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Total Chromium Removal and Mass Balance in a Hybrid Constructed Wetland Using *Scirpus americanus* and *Hydrocotyle bonariensis* for Tannery Wastewater Treatment

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Abstract: Tannery effluents contain high concentrations of total and hexavalent chromium, posing severe environmental risks, particularly in developing regions where inadequate treatment persists. Conventional remediation methods are often costly and complex, generating secondary pollutants and underscoring the need for sustainable alternatives. The present research evaluates the effectiveness of a hybrid constructed wetland at pilot scale for removing total chromium from final tannery effluents, applying a mass balance approach. The system comprised two levels: *Scirpus americanus* Pers. in the upper level and *Hydrocotyle bonariensis* Lam. in the lower level, each operated with a seven-day hydraulic retention time. Results showed significant total chromium removal, with the upper level retaining 47.82% in the substrate, 31.85% in roots, and 10.57% in aerial parts of *Scirpus americanus*. The lower level retained 53.53% in roots and 43.31% in aerial parts of *Hydrocotyle bonariensis*. Physicochemical parameters (pH, temperature, TSS, BOD, COD, and total hexavalent chromium) were measured before and after treatment. Tolerance indices decreased in *Scirpus* and increased in *Hydrocotyle*, while both species' bioconcentration and translocation factors rose. Overall, the findings demonstrate this hybrid system's effectiveness and ecological feasibility for chromium removal, underscoring its promise as a cost-efficient alternative for treating industrial effluents.

1. INTRODUCTION

Water is vital for all living organisms; nonetheless, aquatic ecosystems are increasingly threatened by untreated discharges from industrial, agricultural, and domestic activities (Chen et al. 2018). Industrial effluents contribute nearly 16% of the world's wastewater production. Among these, the leather tanning sector, which operates in many countries including Peru (Alemu et al. 2019), manufactures nearly one million square meters of leather annually. This production level the release of approximately 41 million liters of chromium-rich effluents annually (Vilardi et al. 2018).

Tannery wastewater generally shows elevated salinity and oxygen demand parameters (BOD and COD), along with numerous harmful chemical compounds (Younas et al. 2022). Chromium is widely used in tanning because it provides leather with durability and a uniform finish. However, a substantial proportion of chromium salts remains unbound and is discharged with the wastewater, resulting in trivalent and hexavalent chromium. The latter is especially harmful to aquatic environments (Ahmad et al. 2020). Consequently, chromium pollution in receiving waters disrupts trophic chains and networks, creating considerable risks for ecosystems and human health (Elabbas et al. 2016).

Different technologies have been proposed to eliminate chromium from industrial wastewater, involving physicochemical processes including pressure-driven osmosis, sorption methods, membrane technologies, ion-exchange processes, chemical precipitation, and activated carbon treatment (Bibi et al. 2018). In addition, biological approaches using fungi, cyanobacteria, and yeasts have also been tested (Pradhan et al. 2017). Despite their reported effectiveness, these methods are often costly, technically demanding, and may generate secondary toxic sludge (Malaviya & Singh 2016). Consequently, constructed wetlands are increasingly considered an economical and environmentally sustainable option. These systems rely on phytoremediation mechanisms involving macrophytes, microbial communities, and supporting substrates such as gravel to eliminate pollutants, including chromium (Younas et al. 2022).

At the Río Seco Industrial Park (PIRS), the tanning industry discharges large volumes of untreated effluents into oxidation ponds that frequently exceed their holding capacity, leading to the percolation of chromium and other metals into surrounding ecosystems. This situation generates environmental degradation and displeasing odors affecting nearby communities. The Añashuayco Creek receives these discharges, and environmental assessments by the Environmental Evaluation and Control Agency (OEFA) have documented elevated levels of pH, total suspended solids (TSS), BOD_5, COD, and total chromium in the effluents (MINAM 2017). Although constructed wetlands have demonstrated efficiency in pollutant removal, additional studies are required to clarify the distribution and fate of chromium within these systems, particularly under the specific environmental conditions of the Arequipa region.

The wastewater generated at PIRS remains a serious concern because of its elevated concentrations of total and hexavalent chromium, BOD, COD, TSS, pH, and EC. Despite partially reusing of this water within the tanning process, contaminant levels persist well above the maximum permissible limits (MPLs) defined by Peruvian regulations. In addition, untreated effluents are diverted to the sewage network and eventually overflow into oxidation ponds. According to OEFA's reports, these ponds have collapsed, leading to irrigation water contamination and deterioration of environmental quality standards for agricultural use (MINAM 2017).

Although several treatment technologies have been explored, many involve complex operations and require high reagent inputs that result in secondary pollutants (Malaviya and Singh 2016; Younas et al. 2022). In contrast, using constructed or natural wetlands, phytoremediation offers a cost-effective and sustainable solution. These systems rely on the synergistic interaction between plants, substrates, and rhizospheric microorganisms to facilitate the reduction of metallic contaminants through phytoextraction and adsorption processes (Saeed et al. 2021; Liu et al. 2025; Rajput et al. 2025).

Conventional methods for treating industrial effluents are often unfeasible due to their operational complexity, high costs, and hazardous waste production (Bibi et al. 2018). Constructed wetlands offer an effective treatment option, combining substrates such as gravel, macrophyte species, and microbial communities that purify wastewater through mechanisms including absorption, microbial transformation, and plant assisted remediation (Wang et al. 2019; Lin et al. 2025, Rajput et al. 2025). Compared with traditional physicochemical and biological systems, these engineered wetlands standout for their cost effectiveness and ecological compatibility in treating municipal and industrial discharges (Sultanaa et al. 2014).

Recent studies underscore the global interest in developing advanced phytoremediation systems for chromium-contaminated wastewater. Zulfqar et al. (2025) demonstrated that combining *Cannabis sativa* and *Lolium perenne* with biochar and zinc-based nanomaterials (Zn-nZVI) enhances chromium removal efficiency through increased metal uptake and soil amendment. Similarly, Kumar et al. (2025) reported that *Vetiveria spp*., when integrated with *Arbuscular mycorrhizal fungi* (AMF), significantly improved plant tolerance to Cr stress and enhanced translocation mechanisms, suggesting synergistic benefits in wetland systems. These findings highlight innovative pathways for optimizing wetland performance and reinforce the relevance of plant–microbe–substrate interactions in future chromium remediation strategies. Finally, the species used in this research study are endemic to the Arequipa region. In addition, the study incorporated a mass balance analysis to quantify the inputs, outputs, and accumulation of chromium in the different components of the constructed wetland system. Previous studies have not reported research involving these species or analyses of their mass balance, which highlights a knowledge gap and underscores the need for studies that contribute to a better understanding of their dynamics.

Therefore, implementing such constructed wetland systems as cost-effective alternatives to conventional treatments necessitates a comprehensive evaluation of chromium dynamics within the system during the phytoremediation process.

2. MATERIALS AND METHODS

2.1 Treatments setup

The experimental work was undertaken at the Universidad Tecnológica del Perú, campus Arequipa, between September and November 2023. The experimental setup consisted of a hybrid artificial wetland system using 4-liter plastic buckets mounted on a metal frame with wooden supports, maintaining a 1% slope. *Scirpus americanus* Pers. was planted in coarse washed sand at the upper level, while *Hydrocotyle bonariensis* Lam. was allowed to float freely at the lower level.

The independent variable was the hydraulic retention time; that is, a volume of effluent corresponding to 38% of the container's capacity remained in the containers for a period of 7 days for subsequent contaminant removal. At both levels, the treatment conditions involved low oxygen pressure because the wetlands remained continuously flooded with the effluent. The plant species used in the upper level was Scirpus americanus, inserted into an inert substrate (washed coarse sand). Finally, approximately 10 plants per container were used at both the upper and lower levels.

Treatment units were irrigated with tannery effluent diluted to 30%, due to in previous tests the percentage of plant mortality exceeded 50%; therefore, that concentration was selected. When applied to a larger-scale wetland system, the water used to dilute the effluent would be the treated water discharged from the wetlands. Two types of control units were used: one containing only substrate and water and another containing plants but no effluent. All treatments were performed in triplicate to ensure statistical robustness. The system functioned by gravity flow, where the effluent was initially applied to the upper stage with a hydraulic retention period (HRT) of seven days, then directed to the lower stage for another seven days. This sequence was repeated three times, resulting in a total treatment period of 21 days (Fig. 1).

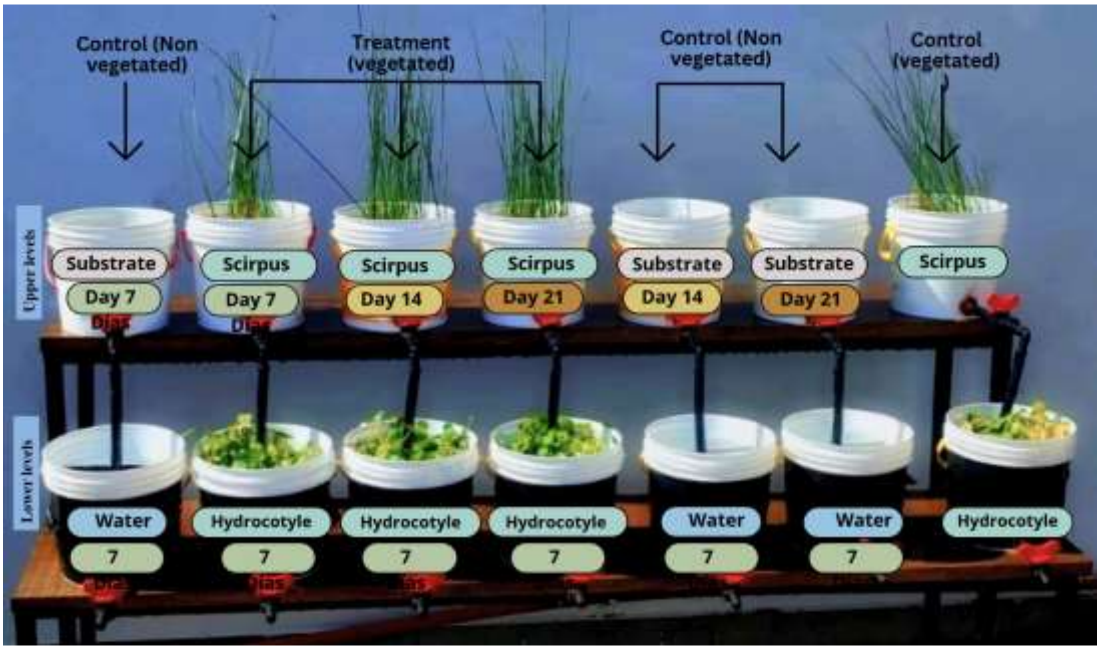

Fig. 1. Schematic of the hybrid artificial wetland system and treatment and sampling schedule

2.2 Plant material and effluent characteristics

The plant species *Scirpus americanus* Pers. and *Hydrocotyle bonariensis* Lam. were collected from the district of Characato, Arequipa (16º28'19.10"S, 71º28'39.41"W; 2459 masl), and transferred to the university laboratory. Upon arrival, the specimens were thoroughly rinsed to eliminate organic matter and associated organisms. *Scirpus americanus* was transplanted into 4-liter containers filled with coarse, washed sand, which served as an inert substrate to support root development. Additional sand was also placed at the faucet outlet of each container to facilitate uniform effluent drainage.

The effluent used in the experiment was a composite sample obtained from multiple stages of the tanning process, including soaking, liming, dehairing, tanning, dyeing, and retanning, collected at the Río Seco Industrial Park (PIRS). These samples were mixed in equal proportions and diluted to 30% prior to application in the treatment units.

2.3 Analytical procedures

The following parameters were monitored at 0, 7, 14, and 21 days. The monitored variables included pH, temperature, TSS, BOD_5, COD, and both total chromium and hexavalent chromium.

Chromium analysis: Total and Cr VI concentrations were determined using colorimetric digestion methods with HNO_3 and H_2SO_4.

BOD_5: Samples were adjusted to pH 6.5–7.5, incubated in Winkler flasks at 20°C for 5 days, and DO was measured before and after.

COD: Samples were digested with $K_2Cr_2O_7$ and H_2SO_4 at 150°C and absorbance measured at 600 nm and chemical oxygen demand was calculated by:

$$COD\ in\ (mgO_2/L) = \frac{mgO_2\ in\ final\ volume \times 1000}{mL\ sample} \tag{1}$$

TSS: The samples were passed through filters, dried in an oven at 105°C, and measured gravimetrically.

$$mg\ SST/L = \frac{(A-B)\times 1000}{sample\ volume\ (mL)} \tag{2}$$

A corresponds to the combined weight of the filter paper and the dried sample, while B represents only the filter paper weight.

2.4 Indicators of plant response

To evaluate phytoremediation efficiency, several indicators were calculated:

Tolerance index (TI): obtained from the ratio between the biomass of plants exposed to chromium (Bt) and that of control plants (Bc) (Shi et al. 2011).

$$TI = \frac{Bt}{Bc} \tag{3}$$

Bioconcentration factor (BCF): determined by dividing chromium concentration in stems (C_{stems}, ppm) by chromium concentration in the water solution ($C_{solution}$, ppm) (Liu et al. 2008).

$$BCF = \frac{C_{stems}}{C_{solution}} \tag{4}$$

Translocation factor (TF): determined by calculating the proportion of chromium present in the aerial tissues (C_{stems}, ppm) relative to its concentration in the roots (A_{roots}, ppm) (Ribeiro de Souza et al. 2012).

$$TF = \frac{A_{stems}}{A_{roots}} \tag{5}$$

Removal efficiency (E%): calculated according to (Meneses Barroso et al. 2019):

$$E(\%) = \frac{C_i - C_s}{C_i} \tag{6}$$

where C_i refers to the chromium concentration entering the system and C_s corresponds to the concentration leaving it after treatment.

2.5 Mass balance and chromium distribution

The distribution of total chromium across the different components of the pilot artificial wetland system was calculated in the following steps: First, the chromium concentrations (in ppm) were measured in water, substrate, roots, and the aerial harvestable parts. Next, the mass (in kilograms) and volume (in liters) of each component were determined. Finally, a mass balance was calculated by multiplying the chromium concentration by the mass or volume of each component, with results expressed as percentages. This evaluation was conducted at 0, 7, 14, and 21 days of testing.

2.6 Statistical analysis

The experimental units were randomly distributed using random numbers in Microsoft Excel software. Statistical tests of the results were performed by repeated measures ANOVA to detect the statistical significance of the variability among treatments; Duncan's multiple range test ($p<0.05$) was performed using STATGRAPHICS CENTURION statistical software. Finally, the graphs were made using SIGMAPLOT 12.0 graphing software.

3. RESULTS

3.1. Determination of physicochemical characteristics in tanning effluents.

Table 1 presents the results of the effluents from the leather tanning process, both before and after treatment with Scirpus americanus Pers. and Hydrocotyle bonariensis. Additionally, the Maximum Permissible Limits (MPL) values according to DS Nº 010-2023-MINAM are included for comparison. Untreated effluents show BOD5, COD, and total chromium concentrations that exceed the MPL. Specifically, BOD5 exceeds the limit by 38 times, COD by 125 times, and total chromium by 484 times. Moreover, the pH of 5.84 is outside the permissible range of 6 to 9. Regarding temperature, TSS, and Cr VI, these values are within the limits established by the MPL.

After applying the wetland treatment, the pH, temperature, TSS, BOD5, Cr VI, and total chromium values were all below the MPL. The removal efficiency was determined to be 86.04% for TSS, 97.39% for BOD5, and 99.98% for total chromium. In the case of COD, although the final value remained above the MPL, it was reduced from an initial value of 6276 mg/L to 80 mg/L, achieving a removal efficiency of 98.73%.

Table 1: Values of physicochemical parameters in the effluents, before treatment (tanning effluent) and after treatment with the wetlands.

Parameter	Unit of Measurement	Before treatment	After treatment	LMP
pH	pH units	5.84	7.16	6 - 9
Temperature	ºC	25.3	22.8	35
TSS	mg/L	4.37	0.61	30
BOD_5	mg/L	1150.50	30	30
COD	mg/L	6276.00	80	50
Chromium VI	mg/L	0.02	<0.02	0.1
Total Chromium	mg/L	242.10	0.05	0.5

3.2. Total chromium accumulation in water, substrate, roots and leaves of the plants *Scirpus americanus* Pers. and *Hydrocotyle bonariensis* Lam.

Fig. 1A illustrates the temporal mobilization of total chromium in the various components of the upper level of the wetland system. In the water component, a notable decrease with statical relevance ($P<0.05$) in total chromium concentration was observed, decreasing from an initial value of 242.10 ppm to 6.55 ppm after seven days of treatment, which corresponds to a removal efficiency of 97.29%. By day 14, the concentration further declined to 3.29 ppm, achieving 98.64% efficiency, and by day 21, it reached 2.79 ppm. However, this final reduction was not statistically significant compared to day 14 ($P>0.05$), with an overall efficiency of 98.85%. In the substrate component, the initial chromium concentration of 0.8 ppm increased significantly ($P<0.05$) over time, reaching 51.32 ppm by day 21. Regarding the plant species *Scirpus americanus* Pers., initial concentrations of total chromium in the roots and aerial parts were 1.67 ppm and 1.55 ppm, respectively. Both plant parts exhibited statistically significant increases ($P<0.05$) throughout the treatment period. By day 21, the roots accumulated a maximum concentration of 109.38 ppm, while the aerial parts reached 90.78 ppm.

In contrast, the control system (non-vegetated wetland) showed a less efficient reduction of total chromium in the water. The concentration dropped significantly ($P<0.05$) from 242.10 ppm to 172.16 ppm after seven days, representing a removal efficiency of 28.89%. At 14 days, the concentration further decreased to 160.75 ppm, although this change was not statistically significant ($P>0.05$), with an efficiency of 33.60%. By day 21, the final concentration was 154.76 ppm ($P>0.05$), corresponding to an efficiency of 36.08%.

For the substrate in the control system, the was a marked rise ($P<0.05$) in total chromium was detected during the first seven days, rising from 1.61 ppm to 70.53 ppm. However, from that point forward, the variation was not statistically significant: 77.34 ppm at day 14 ($P>0.05$) and 71.31 ppm at day 21 ($P>0.05$), indicating a saturation of the substrate. When comparing both systems, during the first seven days, a notable reduction ($P<0.05$) in total chromium was detected within the water of both vegetated and non-vegetated wetlands. Nevertheless, towards the conslusion of the treatment, the vegetated unit demonstrated a considerably higher removal performance, reaching 98.85% efficiency, compared to the 36.08% recorded in the non-vegetated control. In terms of the substrate behavior, while the non-vegetated system exhibited a significant initial increase in chromium content ($P<0.05$), it quickly reached saturation, resulting in no significant variations thereafter.

Conversely, the vegetated system showed a continuous and significant accumulation ($P<0.05$) of chromium in the substrate throughout the 21-day treatment period.

Fig. 1B, shows the distribution of total chromium in the components of the artificial wetland system at the lower level. It can be observed that the concentration of total chromium decreased significantly ($P<0.05$) from an initial concentration of 6.55 ppm to 0.16 ppm after seven days of treatment, achieving an efficiency of 97.56%. At 14 days of treatment, the concentration decreased to 0.12 ppm ($P>0.05$), achieving an efficiency of 98.17%. By 21 days of treatment, the concentration had further decreased to 0.05 ppm ($P>0.05$), resulting in an efficiency of 99.24%. Regarding the root component, it was determined that the initial concentration was 0.35 ppm before applying the effluent; at the end of 21 days, the total chromium content exhibited a notable rise ($P<0.05$) to a value of 5.08 ppm. In the case of leaves, the total chromium concentration showed a significant increase ($P<0.05$) over time, from an initial concentration of 0.38 ppm to a value of 6.85 ppm at 21 days of testing.

Concerning the non-vegetated wetland system, the concentration of total chromium in the influent was found not to vary significantly ($P>0.05$) during the treatment time from zero days to 21 days. In comparison to the constructed wetlands with and without vegetation, results indicated that in the vegetated wetlands, the total chromium concentration declined markedly ($P<0.05$) after seven days of treatment, and also presented a decrease ($P>0.05$) of this value in the rest of the test time, reaching an efficiency of 99.24% at the end of 21 days. In the case of the non-vegetated wetlands, where the total chromium concentration did not show significant variation ($P>0.05$), i.e., it maintained a concentration similar to that of the influent, and the efficiency reached 2.69%.

Consistent with these findings, Table 2 shows the mass balance and distribution of total chromium in the wetland system for treating tannery wastewater at 30% concentration. It is observed that, at the upper level of the wetland system, the concentration of total chromium in the wastewater decreases with time from a total value of 363.15 mg to a value of 4.19 mg, representing 1.36% of the initial concentration. Concerning the substrate component, it is observed that the amount of chromium present increases over time from zero to 21 days.

Besides, the table 2 shows the percentages of chromium removal in the different components of the wetlands. Negative percentages would indicate that both the substrate and the roots are saturated with chromium; therefore, their retention and absorption capacity would be decreasing.

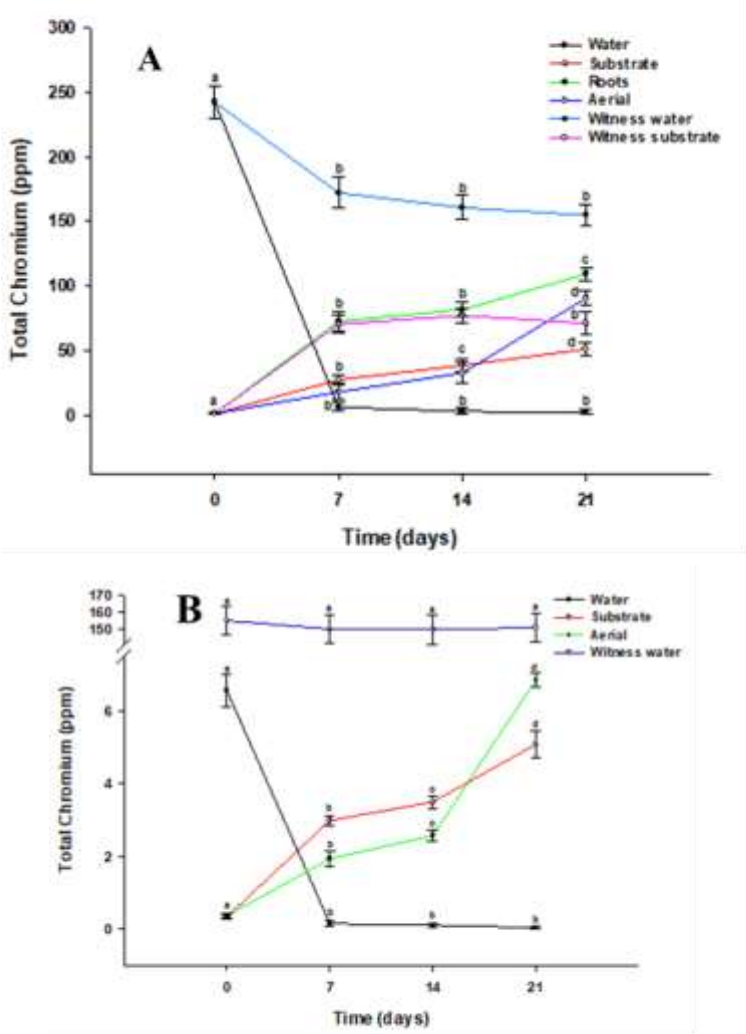

Fig. 1. Distribution of total chromium over time in the different components of the artificial wetland system. A) Upper level (*Scirpus americanus* Pers.) and B) Lower level (*Hydrocotyle bonariensis* Lam.). Values represent the average of three replicates ± SD. The letters placed above the bars denote statistically significant differences among treatments.

Table 2. Values of physicochemical parameters evaluated in the effluents of the tanning process without pretreatment

Component	Quantity	0 days			7 days				14 days				21 days			
Upper level		**[Cr] (ppm)**	**Total [Cr] (ppm)**	**%**	**[Cr] (ppm)**	**Total [Cr] (ppm)**	**%**	**% chromium removal**	**[Cr] (ppm)**	**Total [Cr] (ppm)**	**%**	**% chromium removal**	**[Cr] (ppm)**	**Total [Cr] (ppm)**	**%**	**% chromium removal**
Water (L)	1.50	242.10	363.15	98.26%	6.55	9.83	6.29%	91.97%	3.29	4.94	2.50%	3.79%	2.79	4.19	1.36%	1.14%
Substrate (kg)	2.00	1.61	3.22	0.87%	27.71	55.42	35.47%	34.60%	38.81	77.62	39.30%	3.83%	51.32	102.64	33.43%	-5.87%
Roots (Kg)	1.00	1.67	1.67	0.45%	72.76	72.76	46.56%	46.11%	81.86	81.86	41.45%	-5.11%	109.38	109.38	35.63%	-5.82%
Aerial (Kg)	1.00	1.55	1.55	0.42%	18.25	18.25	11.68%	11.26%	33.08	33.08	16.75%	5.07%	90.78	90.78	29.57%	12.82%
Lower level		**[Cr] (ppm)**	**Total [Cr] (ppm)**	**%**	**[Cr] (ppm)**	**Total [Cr] (ppm)**	**%**	**% chromium removal**	**[Cr] (ppm)**	**Total [Cr] (ppm)**	**%**	**% chromium removal**	**[Cr] (ppm)**	**Total [Cr] (ppm)**	**%**	**% chromium removal**
Water (L)	1.50	6.55	9.83	93.08%	0.16	0.24	4.64%	88.44%	0.12	0.18	2.88%	1.76%	0.05	0.08	0.62%	2.26%
Roots (Kg)	1.00	0.35	0.35	3.32%	2.99	2.99	57.83%	54.51%	3.5	3.50	55.91%	-1.92%	5.08	5.08	42.32%	-13.59%
Aerial (Kg)	1.00	0.38	0.38	3.60%	1.94	1.94	37.52%	33.92%	2.58	2.58	41.21%	3.69%	6.85	6.85	57.06%	15.85%

3.3. Determination of TI, BCF and TF in artificial wetland systems.

Table 3 shows the plant response indicators (TI, BCF and TF) measured in the upper and lower sections of the constructed wetland after effluent treatment.

Table 3: Plant response indicators IT, BCF and TF, values after effluent treatment with the constructed wetland system.

Time (days)	TI	BCF	TF
Higher level			
7	0.93 ± 0.24	0.08 ± 0.02	0.25 ± 0.06
14	0.77 ± 0.21	0.14 ± 0.01	0.40 ± 0.05
21	0.68 ± 0.10	0.37 ± 0.07	0.83 ± 0.08
Lower level			
7	0.83 ± 0.09	0.30 ± 0.04	0.65 ± 0.35
14	0.88 ± 0.07	0.39 ± 0.08	0.74 ± 0.06
21	0.90 ± 0.08	1.05 ± 0.06	1.35 ± 0.05

The values represent the mean and standard deviation for three independent samples.

Regarding the tolerance index (TI), at the upper level, it can be observed that *Scirpus americanus* Pers. decreases in the TI over time from a value of 0.93 at seven days to 0.68 at 21 days. At the lower level, *Hydrocotyle bonariensis* Lam. shows an increase in the tolerance index over time, from a value of 0.83 at seven days to 0.90 at 21 days. Regarding the bioconcentration factor (BCF), it is observed that both in the upper and lower levels, the BCF increases over time, from an initial value of 0.08 to 0.37 for *Scirpus americanus* Pers. and from 0.30 to 1.05 for *Hydrocotyle bonariensis* Lam. from 7 days to 21 days. Finally, the translocation factor also increased over time at both levels of the wetland system, from a value of 0.25 to 0.83 for *Scirpus americanus* Pers. and from 0.65 to 1.35 for *Hydrocotyle bonariensis* Lam. from 7 days to 21 days of effluent treatment.

4. DISCUSSION

Tannery effluents are usually characterized by elevated amounts of chromium compounds, which include salts and oxygen demand parameters (BOD_5 and COD), together with other harmful substances, all of which contribute to considerable environmental degradation when released without treatment (Khajah & Ahmed 2025; Pérez et al. 2024). In the present work, the chromium levels detected in the effluent surpassed the maximum permissible limit (MPL), **which may be attributed to use** of chromium sulfate in tanning processes to stabilize collagen fibers. Of the total chromium applied, only 60–80% binds to the leather, while 20–40% is lost in wastewater. Although hexavalent chromium (Cr^{6+}) was detected in the effluent, its concentration was below the MPL, likely due to reduction to the more stable and less toxic trivalent chromium (Cr^{3+}). This reduction could be attributed to the high organic matter load acting as an electron donor (Rondan-Sanabria et al. 2023; Abd Al-Abbas & Ismail 2024; Kumari & Dutta 2024).

The organic load, reflected in high values of BOD_5, COD, and total suspended solids (TSS), **could** originate primarily from soaking, liming, and fleshing processes. Elevated COD values are likely associated with anilines and dyes used during the dyeing stage, which are known for their resistance to bacterial degradation. The biodegradability ratio ($BOD_5/COD = 0.183$) indicates a non-biodegradable effluent, where most organic and inorganic matter cannot be biologically oxidized. Constructed wetlands are a sustainable and economical alternative (Zhang et al. 2024). These systems interact with plants, microorganisms, and substrate materials (Luna-Pabello & Aburto-Castañeda 2014). In this study, the pilot wetland system achieved a chromium removal efficiency of 99.96%. Similar removal rates have been reported: 99.8% in vegetated wetlands and 92.5% in non-vegetated systems (Kaseva & Mbuligwe 2010). Other studies using *Phragmites australis* and *Typha latifolia* reported of 87% and 90% efficiencies, respectively (Gikas et al. 2013), while several investigations found removal rates exceeding 50% (Younas et al. 2022).

Significant reductions in BOD_5, COD, and TSS were observed in this study. Comparable results include reductions in TDS from 4.81 g/L to 0.73 g/L and COD removal of 70% (Javeed & Nazir 2022), as well as 88% COD, 93% BOD, and 96–98% TSS removal in other studies (Ali-Hassoon et al. 2020). Wetlands have also demonstrated removal efficiencies of 35–50% for various dissolved ions and about 50% for BOD and COD (Panneerselvam & Shunmuga 2021). A local study in Arequipa using a hybrid wetland system *with Eleocharis montevidensis, Scirpus americanus* Pers., and *Eichhornia crassipes* also achieved more than 95% pollutant removal with a 7-day hydraulic retention time (Rondan-Sanabria et al. 2023; Khajah & Ahmed 2025). Organic matter removal **could be** facilitated mainly by microbial degradation. Plant roots provide a surface for microbial colonization, promoting complex interactions in the rhizosphere (Liang et al. 2017). Anaerobic degradation dominates most of the bed, with aerobic degradation limited to zones around roots and the surface layer (Stottmeister et al. 2003; Riggio et al. 2018). The elimination of suspended solids **could occur** through physical and biological processes, mainly involving sedimentation, flocculation, and substrate and rhizome filtration (Younas et al. 2022).

Chromium, being non-biodegradable, **could be** removed through three main mechanisms: (1) adsorption onto substrate and sediment particles, enhanced by high organic matter improving cation exchange capacity (Chrysochoou et al. 2016); (2) chemical precipitation due to rhizosphere exudates and organic acid production during microbial degradation, leading to chromium complexation and sedimentation (Al-Baldawi et al. 2015; Morris 2004); and (3) phytoextraction through root uptake, with chromium transported to shoots and stored in vacuoles or cell walls (Liang et al. 2017; Kafle et al. 2022). Four possible models have been proposed for Cr^{3+} uptake: apoplastic retention; passive diffusion into the vacuole; transport via phytosiderophores to the tonoplast; and microbial oxidation to Cr^{6+} followed by apoplastic fixation. Cr^{6+} is actively transported via sulfate transporters and reduced intracellularly to Cr^{3+} before sequestration (Shanker et al. 2005; Abd Al-Abbas & Ismail 2024).

This study found that most chromium accumulated in the upper-level substrate. Chromium content in plant roots exceeded that in the aerial parts, consistent with findings from studies using *Pistia stratiotes*, *Eichhornia spp.*, *Lemna spp.*, and *Salvinia spp.* (Rezania et al. 2016) and *Phragmites australis* (Fibbi et al. 2012). Plant tolerance and phytoremediation capacity were assessed using indicators of plant response. The upper level showed a decreased TI, likely due to higher contaminant concentrations, while BCF and TF increased in both levels, indicating effective uptake and translocation. *Scirpus* showed high tolerance, with a strong physiological response after 21 days, in line with other studies reporting limited wilting and higher growth rates under exposure (Ali-Hassoon et al. 2020; Zhang et al. 2024). More broadly, reviews of CWs report that metals are typically retained in roots with limited translocation to shoots, and that substrate layers capture a substantial fraction of dissolved metals via adsorption and precipitation, while plant–microbe interactions enhance tolerance (Younas et al. 2022; Zhang et al. 2024).

However, growth inhibition has been observed in other studies, such as a 17% reduction in root and 33.3% reduction in stem dry weight under contamination (Liu et al. 2018) and reduced heavy metal accumulation in watercress. Similar patterns were observed in *Plantago major* L. and aquatic bryophytes exposed to various metals (Galal & Shehata 2015; Favas et al. 2018). Finally, in *Pistia stratiotes* exposed to arsenic, toxicity symptoms such as chlorosis and root browning occurred at higher concentrations (Vidal de Campos et al. 2019), while in *Eichhornia crassipes* growth was stimulated at low Cr levels (0.5–2 mg/L) but inhibited at concentrations above 5 mg/L (Panneerselvam & Shunmuga 2021).

5. CONCLUSIONS

The findings of this study confirm that the analyzed tannery effluents contained high concentrations of total chromium (242.10 mg/L), along with elevated values of biochemical (BOD_5 = 1150.50 mg/L) and chemical (COD = 6276.0 mg/L) oxygen demand. All of these parameters surpassed the maximum permissible limits established for effluents from tanning operations.

In the artificial wetland system, the total chromium concentration in the substrate of the upper level increased over time, from 1.61 ppm to 51.32 ppm. A similar pattern was observed in the vegetative components, with concentrations in the roots rising from 1.67 ppm to 109.38 ppm, and in the aerial (harvestable) parts from 1.55 ppm to 90.78 ppm.

At the lower level of the wetland, chromium accumulation also showed an upward trend, with values rising from 0.35 to 5.08 ppm in roots and from 0.38 to 6.85 ppm in aerial parts.

The pilot system achieved high treatment efficiencies, removing 99.98% of total chromium, 97.39% of BOD_5, and 98.73% of COD.

For *Scirpus americanus* Pers., the tolerance index (TI) declined over time (from 0.93 to 0.68), whereas the BCF and TF increased (0.08 to 0.37 and 0.25 to 0.83, respectively). In contrast, *Hydrocotyle bonariensis* Lam. showed increases in all three indicators, with TI ranging between 0.83 and 0.90, BCF from 0.30 to 1.05, and TF from 0.65 to 1.35.

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