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Horizontal Flow Floating Treatment Wetlands (HFFTWs) for Reclaiming Safer Irrigation Water from Tannery Effluent

Aisha Nazir [1], Haiqa Tanveer [1], Muhammad Shafiq [2,*], Muhammad Ihsan [1], Tasmia Maqbool [2] and Micklas Scholz [3,4,5,*]

[1] Environmental Biotechnology Lab, Institute of Botany, University of the Punjab, Lahore 54590, Pakistan; aisha.botany@pu.edu.pk (A.N.); haiqa.tanveer123@gmail.com (H.T.); mi6377337@gmail.com (M.I.)
[2] Sustainable Services in Built Environment, Institute of Botany, University of the Punjab, Lahore 54590, Pakistan; mshafiq.botany@pu.edu.pk (M.S.); tasmiamaqbool12@gmail.com (T.M.)
[3] Department of Water Management, Sector of Regional Development, Environment and Construction, District of Herzogtum Lauenburg, Barlachstraße 2, 23909 Ratzeburg, Germany
[4] Department of Civil Engineering Science, School of Civil Engineering and the Built Environment, Faculty of Engineering and the Built Environment, University of Johannesburg, Kingsway Campus, Aukland Park 2006, Johannesburg P.O. Box 524, South Africa
[5] Kunststoff-Technik Adams, Specialist Company According to Water Law, Schulstraße 7, 26931 Elsfleth, Germany
* Correspondence: mshafiq.botany@pu.edu.pk (M.S.); m.scholz@kreis-rz.de or mscholz@uj.ac.za or miklas.scholz@kunststoff-technik-adams.de (M.S.)

Abstract

Untreated tannery wastewater (UTW) poses unprecedented threats to the aquatic and irrigation systems due to severely limited pollution removal efficiency (RE %) by the limited capacity and design of wastewater treatment plants in developing countries. An exploitation of treatment wetlands (TWs) like floating treatment wetlands (FTWs) face hydraulic performance and survivability and establishment challenges of transplanted hydrophytes in the severely toxic UTW. Such challenges were overcome by designing a horizontal flow floating treatment wetland (HFFTW) and diluting UTW at 0, 25, 50, and 75 with harvested rainwater (HRW), viz. UTW:HRW (% *v*:*v*) for lowering phytotoxicity to the phytotolerance range of the tested hydrophytes, viz. *Eichhornia crassipes* (EC) and *Pistia stratiotes* (PS) in the HFFTW, i.e., EC-HFFTW and PS-HFFTW. Both hydrophytes showed heavy metals' translocation factor being ≥1, i.e., and acted as excellent hyperaccumulators of heavy metals. The average metal RE (%) was 64 (Cr), 61 (Cd), 45 (Pb), 44 (Cu), and 50.1 (BOD) for *E. crassipes*, and 44 (Cr), 54 (Cd), 42.2 (Pb), 42 (Cu), and 40 (BOD) for *P. stratiotes*. Significant reductions in the organic pollution load witnessed by significant drops in BOD and COD made UTW a safer irrigation medium for *Petunia hybrida* while inducing an increase in the bioconcentration factor (BCF) of PS and EC. The study concluded that the designed HFFTW showed significantly greater RE (%) and yield of reclaimed water than conventional FTWs based on its hydraulic performance. The design HFFTW carries a field scale application capacity for improvising treatment efficiency of the combined effluent plant of KTWMA (Kasur Tannery Waste Management Agency), Kasur, Pakistan.

Keywords: artificial wetlands; hyperaccumulator plants; treatment wetlands; tannery wastewater management; *Eichhornia crassipes*; *Pistia stratiotes*; *hydrophytes*; phytoremediation; bioremediation; hydraulic limitations of wastewater; floating wetlands

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1. Introduction

The water demand is expected to rise by 55% worldwide, and over 25% of large cities are currently experiencing some form of water scarcity [1]. Water shortage affects around 4 billion people for at least one month every year because of variables like climate change, severe droughts, population growth, increasing water demand, and poor resource management that have further pressured freshwater resources over the past few decades [2]. About 40% of the world population faces water deficiency, and around 700 million people lack access to clean and safe water [3].

Heavy metal-laden wastewater is produced by a variety of human activities, including petroleum refining, mining, electroplating, acid mine drainage, tanning in the leather industry, landfill leachate, steel, and fertilizer production operations. Tannery industries discharge UTW in the environment containing a significant number of pollutants and pose a high risk to air and water quality [4]. UTW frequently contains harmful contaminants and pollutants, particularly heavy metals such as Cr, Pb, Cd, and Hg, which represent significant ecological impacts and health hazards. The concentration of these heavy metals from tanneries can often lead to significant environmental dangers, as the leather often generates high volumes of hazardous substances, including pathogens, synthetic compounds, organic matter, and toxic metals, and are now widely present in both surface and groundwater, endangering ecosystems and human health. Heavy metal pollution caused by UTW has become a major environmental problem of the developing countries [5]. The entire food chain may be impacted by the disturbance of plant metabolism and heavy metal accumulation, which may also result in a decline in species diversity, changes to the makeup of communities, and a loss of vegetative cover. Because of biomagnification within the food chain, the high concentration of heavy metals in the soil and their buildup in plants pose major health concerns to both humans and animals [6]. At even low levels, heavy metals can build up inside living things and transform into dangerous or active chemicals, causing important health issues for humans [7]. Therefore, the liquid and solid waste discharged from tanneries needs effective treatment prior to discharge due to its increasing impact on the environment.

Efforts to control and mitigate the impact of tanneries on the environment have been taking place; however, further actions need to be taken to address this challenge [8]. However, multiple socio-economic constraints lead to the unavailability of conventional wastewater treatment infrastructure in developing countries; hence, there has been a strong reliance on applied bioremediation approaches such as constructed wetlands for wastewater treatment, also called treatment wetlands [9–14]. The treatment wetlands are preferred for being environmentally safe and sustainable methods for treating municipal sewer and industrial wastewater [15] including tannery industrial effluent [16], especially for the treatment of metallic pollution load of wastewater [17,18]. Being a biomimicry of the natural wetlands, the treatment wetlands have demonstrated significant promise in cleaning polluted water, including organic and inorganic pollutants [19]. Expanding on this idea, a variety of artificial wetlands have been created and used to treat human-generated discharges, such as industrial wastewater, agricultural runoff, and municipal sewage [20–22]. However, treatment wetlands inherently carry multiple challenges causing poor wastewater treatment capacity caused by seasonal limitations, aquatic plant vulnerabilities, land area intensifications, clogging risk, operational, structural design, and compatibilities with the local wastewater issues of a place [23]. Hence, treatment wetlands carry a large potential for basic and applied research opportunities for the wastewater treatment research domains.

One of the key variants of treatment wetlands is floating treatment wetlands (FTWs). The FTWs include floating surfaces/mats on the water supplied with solid filter media

such as gravel or sand and treatment plants such hydrophytes [24,25]. They depend on the relationships between plants, water, air, and microorganisms to address the removal of contaminants and pollutants. During the operation of FTWs, aquatic plants' roots protrude out of the floating surface and hang down into the water column, allowing for nutrient absorption and pollution removal, while the above-water sections of the plants continue to develop on floating surfaces/mats. The longer roots in the water and bedding materials on the floating surfaces/mats offer high surface for biofilm growth, releasing of oxygen through the roots of hydrophytes and help replenish dissolved oxygen level in the water [26]. Like other types of treatment wetlands, FTWs carry low cost, minimal impacts on water supplies, and are an eco-friendly technology for removal of heavy metals from diverse types of wastewater. Because of their affordability, high effectiveness, and environmental sustainability, they are frequently utilized for wastewater treatment [27]. However, the conventional design of FTWs also carries inherent limitations in terms of design and efficiency for pollutant removal, especially during the treatment of industrial wastewater treatment [28,29], especially UTW. Removal of multiple inorganic and inorganic pollutants from UTW through FTWs has been at the emerging stage with very limited literature [30]. The removal of chromium from wastewater through treatment wetlands with vertical, horizontal, and hybrid flow systems has been quite effective [31,32]; however, its efficacy for chromium removal from UTW is highly limited and multiple improvisations are required for increasing treatment efficiency of FTWs for UTW.

However, the conventional FTWs have been facing several design, operational, and performance efficiency challenges for treating industrial wastewater [28]. FTWs have been based on the hydraulically static retention of water in the batch reactors, i.e., the ponds or troughs throughout treatment process, with a great rate of silting, leading to sedimentation of total solids and rise in the treatment bed. Consequently, the treatment efficiency of the conventional FTWs is limited. The area covered with the floating assemblies is significantly lesser than the area left open to active evaporative loss of water from the treatment pond/trough. Both silting and evaporative loss result in limited treatment efficiency as well as low yield of the treated wastewater. Another limitation associated with the stagnant retention of wastewater in the treatment ponds/troughs is poor flow of air through the wastewater, particularly in the deeper layers, which causes anaerobic decomposition of organic pollution load, i.e., the BOD removal is limited both quantitatively and qualitatively by producing anaerobic gaseous products like NH_3, H_2S, CH_4, etc. Overcoming the highlighted limitations of conventional FTWs requires the introduction of design improvisations. Hence, the current study designed and tested HFFTW.

The five key components of the treatment wetlands include (i) wastewater to be treated; (ii) hydraulic flow gradient; (iii) bedding material for development of microbial biofilm, offering surfaces for biophysical sorption of pollutants; (iv) vegetation, preferably hydrophytes; and (v) physical containment for keeping the former four components fabricated together either in an open land-based containment or enclosure-based containment. The effective hydrophytes for treatment wetlands are preferably fast growing and high biomass (root and shoot) yielding, and have a longer growing time (preferably being perennial), easy availability and accessibility, robust metal tolerance, a high translocation index of metals from roots to the aerial biomass, and a wide ecological amplitude for multiple types and concentrations of pollutants. In reality, no wild hydrophyte with such ideal features and characteristics exists for concurrent remediation of inorganic and organic pollutants. However, some hydrophytes have most of the required features of an ideal plant for application in the treatment wetlands. For example, *P. stratiotes* (water lettuce) and *E. crassipes* (water hyacinth) have been some of the very frequently used hydrophytes

for concurrent removal of heavy metals (including Cd, Cr, Cu, Ni, Pb, and Zn) and organic pollution load from wastewater [23–37].

The reclaimed water through applied phytoremediation-based interventions like treatment wetlands must be tested for its biosafety for plants to be cultivated before being recommended for its use at large scale like in agricultural crop irrigation system. For testing the reclaimed water through treatment wetlands, nonedible ornamental plants could be ideal candidates as they have the least probability of letting pollutant flow through a food web [38,39]. *P. hybrida* could be one such candidate for evaluating safer irrigation potential of reclaimed wastewater as it can be irrigated with polluted water and has high ornamental value, which may add a socio-economic benefit to the reclaimed water safety interventions, even at the testing phase. The current study was aimed at designing a HFFTW at the mesocosmic level for reclaiming safer irrigation water from tannery effluent in two sets, viz. *E. crassipes*- and *P. stratiotes*-based HFFTW and assessing safer irrigation potential of the reclaimed water for *P. hybrida* irrigation.

2. Materials and Methods

2.1. Collection of UTW

Due to multiple treatment performance, efficiency, and operational challenges of the combined effluent treatment plant managed by KTWMA, Depalpur Road, Kasur, Pakistan, the UTW was collected from its inlet (31.100262° N, 74.461387° E), i.e., at the first point of entry of UTW into the treatment plant (Figure 1 and Figure 3). At the time of collection, the UTW at the selected inlet spot consisted of a combined effluent from the whole city of Kasur, containing UTW from over 300 leather tannery units being small, medium and large sized, as well as the urban sewer of Kasur. Therefore, the collected UTW was strongly anticipated to have very high concentrations of heavy metals and organic pollution load.



Figure 1. Sampling location for UTW at the inlet of combined effluent treatment plant of KUTWMA, Kasur, Pakistan.

2.2. Collection of Hydrophytes, Viz. E. crassipes and P. stratiotes, Saplings for Application in HFFTW

Being an essential bioremedial component of HFFTW, the hydrophytes, viz. *E. crassipes* and *P. stratiotes* saplings, were collected in Nov 2024 from a pond established near a cottage industrial zone seasonally filled with wastewater from the adjoining areas of Kamahan-Lidher Road, Lahore, Pakistan (31°26′29.7″ N, 74°23′32.4″ E) (Figures 2 and 3). The pond selected as source of hydrophytes had a history of receiving highly polluted wastewater from the cottage industrial units mixed in the surrounding urban sprawl areas of Lahore. The collected hydrophyte saplings were at the early stage (two-leaf) at the time of sampling. Due to a documented pollution history of the selected pond, the hydrophytes saplings were anticipated to show a considerable tolerance to the pollution load in the UTW while being run through HFFTW.



Figure 2. Domestic-cum-cottage industrial wastewater pond along Kamahan-Lidher Road, Lahore, was selected as source of hydrophyte saplings transplanted in the developed HFFTW.

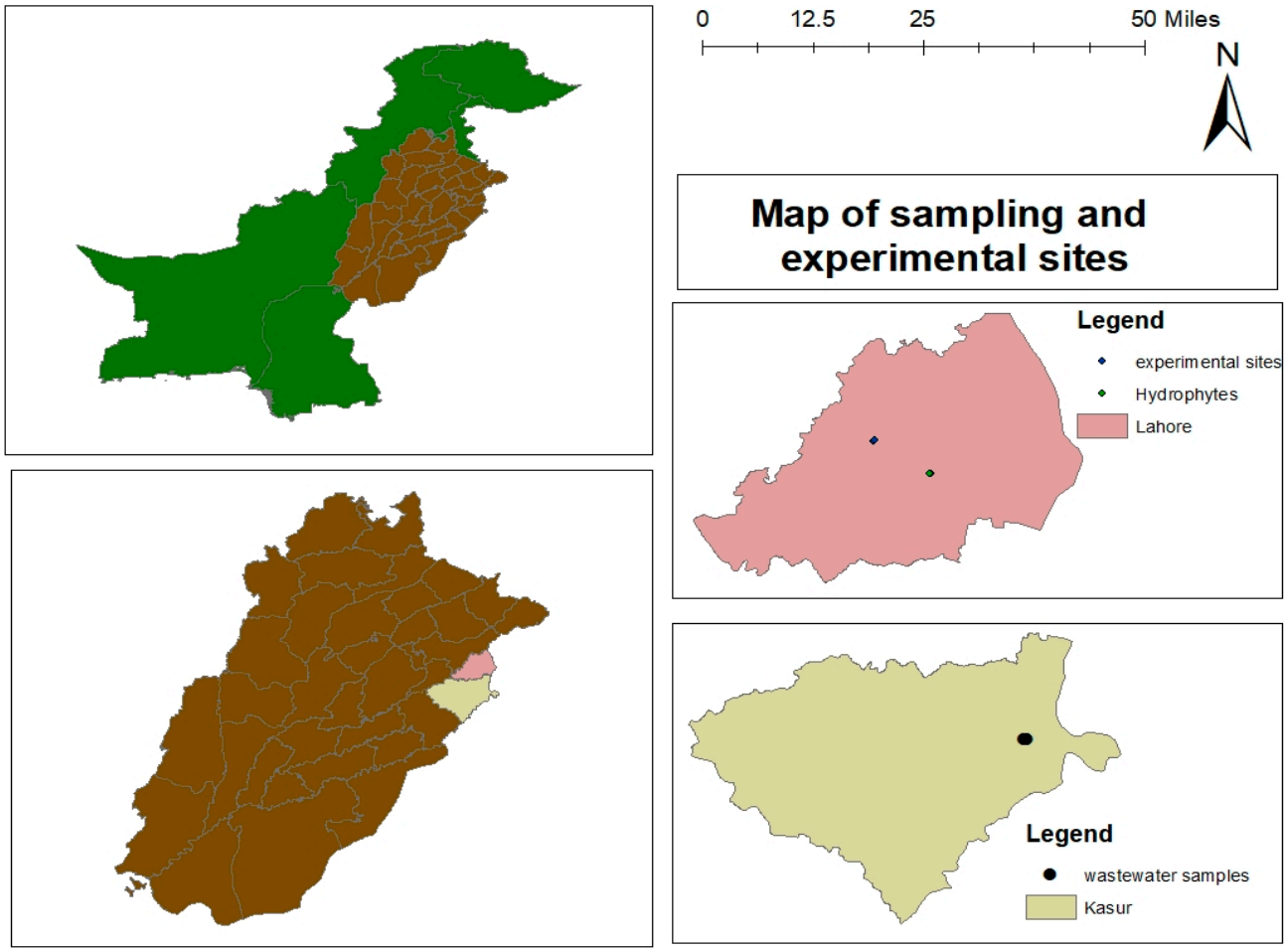


Figure 3. Geospatial representation of UTW collection areas in Kasur, with hydrophyte saplings collection and experimental setup locations in Lahore.

2.3. Physicochemical and Heavy Metal Analysis of UTW at Pre- and Post-Treatment Level

The collected UTW was analyzed for physicochemical parameters of wastewater quality analysis, commonly suggested and given by APHA [40], for characterization of water and wastewater. A benchtop (Hanna, model HI 9835) waterproof microprocessor EC/TDS/NaCl meter was used to measure EC (µS/cm), TDS (mg/L), and NaCl (%). A pH meter (EUTECH pc 510) was used to determine the pH of UTW samples. The COD of the

wastewater samples was determined by the ASTM standard method (ASTM D1252-06) [41]. To determine the BOD (mg/L), a 250 mL aliquot of UTW samples were loaded in the BOD bottles' self-check apparatus (BOD Sensor System 10, Velp, Italy) for monitoring BOD over five days [42]. TSS (mg/L), TDS (mg/L), TVS (mg/L), and SVI (mg/L) were determined by following the standard method envisaged by USEPA Method 1684 [43]. For the determination of heavy metals, the UTW samples were acid digested by following the standard methods given by USEPA Method 3052 [44], and metal (viz. Cr, Cd, Pb, and Cu) in the derived digestate was determined [42] by an atomic absorption spectrophotometer (AAS, Model: GBC SAVANT AA, Australia).

2.4. Designing and Testing HFFTW at Mesocosmic Level

The mesocosmic HFFTW design was based on the introduction of modifications in the selected horizontal flow treatment cells of the Constructed Wetland Field Experimental Station Prototype already installed at the Bioresource Unit in the Botanical Garden, University of the Punjab (31.499751° N, 74.301066° E), established and operated by the Environmental Biotechnology Research Laboratory, Institute of Botany, University of the Punjab Lahore-54590, Pakistan [42,45]. The experimental setup comprised two HFFTW treatment series, viz. *E. crassipes*-HFFTW (EC-HFFTW) series and *P. stratiotes*-HFFTW (PS-HFFTW) series, each having a treatment capacity of 222 L.

During the screening trials, the high pollution load of UTW did not let any plants grow in it. So, before introducing UTW in both HFFTW series, it was diluted at four levels of dilutions with harvested rainwater (HRW), viz. 0, 25, 50 and 75 (UTW:HRW % *v*:*v*). The detailed layout of the experimental design for UTW treatment through HFFTW is given in Table 1 and Figure 4A. The HRW used for making dilutions of UTW had been collected, stored, and maintained on a sustainable basis with details as given in Mahtab et al. [46]. In each HFFTW series, the hydrophytes were introduced by applying a Styrofoam lid, having holes for holding LDPE containers of hydrophyte sapling provisioned to protrude its root through the bottom holes of the container and contacting the horizontally flowing UTW through the HFFTW cells (Figure 4B–E).

Table 1. Experimental layout of the designed HFFTW series for treating UTW:HRW dilutions taken as treatments.

		HFFTW Series	HFFTW Treatment Cells			UTW:HRW Treated		Safer Irrigation Trials of Reclaimed Water from UTW	
			Cell-I	Cell-II	Cell-III				
Hydrophyte	*E. crassipes*	EC-HFFTW				0	UTW:HRW Dilutions (% *v*:*v*)	Post-treatment application of UTW:HRW dilutions	*P. hybrida*
		EC-HFFTW				25			*P. hybrida*
		EC-HFFTW				50			*P. hybrida*
		EC-HFFTW				75			*P. hybrida*
	P. stratiotes	PS-HFFTW				0	UTW:HRW Dilutions (% *v*:*v*)		*P. hybrida*
		PS-HFFTW				25			*P. hybrida*
		PS-HFFTW				50			*P. hybrida*
		PS-HFFTW				75			*P. hybrida*

Notes: HFFTW: horizontal flow floating treatment wetlands; UTW: untreated tannery wastewater; HRW: harvested rainwater.

The hydrophyte sapling in the HDPE container was mechanically supported by the anchorage provided by the substrates' layer comprising a combination of pebbles (15–40 mm diameter), coconut coir, soil, and rice straw biochar (Figure 4B). The applied substrate mixtures had already been found effective for establishing hydrophyte saplings in the HFFTW while offering an effective physisorption substratum with increasing surface area over time due to the development of microbial biofilms. The increased surface area of the bedding materials (Figure 4B) was facilitated in the substratum of hydrophytes to provide

circulation of air for provisioning aerobic decomposition of the organic pollution load and biophysical sorption of heavy metals from the UTW, i.e., for maximizing cumulative pollution removal efficiency of the HFFTW. Three treatment cells in a horizontal flow hydraulic flow pattern were connected to the sample feeding tank to make a set of HFFTW series for each UTW:HRW dilution (Figure 4A). Each HFFTW series was arranged as batch reactors with equal retention time, i.e., nearly 5 days in each treatment cell while total hydraulic retention time spanning over 15 days. The flow of water from one HFFTW treatment cell to the next was regulated with the help of a flow-control handle valve while hydraulic flow was being driven by artificial surface gradient, introduced by placing treatment cells in a series at a descending level than the preceding cell (Figure 4A), with further details given by Javeed et al. [42].

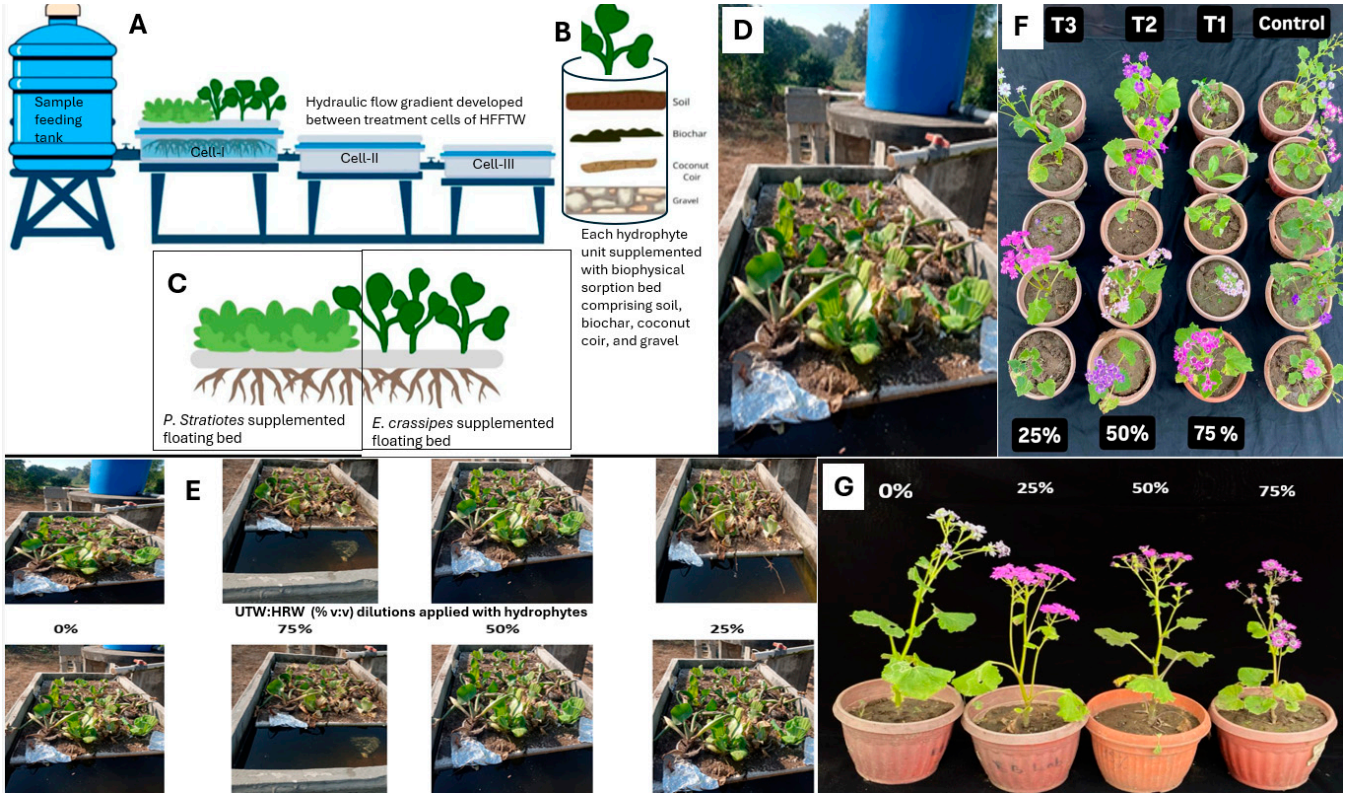


Figure 4. Experimental layout of the current study showing the experimental layout of the HFFTW, comprising a sample feeding tank followed by three treatment cells' supplemented with hydrophyte floating assembly (**A**); a hydrophyte unit in the floating assembly supplemented with biophysical sorption bed comprising soil, biochar, coconut coir, and gravel (**B**); floating assembly provided with hydrophytes, viz. *P. stratiotes* and *E. crassipes* (**C**); actual view of the treatment cell of HFFTW connected to a sample feeding tank (**D**); actual view of the HFFTW treatment cell series provided with UTW:HRW (% *v*:*v*) dilutions (**E**); safer irrigation testing of treated UTW with *P. hybrida* (**F**); and growth variations in *P. hybrida* to UTW:HRW (% *v*:*v*) dilutions treated through HFFTW (**G**).

The direct evaporation from the treatment cells was limited by the floating assemblies. However, transpiration loss of water from the hydrophyte leaves was determined using the relative weight monitoring of five independent 2 L pots placed analogous to a potometer for each UTW:HRW dilution after every 24 h. The control (reference for comparison purposes) set of five pots analogous to a potometer comprised the first pot filled with ground water left to evaporate, the second pot filled with UTW left to evaporate, the third pot filled with HRW left to evaporate, the fourth pot filled with groundwater and a hydrophyte sapling, and the fifth pot filled with HRW and hydrophyte. Compared to the relative weight difference in five reference pots, two representative pots for each UTW:HRW dilution filled

in the actual treatment cell were placed filled with similar UTW:HRW (% *v*:*v*) water, one with UTW:HRW water only and the other provided with HTW:HRW water and hydrophyte sapling. Here, the weight (g) loss due to transpiration was converted to the volume (mL) of transpired water from each type of reference pot, assuming that approximately 1 g is equal to 1 mL.

2.5. Phytoremediation Performance of P. stratiotes and E. crassipes

The phytoremediation performance of *P. stratiotes* and *E. crassipes* was compared on the basis heavy metal translocation factor (TF by Equation (1)) and heavy metal bio-concentration factor (BCF by Equation (2)). TF and BCF were computed based on the following formulae:

$$\mathrm{TF}_{\mathrm{root/leaf}} = \frac{\text{Heavy metal conc.}\left(\frac{\mathrm{mg}}{\mathrm{kg}}\right)\text{ in leaf}}{\text{Heavy metal conc.}\left(\frac{\mathrm{mg}}{\mathrm{kg}}\right)\text{ in roots}} \quad (1)$$

$$\mathrm{BCF} = \frac{\text{Heavy metal conc.}\left(\frac{\mathrm{mg}}{\mathrm{kg}}\right)\text{ in whole plant}}{\text{Heavy metal conc.}\left(\frac{\mathrm{mg}}{\mathrm{kg}}\right)\text{ in UTW : HRW dilution}} \quad (2)$$

2.6. Safer Irrigation Trials of Reclaimed Water from UTW with P. hybrida

Considering the 75% UTW:HRW (*v*:*v*) dilution with the highest UTW percentage, the reclaimed water from 75% treatment cells of both HFFTW series was applied as an irrigation source to the potted *P. hybrida* for assessing safer irrigation potential of the reclaimed water. The safer irrigation trials of the reclaimed water from UTW with *P. hybrida* were based on the experimental design given in Table 1. The safer irrigation response of *P. hybrida* was evaluated based on growth parameters and indicators of potential phytotoxicity assays. The growth parameters of the ornamental plant consisted of the number of leaves, shoot length, root length, fresh weight, and number of flowers. Heavy metal bioaccumulation factor (BAF by Equation (3)) in the harvestable parts of the plants was mainly taken as an indicator of potential phytotoxicity assay of the plants. For determination of BAF, the heavy metals analysis of plants was performed, for which *P. hybrida* plants were chemically (double acid) digested [44] after harvest from each type of UTW:HRW treatment cell. The metal conc. (viz., Cr, Cd, Pb, and Cu) was determined in the plant digestate through AAS by using methods given by Javeed et al. [42]. BAF of *P. hybrida* was determined by using the following formula:

$$\mathrm{BAF} = \frac{\text{Heavy metal conc.}\left(\frac{\mathrm{mg}}{\mathrm{kg}}\right)\text{ in whole plant}}{\text{Heavy metal conc.}\left(\frac{\mathrm{mg}}{\mathrm{kg}}\right)\text{ in UTW : HRW dilution}} \quad (3)$$

The heavy metal (Cr, Cd, Pb, and Cu) BAF of *P. hybrida* in each UTW:HRW dilution was plotted against the respective heavy metal (Cr, Cd, Pb, and Cu) BCF values of each of *P. stratiotes* and *E. crassipes* for assessing potential biosafety of the reclaimed water from UTW:HRW dilutions for the tested ornamental plant.

2.7. Silting Rate (mm/hr), Evaporation Rate (mm/day), and Yield (m^3/m^3) of Reclaimed Water from UTW:HRW Dilutions Through PS- and EC-HFFTW Series

For quantifying hydraulic performance of the HFFTW compared to the current lagoons of KTWMA, triplicate retention cells (horizontal cuboid glass containers) were established for UTW analogous to the treatment lagoons of KTWMA filled with UTW. The hydraulic performance of HFFTW was based on quantifying silting rate (kg/day by Equation (4)) of

mass accumulation rate of settled solids, evaporation rate (kg/m^2/day by Equation (5)), and yield (m^3/m^3 by Equation (6)) of the reclaimed water from UTW:HRW dilutions through the PS- and EC-HFFTW series.

$$\text{Silting rate (kg/day)} = \frac{\text{sludge density } \left(\frac{\text{kg}}{\text{m}^3}\right) \times \text{sludge layer volume at basin } \left(\text{m}^3\right)}{\text{time (day)}} \quad (4)$$

$$E_\Delta \left(\text{kg/m}^2\text{/day}\right) = -dW/Adt \approx -(W_t + \Delta t - W_t)/(A\Delta t) \quad (5)$$

Here, $E\Delta$: evaporation rate from the treatment cell (kg/m^2/day); W: wt. (kg) of water; t: time (day) based on time interval Δt (hrs); and A: surface area (m^2) of the treatment cell based on its top open surface (l × w) of closed cuboid treatment cell.

$$\text{Reclaimed water yield} = \text{Treated water volume } \left(\text{m}^3\right) / \text{Total fed volume } \left(\text{m}^3\right) \quad (6)$$

The hydraulic performance of the PS- and EC-HFFTW series was compared with conventional treatment lagoons of the KTWMA plant and was determined based on comparisons of above given parameters.

2.8. Data Analysis

Descriptive statistical measures such as mean, standard deviation, and standard error were used to summarize the data. The comparison of treatment effects and inter-variable relationships is performed through inferential statistical techniques. One-way Analysis of Variance (ANOVA) was used to make the comparison of significant differences between group means, and then a Least Significant Difference (LSD) test for post hoc. Pearsons' correlation was applied to find relationships between multiple independent and dependent variables and concurrently plotted through a heatmap. Microsoft Excel 2021 and IBM SPSS Statistics version 30 were used for all statistical tests and data visualizations.

3. Results

3.1. Pre-Treatment Characterization of UTW, HRW, and Groundwater

UTW at the pre-treatment level showed a highly significantly greater organic pollution load and conc. of basicity causing factors (Table 2). pH of UTW was alkaline compared to the slightly basic pH of ground water and acidic pH of HRW. Almost all the physicochemical parameters of UTW showed values way greater than the FAO (UN) guidelines for safer and sustainable use of reclaimed wastewater for irrigation. The EC (µS/cm) of the UTW was significantly greater than the ground water and HRW, being almost sixteen and two-hundred times greater, respectively. The high EC (µS/cm) of UTW, HRW, and ground water conformed with their NaCl (%), HCO_3^-, Cl^-, and TDS values, respectively.

The TSS contents in UTW were significantly greater than the ground water and HRW being over eight and fifteen times greater, respectively. SVI of UTW indicated poor settling characteristics, i.e., the values remained closer to the bulking sludge and required considerable adjustment for removal during its treatment. Regarding organic pollution load, BOD_5 of UTW was significantly greater, being over seven hundred times than ground water and HRW. Likewise, the COD of the HRW was over five hundred and fifty times greater than the ground water and HRW. There was a closer conformity of TVS with BOD_5 and COD of UTW. Thus, UTW was totally unfit for irrigating agricultural soils and a plant seed could neither germinate, nor could a plant seedling withstand UTW stress upon transplanting. Therefore, 100% UTW was only used for treatment though HFFTW, and its plant cultivation trials were not carried along during further experiments.

Table 2. Physicochemical properties of UTW, HRW, and groundwater used in the HFFTW series experiments.

Physicochemical Properties		UTW:HRW Dilutions (% *v*:*v*)					HRW	Ground Water
		0	25	50	75	100		
pH		5.6 ± 0.01	6.5 ± 0.02	7.4 ± 0.01	7.9 ± 0.03	8.9 ± 0.01	5.6 ± 0.01	7.6 ± 0.02
EC (µS/cm)		69.63 ± 1.1	198.3 ± 2.3	389.8 ± 2.7	572.9 ± 3.1	13,993 ± 14	69.63 ± 0.6	861 ± 2.9
NaCl (%)		0.0009 ± 0.001	0.04429 ± 0.002	0.07154 ± 0.03	0.31 ± 0.09	0.93 ± 0.1	0.0009 ± 0.003	0.013 ± 0.002
TDS	mg/L	67 ± 2.1	449.76 ± 4.3	726.54 ± 6.1	3148.3 ± 8.6	9445 ± 12	67 ± 2.1	581 ± 7.6
TSS		34 ± 1.1	24.29 ± 0.8	39.23 ± 1.4	170 ± 2.1	510 ± 2.8	131 ± 1.3	61 ± 2.1
TVS		BDL	22.52 ± 0.7	36.38 ± 0.9	157.67 ± 2.1	473 ± 5	1.43 ± 0.12	BDL
SVI		BDL	68.76 ± 0.7	54.15 ± 0.8	41.33 ± 2.1	38.2 ± 2.7	BDL	BDL
HCO_3^-		11.25 ± 0.8	9.67 ± 0.6	15.62 ± 1.1	67.67 ± 1.8	203 ± 2.7	11.25 ± 0.7	73.4 ± 1.9
Cl^-		35.97 ± 0.9	266.14 ± 4.2	429.92 ± 8.1	1863 ± 9.2	5589 ± 13.4	35.97 ± 0.9	21.8 ± 0.8
BOD_5		0.38 ± 0.01	66 ± 2.1	106.62 ± 2.5	462 ± 7.9	1386 ± 8.1	0.38 ± 0.001	1.94 ± 0.11
COD		3.81 ± 0.8	204.6 ± 2.8	330.5 ± 4.9	1432 ± 7.4	4297 ± 12.9	3.81 ± 0.09	7.8 ± 0.72
Cr		BDL	140.9 ± 1.5	305.2 ± 2.8	404.8 ± 3.3	549.4 ± 2.9	BDL	0.068 ± 0.008
Cd		BDL	45 ± 0.91	87.86 ± 1.1	140.6 ± 1.3	184.5 ± 2.1	BDL	0.046 ± 0.005
Pb		BDL	36.14 ± 0.85	77.7 ± 0.98	117.5 ± 1.89	155.4 ± 1.89	BDL	0.035 ± 0.002
Cu		BDL	32.65 ± 0.63	63.79 ± 0.93	96.76 ± 1.4	124.4 ± 1.63	BDL	0.893 ± 0.071

Notes: UTW: untreated tannery wastewater, HRW: harvested rainwater, HFFTW: horizontal flow floating treatment wetland, BDL: below detection limits (of the respective instrument).

UTW:HRW dilutions showed significant decline in all the physicochemical properties with the increasing percentage (*v*:*v*) of HRW (Table 1). Compared to 100% UTW, pH, EC, NaCl (%), TDS, TSS, TVS, SVI, and HCO_3^-, Cl^-, BOD_5, and COD values dropped by nearly one-fourth, half, and one-third with 75, 50, and 50% HRW (*v*:*v*), respectively.

3.2. Pollution Reduction Potential of HFFTW Series for UTW:HRW Dilutions

3.2.1. Reduction in Physicochemical Characteristics of UTW:HRW Dilutions Under PS- and EC-HFFTW Series

The conc. of physicochemical characteristics UTW:HRW (% *v*:*v*) dilutions at pre- and post-treatment level, and RE (%) in the PS-HFFTW series are given in Table 3. In 25% (*v*:*v*) dilution, all the physicochemical parameters showed significant optimization by a drop of values at post-treatment except pH and TSS, which showed an increase after treatment. The RE of physicochemical parameters for 25% (*v*:*v*) dilutions was 21, 50, 17, 23, 39, 25, 50, 63, and 60 for EC (µS/cm), NaCl (%), TDS, TVS, SVI, HCO_3^-, Cl^-, BOD_5, and COD, respectively. For 50% (*v*:*v*) dilutions, the PS-HFFTW treatment cells were 34, 20, 51, 35, 37, 46, 47, 44, 51, 56, and 56% RE for pH, EC (µS/cm), NaCl (%), TDS, TSS, TVS, SVI, HCO_3^-, Cl^-, BOD_5, and COD, respectively. In 75% (*v*:*v*) dilutions of the PS-HFFTW treatment cell series, RE (%) was 53, 35, 73, 78, 69, 57, 56, 80, 73, 79, and 78 for pH, EC (µS/cm), NaCl (%), TDS, TSS, TVS, SVI, HCO_3^-, Cl^-, BOD_5, and COD, respectively. In PS-HFFTW, the relative RE (%) variations in 25, 50, and 75% (*v*:*v*) UTW:HRW dilutions for pH, NaCl, TDS, TVS, HCO_3^-, and Cl^- were in the order of 75% > 50% > 25%. The comparative RE (%) variations in 25, 50, and 75% (*v*:*v*) UTW:HRW dilutions for EC (µS/cm), BOD5, and CD were in the order of 75% > 25% > 50%.

Based on its heavy metal removal efficiency, the PS-HFFTW treatment series showed promising potential for treating UTW. For 25% (*v*:*v*) dilutions, RE (%) for Cr, Cd, Pb, and Cu were 97, 91, 88, and 99, respectively. For 50% (*v*:*v*) dilutions, RE (%) were 96, 89, 94, and 95 for Cr, Cd, Pb, and Cu, respectively. In the case of 75% (*v*:*v*) dilutions, 95, 88, 92, and 95% RE were observed for Cr, Cd, Pb, and Cu, respectively. Physicochemical characteristics at pre- and post-treatment level, and RE (%) of UTW:HRW (% *v*:*v*) dilutions in the EC-HFFTW series, are given in Table 4. It was observed that in 25% (*v*:*v*) dilution, all the physicochemical parameters showed significant optimization by drop a of values at the post-treatment stage except for pH and TSS, which showed an increase after treatment.

Table 3. Pollution reduction potential of PS-HFFTW series for UTW:HRW dilutions.

Physicochemical Characteristics		UTW:HRW Dilutions (% *v*:*v*)								
		25			50			75		
		Pre-	Post-	RE (%)	Pre-	Post-	RE (%)	Pre-	Post-	RE (%)
pH		6.5	7.1	−92	7.4	7.15	34	7.9	7.48	53
EC (µS/cm)		198.3	156	21	389.8	313.2	20	572.9	373.45	35
NaCl (%)		0.0439	0.0221	50	0.0709	0.0349	51	0.3074	0.0828	73
TDS	mg/L	449.76	374	17	726.54	473.31	35	3148	679.4	78
TSS		24.29	32	−32	39.23	24.52	37	170	52.1	69
TVS		22.52	17.4	23	36.38	19.65	46	157.67	67.6	57
SVI		68.76	52.32	26	54.15	47.54	15	41.33	29.8	28
HCO_3^-		9.67	7.21	25	15.62	8.78	44	67.67	13.65	80
Cl^-		266.14	134.1	50	429.92	211.65	51	1863	501.9	73
BOD_5		66	24.4	63	106.62	46.81	56	462	94.73	79
COD		204.6	81.1	60	330.5	143.89	56	1432	311.89	78
Cr		140.9	4.23	97	305.2	13.21	96	404.8	19.81	95
Cd		45	4.23	91	87.86	9.66	89	140.6	17.4	88
Pb		36.14	4.23	88	77.7	4.66	94	117.5	8.9	92
Cu		32.65	0.33	99	63.79	3.05	95	96.76	5.04	95

Notes: UTW: untreated tannery wastewater; TTW: treated tannery wastewater, UTW dilutions: (% *v*:*v*) with harvested rainwater; RE: removal efficiency (%); PS-HFFTW: *P. stratiotes*-fed horizontal flow floating treatment wetland.

Table 4. Pollution reduction potential of EC-HFFTW series for UTW:HRW dilutions.

Physicochemical Characteristics		UTW:HRW Dilutions (% *v*:*v*)								
		25			50			75		
		Pre-	Post-	RE (%)	Pre-	Post-	RE (%)	Pre-	Post-	RE (%)
pH		6.5	6.99	−75	7.4	7.19	28	7.9	7.26	81
EC (µS/cm)		198.3	148.5	25	389.8	281.3	29.8	572.9	361.4	37
NaCl (%)		0.0439	0.0184	58	0.0709	0.0310	56	0.3074	0.0764	75
TDS	mg/L	449.76	324.8	28	726.54	411.4	43	3148	679.4	78
TSS		24.29	29.3	−21	39.23	19.78	50	170	52.1	69
TVS		22.52	14.76	34	36.38	15.64	57	157.67	67.6	57
SVI		68.76	49.93	36	54.15	45.91	15	41.33	26.9	35
HCO_3^-		9.67	6.89	29	15.62	6.49	56.2	67.67	13.65	80
Cl^-		266.14	111.8	58	429.92	187.9	56	1863	463.2	75
BOD_5		66	21.3	68	106.62	41.59	61	462	89.78	81
COD		204.6	68.89	66	330.5	117.81	64	1432	256.8	82
Cr		140.9	3.76	97	305.2	11.75	96	404.8	17.63	96
Cd		45	3.8	92	87.86	8.60	90	140.6	15.5	89
Pb		36.14	3.76	90	77.7	4.15	95	117.5	7.9	93
Cu		32.65	0.29	99	63.79	2.72	96	96.76	4.48	95

Notes: UTW: untreated tannery wastewater; TTW: treated tannery wastewater, UTW dilutions (% *v*:*v*) with harvested rainwater; RE: removal efficiency (%); EC-HFFTW: *E. crassipes*-fed horizontal flow floating treatment wetland.

The RE of physicochemical parameters for 25% (*v*:*v*) dilutions was 25, 58, 28, 34, 44, 29, 58, 68, and 66% for EC (µS/cm), NaCl (%), TDS, TVS, SVI, HCO_3^-, Cl^-, BOD_5, and COD, respectively. For 50% (*v*:*v*) dilutions, the EC-HFFTW treatment cells showed 28, 29.2, 56, 43, 50, 57, 58, 56.2, 56, 61, and 64% RE for pH, EC (µS/cm), NaCl (%), TDS, TSS, TVS, SVI, HCO_3^-, Cl^-, BOD_5, and COD, respectively. In 75% (*v*:*v*) dilutions of the EC-HFFTW treatment cell series, RE (%) was 81, 37, 75, 78, 69, 57, 56, 80, 75, 81, and 82 for pH, EC (µS/cm), NaCl (%), TDS, TSS, TVS, SVI, HCO_3^-, Cl^-, BOD_5, and COD, respectively. In

EC-HFFTW, the relative RE (%) variations in 25, 50, and 75% (*v*:*v*) UTW:HRW dilutions for pH, NaCl, TDS, TVS, HCO_3^-, and Cl^- were in the order of 75% > 50% > 25%. The comparative RE (%) variations in 25, 50, and 75% (*v*:*v*) UTW:HRW dilutions for EC (µS/cm), BOD5, and CD were in the order of 75% > 25% > 50%. Overall, the EC-HFFTW treatment series showed promising potential for treating UTW:HRW dilutions.

Overall, the EC-HFFTW treatment series showed promising potential for treating UTW based on its heavy metal removal efficiency. For 25% (*v*:*v*) dilutions, RE (%) for Cr, Cd, Pb, and Cu were 97.3, 91.6, 89.6, and 99.1, respectively. For 50% (*v*:*v*) dilutions, RE (%) were 96.1, 90.2, 94.7, and 95.7 for Cr, Cd, Pb, and Cu, respectively. In case of 75% (*v*:*v*) dilutions, 95.6, 89, 93.3, and 95.4% RE were observed for Cr, Cd, Pb, and Cu, respectively.

The comparisons of PS- and EC-HFFTW for RE (%) of the physicochemical properties of UTW:HRW dilutions are given in Table 5. The RE (%) pattern of the PS- and EC-HFFTW treatment series contemplated for all the physicochemical parameters. However, the EC-HFFTW series showed a significantly greater RE (%) than the PS-HFFTW series for all the physicochemical parameters in all UTW:HRW dilutions except pH and TSS of 25% dilutions (*v*:*v*). Heavy metals RE (%) of UTW:HRW dilutions (% *v*:*v*) under PS-HFFTW were less significant than the heavy metals RE (%) of UTW:HRW dilutions in CS-HFFTW.

Table 5. Comparison of PS- and EC-HFFTW for RE (%) of the physicochemical properties of UTW:HRW dilutions.

Physicochemical Characteristics		UTW:HRW Dilutions (% *v*:*v*)					
		25		50		75	
		PS-HFFTW	EC-HFFTW	PS-HFFTW	EC-HFFTW	PS-HFFTW	EC-HFFTW
pH		−92.3	−75.4	33.8	28.4	53.2	81
EC (µS/cm)		21.3	25.1	19.7	27.8	34.8	36.9
NaCl (%)		49.6	58	50.8	56.3	73.1	75.1
TDS		16.8	27.8	34.9	43.4	78.4	78.4
TSS		−31.7	−20.6	37.5	49.6	69.4	69.4
TVS		22.7	34.5	46	57	57.1	57.1
SVI		39.3	43.7	46.7	58.2	56.1	56.1
HCO_3^-		25.4	28.7	43.8	58.5	79.8	79.8
Cl^-	mg/L	49.6	58	50.8	56.3	73.1	75.1
BOD_5		63	67.7	56.1	61	79.5	80.6
COD		60.4	66.3	56.5	64.4	78.2	82.1
Cr		97.0	97.3	95.7	96.1	95.1	95.6
Cd		90.6	91.6	89.0	90.2	87.6	89.0
Pb		88.3	89.6	94.0	94.7	92.4	93.3
Cu		99.0	99.1	95.2	95.7	94.8	95.4

Notes: UTW: untreated tannery wastewater; TTW: treated tannery wastewater, UTW dilutions (% *v*:*v*) with harvested rainwater; RE: removal efficiency (%); EC-HFFTW: *E. crassipes* fed horizontal flow floating treatment wetland.

3.2.2. Heavy Metal Conc. in Roots and Shoots of *P. stratiotes* and *E. crassipes* and Their Phytoremediation Performance

From UTW:HRW (% *v*:*v*) dilutions, heavy metal concentration (mg/kg) in roots, shoots and $Ti_{s\text{-}r}$ of *P. stratiotes* in PS-HFFTW and *E. crassipes* in EC-HFFTW are given in Table 6.

Considerably high conc. of all heavy metals from all UTW:HRW dilutions (*v*:*v*) were absorbed by the roots and subsequently translocated to the shoots of *P. stratiotes* and *E crassipes*. Highest Cr accumulation was observed in shoots of *E. crassipes* (98.6 mg/kg) and *P. stratiotes* (85.2 mg/kg), while the least Cr absorption was observed in roots of *P. stratiotes* and *E. crassipes* at 54.3 mg/kg, 30.5 mg/kg, respectively. The relative metal absorption in shoots of *P. stratiotes* followed the order Cr > Cu > Pb > Cd and in shoots of *E. crassipes*

followed the order Cr > Cd > Pb > Cu. The relative metal absorption in roots of *P. stratiotes* followed the order Cr > Cu > Pb > Cd and in roots of *E. crassipes* followed the order Cr > Cd > Pb > Cu.

Table 6. Comparison of bioaccumulation of heavy metals in shoots and roots and translocation index of *P. stratiotes* and *E. crassipes* in 75% UTW dilution.

Metals	Plant Attribute	*P. stratiotes*	*E. crassipes*
Cr	Shoot (mg/kg)	85.2 ± 0.66	98.6 ± 0.86
	Root (mg/kg)	30.5 ± 0.6	54.3 ± 0.76
	$TE_{root\text{-}shoot}$	*2.79*	*1.82*
Cd	Shoot (mg/kg)	45.1 ± 0.67	58.8 ± 0.75
	Root (mg/kg)	13.6 ± 0.62	31.7 ± 0.64
	$TE_{root\text{-}shoot}$	*3.12*	*1.85*
Pb	Shoot (mg/kg)	49.2 ± 0.73	49.7 ± 0.83
	Root (mg/kg)	21.7 ± 0.36	28.3 ± 0.6
	$TE_{root\text{-}shoot}$	*2.27*	*1.76*
Cu	Shoot (mg/kg)	51.2 ± 0.59	35.2 ± 1.01
	Root (mg/kg)	24.5 ± 1.12	18.3 ± 0.56
	$TE_{root\text{-}shoot}$	*2.09*	*1.92*

Translocation index for all the heavy metals was ≥1 for both hydrophytes, i.e., *E. crassipes* and *P. stratiotes*, and proved to be heavy metal hyperaccumulators in the 75% UTW dilution; i.e., both hydrophytes showed promising metal removal potential from a relatively concentrated UTW treatment, i.e., 75% for yielding reclaimed wastewater from tannery industries and prospects of its application as a relatively safer irrigation source. The relative order of Tis-r for *P. stratiotes* was Cd > Cr > Pb > Cu and Tis-r for *E. crassipes* was Cu > Cd > Cr > Pb.

The BCF comparisons of *P. stratiotes* and *E. crassipes* in UTW:HRW dilutions under PS- and EC-HFFTW are given in Figure 5.

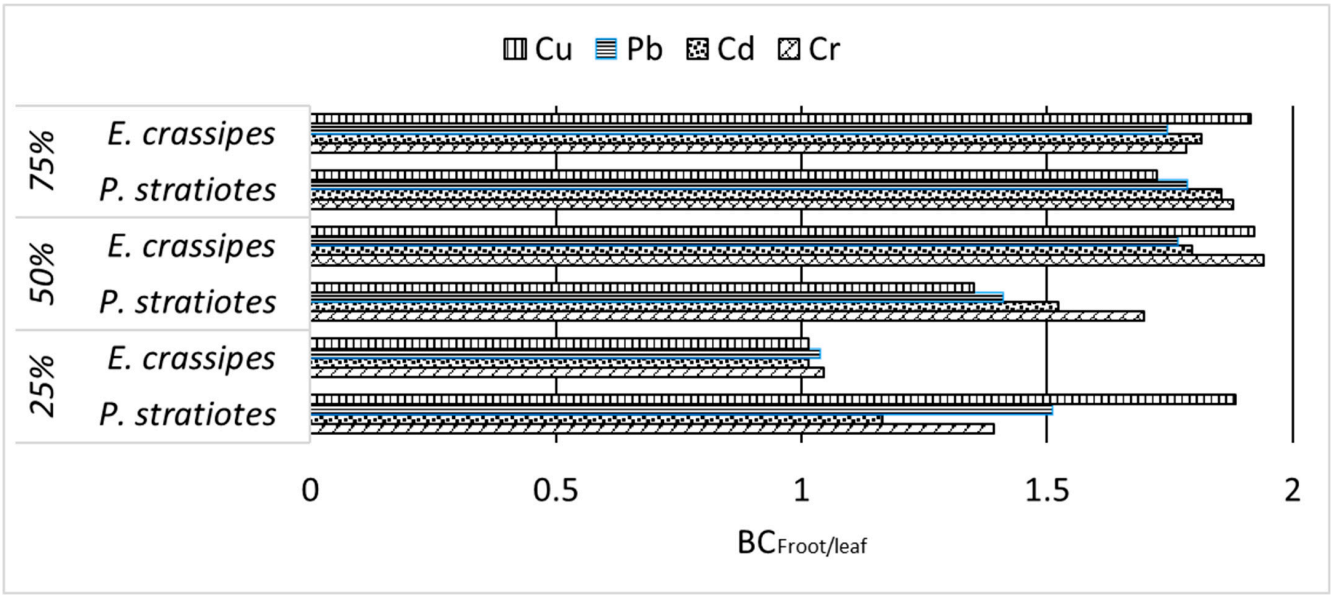


Figure 5. Comparisons of heavy metals BCF in UTW:HRW (% *v:v*) dilutions treated through PS- and EC-HFFTW.

Both *P. stratiotes* and *E. crassipes* showed a BCF value ≥ 1, i.e., and they performed as promising hyperaccumulators for significant removal of Cr, Cd, Pb, and Cu from UTW:HRW dilutions. *E. crassipes* showed a significantly greater value of BCF than *P. stratiotes* for Cr, Cd, Pb, and Cu. The BCF values of *E. crassipes* were highest and lowest in 75% and 25% UTW:HRW dilutions, i.e., *E. crassipes* acted as an ideal hyperaccumulator hydrophyte for EC-HFFTW. *P. stratiotes* also gave highly encouraging results as its BCF in 75% UTW:HRW, i.e., its establishment and subsequent propagation in the treatment cells of PS-HFFTW, was stronger.

3.3. Safer Irrigation Performance of P. hybrida in Reclaimed Water from UTW:HRW Dilutions Through PS- and EC-HFFTW

After 63 days of cultivation while being irrigated with reclaimed water from UTW:HRW dilutions (*v*:*v* %) through PS- and EC-HFFTW, *P. hybrida* plants showed a promisingly safer biomass with very low BAF (Figure 6).

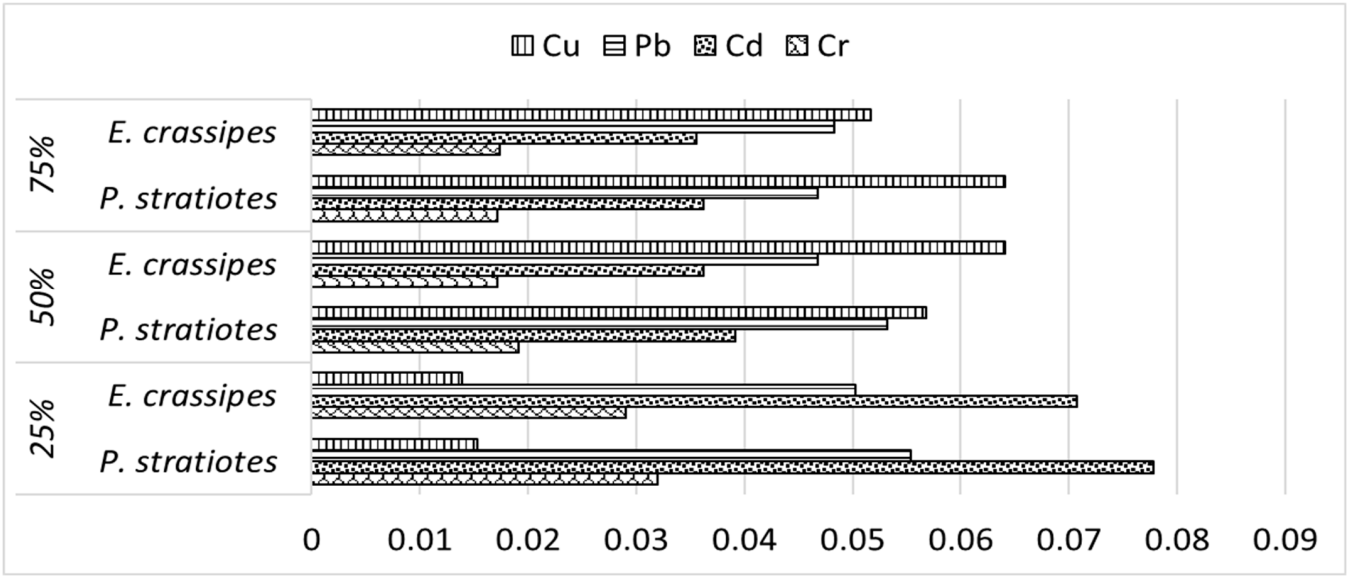


Figure 6. Comparisons of heavy metals BAF in 63-days-old *P. hybrida* irrigated with UTW:HRW (% *v*:*v*) dilutions treated through PS- and EC-HFFTW.

BAF of Cr, Cd, Pb, and Cu under irrigation of the reclaimed water from UTW:HRW were <0.08 in *P. hybrida.* The reclaimed water acted as an ecological, safer aquatic resource for the cultivated ornamental plants and potential phytotoxicity in the harvested ornamental plants were highly unlikely, even for reclaimed water derived from 75% UTW:HRW.

As given in Figure 7, there was strong negative Pearson's correlation between BAF heavy metals (Cr, Cd, Pb, and Cu) of *P. hybrida* vs. BCF heavy metals of *P. stratiotes* (Cr, Cd, Pb, and Cu) in UTW:HRW (% *v*:*v*) dilutions. The values of coefficient of Pearson's correlation for the UTW:HRW (% *v*:*v*) dilutions were in the order of 25% > 50% > 75%. The values of the coefficients of Pearson's correlation were near −1 (−0.95) for 75% UTW:HRW dilutions for 25% and near −4 (−0.38) for 75% UTW:HRW dilutions. Amongst the heavy metals, the coefficients of Pearson's correlation were in the order of Cu > Pb > Cd > Cr. The coefficients of Pearson's correlation for heavy metals were near −1 for Cu (−0.949) and near −4 (−0.366) for Cr.

As given in Figure 8, there was a strong negative Pearson's correlation between BAF heavy metals (Cu, Pb, Cd, and Cr) of *P. hybrida* vs. BCF heavy metals (Cr, Cd, Pb, and Cu) of *E. crassipes* in UTW:HRW (% *v*:*v*) dilutions. The coefficients of Pearson's correlation for the UTW:HRW (% *v*:*v*) dilutions were in the order of 25% > 50% > 75%.

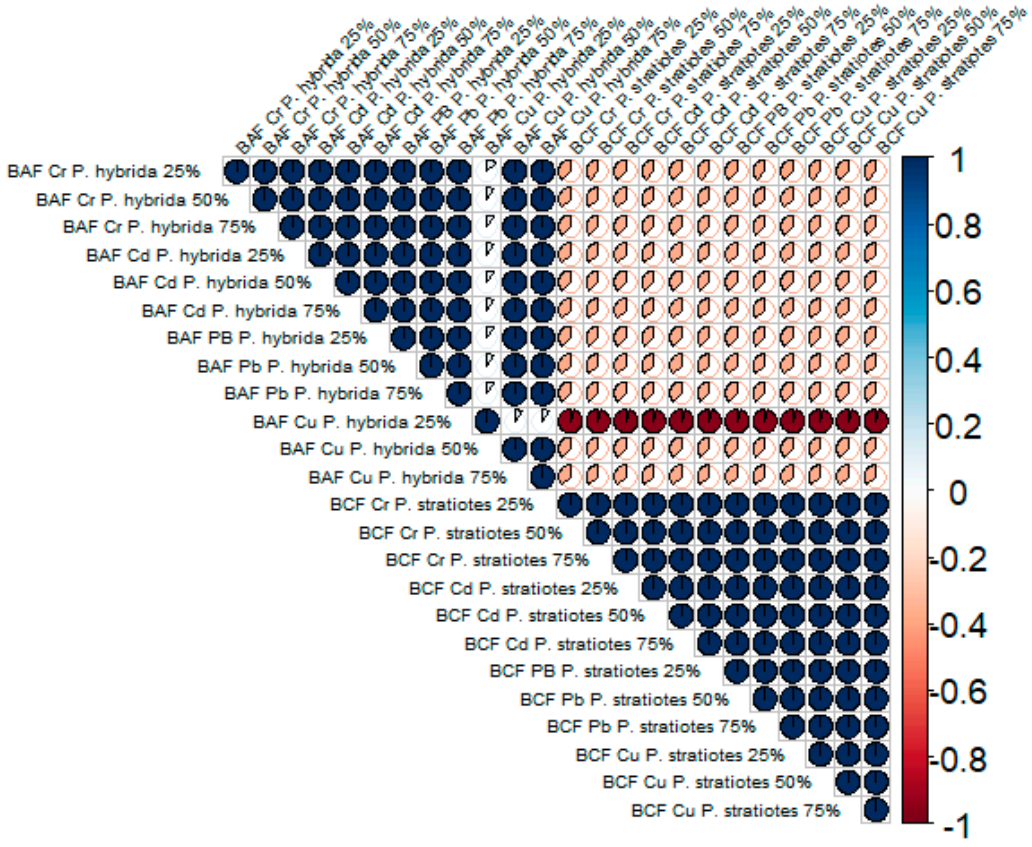


Figure 7. Pearson's correlation coefficients between BAF heavy metals (Cr, Cd, Pb, and Cu) of *P. hybrida* and heavy metal (Cr. Cd Pb, Cu) BCF of *P. stratiotes* in UTW:HRW (% *v*:*v*) dilutions.

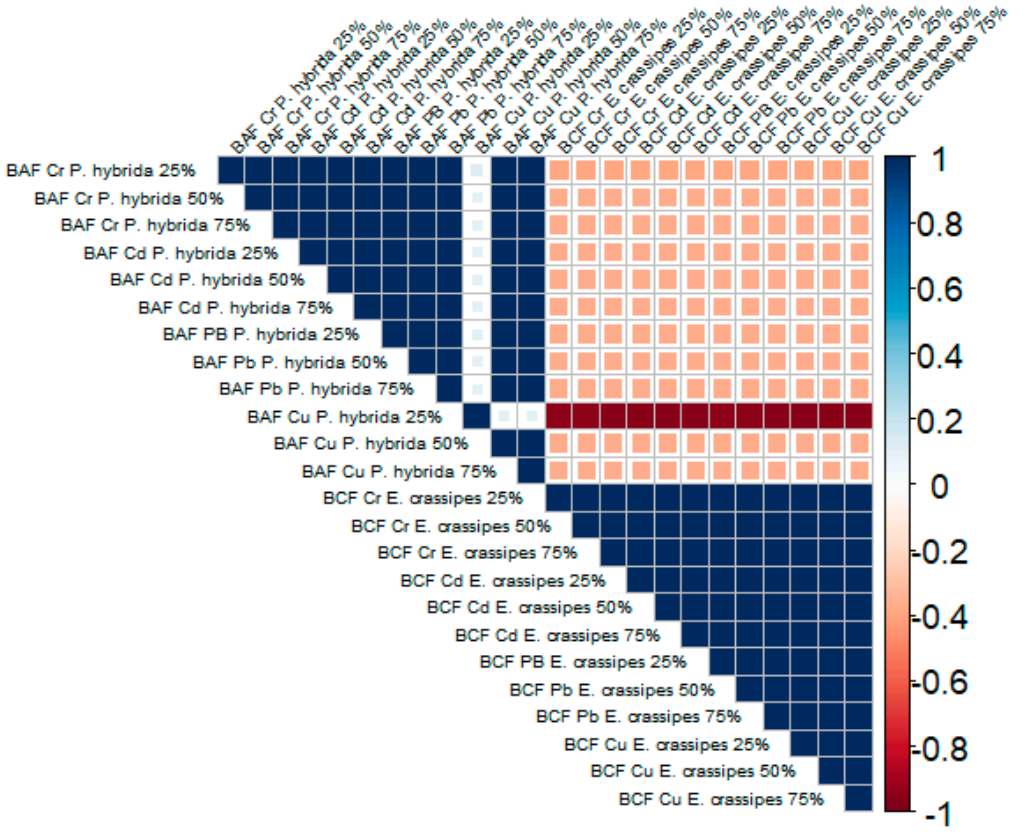


Figure 8. Pearson's correlation coefficients between BAF heavy metals (Cr, Cd, Pb, and Cu) of *P. hybrida* and heavy metal (Cr. Cd Pb, Cu) BCF of *E. crassipes* in UTW:HRW (% *v*:*v*) dilutions.

The values of the coefficients of Pearson's correlation were near −1 (−0.944) for 25% UTW:HRW dilutions and near −4 (−0.346) for 75% UTW:HRW dilutions. Amongst the heavy metals, the coefficients of Pearson's correlation were in the order of Cu > Pb > Cd > Cr. The values of coefficient of Pearson's correlation for heavy metals were near −1 for Cu (−0.945) and near −4 (−0.37) for Cr. Overall, values of coefficient of correlation for BAF heavy metals of *P. hybrida* vs. BCF heavy metals of *P. stratiotes* were greater than BAF heavy metals of *P. hybrida* vs. BCF heavy metals of *E. crassipes* for UTW:HRW dilutions.

3.4. Variations in Silting Rate, Evaporation Rate (mm/day), and Yield of Reclaimed Water

For assessing hydraulic performance, comparisons of silting rate, evaporation rate, and yield of reclaimed water from UTW:HRW dilutions through the PS- and EC-HFFTW series are given in Figure 9. The silting rate of sludge was highest for 75% UTW:HRW dilution in PS-HFFTW and it was significantly improved as compared to the silting rate in settling cell analogous to the settling lagoon of KTWMA plant of Kasur. The lowest silting rate of sludge was observed in 25% UTW:HRW dilution in PS-HFFTW. The evaporation rate of water from the treatment cells was highest for 25% UTW:HRW dilutions in PS-HFFTW and lowest for 75% UTW:HRW dilutions in EC-HFFTW, being near to the evaporation rate for settling cell analogous to the settling lagoon of KTWMA plant of Kasur. The yield of reclaimed water was highest for 75% UTW:HRW dilutions in PS-HFFTW and lowest for 25% UTW:HRW dilutions in EC-HFFTW.

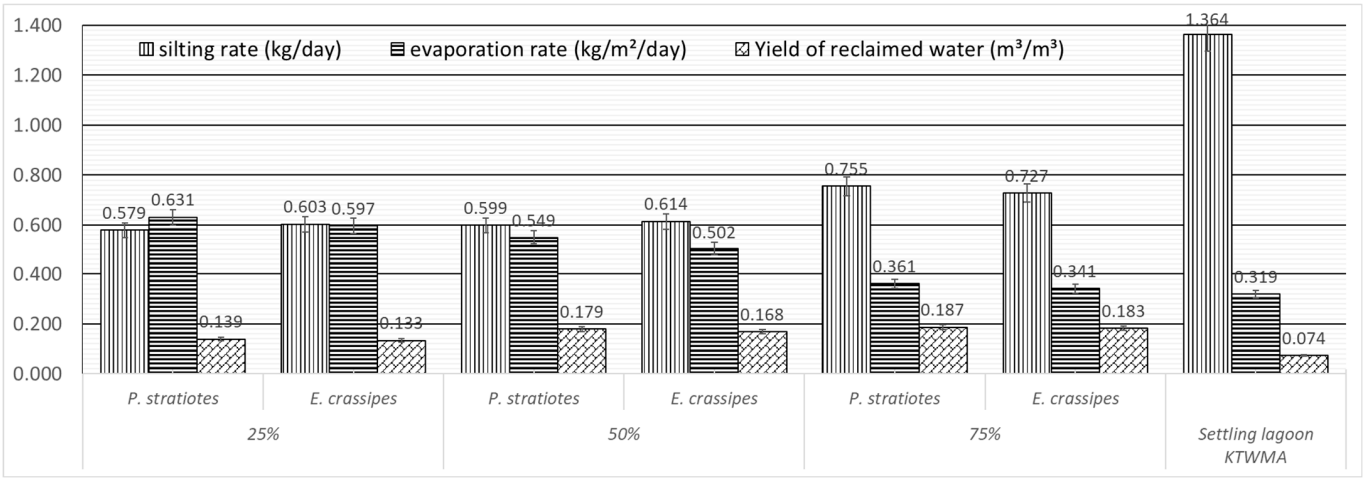


Figure 9. Comparisons of silting rate, evaporation rate, and yield of reclaimed water from UTW:HRW dilutions through PS- and EC-HFFTW.

4. Discussion

Pollution load (non-metallic radicals, heavy metals and organic pollution) in the UTW was way greater than the permissible limits envisaged for its discharge into inland waters at a national level (at Pakistan level) [47] and at guidelines for safer use of reclaimed water in agriculture given by FAO/WHO [48]. UTW in its actual form was highly toxic and had the least provision for its treatment through conventional FTWs, as it did not let either PS or EC grow on the transplantation during screening trials. The discharge of poorly treated or UTW into inland water carried a potential risk of pollution of the receiving of freshwater bodies and irrigated agricultural soils with heavy metals and organic pollution load. The chrome tanning method inherently carries excessive application and discharge of Cr and other heavy metals, which are highly toxic to the flora and fauna of the receiving bodies. High organic pollution load (high values of BOD and COD) of the UTW with high TSS

and TS load caused inherent resistance to the applied phytoremediation-based wastewater treatment approaches like conventional FTWs.

Conventionally, FTWs have been commonly exploited for the treatment of wastewater under shallow conditions, i.e., while retaining stagnant water in pools and introducing floating assemblies on surface of stagnant water with around 50% cover of the floating assemblies. Such designs of FTW have been extremely limited in RE (%) pollution from wastewater due to severely restricted interaction of hydrophytes with the wastewater. With nearly $\leq$50% coverage of floating assemblies and depth of stagnant water in the wastewater pools way greater than the length and number of hydrophyte roots, the conventional FTWs remain restricted to the surface of wastewater up to a couple of centimeters deep only. Generally, stagnant water undergoes limited mixing of oxygen and removal of BOD while undergoing severe silting and raising of the bed of wastewater treatment ponds. In such a situation, conventional FTWs show limited efficacy for treating even municipal sewers, though they contain a highly reduced pollution load compared to industrial effluents. Applying conventional FTWs for the treatment of industrial effluents has been quite an incompatible combination as reported by much of the literature published on the treatment of industrial effluent with conventional FTWs [29,49–51], reporting a significant reduction in pollution load. In view of the challenges faced by the conventional FTWs, this study developed HFFTW, a design to overcome highlighted limitations of the conventional FTWs.

The foremost challenge was incompatibility of the hydrophytes with the high pollution (heavy metals and BOD) load of UTW as neither PS nor EC survived in the 100% (*v*:*v*) UTW, i.e., the phytotoxicity of UTW was beyond phytotolernace of PS and EC. To overcome this challenge, dilution of UTW with unpolluted water was a plausible solution to treat UTW through hydrophytes applied in FTWs. However, using fresh water as dilution factor for UTW could have intensified water footprints of FTWs. Hence, HRW was used to dilute UTW for bringing its pollution load within the phytotoxicity limits of the selected hydrophytes by making UTW:HRW dilutions (25, 50, and 75% *v*:*v*), as has been performed and found effective earlier in the same research laboratory [46]. Consequently, both PS and EC were established in the UTW:HRW dilutions and showed a promising relative growth rate after transplantation in the treatment cells of HFFTW. Consequently, two series of HFFTW were derived, viz. HS- and EC-HFFTW. The application of HRW as a diluting factor for UTW enabled HFFTW to become suitable for treating UTW along with the addition of sustainability to the FTWs by lowering water footprints of the FTWs, though they were not computed during the current study. At a filed scale, an accidental addition of HRW to UTW for lowering its pollution load has been generally observed for the sludge-settling lagoons of the combined effluent plant of KTWMA, Kasur, Pakistan, during summer monsoon seasons witnessed by the induction and establishment of some tolerant algae. The addition of algae in the UTW driven by HRW dilutions has been reported [40] while providing improved oxidation of the UTW for improving BOD removal and evaporation loss. Diluting UTW with HRW improved performance of the floating assemblies of conventional FTWs by avoiding development of anoxic conditions in the treatment cells of HFFTW. Addition of HRW to UTW as a dilution factor kept hydrophytes living as active phytoremediation agents in the HFFTW throughout the treatment cycles of the current study. In other words, diluting UTW with HRW enabled hydrophytes' survival, being essential for keeping HFFTW functional for pollution removal until the batch of UTW reaches to the desired pollution RE (%).

Another improvement applied to the conventional FTWs was feeding UTW:HRW dilutions into a series of concrete-made treatment cells interconnected through hydraulic flow pipes (Figure 4A,E). Treating UTW:HRW dilutions through closed cuboid cells with the surface covered with a floating assembly added multiple advantages to the developed

HFFTW. The loss of UTW:HRW through lateral and vertical infiltration and percolation was omitted, which enhanced yield of reclaimed water from UTW:HRW dilutions. Introduction of continuous horizontal flow up to 0.81 m deep had enabled continuous mixing of atmospheric oxygen in the UTW:HRW dilutions while maximizing its contact with the roots of the hydrophytes applied in the floating assemblies. Such factors helped in bringing the hydraulic load of the HRW:HRW dilutions within the treatment range of the hydrophytes and oxidation due to hydraulic flow and significant reduction in silting as indicated by significant reduction in sludge silting rate in the treatment cells.

In the current study, the EC-HFFTW series was more effective than the PS-HFFTW series for the removal of non-metallic radicals, heavy metals, and BOD. EC exhibited a larger size and number of roots and shoots than PS, i.e., greater biomass of PS enabled greater uptake and accumulation of heavy metals. Hence, the BAF values of EC were larger than the BAF values. Overall, the uptake of non-metallic radicals and metals by both hydrophytes had rendered a significant drop in the TDS values of UTW:HRW dilutions in the PS- and EC-HFFTW. Vigorous growth of both hydrophytes in the confined water within the closed cuboid treatment cells led to establishment of an extensive contact of hydrophyte roots throughout the column of UTW:HRW dilutions. The drop in TDS values of UTW:HRW dilutions had also led to a drop in its salinity factor values. Cumulatively, there was a significant drop in the pollution load of UTW:HRW dilutions in both the PS- and EC-HFFTW series. Both PS [52] and EC [52] have been reported to show promising phytoremediation of excessive nutrients and heavy metals after gaining healthy growth in the chrome tanning wastewater. Significantly high values of RE (%) of PS and EC made it evident that the reduced values of TDS, soluble salinity factors, and heavy metals conformed with bioaccumulation in the shoots and roots of PS and EC. The high values of heavy metal $TE_{root\text{-}shoot}$ (%) conformed with the removal of heavy metals in the treated UTW:HRW dilutions i.e., removal of heavy metals was due to strong hyperaccumulator performance of both hydrophytes.

In the present study, *E. crassipes* outperformed *P. stratiotes* in terms of BCF and average metal RE (%) mainly because of significantly greater root and shoot sizes and overall biomass production. Roots of *E. crassipes* were larger with a greater fibrous network, giving it more root density than *P. stratiotes.* Consequently, *E. crassipes* had a larger root surface area than *P. stratiotes*, being ideal for greater sorption of metals and its subsequent translocation into its aerial parts for storage and retention. Generally, *E. Crassipes'* cell wall contains more polysaccharides (pectin, lignin, and hemicellulose) and functional groups with a negative charge such as -COOH and -OH [53–55], which enable their roots to show strong affinity for cationic metals in the wastewater. On the contrary, *P. stratiotes'* roots being shorter in size, having reduced fibrousness and low polysaccharide contents, show limited ion exchange and metal sorption capacity.

The safer irrigation potential of the reclaimed water from UTW:HRW dilutions was based on irrigation of *P. hybrida.* Heavy metal BCF of *P. hybrida* was significantly lowered in treatments containing reclaimed water with high RE (%). Concurrently, BAF of both hydrophytes, viz. PS and EC, had increased, which conformed mass flow of heavy metals, excessive nutrients, and salinity factors within the biotic components of the PS- and EC-HFFTW series. The coefficients of Pearson's correlation between the BCF of *P. hybrida* and the BAF of each of PS and EC are highly negative, i.e., the BCF of *P. hybrida* had dropped with the increased values of the BAF of PS and EC. These results confirmed that the potential biosafety risk of reclaimed water had significantly dropped after treating UTW:HRW through the PS- and EC-HFFTW series. The total concentration of pollutants remains constant in the wastewater treatment systems while undergoing shifts in the pools of heavy metals and excessive nutrients [56]. The pollutant storage dynamics of the

phytoremediation agents in the applied phytoremediation wastewater treatment systems are monitored by indices like BAF, BCF, etc. [57]. Irrigating ornamental plants for assessing the potential biosafety of reclaimed water based on its BCF and plotted against the BCF of hydrophytes proved effective as an anticipatory way of drawing compatibility of reclaimed water for its applications.

The silting rate decreased with increased concentrations of HRW in all the UTW:HRW dilutions except for 75% dilution in EC-HFFTW. As well, the evaporation rate of water from treatment cells increased with increasing concentrations of HRW in UTW:HRW dilutions. On the contrary, the yield of reclaimed water decreased with increasing concentrations of HRW in UTW:HRW dilutions. The silting rate for PS-HFFTW was greater than the corresponding EC-HFFTW series for all the UTW:HRW dilutions except for 25% dilutions. The evaporation rate of water from treatment cells of the EC-HFFTW series was greater than the PS-HFFTW series for all the UTW:HRW dilutions. The yield of reclaimed water was greater in the PS-HFFTW series than the respective EC-HFFTW series for all the UTW:HRW dilutions. Overall, hydraulic performance of both the PS- and EC-HFFTW was significantly greater than the settling cells analogous to the settling lagoons of KTWMA plant Kasur.

The developed HFFTW lowered the silting rate of sludge compared to the conventional FTWs, resulting in less clogging of the bedding media. Generally, the conventional FTWs [50,51] keep wastewater retained in the treatment ponds/troughs under stagnant conditions for longer periods, which leads to poor agitation and wave action in the standing water, and results in high silting rate. On the other hand, the continuous flow in the HFFTW established high wave action and agitation in the treatment cells throughout treatment time, establishing a stronger mixing of air while lowering silting rate and clogging of bedding media. The mixing of air throughout the wastewater column caused by the continuous agitation in the treatment cells of HFFTW strongly drove aerobic decomposition of organic pollution, which resulted in significantly greater removal of BOD in HFFTW than the conventional FTW. Establishment of aerobic niche in the UTW for the aerobic microbial consortia of UTW also enhanced mineralization of metals for an efficient uptake by the hydrophytes, leading to their increased BCF and rendering high average metal RE (%). The continuous horizontal flow of UTW below the floating assemblies of HFFTW underwent significantly lower evaporation loss, lower than the conventional FTWs, resulting in a higher yield of treated UTW for HFFTW than conventional UTW. Hence, HFFTW retrofitted the deep wastewater constraints of the FTW as well as lowered its water footprints.

Overall, introducing dilution of UTW with HRW in the conventional FTWs brought the treatment probability of UTW within the RE (%) capacity of the HFFTW, contrary to the conventional FTWs. It could pave the way for annexing HFFTW as a potential replacement of the highly inefficient plants, mainly based on the passive retention of wastewater in treatment ponds for many weeks to months, like the current design of the KTWMA plant. Introducing dilution of UTW with HRW in the conventional FTWs kept hydrophytes viable and actively involved in pollution treatment for prolonged durations compared to conventional FTWs. The continuous flow through the treatment cells of modified FTWs helped in avoiding depth reduction of FTW's treatment cells while optimizing desilting of both PS- and EC-HFFTW series and ensuring sufficient mixing of oxygen for the removal of BOD.

5. Conclusions

The current study concluded that the designed HFFTW retrofitted hydraulic and pollution load limitations of conventional FTWs by increasing yield and treatment levels of UTW. *E. crassipes* and *P. stratiotes* planted in an HFFTW showed promising pollutant removal efficiency for UTW after it was diluted with HRW as it reduced the phytotoxicity

of UTW to the phytotolerance range of both hydrophytes. Introducing horizontal flow within the treatment cells reduced the silting and evaporation rate of UTW while increasing the yield of reclaimed water. The HFFTW is another alternative approach to the traditional methods used for wastewater treatment, as it utilizes hydrophytes that float over wastewater, and the root biomass develops in contact with the water column below the floating bed and is responsible for processes such as filtration, adsorption, and microbial activities. There was a significant decline in heavy metals; *E. crassipes* demonstrated a sizable decrease in Cr, Cd, Pb, and Cu for a UTW concentration of 75%. Rice biochar, soil, coconut coir, and pebbles used in the floating bed assembly also enhanced the removal efficiency of wastewater pollutants such as BOD_5, COD, and others. HFFTWs are environmentally friendly, cost effective, and have high phytoremediation potential. The current research also observed that *P. hybrida* irrigated with treated wastewater from the floating wetland system promoted a promising growth of plants, suggesting that the UTW through HFFTW could be reused for irrigation for agricultural purposes.

The study contributed to circular water use while overcoming inherent capacity limitations of the conventional UTWs, which could be employed for addressing potential policy implications related to UTW management prospects of KTWMS, Kasur, Pakistan, and similar scenarios in other parts of the world. The current study included quantifying the optimization of water footprints of the HRW on adding to the UTW as a dilution factor. Deriving concrete of the HFFTW treatment cells by recycling and reusing of construction and road demolition waste could be another future endeavor of the current study.

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Abbreviations

The following abbreviations are used in this manuscript:

AAS	Atomic absorption spectrophotometer
APHA	American Public Health Administration
BAF	Bioaccumulation factor
BCF	Bioconcentration factor
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
EC	*Eichhornia crassipes*

EC-HFFTW	E. crassipes-HFFTW
FAO (UN)	Food and Agriculture Organization of the United Nations
FTWs	Floating treatment wetlands
HFFTWs	Horizontal flow floating treatment wetlands
HRW	Harvested rainwater
KTWMA	Kasur Tannery Waste Management Agency (Kasur, Pakistan)
PS	*Pistia stratiotes*
PS-HFFTW	*P. stratiotes*-HFFTW
SVI	Sludge volume index
TDSs	Total dissolved solids
$Ti_{s\text{-}r}$	Translocation $index_{shoot\text{-}root}$
TSSs	Total suspended solids
TTW	Treated tannery wastewater
TVSs	Total volatile solids
TWs	Treatment wetlands
USEPA	United States Environmental Protection Agency
UTW	Untreated tannery wastewater

References

1. Bocquier, P. World Urbanization Prospects. *Demogr. Res.* **2005**, *12*, 197–236. [CrossRef]
2. Orimoloye, I.R.; Belle, J.A.; Olusola, A.O.; Busayo, E.T.; Ololade, O.O. Spatial Assessment of Drought Disasters, Vulnerability, Severity and Water Shortages: A Potential Drought Disaster Mitigation Strategy. *Nat. Hazards* **2020**, *105*, 2735–2754. [CrossRef]
3. Rajapakse, J.; Otoo, M.; Danso, G.K. Progress in Delivering SDG6: Safe Water and Sanitation. *Camb. Prism. Water* **2023**, *1*, e6. [CrossRef]
4. Bhardwaj, A.; Kumar, S.; Singh, D. Tannery Effluent Treatment and Its Environmental Impact: A Review of Current Practices and Emerging Technologies. *Water Qual. Res. J.* **2023**, *58*, 128–152. [CrossRef]
5. Ali, H.Q.; Yasir, M.U.; Farooq, A.; Khan, M.; Salman, M.; Waqar, M. Tanneries Impact on Groundwater Quality: A Case Study of Kasur City in Pakistan. *Environ. Monit. Assess.* **2022**, *194*, 823. [CrossRef]
6. Oruko, R.O.; Edokpayi, J.N.; Msagati, T.A.M.; Tavengwa, N.T.; Ogola, H.J.O.; Ijoma, G.; Odiyo, J.O. Investigating the Chromium Status, Heavy Metal Contamination, and Ecological Risk Assessment via Tannery Waste Disposal in Sub-Saharan Africa (Kenya and South Africa). *Environ. Sci. Pollut. Res.* **2021**, *28*, 42135–42149. [CrossRef] [PubMed]
7. Hassan, Z.; Hassan, A.; Riaz, M.; Khan, A.A.; Ul-Allah, S.; Shehzad, U.; Khurshid, M.; Bakhsh, A.; Shah, J.M.; Manzoor, Z. Increased Health Risk Assessment in Different Vegetables Grown under Untreated Sewerage Irrigation Regime due to Higher Heavy Metals Accumulation. *Environ. Sci. Pollut. Res.* **2023**, *30*, 86189–86201. [CrossRef] [PubMed]
8. Hansen, É.; Cardoso, J.K.; Gutterres, M.; Monteiro de Aquim, P. Scale-up Testing for Reducing Pollution Load of Chemicals in Wastewater of Leather Post-Tanning. *Process Saf. Environ. Prot.* **2021**, *155*, 466–472. [CrossRef]
9. Werkneh, A.A. Decentralized Constructed Wetlands for Domestic Wastewater Treatment in Developing Countries: Field-Scale Case Studies, Overall Performance and Removal Mechanisms. *J. Water Process Eng.* **2024**, *57*, 104710. [CrossRef]
10. de Campos, S.X.; Soto, M. The Use of Constructed Wetlands to Treat Effluents for Water Reuse. *Environments* **2024**, *11*, 35. [CrossRef]
11. Marín-Muñiz, J.L.; Sandoval Herazo, L.C.; López-Méndez, M.C.; Sandoval-Herazo, M.; Meléndez-Armenta, R.Á.; González-Moreno, H.R.; Zamora, S. Treatment Wetlands in Mexico for Control of Wastewater Contaminants: A Review of Experiences during the Last Twenty-Two Years. *Processes* **2023**, *11*, 359. [CrossRef]
12. Agaton, C.B.; Guila, P.M.C. Ecosystem Services Valuation of Constructed Wetland as a Nature-Based Solution to Wastewater Treatment. *Earth* **2023**, *4*, 78–92. [CrossRef]
13. Retta, B.; Coppola, E.; Ciniglia, C.; Grilli, E. Constructed Wetlands for the Wastewater Treatment: A Review of Italian Case Studies. *Appl. Sci.* **2023**, *13*, 6211. [CrossRef]
14. Kumar, S.; Sangwan, V.; Kumar, M.; Deswal, S. A Survey on Constructed Wetland Publications in the Past Three Decades. *Environ. Monit. Assess.* **2023**, *195*, 992. [CrossRef]
15. Almuktar, S.A.A.A.N.; Abed, S.N.; Scholz, M. Wetlands for Wastewater Treatment and Subsequent Recycling of Treated Effluent: A Review. *Environ. Sci. Pollut. Res.* **2018**, *25*, 23595–23623. [CrossRef] [PubMed]
16. Ashraf, S.; Naveed, M.; Afzal, M.; Ashraf, S.; Ahmad, S.R.; Rehman, K.; Zahir, Z.A.; Núñez-Delgado, A. Evaluation of Toxicity on *Ctenopharyngodon idella* due to Tannery Effluent Remediated by Constructed Wetland Technology. *Processes* **2020**, *8*, 612. [CrossRef]

17. Singh, S.; Benny, C.K.; Chakraborty, S. An Overview on the Application of Constructed Wetlands for the Treatment of Metallic Wastewater. In *Biodegradation and Detoxification of Micropollutants in Industrial Wastewater*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 103–130. [CrossRef]
18. Rabbi, F.M.; Hasan, M.K.; Rahman, M.A.; Islam, M.S.; Shohugh, P.K.; Ahmed, M.I.; Khan, M.W.; Rafi, T.; Rahman, M.M.; Rahaman, M.H.; et al. Waste-Derived Substrates in Vertical-Flow Constructed Wetlands for an Efficient Removal of High-Concentration Heavy Metals. *Water Sci. Technol.* **2024**, *91*, 21–39. [CrossRef]
19. Wu, H.; Wang, R.; Yan, P.; Wu, S.; Chen, Z.; Zhao, Y.; Cheng, C.; Hu, Z.; Zhuang, L.; Guo, Z.; et al. Constructed Wetlands for Pollution Control. *Nat. Rev. Earth Environ.* **2023**, *4*, 218–234. [CrossRef]
20. Li, L.; Zhang, W.; Zhang, M.; Zhang, G.; Hu, X.; Liu, C.; Cao, X.; Liang, W. Applications of Phytoremediation to Treat Reclaimed Water in Urban Parks Using Aquatic Macrophytes. *Aquat. Ecol.* **2021**, *56*, 75–88. [CrossRef]
21. Tan, H.W.; Pang, Y.L.; Lim, S.; Chong, W.C. A State-of-The-Art of Phytoremediation Approach for Sustainable Management of Heavy Metals Recovery. *Environ. Technol. Innov.* **2023**, *30*, 103043. [CrossRef]
22. Rahi, M.A.; Faisal, A.A.H.; Naji, L.A.; Almuktar, S.A.; Abed, S.N.; Scholz, M. Biochemical Performance Modelling of Non-Vegetated and Vegetated Vertical Subsurface-Flow Constructed Wetlands Treating Municipal Wastewater in Hot and Dry Climate. *J. Water Process Eng.* **2020**, *33*, 101003. [CrossRef]
23. Liu, S.; Zhang, Y.; Feng, X.; Pyo, S.-H. Current Problems and Countermeasures of Constructed Wetland for Wastewater Treatment: A Review. *J. Water Process Eng.* **2024**, *57*, 104569. [CrossRef]
24. Oliveira, G.A.; Colares, G.S.; Lutterbeck, C.A.; Dell'Osbel, N.; Machado, Ê.L.; Rodrigues, L.R. Floating Treatment Wetlands in Domestic Wastewater Treatment as a Decentralized Sanitation Alternative. *Sci. Total Environ.* **2021**, *773*, 145609. [CrossRef]
25. Gaballah, M.S.; Ismail, K.; Aboagye, D.; Ismail, M.M.; Sobhi, M.; Stefanakis, A.I. Effect of Design and Operational Parameters on Nutrients and Heavy Metal Removal in Pilot Floating Treatment Wetlands with *Eichhornia crassipes* Treating Polluted Lake Water. *Environ. Sci. Pollut. Res.* **2021**, *28*, 25664–25678. [CrossRef] [PubMed]
26. Yu, G.; Li, P.-Y.; Wang, G.-L.; Wang, J.; Zhang, Y.; Wang, S.; Yang, K.; Du, C.; Chen, H. A Review on the Removal of Heavy Metals and Metalloids by Constructed Wetlands: Bibliometric, Removal Pathways, and Key Factors. *World J. Microbiol. Biotechnol.* **2021**, *37*, 157. [CrossRef]
27. Shahid, M.J.; Arslan, M.; Ali, S.; Siddique, M.; Afzal, M. Floating Wetlands: A Sustainable Tool for Wastewater Treatment. *CLEAN-Soil Air Water* **2018**, *46*, 1800120. [CrossRef]
28. Mao, J.; Hu, G.; Deng, W.; Zhao, M.; Li, J. Industrial Wastewater Treatment Using Floating Wetlands: A Review. *Environ. Sci. Pollut. Res.* **2024**, *31*, 5043–5070. [CrossRef]
29. Younas, A.; Kumar, L.; Deitch, M.J.; Qureshi, S.S.; Shafiq, J.; Ali Naqvi, S.; Kumar, A.; Amjad, A.Q.; Nizamuddin, S. Treatment of Industrial Wastewater in a Floating Treatment Wetland: A Case Study of Sialkot Tannery. *Sustainability* **2022**, *14*, 12854. [CrossRef]
30. Arias, L.; Franco, D.; Medina, L.; Benítez, C.; Medina, L.; Villagra, V.; McGahan, S.; Mariza Duré, G.; Kurita-Oyamada, H.G. Removal of Chromium (III) and Reduction in Toxicity in a Primary Tannery Effluent Using Two Floating Macrophytes. *Toxics* **2024**, *12*, 152. [CrossRef]
31. Javeed, F. Optimization of Design and Operational Parameters of Constructed Wetland System (CWS) for the Treatment of Textile and Sewage Effluents. Ph.D. Thesis, University of the Punjab, Lahore, Pakistan, 6 December 2024.
32. Younas, F.; Niazi, N.K.; Bibi, I.; Afzal, M.; Hussain, K.; Shahid, M.; Aslam, Z.; Bashir, S.; Hussain, M.M.; Bundschuh, J. Constructed Wetlands as a Sustainable Technology for Wastewater Treatment with Emphasis on Chromium-Rich Tannery Wastewater. *J. Hazard. Mater.* **2022**, *422*, 126926. [CrossRef]
33. Das, M.; Bramhanand, P.S.; Laxminarayana, K. Performance and Efficiency Services for the Removal of Hexavalent Chromium from Water by Common Macrophytes. *Int. J. Phytoremediation* **2021**, *23*, 1095–1103. [CrossRef]
34. Panneerselvam, B.; Priya K, S. Phytoremediation Potential of Water Hyacinth in Heavy Metal Removal in Chromium and Lead Contaminated Water. *Int. J. Environ. Anal. Chem.* **2021**, *103*, 3081–3096. [CrossRef]
35. Das, E.J.; Bhuiyan, M.A.R.; Hasan, M.M. Implementation of Water Hyacinth (*Eichhornia crassipes*) and Water Lettuce (*Pistia stratiotes*) in the Re-Treatment of Conventionally Treated Pharmaceutical Wastewater: A Case Study of Radiant Pharmaceuticals Limited, Dhaka, Bangladesh. *Environ. Monit. Assess.* **2023**, *195*, 1210. [CrossRef]
36. Zeb, B.S.; Mahmood, Q.; Irshad, M.; Zafar, H.; Wang, R. Sustainable Treatment of Combined Industrial Wastewater: Synergistic Phytoremediation with *Eichhornia crassipes*, *Pistia stratiotes* and *Arundo donax in* Biofilm Wetlands. *Int. J. Phytoremediation* **2024**, *27*, 128–134. [CrossRef]
37. Samal, K.; Dash, R.R. Experiments and Modeling to Develop a *Pistia stratiotes* Based Floating Vegetated System (FVS) for the Removal of Heavy Metals (Pb, Zn, Cr, Cu, Ni). *Sci. Total Environ.* **2024**, *926*, 171981. [CrossRef]
38. Nagial, K.S.; Kumar, N.; Poddar, A.; Shankar, V.; Rustum, R. Treated Wastewater Irrigation for Ornamental Plants: A Systematic Review. *ISH J. Hydraul. Eng.* **2025**, *31*, 123–132. [CrossRef]

39. Zitácuaro-Contreras, I.; Vidal-Álvarez, M.; Hernández y Orduña, M.G.; Zamora-Castro, S.A.; Betanzo-Torres, E.A.; Marín-Muñíz, J.L.; Sandoval-Herazo, L.C. Environmental, Economic, and Social Potentialities of Ornamental Vegetation Cultivated in Constructed Wetlands of Mexico. *Sustainability* **2021**, *13*, 6267. [CrossRef]
40. Lipps, W.C.; Braun-Howland, E.B.; Baxter, T.E. (Eds.) *Standard Methods for the Examination of Water and WastewaterTM*, 24th ed.; APHA Press: Washington DC, USA, 2023; p. 1516, ISBN 9780875532998.
41. *ASTM D1252-06(2020)*; Standard Test Methods for Chemical Oxygen Demand (Dichromate Oxygen Demand) of Water. ASTM International: West Conshohocken, PA, USA, 2020. Available online: https://store.astm.org/d1252-06r20.html (accessed on 22 July 2025).
42. Javeed, F.; Bareen, F.; Shafiq, M.; Nazir, A.; Scholz, M. Optimization of Selected Parameters in Vertical, Horizontal, and Hybrid Surface Flow Constructed Wetland Systems for Improving the Treatment Efficiency of Textile and Sewage Effluents. *Water* **2025**, *17*, 402. [CrossRef]
43. Telliard, W.A. *Method 1684: Total, Fixed, and Volatile Solids in Water, Solids, and Biosolids*; USEPA-821-R-01-015; United States Environmental Protection Agency: Washington, DC, USA, 2001. Available online: https://www.epa.gov/sites/default/files/2015-10/documents/method_1684_draft_2001.pdf (accessed on 22 July 2025).
44. USEPA. *SW-846 Test Method 3052: Microwave Assisted Acid Digestion of Siliceous and Organically Based Matrices*; United States Environmental Protection Agency: Washington, DC, USA, 1996. Available online: https://www.epa.gov/sites/default/files/2015-12/documents/3052.pdf (accessed on 22 July 2025).
45. Javeed, F.; Nazir, A.; Firdaus-e-Bareen; Shafiq, M.; Scholz, M. Industrial Water Treatment within a Wetland Planted with *Hemarthria compressa* and Subsequent Effluent Reuse to Grow *Abelmoschus esculentus*. *J. Water Process Eng.* **2022**, *45*, 102511. [CrossRef]
46. Mahtab, S.; Nazir, A.; Shafiq, M. Coupling of Phycoremediation and Phytoremediation Technologies to Treat Tannery Effluents with Rainwater Dilutions. *Int. J. Phytoremediation* **2024**, *26*, 1667–1675. [CrossRef]
47. Government of Pakistan, Ministry of Environment, Local Government and Rural Development. *Statutory Notification S.R.O. 549(I)/2000, National Environmental Quality Standards (NEQS)*; The Gazette of Pakistan: Islamabad, Pakistan, 2000. Available online: https://environment.gov.pk/SiteImage/Misc/files/Rules/SRO549I2000NEQS.pdf (accessed on 22 July 2025).
48. Food and Agriculture Organization of the United Nations (FAO); World Health Organization (WHO). *Guidelines for the Safe Use and Reuse of Water in Food Production and Processing (Codex Alimentarius Guideline CXG 100–2023)*; Codex Alimentarius Commission: Rome, Italy, 2023. Available online: https://www.fao.org/fao-who-codexalimentarius/sh-proxy/jp/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FStandards%252FCXG%2B100-2023%252FCXG_100e.pdf (accessed on 22 July 2025).
49. Sahreen, S.; Mukhtar, H. Floating Treatment Wetlands (FTW) for Sustainable Industrial Wastewater Treatment. In *Microbial Bioremediation and Multiomics Technologies for Sustainable Development: Recent Trends*; Royal Society of Chemistry: London, UK, 2024; pp. 291–318. [CrossRef]
50. Wei, F.; Shahid, M.J.; Alnusairi, G.S.H.; Afzal, M.; Khan, A.; El-Esawi, M.A.; Abbas, Z.; Wei, K.; Zaheer, I.E.; Rizwan, M.; et al. Implementation of Floating Treatment Wetlands for Textile Wastewater Management: A Review. *Sustainability* **2020**, *12*, 5801. [CrossRef]
51. Afzal, M.; Arslan, M.; Müller, J.A.; Shabir, G.; Islam, E.; Tahseen, R.; Anwar-ul-Haq, M.; Hashmat, A.J.; Iqbal, S.; Khan, Q.M. Floating Treatment Wetlands as a Suitable Option for Large-Scale Wastewater Treatment. *Nat. Sustain.* **2019**, *2*, 863–871. [CrossRef]
52. Rizvi, Z.F.; Jamal, M.; Parveen, H.; Sarfraz, W.; Nasreen, S.; Khalid, N.; Muzammil, K. Phytoremediation Potential of *Pistia stratiotes*, *Eichhornia crassipes*, and *Typha latifolia* for Chromium with Stimulation of Secondary Metabolites. *Heliyon* **2024**, *10*, e29078. [CrossRef]
53. Tanpichai, S.; Biswas, S.K.; Witayakran, S.; Yano, H. Water Hyacinth: A Sustainable Lignin-Poor Cellulose Source for the Production of Cellulose Nanofibers. *ACS Sustain. Chem. Eng.* **2019**, *7*, 18884–18893. [CrossRef]
54. Kumar, A.; Devnani, G.L.; Pal, D.B. Thermal Kinetic Analysis and Characterization of Water Hyacinth Biomass for Renewable Energy Application. *Biomass Convers. Biorefinery* **2024**. [CrossRef]
55. Kings, A.J.; Suyambulingam, I.; Narayanaperumal, S.; Miriam, L.M.; Divakaran, D.; Murali, A.; Han, S.S. Exploring Biomass Derived Microcrystalline Cellulose from the Waste Aquatic Plant *Pistia stratiotes*: A Comprehensive Characterization for Polymer Composite Reinforcement. *Int. J. Biol. Macromol.* **2025**, *300*, 140217. [CrossRef]
56. Lee, L.T.; Blatchley, E.R. Long-Term Monitoring of Water and Air Quality at an Indoor Pool Facility during Modifications of Water Treatment. *Water* **2022**, *14*, 335. [CrossRef]
57. Petrov, D.S.; Korotaeva, A.E.; Pashkevich, M.A.; Chukaeva, M.A. Assessment of Heavy Metal Accumulation Potential of Aquatic Plants for Bioindication and Bioremediation of Aquatic Environment. *Environ. Monit. Assess.* **2022**, *195*, 122. [CrossRef] [PubMed]

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