, respectively. These biomass categories facilitated an assessment of pollutant uptake efficiency and the scalability of the phytoremediation process. Pre-weighed WH samples (WH1: 100 g, WH2: 120 g, WH3: 150 g) and WL samples (WL1: 100 g, WL2: 120 g, WL3: 150 g) were each submerged in 3.5 liters of paint effluent. A total of 12 hydroponic systems were set up (six for each plant species) and maintained for 14 days, with sampling conducted at 7-day intervals.

2.3. Laboratory analysis.

Initial wastewater quality was analyzed for parameters such as the pH, total dissolved solids (TDS), total suspended solids (TSS), Nitrate (NO_3^-), Phosphate (PO_4^{3-}), Ammonia (NH_3), biological oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), and heavy metals concentrations. Heavy metals (HMs) investigated in this study are Cadmium (Cd), Chromium (Cr), Copper (Cu), Lead (Pb), and Zinc (Zn). The focused HMs were selected based on their common presence in paints [2, 3, 18, 21, 22]. Subsequently, water samples collected from each phytoremediation set-up at the interval of seven days were analyzed for all the parameters. Pre-calibrated handheld multiparameter water analyzer (Hannah 9828) was used to measure the physicochemical parameters (pH, TSS, TDS). US EPA 600/4-79-020 methods of chemical analysis of water and wastes was adopted in the laboratory analysis of samples for target parameters. Jenway 6400 ultraviolet/visible spectrophotometer was used to determine the nutrients, NO_3^-, PO_4^{3-}, and NH_3, levels in the samples at absorbances of 880, 420, and 640 nm, respectively. Elemental analysis via atomic absorption spectrophotometer (AAS model 211 VGP buck scientific) was used to determine HMs concentration in samples after digestion with nitric acid. Different concentrations of standard solutions were used to prepare the calibration curves for the HMs determination at specified wavelengths. The analyses were carried out at the Chemical Oceanography Laboratory, Department of Marine Science and Technology, Federal University of Technology Akure, Nigeria.

2.4. Data collection and statistical analysis.

Differences between the initial and final concentrations of the target parameters at the end of the experiment were used to estimate the removal efficiencies (REs). Removal efficiency (RE), expressed as a percentage, indicates the uptake of the selected parameters (nutrients and heavy metals) by the plants and was calculated using the following formula [17, 23]:

$$\mathrm{RE} = \frac{(\text{Initial concentration} - \text{Final concentration})}{\text{Initial concentration}} \text{x } 100 \qquad (1)$$

In addition, heavy metal REs were correlated with macrophyte species and plant biomass. Statistical significance was analyzed using Microsoft Office 365 Excel's two-way ANOVA, with a significance level set at 0.05. Morphological variations in the macrophytes during the treatment period were also observed. These variations provided critical insights into the plants' tolerance to pollutants, overall performance, adaptability, and survival in the toxic solution.

2.5. Quality control/quality assurance.

Water samples were analyzed in duplicates, and the average values were recorded as the results. If duplicate measurements showed a wide variation exceeding the acceptable threshold of 10% specified by the standard method used, the analysis was repeated. Only analytical-grade reagents were used throughout the experiment, and standard analytical methods were adopted. Certified reference materials were utilized to validate the accuracy of measurements and estimates.

3. Results and Discussion

3.1. Treatment effect on pH, TDS, and TSS.

The initial status of the paint industry wastewater and the final concentrations of the studied parameters after phytoremediation are presented in Table 1 for each plant species and biomass level. The influence of plant biomass and species on the removal of nutrients, organic pollutants, and heavy metals can be observed from the results. Figures 1 illustrate the effects of the plant treatments on pH, TDS, and TSS.

Table 1. Physico-chemical properties and heavy metal content in paint effluent before and after treatment.

Parameters	BP[1]	AP[2] for WH			AP for WL		
		WH1	WH2	WH3	WL1	WL2	WL3
pH	8.180	6.210	6.320	6.150	6.270	6.100	5.970
TDS (mg/L)	3020	1847	1806	1929	2176	2166	2101
TSS (mg/L)	5.600	2.775	3.975	3.215	3.200	2.540	4.000
NO^{3-} (mg/L)	14.25	19.17	20.97	24.36	14.66	16.65	10.77
PO_4^{3-} (mg/L)	0.240	0.156	0.167	0.093	0.095	0.084	0.097
NH_3 (mg/L)	4.611	6.120	6.767	7.907	4.947	5.053	3.279
Cr (mg/L)	1.424	0.075	0.050	0.050	0.163	0.131	0.127
Cu (mg/L)	0.570	0.141	0.036	0.053	0.104	0.063	0.023
Cd (mg/L)	0.066	0.044	0.018	0.003	0.036	0.034	0.015
Pb (mg/L)	0.095	0.0155	0.0075	0.003	0.0395	0.036	0.032
Zn (mg/L)	1.223	0.3585	0.3145	0.235	0.150	0.128	0.089
DO (mg/L)	9.380	5.430	5.957	6.125	7.070	6.850	7.240
BOD (mg/L)	15.21	27.93	23.39	18.23	40.68	39.09	44.80
COD (mg/L)	108.0	112.0	110.1	102.8	151.7	146.9	162.0

[1]BP status quo values before phytoremediation. [2]AP values after phytoremediation

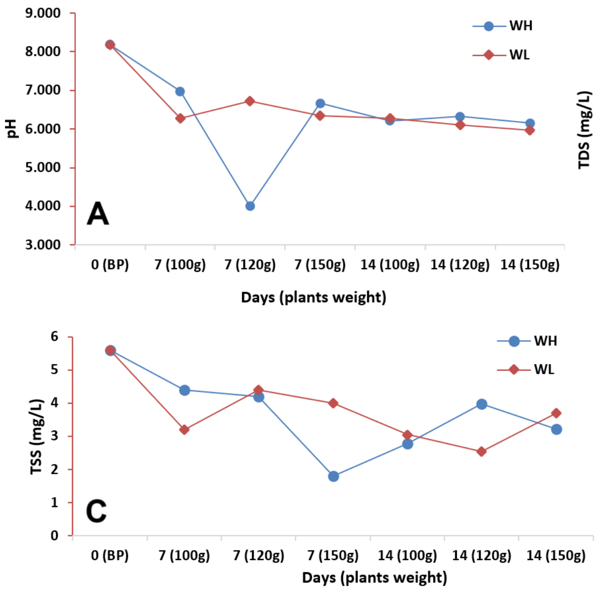

Figure 1. Effect of plants treatment on pH of the effluent (A), total dissolved solid of the effluent (B), and total suspended solid of the effluent (C).

The initial pH of the effluent was 8.18 (basic). Post-remediation values in Table 1 show a decrease in pH across all treatments. Higher plant biomass exhibited the greatest reduction in pH, with WL3 (150 g) achieving the highest reduction efficiency of 27.02%. Similar results were recorded by [20], where WL effectively reduced pH while treating paper mill effluent. For both plants, the higher the biomass, the greater the reduction in pH. The shift from basic to acidic pH during phytoremediation could be attributed to plant root decomposition, which releases carbon dioxide and organic acids into the effluent [24].

A reduction in TDS was observed; however, no consistent trend was noted for WH. In contrast, WL exhibited a clear trend, with higher biomass levels correlating with greater TDS reduction. By day 7, both plants achieved higher TDS removal efficiencies than by day 14, likely due to the accumulation of dead leaves from yellowing and wilting plants, which elevated TDS levels after day 7. WH achieved an average TDS removal efficiency of 38.39% across biomass levels, compared to 28.90% for WL. This aligns with findings by [25], where both WH and WL demonstrated significant TDS removal when used to treat various wastewaters. Factors such as contaminant removal, water uptake, and macrophyte exudation characteristics influenced TDS levels in the effluent.

The concentration of total suspended solids (TSS) dropped after treatment, from an initial value of 5.6 mg/L to final values of 2.775, 3.975, and 3.215 mg/L for WH1, WH2, and WH3, respectively. Similarly, WL1, WL2, and WL3 achieved final values of 3.2, 2.54, and 4.0 mg/L, with reduction efficiencies (REs) of 42.86%, 54.64%, and 28.57%, respectively. The highest TSS reduction efficiency was observed with WL2. The decrease in TSS can be attributed to the plants' high affinity for nutrient uptake and contaminant removal [26, 27]. Organic matter and nutrients adhered to or were absorbed by plant roots, further reducing TSS.

Effective pH control is critical in wastewater treatment, particularly for complex effluents like those from paint manufacturing. After phytoremediation, the effluent pH ranged from 5.97 to 6.32 across all biomass levels, aligning with the optimal range for E. crassipes and P. stratiotes growth and efficient pollutant uptake [28, 29]. Adjusting plant density and introducing multiple species can optimize nutrient and pollutant uptake for large-scale operations. Additionally, increasing hydraulic retention time can enhance TSS reduction efficiency by providing more time for plants and associated microorganisms to interact with the wastewater.

3.2. Treatment effects on BOD, COD, and DO.

BOD and COD were measured only at the beginning and end of the experiment. A significant reduction in dissolved oxygen (DO) was observed over the 14-day period, accompanied by an increase in BOD and COD. Higher biomass levels resulted in lower DO reduction efficiencies. The highest DO reduction, 42.1%, was achieved with WH, close to the 50% reduction observed by [19]. The decrease in DO suggests that more oxygen was consumed during the breakdown of organic matter introduced by the plants. As DO levels decreased, aerobic degradation slowed, leading to the accumulation of organic material. In contrast, [30] observed an increase in DO when WL was used to treat various eutrophic water samples. In this study, a 100% survival rate of the plants was recorded at the end of the experiment, with no visible signs of toxicity. However, in highly contaminated effluents such as paint wastewater, nutrient balance is essential for plant survival and effectiveness. The plants in this study could not survive beyond 14 days. Diluting the effluent with clean water could improve plant survival and optimize phytoremediation performance.

COD levels increased in all setups except for WH3, which showed a marginal removal efficiency of 4.8%. WL treatments with higher biomass recorded greater increases in COD concentrations. The slight COD reduction in WH3, paired with a 19.83% increase in BOD, was attributed to plant decomposition releasing organic matter into the wastewater due to delayed harvesting [31]. The BOD and COD levels reflect the extent of biodegradable organic pollution in the effluent, with the biodegradable index (BI) estimated as the BOD/COD ratio [32]. At the end of the experiment, BI values rose from an initial 0.14 to a maximum of 0.27 in WL3, indicating increased biodegradability. However, all BI values remained below the 0.3 threshold, above which complete biodegradation can occur [33]. Advanced oxidation processes (AOPs) such as Fenton's oxidation, photo-Fenton, ozonation, and photocatalytic degradation have been recommended to enhance biodegradability and prepare industrial effluents for biological treatment [2].

3.3. Nutrient uptake efficiency.

The macrophytes significantly removed NO_3^- by day 7 of the phytoremediation, with removal efficiencies (REs) for WH following the order WH3 (45.18%) > WH2 (29.14%) > WH1 (18.44%). For WL, the RE trend was WL3 (37.16%) > WL1 (21.11%) > WL2 (4.40%). By day 14, the trends reversed for all WH treatments as well as for WL1 and WL2, leading to negative REs and an increase in the initial NO_3^- concentration in the effluent. This reversal, also reported by [34] using WH and WL for wastewater treatment, may be attributed to plant decomposition, which releases nitrogen compounds into the effluent. These compounds are subsequently converted to nitrates by microbial activity. For WL3, the RE remained positive but decreased from 37.16% on day 7 to 24.43% on day 14. Contrary to [35], which found WH to be more effective than WL in NO_3^- removal, our study showed that WL outperformed WH in removing NO_3^-. As the plants decayed, nitrates absorbed earlier were leached back into the effluent. Similarly, NH_3 exhibited trends parallel to NO_3^-, with both plants achieving positive

REs by day 7 but recording negative REs by day 14, except for WL3. For WH, the highest biomass level (WH3) achieved the greatest NH_3 removal efficiency of 45.86% by day 7. However, WL did not display a consistent trend between biomass levels and NH_3 removal.

The average final removal efficiency of NH_3 was 28.88%. As retention time increased, NH_3 was leached back into the effluent due to plant decomposition. While WH showed better short-term NH_3 removal, WL demonstrated higher removal rates over time. Excess nitrates in the effluent significantly affect aquatic plant growth by promoting algal blooms, which reduce oxygen levels. The rise in NH_3 concentrations contributed to increased BOD in the effluent, partly caused by decomposing plant material [36]. Orthophosphate (PO_4^{3-}) concentrations in the effluent decreased steadily with WL treatments from day 0 to day 14. By day 7, WL achieved REs of 56.69%, 62.94%, and 48.36% for WL1, WL2, and WL3, respectively. The downward trend in PO_4^{3-} concentrations continued, with final REs of 60.34%, 65.01%, and 59.81%. Conversely, WH treatments initially resulted in increased PO_4^{3-} concentrations by day 7, yielding negative REs. However, by day 14, PO_4^{3-} levels dropped, with final REs of 34.87%, 30.48%, and 61.07% for WH1, WH2, and WH3, respectively. WL consistently demonstrated higher phosphate removal, with WL2 achieving the lowest final concentration of 0.084 mg/L. The reduced survival of plants beyond 14 days in the effluent could be linked to phosphorus deficiency, as phosphorus is vital for metabolic processes, protein activation, and energy generation [34]. Similar observations were made by [24], where PO_4^{3-} concentrations initially increased during phytoremediation due to plant decay but decreased later. Early harvesting of plants is recommended to prevent the release of nutrients and exudates from decaying plants into the wastewater. While phosphorus is essential for plant growth, its deficiency or excess can impede growth [35, 37].

3.4. Metals removal efficiency.

The removal efficiencies of heavy metals (HMs) from the effluent were assessed at the end of the treatment period. WH achieved the highest removal efficiency for Cr (95.92%), while WL recorded 90.16%. WH also demonstrated higher accumulation of Cd and Pb, with average REs of 67.68% and 90.88%, compared to WL's REs of 57.07% and 62.28%. However, WL outperformed WH in removing Cu and Zn, with REs of 88.89% and 90%, respectively. The orders of HMs removal for each plant species and biomass are such that the higher the biomass the higher the HMs bioaccumulation. In the treatments with WH1, the REs order is Cr (94.77%) > Pb (83.68%) > Cu (75.35%) > Zn (70.68%) > Cd (34.09%) while for WH2 is Cr (96.49%) > Cu (93.68%) > Pb (92.11%)> Zn (74.28%) > Cd (73.48%) and for WH3 is Pb (96.84%) > Cr (96.49%) > Cd (95.45%) > Cu (90.70%) > Zn (80.79%). Similarly, the REs order for WL1 is Cr (88.55%) > Zn (87.74%) > Cu (81.75%) > Pb (58.42%) > Cd (45.45%) and for WL2 is Cr (90.84%) > Zn (89.53%) > Cu (88.95%) > Pb (62.11%) > Cd (48.49%). While the decreasing order of accumulation of the HMs followed the same trend for both WL1 and WL2, the removal trend differs for the WL3. Exceptionally, WL3 recorded the highest removal of Cu (95.97%) followed by Zn (92.72%), Cr (91.08%), Cd (77.27%), and Pb (66.32%) in a decreasing order of RE. The lowest HM concentrations were achieved in setups with the highest plant mass, indicating that higher biomass enhances HM bioaccumulation. Both plant species exhibited a strong relationship between biomass levels and HM removal, with R^2 values ranging from 0.6922 to 0.9796 at a 95% confidence interval. Figures 2-6 illustrate the behavior of WH and WL across biomass levels, confirming their effectiveness in HM removal.

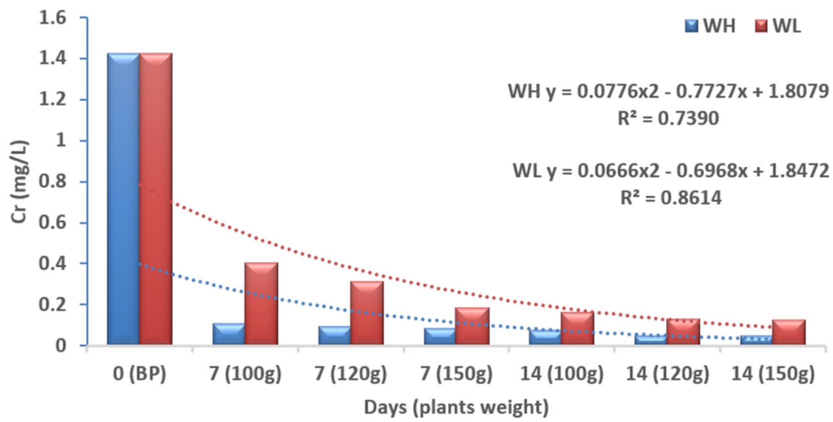

Figure 2. Changes in the concentration of Cr in the effluent by WH and WL over the treatment period.

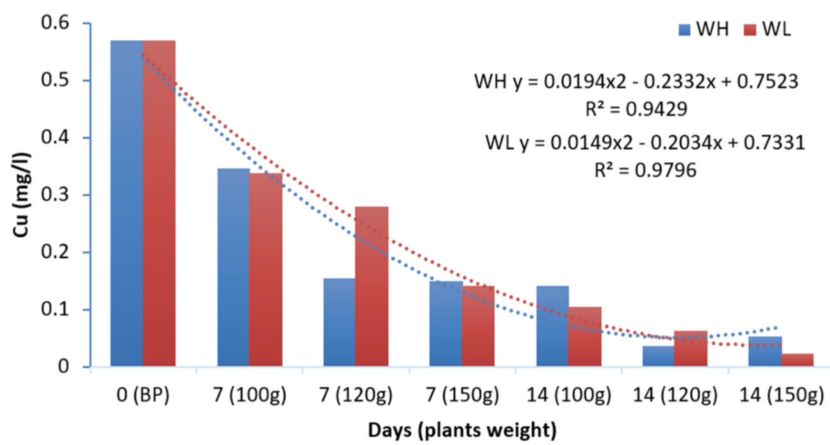

Figure 3. Changes in the concentration of Cu in the effluent by WH and WL over the treatment period.

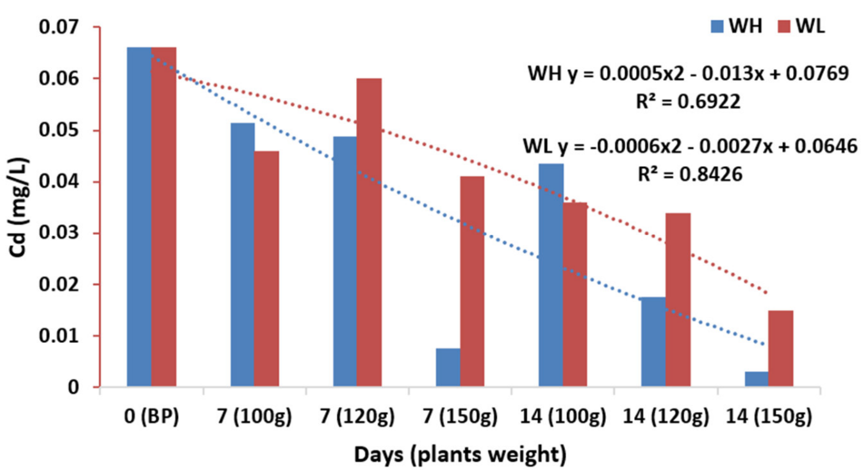

Figure 4. Changes in the concentration of Cd in the effluent by WH and WL over the treatment period.

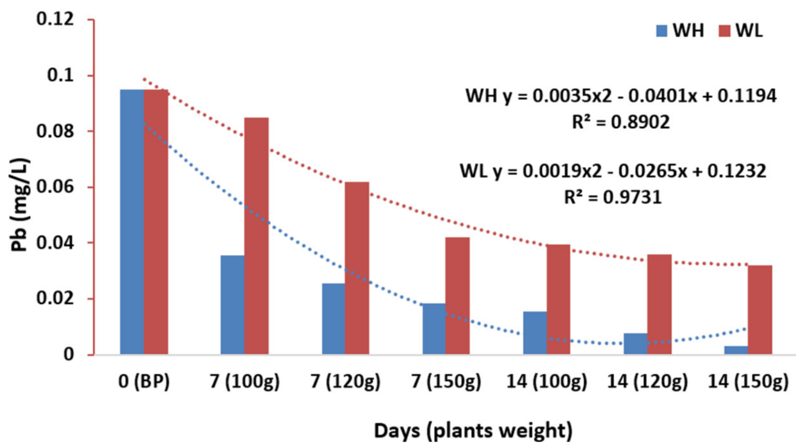

Figure 5. Changes in the concentration of Pb in the effluent by WH and WL over the treatment period.

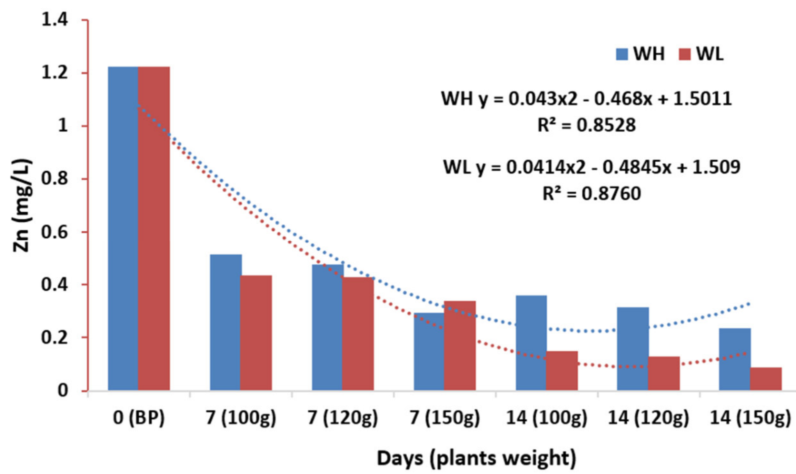

Figure 6. Changes in the concentration of Zn in the effluent by WH and WL over the treatment period.

Both macrophytes demonstrated relatively low Cd removal compared to other HMs. Additionally, Pb absorption by WL was notably lower than that by WH, which exhibited a higher capacity for Pb accumulation. The extensive root system and larger biomass of WH gave it a significant advantage in pollutant accumulation from contaminated water. Overall, WH achieved higher average removal efficiencies for total HMs and at all biomass levels compared to WL. At an alpha value of 0.005, ANOVA analysis revealed no significant difference between the mean HMs removal values for the two plant species ($p = 0.911$). However, biomass quantity significantly affected HM removal ($p = 0.0003$), while the interaction between plant species and biomass levels showed no significant effect ($p = 0.999$). The data confirmed that higher biomass resulted in higher removal efficiency for both plants. This aligns with findings by [38], which demonstrated that using higher biomass levels of selected bryophytes improved HM removal. Similarly, the nutrient removal trend observed in this study is consistent with Adelodun et al. and Ajibade et al. [24, 39], who reported that higher WH densities resulted in greater nutrient absorption. Both macrophytes significantly accumulated Cr, Cd, Cu, Pb, and Zn, with accumulation influenced by factors such as plant species, root systems, growth rate, age, and metal concentrations in the treated medium [24, 40–43]. For broader pollutant removal, combining the two plant species may enhance efficiency in industrial applications.

4. Conclusions

This experiment demonstrated that *Eichhornia crassipes* (water hyacinth) and *Pistia stratiotes* (water lettuce) effectively remediate paint industry wastewater. Significant reductions in HM concentrations were achieved during the first week of phytoremediation, with continued but slower removal rates in the second week. Nutrient levels (NO_3^-, NH_3, and PO_4^{3-}) also decreased significantly within the first 7 days, but plant decay led to nutrient release into the effluent by day 14. Our findings confirmed that higher biomass levels of the macrophytes improved HM and nutrient removal efficiencies. However, careful monitoring is essential to prevent decomposing plant material from leaching nutrients and metals back into the effluent. Understanding the short- and long-term dynamics of the phytoremediation process is critical for optimizing system efficiency. This study's findings can be integrated into existing wastewater treatment facilities, using floating plant systems or hydroponic setups in effluent ponds. We recommend using WH and WL for industrial wastewater phytoremediation, with a detailed assessment of their chemical properties before, during, and after treatment. This approach will help identify plant-specific variability and guide the selection of the most suitable species for optimal remediation of different industrial effluent types.

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Competing Interests

The authors declare no conflict of interest.

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