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Treatment of Industrial Wastewater in a Floating Treatment Wetland: A Case Study of Sialkot Tannery

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Abstract: The city of Sialkot in Pakistan is a hub of leather tanneries, with approximately 260 tanneries in operation and, while producing millions of leather products per day, the city discharges millions of gallons of untreated effluent into drains each day. In order to devise a cost-effective system for the treatment of tannery wastewater, a floating treatment wetland (FTW) was established to treat the effluent using local plant species through phytoremediation. The efficiency of the FTW was tested with three different plant species, each grown separately and operating for three months in the FTW tank. Two of the plant species introduced, water hyacinth and water lettuce, were floating and vascular; the third plant species *Typha latifolia* was vegetated on a floating mat of styrofoam while the roots extended down to the contaminated water. Wastewater from a tannery drain was pumped into the FTW tank with a flow of 0.5 L per minute and was given a retention time of six days. The influent and effluent from the FTW were periodically tested to determine the percentage removal of contaminants, primarily the total suspended solids, biochemical oxygen demand, chemical oxygen demand, and chromium. After two months with each species, a significant change in the quality of wastewater was measured: chromium was removed by up to 95 percent by the water hyacinth and water lettuce and 33 percent by the *Typha latifolia*. The pilot model indicates that FTWs are an effective system to treat effluent from tanneries in a cost-effective way as an alternative to establishing an expensive treatment system with high associated operational costs. It can help in achieving the circular economy concept of conventional wastewater schemes towards more sustainable ones. Moreover, to achieve the principles of circular economy and environmentally friendly development, it is crucial that the substances used for a wetland foundation have the capacity to be recycled, are available at a cheap price, and are locally available.

Keywords: circular economy; circular bioeconomy; floating treatment wetland; phytoremediation; tannery wastewater; tropical wetlands; *Typha latifolia*

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1. Introduction

Water availability and quality are global challenges [1]. Worldwide, organic and inorganic pollutants from commercial, agricultural, and domestic sectors have polluted around 70% of the available freshwater resources [2]. Contamination by heavy metals [3] and other pollutants through industrialization and urbanization poses a serious threat to aquatic and human life [4–6]. Industrial processes in industries such as textiles, mining, electroplating, and leather processing release many inorganic contaminants into the environment including lead, chromium, copper, and cadmium [7–10]. While processes such as filtration, complexation, coagulation, flocculation, chemical precipitation, chemical oxidation/reduction, membrane technology, electrochemical treatment, biosorption, and complexation are commonly used for the removal of wastewater contaminants [1,11–14], many of these methods require wastewater treatment plants with chemicals, ions, and other materials [1]. These methods are expensive, do not sufficiently remove these contaminants, and require high energy [15,16].

In many countries, such as Pakistan, India, Argentina, China, Mexico, Brazil, and South Korea, leather tanneries and related industries are a main driver of the economy [17]. The leather value chain begins with the husbandry of animals and ends with the leather goods, with the intermediate steps including the collection of skins and hides from the slaughtered animals and processing of hides, which is often conducted in small labor-intensive workshops in larger capital-intensive factories [18]. Growing demand for leather products worldwide has placed pressures on manufacturers of all sizes to produce garments more quickly. To meet these demands, manufacturers may turn to different methods that allow more efficient production [19–21], often without considering the cost; for example, in recent years, most tanneries changed their production from traditional vegetable tanning to chromium tanning technology [17].

The leather industry is also dependent on sub-industries, such as meat production, livestock rearing, and tanning, as part of leather production, which raises extensive environmental concerns [22]. According to the INETI (Instituto Nacional de Engenharia, Tecnologia e Inovação) organization, tanneries cause many environmental problems such as wastewater discharge from tannery industries; this wastewater has high inorganic and organic chemicals including chromium and trace organic and synthetic chemicals such as the dyes, pesticides, processing chemical solvents, and finishing agents [23]. The contamination of groundwater occurs when wastewater from these industries seeps through the soil from the unlined pipes, drains, and ponds, or from spills and dumps [23,24]. In large leather-producing cities such as Sialkot in Pakistan (the largest leather producing city in the country), the discharge of effluents from the Sialkot tanneries adds up to approximately 1.1 million liters per day, which causes the contamination of the surface and groundwater of Sialkot [23]. Given the threat it poses to human health and aquatic life, there is an urgent need to deal properly and scientifically with the large amount of effluent from the leather industry.

Conventional wastewater treatment methods are costly and environmentally intrusive, and they require engineering expertise, labor management, and process activities [14]. They also require a lot of time and money [25]. In contrast, methods for improving water quality based on natural mechanisms can avoid many of these challenges [26]. In the field of environmental engineering, one such modern nature-based solution for water treatment is floating treatment wetlands (FTWs). This soil-less planting technique has been developed to treat different types of wastewater to the point where it can be discharged and used again for purposes such as fisheries and agriculture without a measurable effect on life and the environment [27–29]. FTWs are a reliable method to treat wastewater and surface water runoff [30,31]. To enhance the purification reactions in FTWs, hydrophytes are often used to accumulate pollutants in the tissues, usually in the rhizosphere, of plants. For the removal of contaminants, some plants prompt additional physicochemical and biological processes leading to the additional removal of contaminants [32]. Some hydrophytes such as water hyacinth [32] are well-known for their capacity to remove contaminants in polluted water, owing to its ability to absorb pollutants. According to previous studies, regional hydrophyte species should be selected when designing the plant community of FTWs so that the selected plants are adapted to the climate conditions [32]. The floating mat underside the plant roots supplies a significant contact area for the formation of connected biofilms and the trapping of dispersed particles. The plants must obtain their energy straight from the water column because they are not rooted in the soil like in subsurface flow-built wetlands, which may increase the rates of nutrient and component absorption into the biomass. Due to their stability, they can withstand large variations in water depth and have the potential to improve treatment efficiency by retaining more water during flow periods, therefore extending the period that the wastewater is held in the wetland. Due to the oxygen carried by the roots, the roots of these species can survive in hypoxic or anoxic conditions. The microbial transformation of aquatic contaminants is supported by the radial oxygen loss to the rhizosphere [33,34]. Despite the fact that FTWs and conventional CWs are considered as processes that are straightforward to build and operate, many complicated processes take place that have a direct impact on system performance and the efficacy of the removal of pollutants, including inlet contaminant concentrations, hydraulic loadings, pH, the presence of micro-organisms in the rhizosphere, redox conditions, and temperature [35]. Similar to how CW uses plants that float freely, in FTWs, the roots of the plants are in a constant physical relationship with the water. Macrophytes in these environments take up nutrients directly from the water. Through a hanging network of roots, rhizomes, and the connected biofilm, which is in charge of both biochemical activities and significant physical functions such as filtration and particulate capture, the plants offer a biologically active surface area [36]. The root growth of FTWs offers a bigger surface area than other conventional methods of treatment, such as built wetlands, for the establishment of a biofilm [37]. While reducing wastewater flow and turbulence, increasing sedimentation, and trapping/filtering suspended material, this biofilm serves as an ecosystem for several bacterial communities and becomes essential for the sequestration of nutrients from the water through nitrification, nitrification for nitrogen and adsorption for retaining phosphorous [38]. Sedimentation, in addition to vegetation, is crucial to the function of FTWs. One or more of the key methods for lowering oxygen, nitrogen, total phosphorus, and orthophosphate is the settling of suspended materials and their trapping in plant roots. However, it is likely that phosphorus from sediments is transferred back into the water section during a lengthy hydraulic retention time, leading to an increase in P levels [39]. Studies have demonstrated that FTWs can be a productive, low-cost [40,41], and low-maintenance method of improving water quality across a wide range of uses; for example, there has recently been interest in evaluating the effectiveness of FTWs in the treatment of industrial wastewater and stormwater runoff [38,42,43]. Floating wetlands can be built in any lagoon, existing water body, or built structure without the need for any digging or earth shifting to remove contaminants from the water and without the need for further land acquisition [38]. The present study aims to assess the ability of different plant species to treat wastewater from a tannery production plant using an FTW system. This study serves as a reference and guide for academics and policymakers in the design and use of FTWs to remediate water contamination from diverse sources.

2. Current Problems and Prospects of Using Plants for Wastewater Treatment

Plants and media have a key part in the removal of manmade wetland technologies. Phytoremediation allows plants in FTWs to lower pollutant levels [38]. Plant growth material supplies physical support for vegetation formation. Moreover, extra surfaces for biofilm growth and nutrient adsorption may enhance the sedimentation and pollutant filtration [42,43]. Gravel is the media mostly used in constructed wetlands [44], though Priya et al. (2013) found that sand was a more effective treatment than gravel. Sirianuntapiboon et al. (2006) reported that constructed wetlands with media including both sand and soil in combination results in the maximum contaminant removal efficiency. Various studies have used different types of media (e.g., vermiculite, zeolite, and lime) for extraction of certain compounds from waste effluent [45–47]. To compare how well two parallel hybrid wetlands remove pollutants after being fed industrial wastewater (with limited biodegradability), Saeed et al. (2019) studied a system that had two stages of vertical flow (VF) wetlands, following the final surface flow (SF) wetland round of treatment. They found that in both systems, the concentration-based mean overall reduction rates for all of the different types of waste (specifically, NH4-N, TN, P, BOD, and COD) were removed by at least 90% [48]. Cristina et al. used a light expanded clay substrate composed of plants and without plants. They found 41–58% BOD removal, and lower nutrient removal. Moreover, they found no changes in the removal over the 17 months of study [49]. In FTWs, the influence of the plant type depends on several factors such as plant production, the physical effects of root systems, micro-organisms, evapotranspiration, the uptake by plants, and the weather [50–53]. Multiple studies have indicated that adsorption and sedimentation are the primary reduction tools for metals in FTWs [37,40,42]. According to the research, pH values from 6 to 8 and higher temperatures (from 6 to 26 °C) preferred positively charged adsorption on small particles and organic materials. Metals are generally linked with sulfides in anaerobic soils, forming insoluble sulfides in water. Moreover, the physicochemical parameters of water in FTWs, such as pH, temperature, DO, and organic material levels might alter heavy metal removal effectiveness and subsequent release [54–56].

Priya and Selvan [57] found that contaminants are stored in the plant root system, then moved to the shoots and other parts of the plant. When the plant is harvested, these contaminants are removed from the system. A hyperaccumulator or accumulator can remove pollutants from water and soil. This green technology is seen as a long-term and promising alternative to conventional water and soil treatment methods for developing countries. More than 500 species have been found to be capable of storing metals from contaminated soils in their roots [58,59]. It is difficult to determine how the metal (Cu, Ni, and Pb) is distributed between the roots and the plant leaves and stems [60]. Due to their carcinogenic and bioaccumulative properties, metal ions are among the most dangerous water pollutants. Wastewaters containing metal ions are produced in a variety of industries, including metal finishing, mining, cement, leather, textiles, and paints. Various hazardous metal ions, including chromium, nickel, zinc, lead, arsenic [3], cobalt, cadmium, and copper are found in industrial effluents and pose a threat to ecosystems [1].

Climate change, particularly temperature changes, may impact the development of microalgae. Overall, increased temperatures can encourage the formation of organic carbon in manmade wetlands, which, in turn, can help the expansion of microalgae in such areas [61]. In addition, increasing the temperature and irradiance of microalgae to a proper range could promote enzyme activity and metabolic activity and improve nutrient removal efficiency and biomass production, all of which would be beneficial for pollutant removal [62]. While numerous methods have demonstrated good results in terms of pollutant removal, its application in cold climates has been a neglected topic. Rarely has research been undertaken to create treatment methods that are effective at low temperatures. The performance of treatment processes is reduced in cold climates where the average temperature is around 10 degrees Celsius or less and the average temperature in winter is less than 3 degrees Celsius. Micro-organisms and plants cease to function efficiently in cold climates, resulting in the reduced efficiency of treatment methods [63,64].

Other factors may also limit the capacity of FTWs to reduce pollutant concentrations. While BOD, COD, and chromium are efficiently handled by some of the plants used in this study, these plants may not be as efficient at reducing concentrations of other metals or pollutants. Higher pollutant concentrations may also constrain efficiency: the net change may be the same, but if the concentrations of pollutants are higher in the FTW inflow, the percentage of reduction would be lower. Finally, in our study, FTW size and inflow were constant; further research would be beneficial to assess whether and how FTWs could scale up in size to treat higher inflow volumes or higher concentrations of pollutants [65,66]. Any inability, loss, or unknown reaction may deviate as a contributing factor to plant species, and it may also produce increased disadvantages of phytoremediation. Phytoremediation has certain drawbacks according to the literature. These include the concentration, toxicity, and bioavailability of contaminants as well as the capacity of plants to withstand pressure. Low effectiveness or wake of phytomanagement, lack of sufficient macro/micronutrients in contaminated media, and finally, the physiological qualities and limitations of plant species are some of the potential drawbacks of phytoremediation. Multicontaminant interactions, adaptation of plant species to climate change and pollution in urban environments, and genetic traits and specifications of plant species classify them into groups such as "indicators", "low tolerance", "high tolerance", and "hyperaccumulator". Hyperaccumulator plant species often serve as an extractor of rare metals [65]. These are all important topics for further research on FTWs in developing countries. This study provides important information on how small and medium enterprises (SMEs) can employ low-cost tools for effective wastewater treatment. The specifications for design, construction, and operation provided here are from an actual SME producer in Sialkot; if applied broadly, the cumulative benefit of several SMEs adopting this type of treatment tool can help to achieve local water quality goals. In places such as Sialkot where SMEs are a predominant type of production facility, small-scale treatment through FTWs may be the most feasible type of wastewater treatment SMEs can employ. Like many developing regions, Pakistan is promoting the incorporation of cleaner production concepts into its industries [67,68], wherein cost-effective strategies are employed to increase overall efficiencies and reduce the risks to human health and ecosystems [69]. FTWs align with these goals. More research on the use of floating treatment wetlands as a low-cost, energy-efficient wastewater treatment process in developing countries can help to highlight the value of such tools as well as explore the parameters and limitations that make them successful in reducing pollutants from wastewater discharge.

3. Methodology

3.1. Study Area

The city of Sialkot, located in the northeastern Punjab province in Pakistan, is known as one of Pakistan's most industrialized regions. Major industrial sectors include the production of leather products, surgical instruments, diesel engines, beverages, iron and steel, and pharmaceuticals. There are approximately 264 tanneries, 244 leather garment manufacturing units, and 900 leather sports product manufacturing units present in Sialkot [70]. Leather tanning facilities generate large quantities of wastewater from their processes. Therefore, one leather tannery was selected to participate in a pilot FTW system to treat its wastewater using cost effective and environmentally friendly techniques.

The weather in Sialkot changes a lot over the course of the year and even on a single day. The region usually has hot, dry summers and cold monsoon rains. In January, the average temperature is 5 °C, and in June, it is 40 °C. Sialkot gets most precipitation during a monsoon season (July to September), with less intense precipitation continuing through cold winters (December and February), and spring (March and April), before a relatively dry premonsoon season (summer between May and June) [71].The average amount of rain that Sialkot gets each year is 934.7 mm [72].

3.2. Sample Collection and Analysis

A total of 18 composite influent wastewater samples were collected twice every 15 days from the inlet of the FTW tank, which was located on the drain of a tannery that collected the effluent from all the operations from raw hide to finished leather. An additional 18 composite effluent wastewater samples were collected twice after every 15 days at the outlet of the FTW tank to assess contamination and removal efficiency (Figure 1). The samples were collected at a rate of 0.5 L per minute, approximately the rate at which the equalized wastewater flowed into the pilot system. The hydraulic retention time of the FTW tank was 14 days. This study ran from September to April. The color of the collected wastewater samples was visually analyzed. The temperature of the samples was assessed using industrial thermometer with a range from 0 to 100 °C [73].

The total suspended solids (TSS), biological oxygen demand (BOD), and chemical oxygen demand (COD) were determined by AWWA/APHA Standard Methods for the Examination of Water and Wastewater, 2340 D, 5210 D, and 5220 D, respectively. The heavy metal chromium (Cr) was qualified in water samples using atomic absorption as outlined by AWWA/APHA method 3111/3120B. The pilot scale FTW system was designed and established at a drain of a tannery in Sialkot; the pilot unit consisted of 3 chambers designed at the flow rate of 0.72 m^3/day (0.5 L per minute, as described above). The design and selection of model was decided reviewing some local and international studies. Ayaz et al. (2020) used four chamber wetland sizes of 70, 145, 50 and 50 liters. They used four different species for the treatment of industrial wastewater [74]. Moreover, a similar type of design was used in serval studies for other pilot projects [75–78]. The unit was made of steel with the design characteristics shown in Table 1.

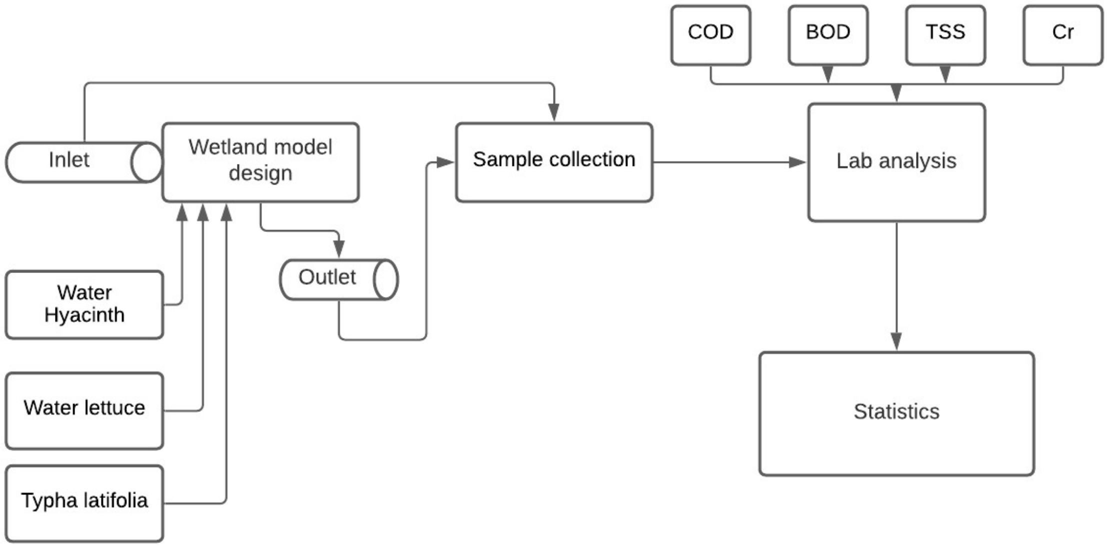

Figure 1. Methodology flow diagram.

Table 1. Design aspects of the floating treatment wetland used to treatment tannery wastewater.

Design	Measurement	Unit
Design flow	0.72	m^3/day
Detention time	6	days
Width	1.37	M
Length	3.6	m
Depth	0.84	m
Area	5.01	m^2
Volume	4.31	m^3

The selection of the plants used in pilot FTW system was based on vascular species that locally originate in Sialkot. Three vascular plant species (water hyacinth, water lettuce, and *Typha latifolia*) were introduced in the tanks as shown in Figures 2–4, respectively. These plants were resettled from the local areas of Sialkot to the pilot FTW system. The vegetation was planted by hand. The plants were sited at the depth equal to the introduced water level inflow. The number of plants was monitored through the operation. After the selection of plants and installation of the FTW system, the tannery wastewater flowed from the inlet into the FTW. The plants were grown during different periods of time to check the intake of contamination from the plant and the treatment of wastewater.

Water hyacinth (*Eichhornia crassipes*) was the first species introduced in the FTW tank (Figure 2), followed by water lettuce (*Pistia stratiotes*) (Figure 3), and then *Typha latifolia* (Figure 4). These plants were primarily selected because they are locally available, and secondly, these are widely used in the region by researchers in domestic and industrial wastewater treatment [74,75,79–82]. Each plant species was trialed for two months at a time, mid-September 2018 to mid-November 2018, mid-November 2018 to mid-January 2019, and mid-January 2019 to mid-April 2019, respectively. The water was pumped with the help of small pump at a rate of 0.72 m^3/day, and the treated wastewater was discharged back to the drain from the outlet of the FTW. Water sampling and testing was carried out fortnightly (with six sampling events for each plant type) at the inlet (In-1 through In-6) and outlet (Ef-1 through Ef-6) of the floating treatment wetland to obtain effective results.

Figure 2. Water hyacinth in the Sialkot floating treatment wetland (photo: A. Youns and J. Shafiq).

Figure 3. Water lettuce in the Sialkot floating treatment wetland (photo: A. Youns and J. Shafiq).

Figure 4. *Typha latifolia* in the Sialkot floating treatment wetland (photo: A. Youns and J. Shafiq).

Sustainable crop production includes methods of raising vegetables, fruits, grains and other food, and fiber crops in ecologically mindful ways that focus on soil health and biodiversity instead of chemical fertilizers and pesticides. These growing practices require more labor and specialized expertise than chemical-based production, which means that the resulting products are often more expensive. Water lettuce is a floating plant and is popular for those with water gardens because its presence inhibits the growth of algae and cleans the water. For our FTW, water lettuce was harvested on a specified designed area of FTW which gets its nutrients from wastewater. Water lettuce grows best in the early part of the summer when temperatures reach at least 15.5 °C and does not require external thermal devices [81]. Water hyacinth can form thick mats that cover the entire surface of ponds, choking out native species and oxygen in the water [43]. Fish cannot survive in water without oxygen, so it is important to control the growth of the plant. Thus, harvesting water hyacinth in designed wetlands can help with preserving ecosystems. The benefits for the environment are equally important reasons to consider growing *Typha*. *Typha* was grown in peat with a higher water level; this means the peat was functioning as it should for pollution reduction, reducing the carbon emissions from the peat, and the established plants actively stored the carbon. Both actions contribute towards the CO_2 emission reduction targets [83,84]. FTWs were inspected on a weekly basis to check and examine the overall functioning. Key attention was given to the inlet flow of the system, which was checked twice a week, as blockages in the pump and pipe could occur due to suspended solids in the wastewater.

4. Results and Discussion

Tanning industries are a major wastewater source, and tanning industry wastewater has a high organic load due to the process used to turn raw skins or hide into leather [85,86]. In this study, tannery wastewater flowed through floating treatment wetlands to remove pollutants. In the following sections, we describe the results of the treatment of wastewater using three different species.

4.1. Water Hyacinth

Water hyacinth (*Eichhornia Crassipes*) grows abundantly in tropical and subtropical areas of the world. Water hyacinth is a floating water plant that has been named one of the world's 100 most invasive global plants [87]. In recent years, water hyacinth has received attention because of its potential for the abstraction of pollutants when it is used in biological treatment systems [88]. The thick growth of water hyacinth can reduce the quantity of sunlight that reaches the water, thus impeding many photosynthetic species and disturbing the ecological equilibrium. Furthermore, its extensive coating on the surface of bodies of water reduces oxygen transmission into the water [88]. Water hyacinth has lengthy roots floating in water which are believed to provide a medium for aerobic microbes in sewage treatment systems. These microbes eat organic materials and nutrients in wastewater and convert them into inorganic compounds that plants may absorb. Water hyacinth often develops swiftly in non-native countries due to a lack of natural enemies or consumers [87,89].

Water treated by water hyacinth had low amounts of COD, BOD, TSS, and chromium (Cr) after two months compared to the flow into the floating treatment wetland (Figures 5 and 6). The influent value of COD was more than 1500 mg/L, which decreased to less than 10 mg/L after treatment. The BOD influent value was found to be 1000 mg/L, which was reduced to 10 mg/L after treatment. The TSS values were noted to be above 150 mg/L, which reduced to under 50 mg/L after the treatment. The chromium inflow values were noted as above 14 mg/L, whereas the effluent values were reduced to below 2 mg/L. Additional processes such as the gravitational settling of solids and coprecipitation with insoluble compounds may have contributed to the high chromium removal in the wetlands [90]. Overall, the average reduction in the pollution in tannery wastewater by the water hyacinth was more than 90 percent for COD, BOD, and Cr, and 85% for TSS (Table 2). The results for Cr were similar to those reported in a previous study, which found that the water hyacinth removed 87.52% of Cr from the contaminated water source [91].

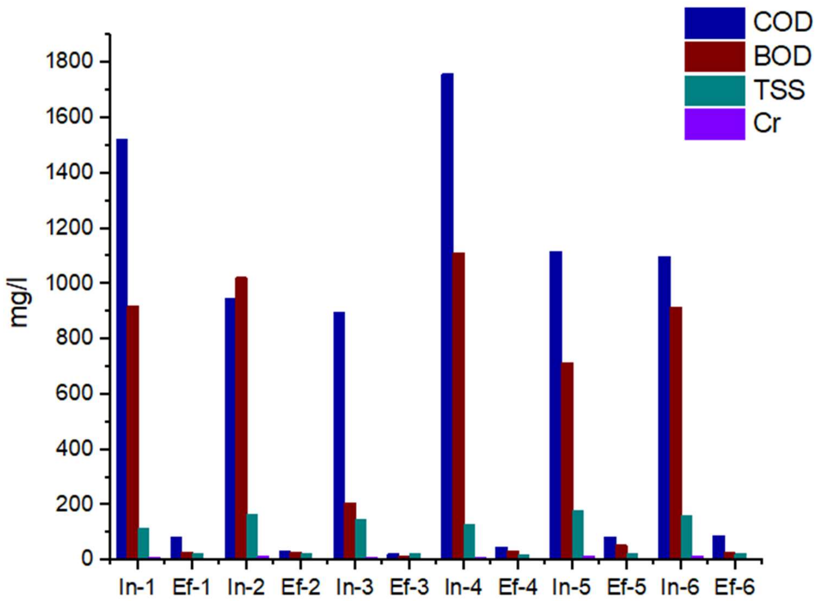

Figure 5. Pollutant concentrations in the FTW inflow (In) and effluent (Ef) over six biweekly sampling periods (1 through 6) using water hyacinth.

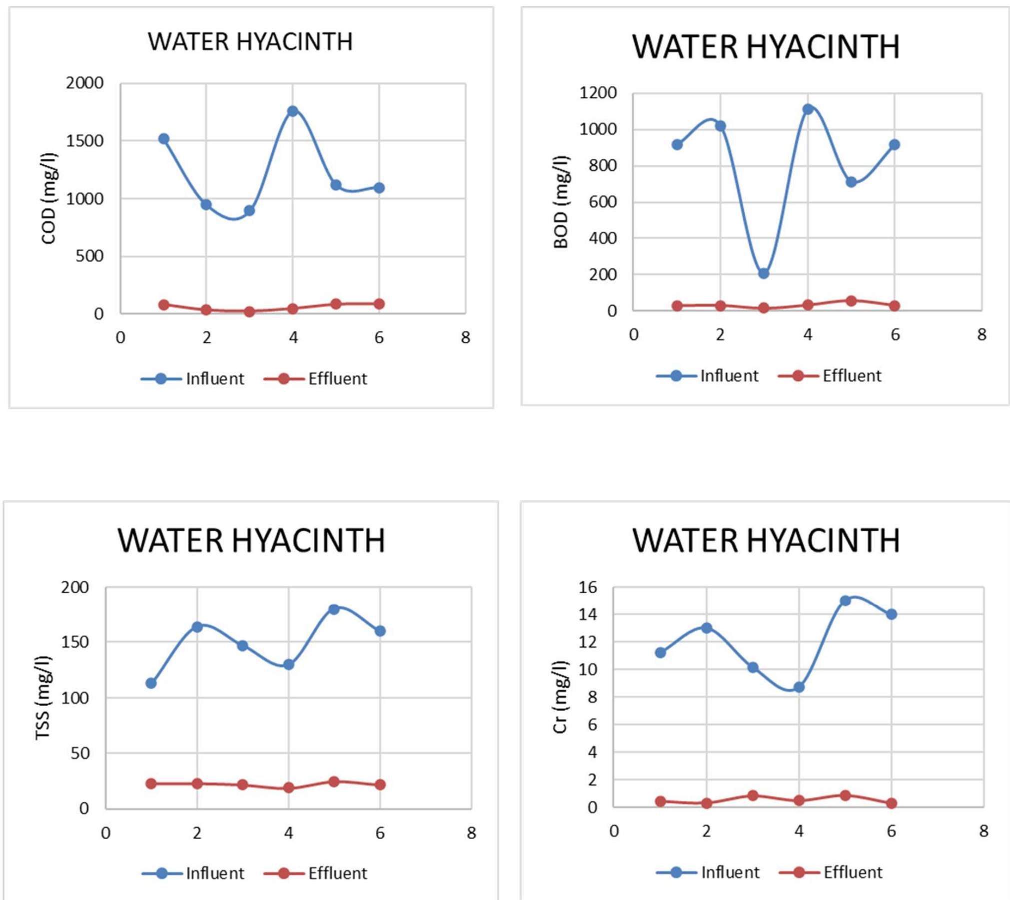

Figure 6. Variations in COD, BOD, TSS, and Cr concentrations into and out of the water hyacinth FTW at each of the six biweekly sampling periods.

Table 2. Averaged effluent concentrations and removal efficiencies for COD, BOD, TSS, and Cr with the hyacinth species.

Parameters	Average Inlet Concentration (mg/L)	Average Outlet Concentration (mg/L)	Removal Efficiency (%)
COD	1222.16	59.83	95
BOD	814.7	31.76	96
TSS	149	22.41	85
Cr	12	0.67	94

4.2. Water Lettuce

Water lettuce, (*Pistia stratiotes*) from the Araceae family, floats on the water surface and its roots hang submerged beneath floating leaves [92]. It is used for medicine and fodder in different countries across the world. Water lettuce is larger in yield compared to other small aquatic weeds such as *Lemna* spp. and may be used in the phytoremediation of a variety of contaminants found in industrial effluent [93]. It has a high capacity for the absorption of pollutants including hazardous heavy metals as well as a high level of cellular proliferation [94]. As a result, it can grow in stressful circumstances and absorb a variety of pollutants inside its plant components.

During the two-month period when water lettuce was in the FTW system, BOD and COD in the tannery effluent ranged from 400 to 1200 mg/L; these values decreased after treatment using water lettuce (Figure 7). However, water lettuce was not as efficient at reducing BOD or COD as water hyacinth, reducing COD, on average, by only 27% and BOD by 41% (Figures 7 and 8; Table 3). The removal of TSS (80%) and Cr (more than 90%) was similar to water hyacinth. Our results are in agreement with other studies which found that the removal of metals such as zinc, cadmium, and nickel from wastewater by water lettuce is extensively efficient [93]. Other research observed that water lettuce can efficiently remove Cr from water at different concentrations of 1, 2, 4, and 6 mg Cr/L [95,96]. Other research on treatment wetland (in vertical and horizontal design) found a higher removal percentage of BOD (82%), along with efficient removal of phosphate (95.4%) and chloride (51%). Additionally, the fecal coliform removed by water lettuce (over 98%) suggested the ability of the plant to uptake nutrients and release toxins for pathogen disinfection. It is also suggested that vertical design could be a better option for wetlands using the species of water lettuce [97].

4.3. Typha Latifolia

Typha latifolia is a well-known emergent hyperaccumulator plant. It can collect metals such as copper, mercury, chrome, copper, and lead up to 0.1 percent of the plant dry weight and iron and zinc up to 1% [98]. In recent times, *P. australis* and *T. latifolia* have been used to remove heavy metals [99]. Over the two months when *Typha latifolia* was grown in the FTW, the analysis of the inlet and outlet samples indicated a reduction in COD of 278 mg/L with 48% removal efficiency, BOD 123 mg/L with 31% efficiency, and chromium of 3.36 mg/L with 33% efficiency (Table 4; Figures 9 and 10). The TSS reduction was 72% with an average inlet and outlet concentration of 220.33 mg/L and 61.68 mg/L. Another study reported that *Typha* species removed 96.2% of cadmium, 83.6% of copper, and 95.9% of lead, respectively [100]. In the *Typha latifolia* study, the BOD and COD results varied slightly, whereas the TSS and chromium results varied greatly between the FTW inflow and effluent. The input COD was found to be 800 mg/L, and effluent COD was reduced to 200 mg/L after treatment. The input BOD was as high as 500 mg/L; after treatment, it was reduced to as low as 200 mg/L (Figure 10). The TSS value in the FTW inflow varied from 60 to 400 mg/L and from 20 to 100 mg/L in the effluent. As result of treatment, the inflow chromium levels varied from 5 to 16 mg/L and effluent from 0 to 15 mg/L (Figure 10). It has been shown that the *Typha* species are more tolerant of metal toxicity than other plant species [101,102].

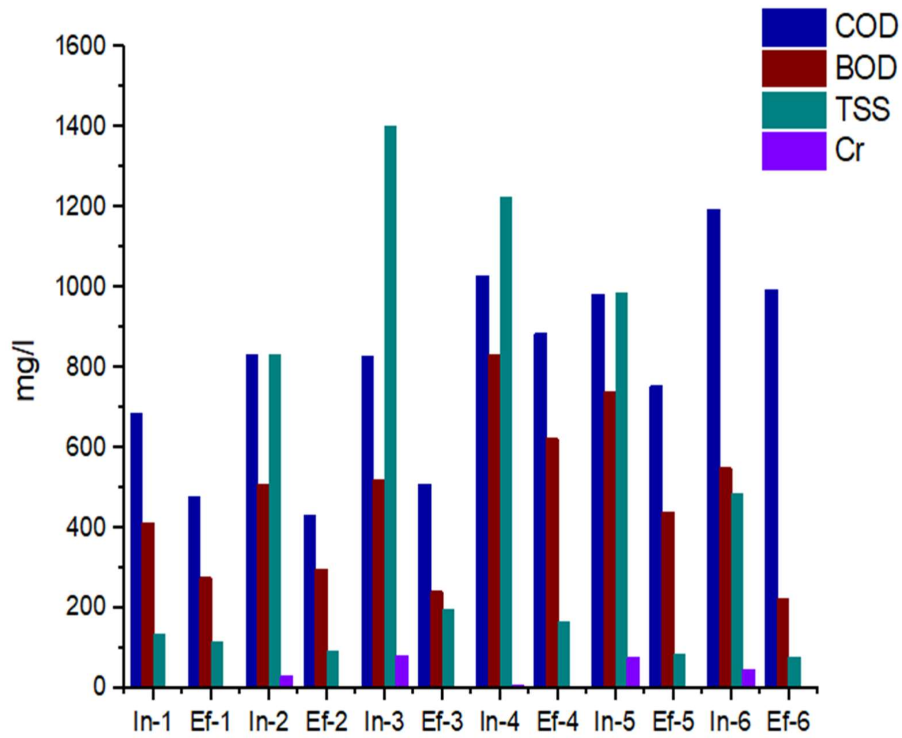

Figure 7. Concentrations of pollutants in the FTW inflow (In) and the effluent (Ef) over the six biweekly sampling periods (1 through 6) using water lettuce.

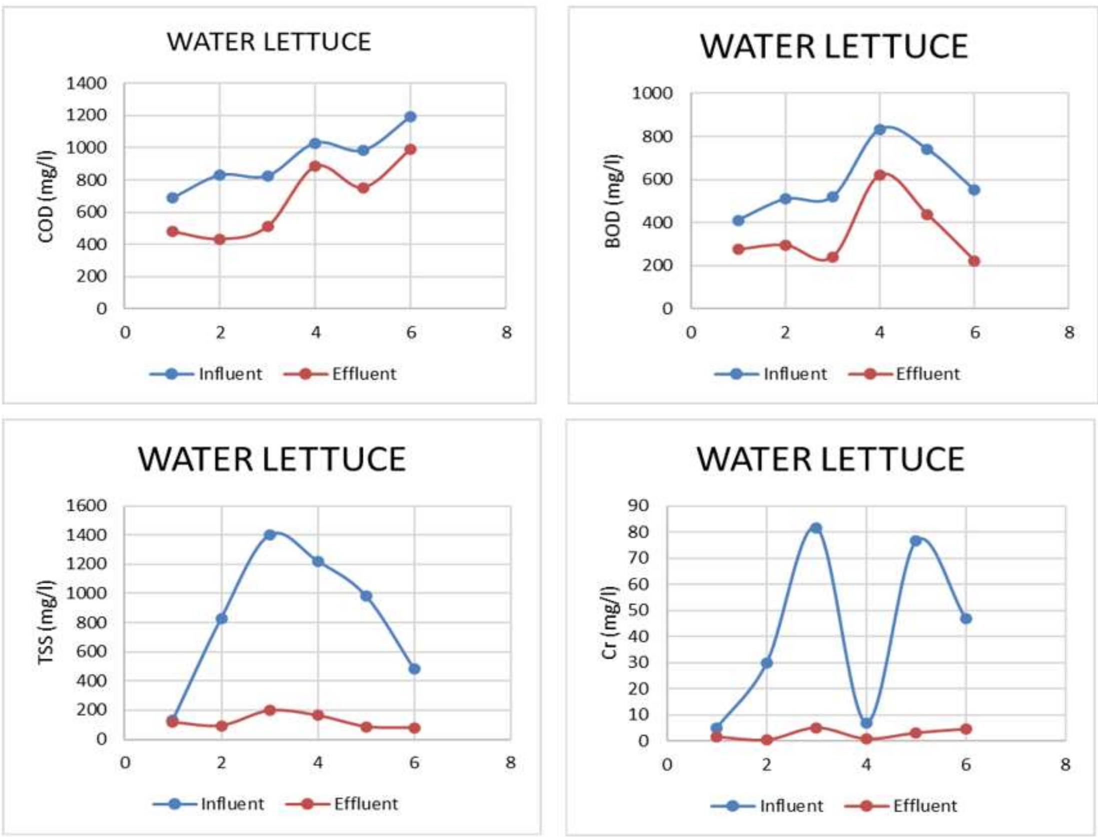

Figure 8. Variations in COD, BOD, TSS, and Cr mass concentration into and out of the water lettuce FTW at each of the six biweekly sampling periods.

Table 3. Averaged effluent concentrations and removal efficiencies for water lettuce.

Parameters	Average Inlet Concentration	Average Outlet Concentration	Removal (%)
COD	924.66	675.16	27
BOD	594.33	349.66	41
TSS	842.66	123.16	85
Cr	41.19	2.5	94

Table 4. Averaged effluent concentrations and removal efficiencies for *Typha latifolia*.

Parameters	Average Inlet Concentration	Average Outlet Concentration	Removal (%)
COD	583.83	305	48
BOD	399.33	276.83	31
TSS	220.33	61.82	72
Cr	10.04	6.68	33

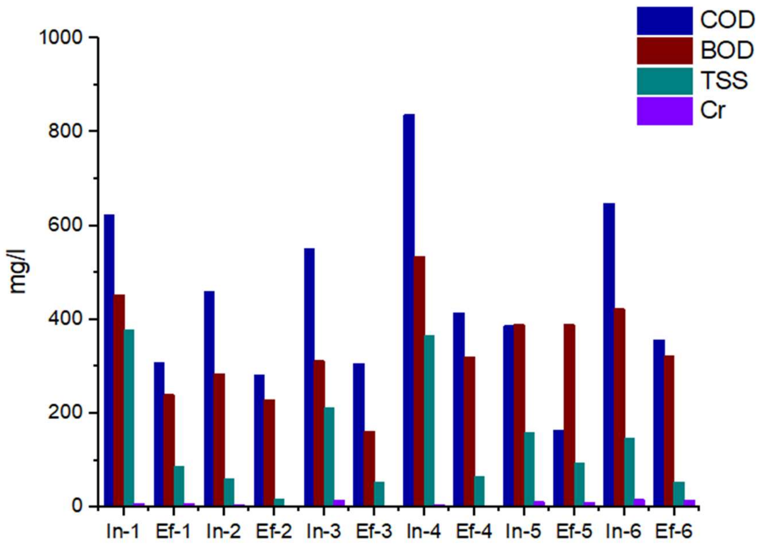

Figure 9. Pollutant concentrations in the FTW inflow (In) and effluent (Ef) over the six biweekly sampling periods (1 through 6) using *Typha latifolia*.

The metal uptake by these wetland plants, precipitation and coprecipitation as insoluble salts, and metal binding to the substrate are processes that are attributed to heavy metal reduction in *T. latifolia* [103]. *T. latifolia* provided substrate and sustaining media for the growth of micro-organisms, which are key players in heavy metal immobilization and uptake by plants. The rhizosphere of these plants may be naturally reduced, which would further augment the cell wall capability to absorb metals through immobilization, which could explain why the overall effect of metal uptake by *T. latifolia* is reduced. Another reason for the decrease in overall heavy metal removal could be that these plants accumulate phytosiderophores [97,104].

Floating treatment wetlands are a less expensive wastewater treatment technique with minimal construction, operation, and maintenance costs [76,82,105] partly because construction materials can be obtained locally and commercially. Moreover, FTWs do not need any complicated technical mechanisms for their installation or manufactured chemical input to sustain functional processes or for maintenance. Hence, low construction and operating costs make this technology a particularly reasonable and practical method in developing countries [56]. According to the research, a 201 m^3 constructed wetland costs approximately 445 USD (1 USD = 176 PKR), a 158 m vertical flow constructed wetland (VFCW) requires 574 USD, a 251 m^3 horizontal flow constructed wetland (HFCW) requires 1425 USD, a 272 m^3 reed system costs 1040 USD, and a secondary constructed wetland costs

1874 USD (it always varies area to area) [106]. The cost of a constructed wetland is around 50%–90% less than the cost of other traditional wastewater treatment technologies [107]. The COD, TSS, TN, and TP removal rates for the HFCW and VFW systems are 61%, 75%, 31%, and 26%, respectively. Another comparison made by the US-EPA is that the life cycle costs for a swamp are lower than the cost of a conventional treatment system designed for the same flow and effluent water quality [104].

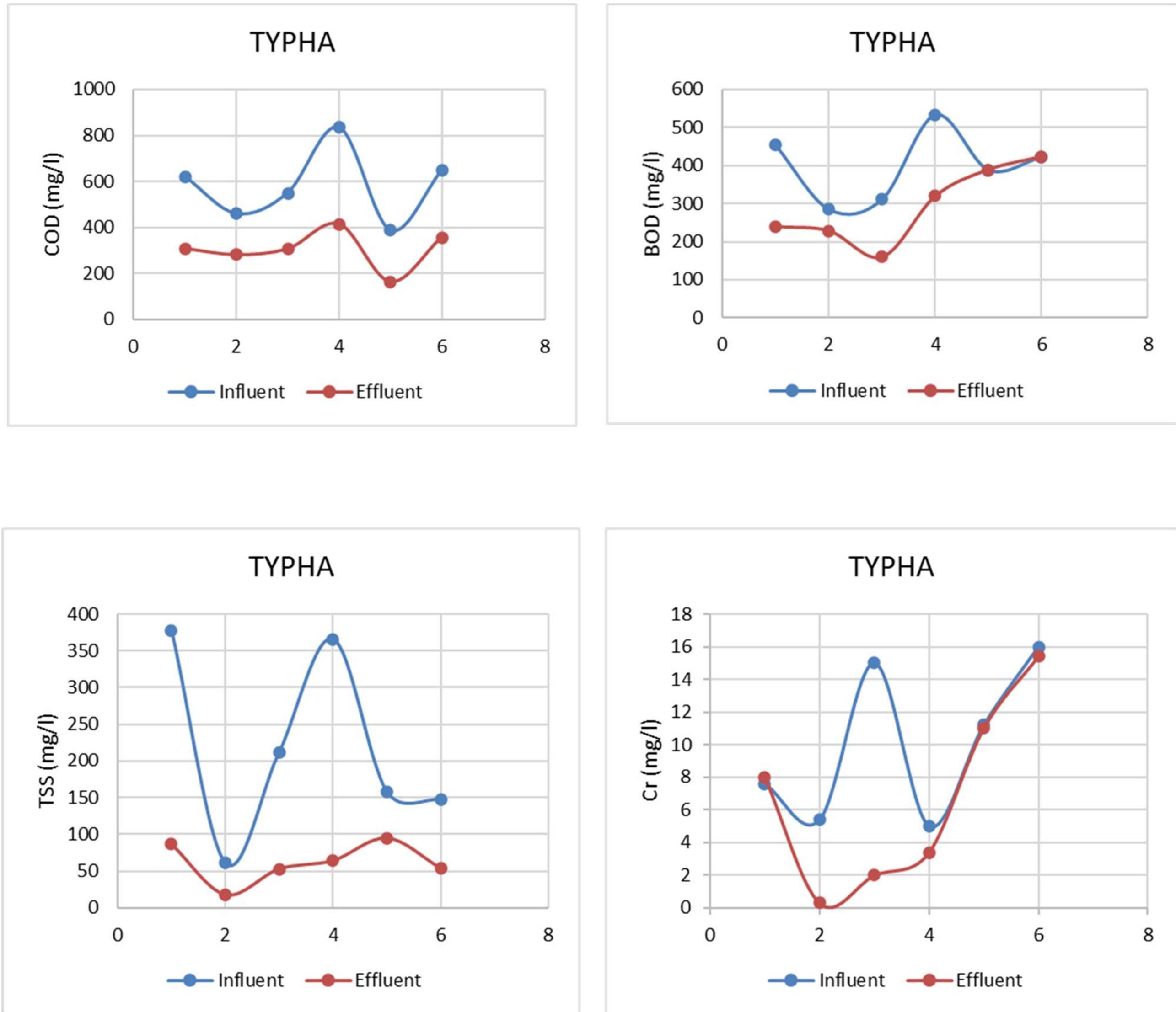

Figure 10. Variations in COD, BOD, TSS and Cr concentration into and out of the *T. latifolia* FTW at each of the six biweekly sampling periods.

A designed floating treatment wetland may be used to treat a wide range of wastewater types (industrial, kitchen, washbasin, etc.). The efficiency of a built wetland is determined by the kind of wetland, species, delivered hydraulic stress, and bed material [105,108]. Water hyacinth (*Eichhornia crassipes*), a free-floating aquatic vegetation that grows quickly, may absorb huge amounts of trace minerals and pollutants through processes that are dependent on root growth. When plants are cultivated in industrial wastewaters with high quantities of macronutrients, their absorption of elements such as heavy metals are frequently boosted. Other factors may limit the capacity for plants used in this study to reduce pollutants; for example, water lettuce is based in hot, humid climates and is not robust in cold areas.

To maintain the optimal plant densities (0.2–0.7 kg dry biomass per m^2), metal- or nutrient-loaded plant biomass must be removed from water bodies for efficient water treatment. If not collected, the bulk of the components would be returned to the water through plant breakdown processes. It has been demonstrated that more intensive management, including more regular and timely harvesting of plant biomass, might result in a greater pollutant reduction. For example, for optimal pollutant reduction, plants in a semitropical environment should be picked every other week during the wet season, when temperatures are also optimal for water lettuce development, to maintain around a three-fourths covering of the surface of the water [91]. The *Typha* genus is commonly applied in wetlands. Most *Typha* research focuses on removal efficiency responses to contaminants. In addition to affecting the ability of a plant to absorb pollutants from water, root structure and root diameter variations are strongly linked to the ecological requirements of plants and removal efficiency [109–111]. Most of the components were gathered in the sediment, which aided in the deposition. The pollutant transfer to above-ground structures was not always considered. Therefore, plants in this study had only a limited effect on reducing pollutants (Table 5). However, macrophytes can operate as phytostabilizers and improve contaminant sequestration, especially when the root biomass grows rapidly. As a whole, the wetlands which were investigated here for the first time in Pakistan have shown a positive performance. This study will be a guiding principle for small and medium enterprises. It will help SMEs to design, construct, assess, and achieve the local wastewater treatment guidelines. Furthermore, detailed research and use of the floating treatment wetland as a low-cost, energy-efficient wastewater treatment process in developing countries are needed. Future research should focus on the efficiency and sustainability of FTWs to improve the environment and operations and to find new ways to improve dead or contaminated plant management and substrates in real-world field trials. Nutrients and other pollutants absorbed by wetlands plants have been found to be released into water when species die and decompose during the cold winter, potentially resulting in poor removal performance. As a result, research and development on optimal plant harvesting methodologies as well as the restoration and regeneration of plant resources in FTWs is critical. It is recommended that floating treatment wetlands be integrated to treat wastewater from tanneries. Many constructed treatment wetlands were designed and considered only for wastewater treatment. However, in addition to their high removal efficiencies, manmade treatment wetlands have lately been demonstrated to offer a significant possibility in the new sustainable and circular economy in industrial and urban environments. As proposed by the "sponge city" idea, treatment wetlands can successfully treat, collect, and recycle nutrients and water for future use. Floating treatment wetlands are a new technique that has proven useful in a variety of applications, including wastewater treatment, bioremediation, and stormwater treatment. The efficiency of their construction and operation as well as the reduced area needed for procedures make them an appealing alternative for integration with treatment ponds and traditional artificial wetlands. However, just one research paper integrating FTW with a mixed CW mechanism was discovered in this review; hence, combining FTW with other technologies, such as advanced oxidation processes, should be investigated further, particularly when the focus is on water reuse.

Table 5. Removal efficiency comparison of plants.

	COD Removal Efficiency %	BOD Removal Efficiency %	TSS Removal Efficiency %	Cr Removal Efficiency %
Water Hyacinth	95	96	84	94
Water lettuce	27	41	85	94
Typha latifolia	48	31	72	33

5. Conclusions

Floating treatment wetland systems are an innovative field that has been demonstrated to be adaptable to multiple tasks, such as domestic wastewater treatment, bioremediation, and industrial wastewater treatment. Their comparatively simple development, operation, and low cost make them an attractive alternative for integration with treatments ponds and conventionally created wetlands. The sustainability of the tannery sector is important for the GDP of Pakistan. The tannery sector utilizes a large amount of water and discharges polluted water. In order to devise a cost-effective system for the treatment of tannery wastewater, a floating treatment wetland model was set up to treat effluent using local plant species through phytoremediation as a pilot. In this study, we found that floating treatment wetland systems can be successfully established for the treatment of the contaminants of tannery wastewater. Our research shows that the water treated by water hyacinth had low amounts of COD, BOD, TSS, and chromium (Cr) after two months compared to the flow into the floating treatment wetland. The influent value of COD was decreased to 10 mg/L from 1500 mg/L, the TSS reduced to 50 mg/L from 150 mg/L, and chromium from 14 mg/L to 2 mg/L. Water lettuce was not as efficient at reducing BOD or COD as water hyacinth, reducing COD, on average, by only 27% and BOD by 41%. The removal of TSS (80%) and Cr (more than 90%) was similar to the water hyacinth. Furthermore, *Typha latifolia* is a well-known emergent hyperaccumulator plant. It can collect metals such as copper, mercury, chrome, copper, and lead up to 0.1 percent of the plant dry weight and iron and zinc up to 1%. Over the two months when *Typha latifolia* was grown in the FTW system, the analysis of inlet and outlet samples indicated a reduction in COD of 278 mg/L with 48% removal efficiency, BOD 123 mg/L with 31% efficiency, and chromium of 3.36 mg/L with 33% efficiency. The TSS reduction was 72%, with an average inlet and outlet concentration of 220.33 mg/L and 61.68 mg/L. The tested pilot-scale FTW was demonstrated to be a successful treatment solution for tannery effluents, and it is a low-cost wastewater treatment method with low development, operating, and maintenance costs.

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