RESEARCH ARTICLE

Sustainable Solutions for Textile Pollution: Evaluating Phytoremediation with *Lemna minor*, *Spirodela polyrhiza*, and *Eichhornia crassipes*

Vibha Jaiman[1], Anuj Sharma[2], Seema Nama[1], Seema Manwani[1], Narain Bhoot[3], Harsh Pandey[4], Kumud K. Awasthi[1] and Garima Awasthi[1*]

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Abstract

While the textile industry is important to the world economy, its environmental effect, which includes the discharge of pollutants such as dyes, heavy metals, and organic compounds, needs long-term solutions. This research looks at the phytoremediation capacities of three plant species, *Lemna minor*, *Spirodela polyrhiza*, and *Eichhornia crassipes*, for which macrophyte survey was undertaken for decreasing different water quality indicators (BOD, COD, Total hardness, alkalinity, Chloride, Manganese, and Iron) in textile effluent, in the drain region of Sanganeri printing companies from three different S-1: Sanganeri print, S-2: Radha prints and S-3: Sanganeri block print. The study looks at how effective these plants are in removing and detoxifying pollutants present in textile effluents. Metrics such as pollutant absorption, plant development characteristics, and biochemical alterations are tracked. The results show that *E. crassipes* consistently outperformed *S. polyrhiza* and *L. minor* across all parameters tested, showing its superior efficacy in textile wastewater phytoremediation. This study adds to the promotion of phytoremediation as an effective instrument for environmental restoration and assists in the creation of low-cost, environmentally friendly solutions to alleviate the textile industry's environmental impact.

Keywords: *Lemna minor*, *Spirodela polyrhiza*, *Eichhornia crassipes*, Phytoremediation, Reduction rate.

Highlights

- The textile industry contributes to pollution with dye, heavy metals, and organic compound discharge.
- Research examines phytoremediation using *L. minor, S. polyrhiza*, and *Eichhornia crassipes.*
- A study was conducted in the Sanganeri printing drain region to assess pollutant reduction in effluents.
- *E. crassipes* shows consistent superior performance in pollutant removal.

Phytoremediation offers cost-effective, eco-friendly solutions for the textile industry's environmental impact.

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Introduction

Water is the most crucial and valuable natural resource necessary for the existence of all living things. Water's physicochemical qualities vary depending on its purity. The contaminants are in water that might be natural or manmade. Effluents from industry, household agriculture, and runoff surface water have an impact on water quality due to their color, high organic content, widely fluctuating pH, presence of heavy metals, and other contaminants (Bishnoi and Roy 2017, Awasthi *et al.,* 2024). The textile industry is one of the most water-intensive businesses, generating a significant volume of effluent. Textile effluent contains a high organic content, total dissolved solids, and refractory compounds such as dyes, as well as high salinity, heavy metals, and changing pH, all of which harm aquatic habitats. Textile effluents are among the most difficult wastewaters to treat due to the presence of a trace quantity of color (1 ppm) in water, which is cause for concern because it is extremely visible, changing the aesthetic value, water transparency, and gas solubility in lakes, rivers, and other sources of water (Parihar and Malaviya 2023; Singh *et al.,* 2022; Jadhav *et al.,* 2024). Textile wastewater has been recognized as one of the major factors contributing to global aquatic pollution fundamentally because it contains chemicals with toxicological concerns; additionally, these substances may block sunlight, thereby impairing photosynthesis and increasing the biological oxygen demand in receiving waters, compromising the fundamental reoxygenation process (de Alkimin *et al.*, 2020). Furthermore, one of the most significant challenges associated with wastewater treatment is the insufficient reduction of the load of all the toxins contained in wastewater to achieve limitations imposed by legislative legislation (Paweska and Bawiec 2017). This disadvantage poses a possible risk to aquatic

[1]Department of Life Sciences, Vivekananda Global University, Jaipur, Rajasthan, India.

[2]Department of Forensic Science, SOS, ITM University, Gwalior, Madhya Pradesh, India.

[3]Rajasthan State Pollution Control Board, Jaipur, India.

[4]Department of Biotechnology and Chemical Engineering, Manipal University, Jaipur, India.

***Corresponding author:** Garima Awasthi, Department of Life Sciences, Vivekananda Global University, Jaipur, Rajasthan, India., Email: garima.awasthi@vgu.ac.in

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creatures exposed to the toxic environment residing in the receiving water bodies. It is required to remove pollutants from textile effluent before it is discharged into water bodies; otherwise, it disturbs the aquatic ecology (Hernando *et al*., 2005). Many conventional congenital methods are used by textile otherwise to treat its effluents (Verma, Dash, and Bhunia 2012). To reduce the environmental effect of industrial effluents, color can be removed by adsorption on inorganic or organic matrices, coagulation, filtering, electrochemical oxidation, ozonation, photo-oxidation processes, photo-catalysis, and microbiological degradation. However, these methods are limited in terms of cost and decolorization efficiency. Among these, adsorption has a key downside since it has limited effectiveness for a wide range of colors, whereas coagulation generates substantial sludge (Parihar and Malaviya, 2023). Phytoremediation has been advocated as an effective, low-cost, and favored cleaning alternative for moderately polluted locations (de Alkimin *et al*., 2020; Sharma *et al.,* 2023). Phytoremediation is an emerging technique that promises to be successful, ecologically safe, and cost-effective in cleaning up settings polluted with harmful metals (Singh and Singh 2017; Mayo and Hanai 2017; Kumari *et al*., 2023). Plants can either directly participate in detoxification processes, such as contaminant incorporation and subsequent metabolization or immobilization within the plant, or indirectly, by promoting or supporting rhizospheric microorganisms that effectively carry out the detoxification process, one of which is phytofiltration. Phytofiltration, in particular, is the use of aquatic plants, whether floating, submerged, or emergent, to remove pollutants from solution, mostly through their root system, but fronds are sometimes directly engaged in the removal process. Plants often absorb and collect pollutants through their roots, transporting them into their biomass (such as the stem and leaf). Some are hyper-accumulators for hazardous metals, prospering at conditions that would be unbearable for other plant species (Ibañéz *et al.,* 2018). Macrophytes, such as duckweed *S. polyrhiza*, *L. minor*, and water hyacinth (*Eichhornia crassipes*), are popular aquatic phyto-accumulators against many contaminants (De Laet *et al*., 2019). *S. polyrhiza* is a freshwater macrophyte that floats freely and has an oval-shaped thallus. The thallus's underside is often reddish-purple, with a cluster of 4-16 roots in water (Singh, Vyas, and Malaviya 2016). It has gained the capacity to quickly collect nutrients essential for growth from the water in which it floats. This is a positive feature of phytoremediation since it decreases nutrient levels in wastewater (Gupta and Prakash 2013). Because of its fast growth rate, ease of handling, high productivity, increased bioaccumulation capacity, and tolerance for living in severe environmental circumstances, *S. polyrhiza* is used as a test organism in several research investigations, establishing them as promising agents for phytotechnology (Ziegler, Sree, and Appenroth 2016). The employment of aquatic macrophytes (e.g., *Lemna spp*.) for the entire treatment of wastewater originating from certain treatment plants might be crucial, especially during the last tertiary treatment phase, which allows cleaned wastewater to be discharged into the environment (Nirola *et al*., 2016). These plants that may be employed in phytoremediation procedures can eventually be put in landfills, but they can also be burnt; incineration has been recommended as a technique of reducing the plant volume while simultaneously generating energy through heat (De Souza and Silva 2019). Furthermore, these plants may be employed in the ceramic sector by combining the biomass used in the treatment of ceramic blocks, which corresponds to an efficient technique of transformation of the acquired products (de Lima, de Souza, and de Albuquerque 2015). *Eichhornia crassipes* appears to be the most fascinating due to its rapid growth rate, toughness, invasiveness, and capacity to live in harsh environmental circumstances. In rivers, lakes, and lagoons, WH (water hyacinth) hampers navigation, fishing, and other human activity on waterways. (Adelodun *et al*., 2021). *E. crassipes* is successful in turning the alkaline pH of wastewater to neutral. *E. crassipes* showed a similar pattern of pH fluctuation across a 10-day study period. *E. crassipes* reduced COD in textile wastewater by reducing it 80% within 18 days (Wickramasinghe and Jayawardana 2018). Despite the potential benefits of employing aquatic macrophytes in phytoremediation of hazardous pollutants, they are widely seen as a nuisance to the normal functioning of water bodies, and most attempts are being made to remove these plants from local water bodies due to their rapid growth rate. This circumstance may intensify the clogging impact on the water intake system in irrigation tanks, the destruction of biodiversity in water bodies, and eventually, the influence on the health of the aquatic system (Varsha, Nidhi, and Anurag 2010). As a result, the current study aims to assess the phytoremediation capacity of the floating macrophytes *Eichhornia crassipes*, *S. polyrhiza*, and *L. minor* for the treatment of textile wastewater. As a result, it was also designed to evaluate the significant capability of pollutant absorption, accumulation, and strength to reduce treatment time.

Materials and methods

Sites of Study

A survey was conducted near the printing industrial area to access the vegetation growing in the area along the drain site. The effluent was collected from 3 following sites (S-1; S-2 & S-3) -

S-1: Sanganeri print, S-2: Radha prints and S-3: Sanganeri block print

Collection of Samples

A macrophyte survey was undertaken in the drain region of Sanganeri printing companies, Radha prints, and Sanganeri Block Print. The investigation was carried out to identify the macrophytes growing near the drain locations. The gathered plants were placed in the Herbarium of the University of Rajasthan in Jaipur, Rajasthan.

Selected macrophytes:

Physiochemical analysis of samples

The selected macrophytes (100 g) as shown in Fig. 1, were acclimatized into effluents and left for 5 days. The effluent was analyzed for the following parameters before and after acclimatization.

BOD (Biochemical Oxygen Demand)

The sample was incubated in an airtight bottle at a set temperature for five days. The sample was incubated at 20°C

A B C

Fig. 1: Experimental Setup – Acclimatization of 100 g of selected macrophytes in textile effluents for a duration of 5 days as part of the phytoremediation study (A) *L. minor*, (B) *S. polyrhiza* & (C) *E. crassipes*

for five days, and the dissolved oxygen (DO) level was tested both before and after. The difference between the initial and final DO readings was utilized to calculate Biochemical Oxygen Demand (BOD). The original DO was determined shortly after dilution, and any additional oxygen absorption was accounted for in the BOD measurement. The following formula was used to obtain the diluted sample's five-day BOD (Jouanneau *et al.*, 2014).

COD (Chemical Oxygen Demand)

The chemical oxygen demand (COD) was determined using the titrimetric method. Initially, 2.5 mL of the sample was mixed with 1.5 mL of $K_2Cr_2O_7$ (0.01 N) solution, followed by the addition of 3.5 mL of sulfuric acid reagent. The resulting mixture was digested for 2 hours at 150°C in a digester and then cooled to room temperature. Subsequently, it was titrated with 0.01 N F.A.S. using ferroin indicator until the color changed from green to brick red (Patel and Vashi 2015).

TH (Total Hardness)

Water total hardness can be measured using complexometric titration with EDTA. First, 20 mL of collected water is pipetted out into a cleaned conical flask. Next, 5 mL of basic buffer solution and 2-3 drops of Eriochrome Black-T indicator are added, turning the color of the solution to wine red. This solution is titrated against EDTA solution taken in the burette until the color changes from wine red to clear blue at the end. Finally, the burette's final reading is noted, and the titration is repeated to obtain a concordant value. Lastly, analytical calculations are used to determine the total hardness of the given water sample in terms of ppm of $CaCO_3$.

TA (Total Alkalinity)

The titrimetric technique was used to calculate the total alkalinity of the water. The material was first pipetted into a conical flask in an amount of 20 mL. 50 or 100 mL of the sample were utilised for low alkalinity. Once the pH was measured, and it was found to be higher than 8.3, 'A' was recorded. Gradually, 0.02 N H2SO4 was added until the pH was 8.3. If the pH was not higher than 8.3, phenolphthalein alkalinity was deemed to be absent. 'B' was recorded for the pH measurement after 0.02 N H2SO4 was added in sample increments starting at pH 8.3 and continuing until pH reached 4.5. As an alternative, 0.02 N H2SO4 and mixed indicator were added to the same solution.

Chloride

First, 20 mL of the sample are collected in an Erlenmeyer flask and its pH is adjusted with a sulfuric acid solution to a range of 7.0 to 8.0. 1 mL of potassium chromate is then added to produce a pale-yellow hue. Following that, the sample is titrated using a normal silver nitrate solution until the color turns brick red instead of yellow. It is specified how much silver nitrate was applied. Distilled water is titrated in the same way to guarantee accuracy, and the amount of silver nitrate added is recorded as well.

Manganese

The procedure is filling a test tube with stoppers or a separator funnel with a predetermined volume of manganese (II) solution, then adding the proper concentrations of Phen and NBASA solutions. Next, buffer solution is added to the total amount until it is diluted to 10 mL. Five mL of solvent are added and the mixture is agitated for a minute. Following the phases' separation, the colored extract is put into a cuvette, and the absorbance concerning water is calculated. An analogous experiment is conducted in the absence of manganese, wherein the absorbance of the reagent extract is also determined in comparison to water.

Iron

During the experiment, the analytical concentration of iron in standard iron solutions was determined. The absorbance was measured and tabulated, and the iron contents for all standards, tap water samples, and unknown samples were determined in ppm and molarity. The estimates included dilution factors. The method's detection and quantification limits were derived using the intercept's standard error. The Beers law equation, A = m [Fe]+b, was derived by plotting absorbance vs. iron content for the standards (including the iron-free solution) using the least-squares (i.e., linear regression) approach. The molar absorptivity of Fe(phen)3 2+ at 508 nm was computed and compared to the published value of 11,100 M-1 cm-1 (Skoog *et al.*, 2013).

Nitrate

The UV spectrophotometric approach was employed to ascertain the nitrate ions present in a water sample following the Standard Procedures for the Examination of Water and Wastewater (APHA, AWWA, and WEF, 21st Edition, 2005). Redistilled water that had been adjusted to 100% transmittance or zero absorbance was used to measure the absorbance or transmittance. The nitrate measurement was obtained at 220 nm, and wavelengths at 275 nm were utilized to correct for interferences caused by dissolved organic debris.

Phosphate

Phosphate in a water sample may be found using a few different methods. A Kjeldhal flask is first filled with 50 mL of the sample, to which 1 mL of concentrated sulfuric acid and 5 mL of nitric acid are added. After allowing the sample to digest until its volume reaches 10 mL, it is cooled to room temperature. Then, 20 mL of distilled water, one drop of phenolphthalein indicator, and 1-mL of 1N sodium hydroxide (NaOH) are added until the color turns pink. After filtering, the mixture is added to a 100 mL capacity. The mixture is then further reduced by adding 10 drops of a reducing agent, such as stannous chloride after 4 mL of ammonium molybdate has been added. The blue color develops once the ammonium molybdate is added, and after

ten but before twelve minutes, the absorbance is measured at 690 nm (He and Honeycutt 2005).

Statistical analysis

Completely randomized design (CRD) under a split plot was used for arranging treatments, where each treatment had three replicates, and data was analyzed by two-way analysis of variance (ANOVA) using computer-based software 'Statistics 8.1®' (USA). Treatment means were compared by pairwise comparison applying HSD Post-hoc Tukey's comparison test at 5% level of significance. All the graphs presented in the results were made using MS Excel worksheets. Treatments having significant differences in post hoc tests were denoted with different alphabetical letters in graphs.

Results and Discussion

The primary environmental problem associated with the textile industry, aside from a few smaller ones including solid waste, resource waste, and workplace health and safety, is wastewater. Because the textile industry—and particularly the portion of it devoted to the dyeing process—contains significant amounts of heavy metals, total suspended solids (TSS), total dissolved solids (TDS), biological oxygen demand (BOD), chemical oxygen demand (COD), and many other contaminants in its wastewater, it is one of the major sources of pollution that continuously pollutes the environment. Adsorption, microprecipitation, ion exchange, complexation, and metal chelation are some of the processes that might lead to these processes (Rai *et al.*, 2002). One technique for treating wastewater that uses plant-based systems to remove toxins from a variety of natural sources is called phytoremediation (Roongtanakiat, Tangruangkiat, and Meesat 2007). From the various list of plant species used for phytoremediation, three plant species, *L. minor*, *S. polyrhiza*, and *E. crassipes* were selected. From the selected plant, the average reduction was noticed from all three water samples before and after acclimatization. The parameters selected for analysis were BOD (mg/L), COD (mg/L), total hardness (mg/L), total alkalinity (mg/L), chloride (mg/L), manganese (mg/L), iron (mg/L), nitrate (mg/L), phosphate (mg/L). Out of all the parameters the result in the present study was significant in all.

In the present study, Fig. 2 shows the results of the mean% reduction ± Standard deviation of all plant species out of all three water samples. *E. crassipes* is the most effective at reducing biological oxygen demand (BOD), BOD levels across the samples were moderately high, ranging between 18.70 to 21.48 mg/L, indicating the presence of biodegradable organics. Post-phytoremediation with duckweed, the BOD reduced to 11.71 to 16.38 mg/L range (Table 1) with an average reduction of 32.75 ± 7.80%, with range of 18.70 to 21.48 mg/L to 12.34 to 18.32 mg/L post acclimatization (Table 1). In comparison, *L. minor* has the average reduction rate of 26.58 ± 10.39%, while *S. polyrhiza* has the lowest average reduction rate of 21.81 ± 10.38%. This is consistent with the findings of Mahmood *et al.*, (2005), who found that using *E. crassipes* in textile water treatment reduced BOD levels by 40 to 70% and in study of Olukanni *et al.*, (2013) the reduction using the same species was 70%.

For the COD, *E. crassipes* continues to be effective, with a reduction of 24.36 ± 1.81% on average, *S. polyrhiza*, on the other hand, consistently reports the lowest reduction, averaging 16.78 ± 3.08% with a range of 44.76 to 51.37 mg/L before acclimatization and 38.84 to 41.86 mg/L post acclimatization (Table 1), with *L. minor* close behind with an average reduction of 20.69 ± 1.79%. In the study of Olukanni *et al.* (2013) showed COD reduction of 41% with *E. crassipes*, (Tables 1 and 2) in another study of Priya and Selvan (2017) the COD reduction using the same species was. In the case of Total Hardness reduction, with *E. crassipes* consistently demonstrated a reduction rate of 17.63 ± 9.01% (Tables 3 and 4). *S. polyrhiza*, on the other hand,

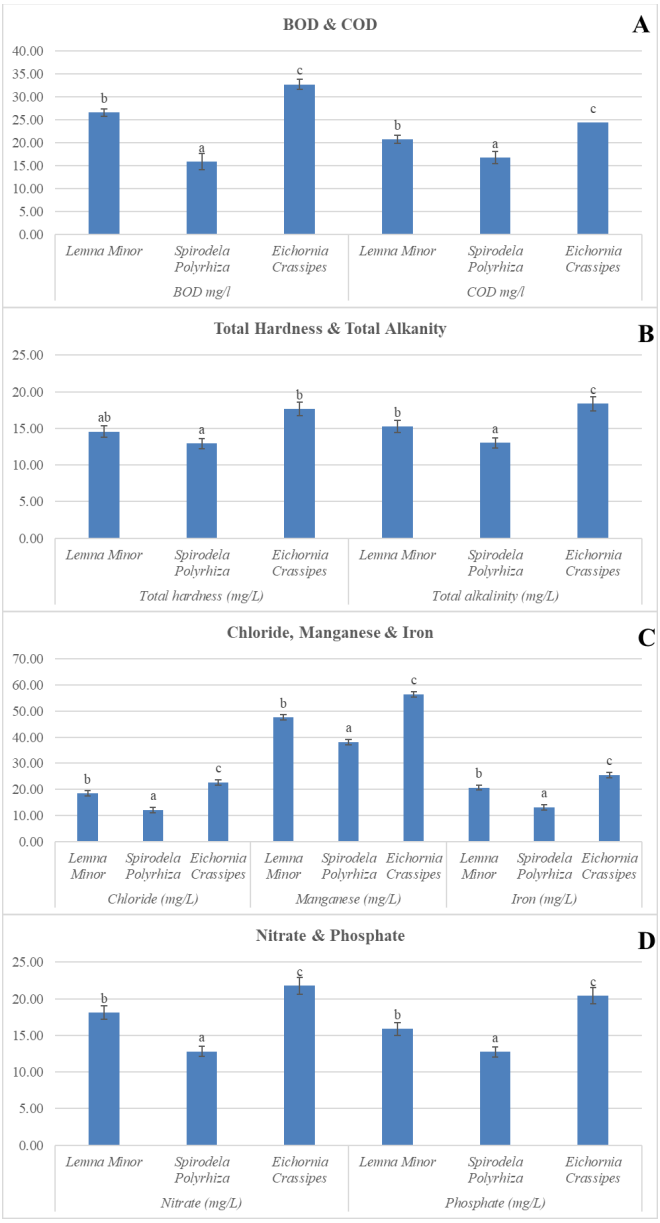

Fig. 2: Graph shows the Mean percentage reduction with error bars showing the Standard deviation of different parameters using different plant species i.e., *L. minor, S. polyrhiza, and E. crassipes* (A) BOD & COD; (B) total hardness & total alkanity; (C) chloride, manganese & iron; (D) nitrate & phosphate**.** All the values are average of three replicates ± Standard error. Treatments sharing the same alphabets are statistically non-significant at p-value <0.05

Table 1: Following table shows the phytoremediation potential of *E. crassipes, Spirodela polyrhiz, L. minor* on Biochemical Oxygen Demand (BOD), and Chemical Oxygen Demand (COD). All are measured in milligrams per litre (mg/L). The evaluation includes S-1, S-2, and S-3 samples, which show the dynamic changes in these essential water quality indicators before and after the acclimatization procedure

Parameter	*Plant type*	*Before acclimatization*						*After acclimatization*					
		S1	*± SD*	*S2*	*± SD*	*S3*	*± SD*	*S1*	*± SD*	*S2*	*± SD*	*S3*	*± SD*
BOD mg/l	*L. minor*	18.7	1.247	19.66	1.229	21.48	1.193	12.34	0.649	13.56	0.904	18.32	0.964
	S. polyrhiza							13.44	0.707	14.26	0.951	19.37	1.019
	E. crassipes							11.71	0.616	12.36	0.824	16.38	0.862
COD mg/l	*L. minor*	44.76	2.798	47.93	2.523	51.37	2.854	36.34	2.271	37.91	2.369	39.88	2.216
	S. polyrhiza							38.84	2.428	39.01	2.438	41.86	2.326
	E. crassipes							34.34	2.146	36.74	2.296	37.78	2.099

Table 2: Following table shows the reduction in Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD) with *E. crassipes, Spirodela polyrhiz, L. minor* The evaluation includes S-1, S-2, and S-3 samples. All measured in milligrammes per litre (mg/L)

Parameter	*Plant type*	*Reduction*					
		S1	*± SD*	*S2*	*± SD*	*S3*	*± SD*
BOD mg/l	*L. minor*	0.3401	0.0227	0.3103	0.0207	0.1471	0.0098
	S. polyrhiza	0.2813	0.0156	0.2258	0.0125	-0.031	-0.002
	E. crassipes	0.3738	0.0415	0.3713	0.0413	0.2374	0.0264
COD mg/l	*L. minor*	0.1881	0.0188	0.2091	0.0209	0.2237	0.0224
	S. polyrhiza	0.1323	0.0078	0.1861	0.0109	0.1851	0.0109
	E. crassipes	0.2328	0.0145	0.2335	0.0146	0.2646	0.0165

Table 3: Following table shows the phytoremediation potential of *E. crassipes, Spirodela polyrhiz, L. minor on* Total Hardness, and Total Alkalinity. All are measured in milligrams per liter (mg/L). The evaluation includes S-1, S-2, and S-3 samples, which show the dynamic changes in these essential water quality indicators before and after the acclimatization procedure

Parameter	*Plant type*	*Before acclimatization*						*After acclimatization*					
		S1	*± SD*	*S2*	*± SD*	*S3*	*± SD*	*S1*	*± SD*	*S2*	*± SD*	*S3*	*± SD*
Total hardness (mg/L)	*L. minor*	162	9.529	180	9.474	206	12.12	121	7.118	167	8.789	183	10.76
	S. polyrhiza							124	7.294	169	8.895	187	11
	E. crassipes							117	6.882	161	8.474	176	10.35
Total alkalinity (mg/L)	*L. minor*	286	15.89	312.66	18.39	345	21.56	201	13.4	287	16.88	318	17.67
	S. polyrhiza							208	13.87	293	17.24	326	18.11
	E. crassipes							195	13	274	16.12	307	17.06

Table 4: Following table shows the reduction in Total Hardness, and Total Alkalinity with *E. crassipes, Spirodela polyrhiz, L. minor* The evaluation includes S-1, S-2, and S-3 samples. All measured in milligrammes per litre (mg/L).

Parameter	*Plant type*	*Reduction*					
		S1	*± SD*	*S2*	*± SD*	*S3*	*± SD*
Total hardness (mg/L)	*L. minor*	0.2531	0.0169	0.0722	0.0048	0.1117	0.0074
	S. polyrhiza	0.2346	0.013	0.0611	0.0034	0.0922	0.0051
	E. crassipes	0.2778	0.0309	0.1056	0.0117	0.1456	0.0162
Total alkalinity (mg/L)	*L. minor*	0.2972	0.0297	0.0821	0.0082	0.0783	0.0078
	S. polyrhiza	0.2727	0.016	0.0629	0.0037	0.0551	0.0032
	E. crassipes	0.3182	0.0199	0.1236	0.0077	0.1101	0.0069

Table 5: Following table shows the phytoremediation potential of *E. crassipes, Spirodela polyrhiz, L. minor on* Chloride, Manganese, and Iron, all measured in milligrammes per litre (mg/L). The evaluation includes S-1, S-2, and S-3 samples, which shows the dynamic changes in these essential water quality indicators before and after the acclimatisation procedure

Parameter	*Plant type*	*Before acclimatization*						*After acclimatization*					
		S1	*± SD*	*S2*	*± SD*	*S3*	*± SD*	*S1*	*± SD*	*S2*	*± SD*	*S3*	*± SD*
Chloride (mg/L)	*L. minor*							53	2.789	69	4.6	72	4.8
	S. polyrhiza	70	3.684	82	4.824	85	5.667	58	3.053	73	4.867	78	5.2
	E. crassipes							50	2.632	65	4.333	69	4.6
Manganese (mg/L)	*L. minor*							0.11	0.006	0.19	0.011	0.23	0.014
	S. polyrhiza	0.25	0.019	0.36	0.02	0.38	0.025	0.14	0.008	0.22	0.013	0.26	0.016
	E. crassipes							0.09	0.005	0.16	0.009	0.19	0.012
Iron (mg/L)	*L. minor*							0.63	0.042	0.68	0.036	0.68	0.043
	S. polyrhiza	0.79	0.053	0.84	0.044	0.88	0.049	0.69	0.046	0.73	0.038	0.76	0.048
	E. crassipes							0.58	0.039	0.63	0.033	0.66	0.041

Table 6: Following table shows the reduction in Chloride, Manganese, and Iron with *E. crassipes, Spirodela polyrhiz, L. minor* The evaluation includes S-1, S-2, and S-3 samples. All measured in milligrammes per litre (mg/L)

Parameter	*Plant type*	*Reduction*					
		S1	*± SD*	*S2*	*± SD*	*S3*	*± SD*
Chloride (mg/L)	*L. minor*	0.2429	0.0162	0.1585	0.0106	0.1529	0.0102
	S. polyrhiza	0.1714	0.0095	0.1098	0.0061	0.0824	0.0046
	E. crassipes	0.2857	0.0317	0.2073	0.023	0.1882	0.0209
Manganese (mg/L)	*L. minor*	0.5600	0.056	0.4722	0.0472	0.3947	0.0395
	S. polyrhiza	0.4400	0.0259	0.3889	0.0229	0.3158	0.0186
	E. crassipes	0.6400	0.04	0.5556	0.0347	0.5	0.0313
Iron (mg/L)	*L. minor*	0.2025	0.0203	0.1905	0.019	0.2273	0.0227
	S. polyrhiza	0.1266	0.0074	0.131	0.0077	0.1364	0.008
	E. crassipes	0.2658	0.0166	0.25	0.0156	0.25	0.0156

Table 7: Following table shows the phytoremediation potential of *E. crassipes, Spirodela polyrhiz, L. minor on* Nitrate, and Phosphate levels, all measured in milligrammes per litre (mg/L). The evaluation includes S-1, S-2, and S-3 samples, which shows the dynamic changes in these essential water quality indicators before and after the acclimatisation procedure

Parameter	*Plant type*	*Before acclimatization*						*After acclimatization*					
		S1	*± SD*	*S2*	*± SD*	*S3*	*± SD*	*S1*	*± SD*	*S2*	*± SD*	*S3*	*± SD*
Nitrate (mg/L)	*L. minor*							64	4.267	68	4.25	71	4.733
	S. polyrhiza	73	4.563	84.68	4.981	91.43	5.714	69	4.6	72	4.5	75	5
	E. crassipes							61	4.067	65	4.063	68	4.533
Phosphate (mg/L)	*L. minor*							0.87	0.046	0.75	0.039	0.64	0.036
	S. polyrhiza	1.12	0.075	0.85	0.053	0.74	0.041	0.89	0.047	0.78	0.041	0.67	0.037
	E. crassipes							0.83	0.044	0.71	0.037	0.6	0.033

consistently records the lowest reduction rates, averaging 12.93 ± 9.25%, while *L. minor* shows promise with an average decrease of 14.57 ± 9.51%.

E. crassipes stands out with an average decrease of 18.40 ± 11.64% in Total Alkalinity. *L. minor* consistently lack behind reduction, averaging 15.25 ± 12.53%, while *S. polyrhiza* has the lowest, averaging 13.02 ± 12.35% (Tables 3 and 4). For Chloride reduction *E. crassipes* is the most efficient species, with an average reduction of 22.71 ± 5.17%. *L. minor* has the highest potential for chloride reduction, with an average of 18.48 ± 5.04%, while *S. polyrhiza* has the lowest rates, averaging 12.12 ± 4.56%. In the reduction of Manganese *E. crassipes* was again efficient species, with an average reduction of 56.52 ± 7.05%. *L. minor* has a high-capacity manganese concentration decreased throughout the three samples, from 0.25 to 0.38 mg/L to 0.11-0.23 mg/L (Tables 5 and 6), with an average of 47.57 ± 8.27%,

Table 8: Following table shows the reduction in Nitrate & Phosphate with *E. crassipes, Spirodela polyrhiz, L. minor* The evaluation includes S-1, S-2, and S-3 samples. All measured in milligrammes per litre (mg/L)

Parameter	*Plant type*	*Reduction*					
		S1	*± SD*	*S2*	*± SD*	*S3*	*± SD*
Nitrate (mg/L)	*L. minor*	0.1233	0.0082	0.197	0.0131	0.2234	0.0149
	S. polyrhiza	0.0548	0.003	0.1497	0.0083	0.1797	0.01
	E. crassipes	0.1644	0.0183	0.2324	0.0258	0.2563	0.0285
Phosphate (mg/L)	*L. minor*	0.2232	0.0223	0.1176	0.0118	0.1351	0.0135
	S. polyrhiza	0.2054	0.0121	0.0824	0.0048	0.0946	0.0056
	E. crassipes	0.2589	0.0162	0.1647	0.0103	0.1892	0.0118

while *S. polyrhiza* consistently has the lowest manganese reduction rates, at 38.16 ± 6.24%.

E. crassipes remained the most effective species for iron reduction, with an average decrease of 25.53 ± 0.91%. *L. minor* has a high capacity for reduction, with an average of 20.68 ± 1.88%, whereas *S. polyrhiza* has the lowest percentage of reduction, with an average of 13.13 ± 0.49%. *E. crassipes* (Tables 5 and 6) consistently has the highest efficiency for nitrate reduction, with an average reduction of 21.77 ± 4.77%. *S. polyrhiza* consistently has the lowest nitrate reduction percentages, averaging 12.81 ± 6.52%, while *L. minor* has significant nitrate reduction potential, averaging 18.12 ± 5.19%. Finally, the phosphate reduction evaluation shows *E. crassipes* to be the most efficient, with an average decrease of 20.43 ± 4.89%. The average phosphate reduction in *L. minor* which produced lower post-remediation residuals of 0.67-0.89 mg/L (Tables 7 and 8) in all three synthetic solutions is 15.87 ± 5.66%, while *S. polyrhiza* consistently reports the lowest percentage of phosphate reduction at 12.74 ± 6.78%.

Conclusion

The assessment of the potential for phytoremediation to alleviate textile effluents reveal that several plant species can greatly reduce the textile industry's negative environmental consequences. Following a detailed study of native and adapted plants of various types, phytoremediation appears to be a realistic and ecologically acceptable technique to alleviate the pollution concerns associated with textile effluents. Taking the findings into account, phytoremediation is a practical, cost-effective, and adaptable strategy for decreasing the harmful impacts of textile effluents. According to the reduction rates reported in the previous discussion, *E. crassipes* consistently shown greater effectiveness across all water quality metrics in this study. Notably, *E. crassipes* consistently beat *S. polyrhiza* and *L. minor* in each category, followed by *S. polyrhiza* and *L. minor*. According to the data, *E. crassipes* is the most efficient aquatic plant species for phytoremediation. This highlights its potential as a key tool for improving water quality and gives important insights into the complex capacities of certain aquatic plant species in alleviating specific water quality challenges. Aside from mitigating the environmental harm caused by wastewater discharges, greater research and use of phytoremediation techniques can aid in the promotion of more eco- friendly textile production processes. The outcomes of the study highlight the need for greater research and real-world application of phytoremediation in the textile industry and other businesses dealing with similar environmental concerns.

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Author contribution

VJ & SN contributed to the experimental design, data collection, and analysis. AS participated in data interpretation, statistical analysis, and manuscript preparation. SM & KKA were involved in conceptualization, supervision, and critical revision of the manuscript. NB & HP provided valuable insights into the experimental methodology and contributed to the manuscript's scientific rigor. GA played a pivotal role in project administration and responsible for overseeing the entire research process and ensuring the integrity of the study.

Conflict of interest

None.

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