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Constructed Wetlands with Aquatic Plants For Municipal Wastewater Treatment: Design and Efficiency Analysis

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Abstract

The severe pollution of water produced by untreated textile waste makes effective wastewater treatment a particularly urgent environmental challenge in industrial regions like Mumbai and Delhi. This is a method that is a method that is a common industrial text that is a common. To test the efficiency of pollutant removal throughout a ten-day retention period, carefully controlled laboratory-scale studies were carried out. *Eichhornia crassipes* demonstrated the most efficient removal of "total dissolved solids (TDS)", "electrical conductivity (EC)", salinity (40.20 %), pH (5.12), total hardness (38.2 %), and chlorides (50.5 percent). For instance, *Pistia stratiotes* and *Lemna minor* demonstrated exceptional success in the elimination of nitrate (98.76%), ammonium (52%), and the "sodium absorption ratio (48.19%)". This is indicative of the potential for species-specific bioremediation.

The findings highlight the variety of affordable, ecologically advantageous, and sustainable nature-based wastewater treatment approaches available in industrial clusters, offering a practical substitute for conventional treatment techniques. A recent study from 2019 to 2021 found that wastewater treatment utilizing a phytoremediation technique, which involves creating artificial wetlands with aquatic vegetation, is a popular and effective method for pollution removal.

Keywords; Water Pollution; Biological Wastewater Treatment; Physicochemical Parameters; Wastewater Reuse; Phytoremediation; Floating Aquatic Plants; Municipal Wastewater Treatment; BOD, COD, TDS, Ph. Value.

INTRODUCTION

Water is an essential natural resource on Earth, necessary for life to exist. The availability of potable water is gradually reducing, which is a significant worldwide problem. Wastewater treatment is a successful approach for restoring original conditions following its industrial, residential, or municipal use, with phytoremediation being the most popular method in the past two decades. This review aims to identify the most efficient aquatic plants for wastewater treatment by conducting a thorough analysis of current trends, with a focus on phytoremediation, a biological treatment achieved via phytostabilization, phytoextraction, phytotransformation (phytodegradation), and hypofiltration. This method increases the level of photosynthesis and development rate of the species used, allowing them to adapt to the contained environment. Aquatic plants are a cost-effective solution for wastewater treatment, with around 30 species used for industrial and 24 for household and agricultural water uses.

According to the most recent United Nations estimate, more than 2.2 billion people worldwide do not have appropriate access to safe drinking water, a problem exacerbated by population expansion, urbanization, and industry. The "United Nations Sustainable Development Goals (SDGs)" seek to decrease untreated wastewater by 50% and improve its safe recycling by 2030-2032. Despite these international duties, a large amount of wastewater, especially in underdeveloped nations, is used for irrigation without proper treatment. There are no precise recommendations or national regulations for wastewater irrigation in many areas, including our study region, apart from basic environmental quality rules for

industrial and municipal waste. Phytoremediation, a kind of biological treatment technology, employs plants and their associated microbial populations to remove toxins from wastewater via processes, like phytodegradation, phytoaccumulation, and hypofiltration. Various macrophytes, consisting of floating species like "water hyacinth (*Eichhornia crassipes*)", "water lettuce (*Pistia stratiotes*)", and "duckweed (*Lemna minor*)", have shown significant efficacy in the removal of contaminants such as nitrogen, phosphorus, and heavy metals. Water hyacinth efficiently extracts heavy metals from the electroplating wastewater, while water lettuce absorbs nutrients and pollutants via phytoaccumulation and hypofiltration

Lemna minor has shown effectiveness in removing phosphorus and nitrogen from wastewater. The efficiency of these plants is determined by a variety of parameters, including the cultivation conditions, density of plants, retention time and pollutant concentration. Aquatic plants are the primary component, with research indicating that somewhere around 30 species are being utilized for wastewater treatment in industries and 24 for household and agricultural wastewater management. The basic operational characteristics and features are based on extraction, degradation, and transformation, or detoxification, through pond or well systems with depths that range from 0.4 to 1.5 meters, where wetlands are used to promote aquatic plant growth.

Despite the extensive study on phytoremediation, significant knowledge gaps persist. For starters, little is known about how these aquatic plants function in different wastewater compositions, especially in mixed industrial waste. The current research lacks detailed comparisons between various macrophytes in controlled experimental conditions to discover the most efficient species for wastewater treatment. Third, although prior studies have evaluated the efficacy of pollutant removal, they typically disregard the long-term viability and practical applications of phytoremediation at a larger scale. This study aims to rectify these shortcomings by evaluating the effectiveness of specific aquatic plants (hyacinth, *Lemna major*, duckweed) in the treatment of mixed industrial effluent. This study investigates the relevance of phytoremediation for complex wastewater mixtures, unlike previous research that mostly focused on individual industrial effluents. Additionally, we examine essential treatment characteristics, including as retention time, plant biomass development, and pollutant removal efficiency. This project seeks to deliver an environmentally sustainable and economically viable phytoremediation method that adheres to both local and

international wastewater treatment standards, facilitating safe disposal and potential agricultural reutilization. Various methods are available for wastewater treatment, encompassing primary, secondary, and tertiary processes. Suitable wastewater treatment technologies for domestic effluent encompass biological treatment methods, like activated sludge, trickling filters, and rotating biological contactor systems. Nevertheless, these treatment systems entail significant operational and capital costs, and they pose difficulties in management and maintenance while maintaining consistent removal efficacy. These limitations may be mitigated through the implementation of alternative, environmentally sustainable wastewater treatment techniques such as phytoremediation. It is economically viable and ecologically sustainable (Brix et al. 1989, Valipour et al. 2011, Lakshmi et al. 2017, Kumar et al. 2015).

PHYTOREMEDIATION

Phytoremediation is a biological method used to remove contaminants from wastewater using plants. The term phytoremediation is derived from the combination of the Latin words for plants and cure. These are used to remediate industrial waste sites, abandoned mines, pesticide-contaminated regions, and to extract heavy metals such as copper, zinc, and radioactive elements from soil and groundwater. The phytoremediation technique involves plants absorbing contaminants by their roots, concentrating, degrading, or stabilizing them in the rhizosphere.

It is a sustainable, cost-effective, and efficient technology. It is a non-invasive alternative to engineering-based repair techniques. The term PHYTOREMEDIATION Technique encompasses the interactions of bacteria, the roots of wetland plants, soil, air, water, and sunlight. This treatment involves built ways for cleaning wastewater as it traverses an artificially produced wetland region. This treatment is particularly successful when using engineered eco-friendly technologies for water filtration (Yuli Nath et al. 2008). The objective of phytoremediation is to remediate polluted water by cultivating aquatic plants capable of absorbing toxins. This method has been used in industrial and household effluent and wastewater treatment to eliminate nutrients, organic compounds, pesticides, oils, explosives, heavy metals, and sewage contaminants. Phytoremediation encompasses several processes, including phytoextraction, phytodegradation, hypofiltration, rhizostabilization, and phytovolatilization (Gupta et al. 2012, Lakshmi et al. 2017). The phytoremediation approach is particularly successful for treating many forms of

wastewater. A diverse array of plant species has been used in phytoremediation. Aquatic plants assimilate nutrients via their roots and branches. Recent interest in *Typha angustifolia*, Duckweed, Water Hyacinth, Water Lettuce, and Vetiver Grass suggests that these plants have the ability to remove a wide range of pollutants, which includes "total suspended solids", dissolved solids, hardness, electrical conductivity, "biochemical oxygen demand", "chemical oxygen demand", nitrogen, heavy metals, phosphorus, and other types of wastewater contaminants (Gupta et al. 2012).

MACROPHYTES AND THEIR ROLE

The three classifications of macrophytes are emergent, free-floating, and submerged, as previously delineated. Macrophytes profoundly influence red beds, altering biological, chemical, and physical treatment processes. The physical effects include the filtering of suspended particles, erosion mitigation through decreased turbulence and flow velocities, sediment stability, and the availability of surface area for microorganisms. The metabolic processes of macrophytes include nutrient intake and oxygen outflow from the roots into the rhizosphere. Macrophytes have developed adaptations to anaerobic circumstances by forming internal air gaps that allow oxygen to be transported to the roots. These air cavities constitute a vast framework within the plants and may account for 60% of the overall tissue volume. Various research findings differ about the ability of macrophytes to release O₂ from their roots into the adjacent rhizosphere, hence promoting aerobic conditions for plant nitrification.

A study shown that internal oxygen transport from roots to the adjacent rhizosphere promotes aerobic conditions essential for plant nitrification. A study shown that internal O₂ transport not only supplied oxygen to underground plant tissues but also emitted O₂ into the rhizosphere. Macrophytes can provide habitat for diverse flora and fauna while improving aesthetic value (Guo et al. 2003, Klomjek et al. 2005, Demarien et al. 2014, Hamizah et al. 2015). The primary motivation for the advancement of phytoremediation technology is the potential for cost-effective cleanup. It entails the utilization of green plant-based systems to remediate contaminated soils, sediments, and water. These plants are designated as pollution mitigators. The primary factors influencing the effectiveness of the remediation process include the characteristics of mine water, environmental climatic conditions, the type of amendment employed, and the selection of plant species (Rezaian et al. 2015). The critical factor in the successful implementation of phytoremediation is the choice of an

appropriate plant that demonstrates significant absorption of both organic and inorganic pollutants, flourishes in contaminated environments, and is easily controllable (Lemna et al. 2014). This research uses four aquatic plants (*Eichhornia crassipes* & *Typha angustifolia*) to treat household wastewater.

MATERIALS AND METHODOLOGY

The use of aquatic plants for phytoremediation of industrial, municipal and household wastewater. A significant collection of recent articles from 2019 to 2021 was obtained via methodical mapping. The data gathered was synthesized to include all important perspectives from researchers, and then comparisons were conducted using tables that define the dimensions and indicators of each variable studied.

Sampling Location

A total of 200 liters of mixed industrial textile waste was collected from a sub-tributary located in the Pharang Drain in Punjab, Mumbai (31.4504 ° N, 73.1350 ° E), a district known for its large textile industry and heavy wastewater output. To protect sample integrity, samples were collected in pre-cleaned, high-density polyethylene, or HDPE, bottles with a capacity of 30L.

Waste Water was collected at one single location during peak discharge for two hours, well mixed, and quickly transferred to the laboratory. To minimize physicochemical changes, samples were stored at 4 °C inside a refrigerated container before testing began within 48 hours after collection. The experiment used 20-liter containers.

Collection of aquatic flora and creation of a nursery

Aquatic plants that are readily available locally. Water hyacinth, water lettuce and duckweed were obtained from the sewage treatment plant and tested in the experimental setting. Wastewater is collected in the unit's input tank. The measurements include pH, COD, BOD, water lettuce and water hyacinth, that were collected at random from my surroundings; these macrophytes were selected based on local availability.

After washing the plants and placing them in big tubs containing tap water under ambient conditions, a nursery was formed. (Figure:1). To attain the best removal efficiency for mixed industrial textile effluent, plants were acclimatized to increasing concentrations of textile effluent (0:100, 25:75, 60:60, 76:26, 100:01) to enhance tolerance. The nursery was maintained in plastic containers to ensure optimum growth prior to investigation. These plants are

known for their quick growth and adaption to regional climate conditions. Previous research by the "National

Institute of Bioremediation (NIB)" and "NARC" has proven the effectiveness of aquatic plants for wastewater treatment



Figure 1: Acquisition and cultivation of laboratory-based aquatic flora

Bech Scale Experiment

The experiment was conducted in 20-liter plastic containers, each containing raw textile waste. Three aquatic plants with similar leaf counts—water hyacinth, duckweed and water lettuce—were rigorously cleaned with deionized water to remove leftover nutrients from their roots or fronds before being transferred from the nursery to the plastic tubs.

Experimental Treatments

Four treatments, each with three replications, were utilized for the comparison of treated and untreated industrial effluent:

- ❖ First: - Control (untreated effluent)
- ❖ Second: - Effluent + *Eichhornia crassipes* {Water Hyacinth}
- ❖ Third: - Effluent + *Pistia stratiotes* {Water Lettuce}
- Fourth: - Effluent+ *lemna minor* {Duckweed}.



Figure 2: Control (untreated Effluent)



Figure 3: Effluent + Eichhornia crassipes



Figure 4: Effluent + Pistia



Figure 5: Effluent + Lemna minor

Sample Collection and Analysis

“Collection and Analysis of Samples”: Samples were taken at 0, 5, and 10-day intervals in polycarbonate bottles that had already been pre-rinsed using distilled water. We may now analyze the measured water quality parameters: The SEBA Hydrometer MPS-16 assessed pH, "total

dissolved solids (TDS)", "electrical conductivity (EC)", salinity, nitrate, temperature, ammonia and chloride. Total hardness is determined by EDTA titration using Eriochrome Black T as the determining indicator. The sodium content was measured utilizing a flame photometer, (JENWAY PFP7).

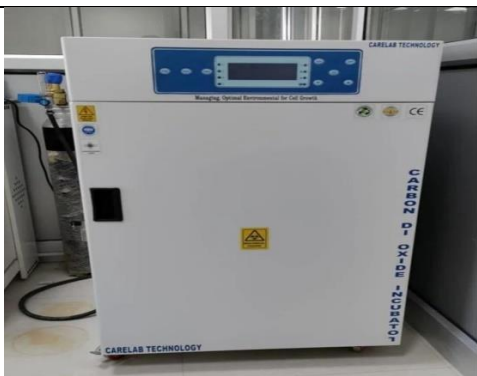



 <p>CARELAB TECHNOLOGY</p>	
<p>COD Incubator</p>	<p>Test Tubes</p>
 <p>OnePlus</p>	
<p>BOD Incubator</p>	<p>TDS & pH meter</p>

Figure 6: Instrument Used

The pH scale serves as a logarithmic scale from 0 to 14 that measures hydrogen ion concentration. pH, which stands for hydrogen potential, refers to the concentration of "hydroxyl ions (OH⁻)" and "hydrogen ions (H⁺)" in water-based solutions or wastes. The pH of a solution indicates whether it is acidic, basic, or neutral. It is represented as a logarithmic reciprocal of the activity of hydrogen ions.

"Total Dissolved Solids (TDS)" denote the minerals that are entirely dissolved in water. Total Dissolved Solids consist of cations and anions. These minerals or solids are invisible to the human eye as they neither float nor reside on the surface. Total Dissolved Solids (TDS) are the principal factor influencing the change in water color. TDS contains no colloids, therefore any type of gas is proportional directly to EC, as shown by the equation.

$$\text{TDS (mg/L)} = \text{EC (ds/m)} + K$$

Where $K = 640$, $K = 735$ for mixed water, or $K = 800$ for electrical conductivity exceeding 5 ds/m. The electrical conductivity of water is directly proportional to the total concentration of dissolved particles within it.

The electrical conductivity (EC) of water is evaluated according to its ability to transmit an electrical current. The minerals solubilized in water comprise Carbonate, Bicarbonate, Phosphate, Chloride, Sulphate, Nitrates, Sodium, Magnesium, and Calcium, among others. Electrical conductivity (EC) is affected by temperature; an increase in temperature results in a corresponding rise in EC. Salinity is defined by the concentration of salt in water. These values likewise conform to the same parameters. Salinity and conductivity are related. The increased salinity of water is harmful to plants.

Salinity - Salinity is a significant environmental concern impacting freshwater supplies, agricultural output, and ecological stability. The salinization of water bodies is escalating owing to industrial effluents, irrigation return flow, and saltwater intrusion caused by climate change. Traditional techniques for salt removal, including reverse osmosis and ion exchange, are sometimes costly and energy-demanding.

Temperature - Temperature is the measurement of thermal energy of a material, which reflects its temperature level. Water's temperature has a direct impact on its characteristics and biological activity. Temperature may be measured in both Celsius and Kelvin. A thermometer and a thermistor are two frequently utilized measuring tools.

Temperature has a significant impact on the efficacy of the therapeutic strategy. Almost all contaminants are removed at varying rates depending on the water temperature & the surrounding air. In addition to the temperature, microbiological activity as well as plant absorption have a significant effect in pollution removal. At temperatures below 10 °C, removal effectiveness is greatly reduced. Microorganisms perform best at temperatures over 15 degrees Celsius.

Chloride- Chloride is produced when gaseous chlorine combines with a metal. Water's activity via weathering facilitates the leaching of chlorides from various rocks. Chlorides exhibit versatility and are found in proximity to basins and seas. The presence of chlorine signifies water hardness since it derives from calcium chloride (CaCl₂). The elevated chloride content in irrigation water renders it hazardous.

Nitrate - Nitrate is a naturally occurring substance in aquatic environments. A designated quantity is consistently found in the water sample; nevertheless, in the event of contamination, the concentration of nitrates also rises. Excessive nitrates are very hazardous to young children and juvenile cattle. Excessive nitrates may impede oxygen transfer in the circulation.

Ammonia - "Ammonium ions" in water or "un-ionized ammonia (NH₄⁺)" are typically dominant and non-toxic at low pH levels. As pH rises, the toxicity associated with ammonium ions increases.

Total Hardness - The hardness of a water sample is determined by the presence of calcium (Ca²⁺) and magnesium (Mg²⁺) ions in it. A water sample is classified as hard water if it fails to produce lather when mixed with soap. There are two categories of hardness: temporary hardness and permanent hardness. The first category of hardness arises from the presence of carbonates (CO₃²⁻), bicarbonates (HCO₃⁻), and hydroxide ions (OH⁻) in conjunction with calcium ions (Ca²⁺) and magnesium ions (Mg²⁺). Permanent hardness results from the presence of chlorides (Cl⁻), sulfates (SO₄²⁻), and any ions other than alkaline ions, namely calcium (Ca²⁺) and magnesium (Mg²⁺).

Calcium - is among the most prevalent elements found in rocks. Calcium exists in water as a result of the concentration of mineral salts leached from rocks. The elevated calcium content is undesirable since it inhibits lather development with soap. SEBA was used to measure calcium concentrations.

The Sodium Adsorption Ratio (SAR) - is a critical irrigation water quality metric used in the management of sodium-affected soils. It assesses the appropriateness of

water use for irrigation purposes. The calculation may be derived from the concentration of alkaline substances and cations in the water.

Table 1 Wastewater Quality Standards.

S/NO	Parameter	Unit	PEQS	FAO
1	PH	-	6-9	7.5-9.4
2	TDS	Mg/l	<4500	1-2002
3	EC	-	-	1-4ms/cm
4	Salinity	-	-	-
5	Temperature	°C	<4 ⁰	-
6	Chloride	Mg/l	-	0-300
7	Nitrate	Mg/l	6-60	11
8	Ammonia	Mg/l	30	0-10
9	Total Hardness	Mg/l	-	-
10	Calcium	Mg/l	-	0-350
11	SAR	Ratio	-	0-15

Statistical Analysis

Statistical Analysis: The acquired data was statistically analysed to establish overall significance, using the "least significant difference (LSD) test" with a confidence interval of 95% to compare treatment averages. The experiment used a "completely random design (CRD)" with 3 replications. All statistical data analysis was carried out using R Studio and Microsoft Excel.

RESULTS

In a laboratory-scale test for the treatment of mixed industrial effluent, nine wastewater quality indicators were evaluated to determine the performance of three aquatic plants. Table 2 illustrates that the removal efficiency of all the aquatic plants in their new habitat was examined over the first several days. On days 0, 5, & 10, we collected samples for the examination. The experiment lasted 10 days.

Table 2 Effect of aquatic plants treatments on physicochemical characteristics of mixed industrial textile effluent.

Treatment	Retention Time (Days)	TDS (mg/l)	EC Ms/cm	Salinity	PH	Total Hardness	Chloride	Nitrate	Ammonium
T ₀	0	4012	5.90	3.04	9.00	560	3188	1981	12.9
	5	3312	4.00	2.54	8.81	490	2312	1290	10.9
	10	2673	3.90	2.13	8.13	385	2134	25.9	8.8
T ₁	0	4012	5.07	3.89	8.6	560	3156	2167	12.9
	5	3013	2.88	2.16	7.87	234	2134	2011	11.7
	10	2233	2.56	2.00	6.78	113	2019	1876	10.9
T ₂	0	4012	5.77	3.67	8.9	460	2234	3266	13.99
	5	2513	4	2.8	8.3	455	2159	3145	12.99
	10	2145	3	2.4	7.76	390	1567	3099	10.89
T ₃	0	4012	5.97	3.8	9.8	460	2088	2191	12.8
	5	3524	4.98	2.90	8.14	360	1905	2081	10.3
	10	3012	3.90	2.5	7.78	280	1543	19.8	9.8

Impact on the chemical characteristics of combined industrial wastewater

The current experiment indicates that the percentage decrease of total dissolved solids for the old treatment was 90.2%, 30.3%, 15.85%, and 13.83% for T₀, T₁, T₂, and T₃,

respectively, at a retention duration of 5 days. Correspondingly, TDS was decreased by 30.81%, 36.12%, 19.43%, and 16.43% for T₀, T₁, T₂, and T₃, respectively, throughout a 10-day retention period. Figure 7(A) illustrates that *Eichhornia crassipes* (T₁) achieved the highest decrease,

decreasing the TDS of industrial water by 38.12% during a retention period of 10 days.

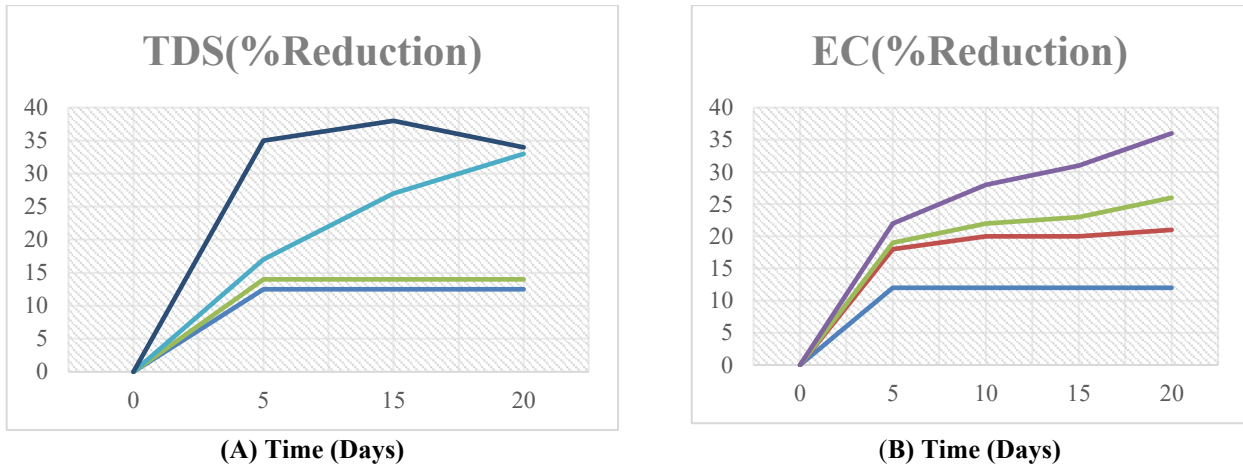
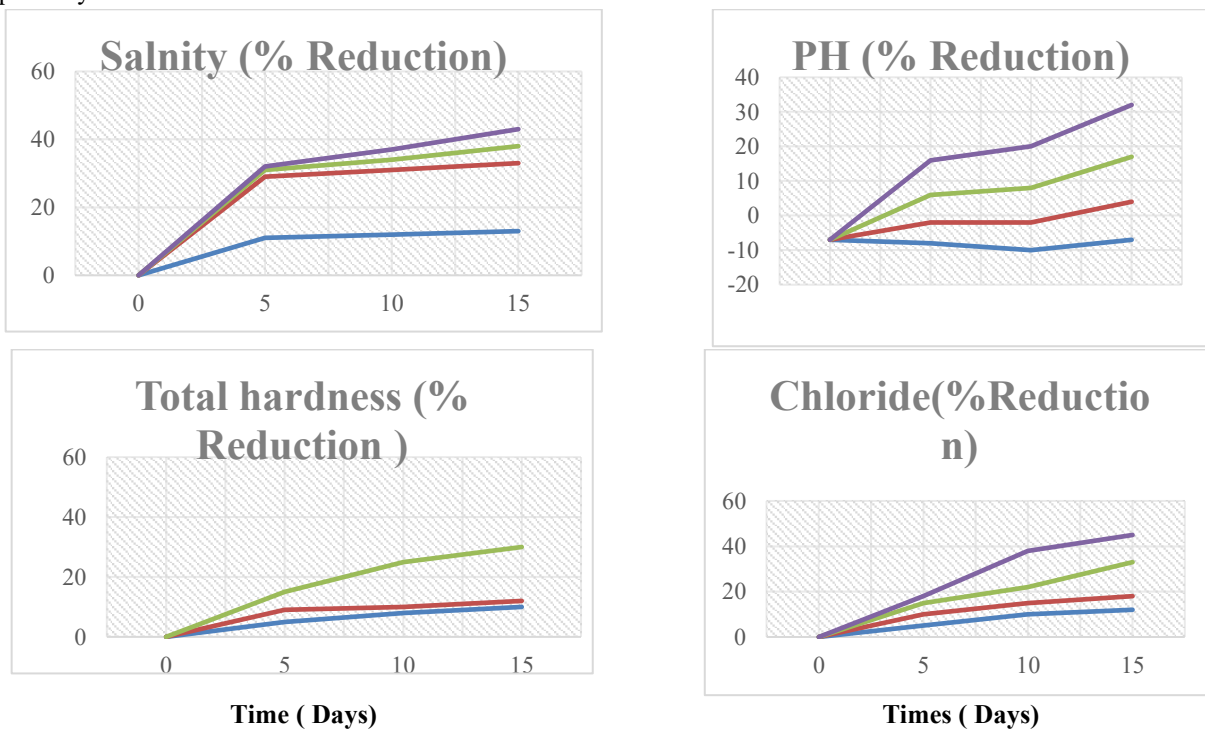


Figure 7 Comparison of the induction of total dissolved solids (TDS) and electrical conductivity (EC) across four distinct treatments, illustrating the variance in treatment efficacy.

The application of therapy resulted in a reduction in EC to 18.62%, 34.30%, 17.63%, and 14% for To, T1, T2, and T3, respectively, after a retention period of five days. The percentage decrease in EC for all treatments was 33.96%, 37.13%, 21.45%, and 14.56% for To, T1, T2, and T3, respectively, during a 10-day retention period (Figure 7b). The aforementioned findings indicate that *Eichhornia crassipes* T1 significantly decreased the electrical conductivity of mixed industrial wastewater to 36.14% during a 10-day retention period, demonstrating its superiority over other treatments

Effects on physical parameters of mixed industrial wastewater:

Salinity decreased by 17.43%, 34.34%, and 16.32% for TO, T1, T2, and T3, respectively, during a retention duration of 5 days. On the tenth day, it was observed that all treatments decreased salinity to 30.78%, 29.90%, 21.05%, and 14.56% for T0, T1, T2, and T3, respectively (Figure 8a). The results showed that *Eichhornia crassipes* T1 considerably reduced the salinity level of mixed industrial effluent to 34.30% over a 10-day retention period



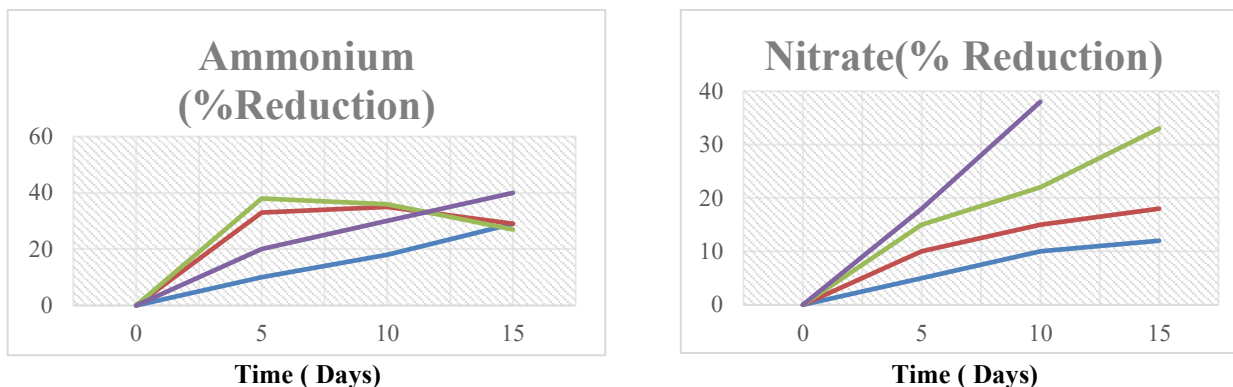


Figure 8: Analysis of the decrease in essential wastewater quality metrics, such as “salinity (a), pH (b), total hardness (c), chloride (d), and ammonia (e)”, using four distinct treatment techniques, emphasizing the differences in treatment efficacy.

The pH reduction for all treatments was 3.65%, 7.78%, 5.78%, and 5.56% for T₀, T₁, T₂, and T₃, respectively, over a 5-day retention period. The values for T₀, T₁, T₂, and T₃ during a 10-day retention period were 3.45%, 4.45%, 1.06%, and 0.35%, respectively (Figure 8(b)). *Eichhornia crassipes* (T₁) significantly reduced the salinity of mixed industrial wastewater to 5.12% over a retention period of 10 days.

The therapy reduced overall hardness by 15.22%, 17.45%, 1.09%, and 8.70% for T₀, T₁, T₂, and T₃, respectively, throughout a five-day retention period. The values for T₀, T₁, T₂, and T₃ were established as 17.17%, 34.30%, 14.15%, and 11.98%, respectively, over a retention period of 10 days (Figure 8c). The data reveal that *Eichhornia crassipes* T₁ significantly reduced the total hardness of mixed industrial wastewater by 34.30% over a retention period of 10 days.

After a retention period of 5 days, the chloride levels for all treatments were diminished to 3.15%, 29.60%, 17.45%, and 0.78% for T₀, T₁, T₂, and T₃, respectively. The values were later diminished to 12.56%, 45.45%, 33.34%, and

6.56% for T₀, T₁, T₂, and T₃, respectively, after a 10-day retention period, as illustrated in Figure 8(d). *Eichhornia crassipes* (T₁) markedly reduced the chloride concentration in mixed industrial effluent by 44.34% throughout a retention period of 10 days.

Ammonium concentrations diminished by 18.45%, 33.56%, 35.45%, and 33.45% for T₀, T₁, T₂, and T₃, respectively, following a 5-day retention period. The percentage decreases for all treatments were 23.45%, 34.56%, 45.65%, and 33.56% for T₀, T₁, T₂, and T₃, respectively, over a 10-day retention period (Figure 8).”

Effects on Agricultural Parameters of Mixed Industrial Wastewater

The percentages of nitrate reduction for each treatment were 32.45%, 34.30%, 85.67%, & 43.30% for T₀, T₁, T₂, & T₃, respectively, after 5 days of retention. During a 10-day retention period, T₀, T₁, T₂, and T₃ showed a nitrate reduction of 98.78%, 99.79%, and 99%, respectively. T₁ lowered the nitrate content in mixed industrial waste by 99.24% during a 10-day retention period.

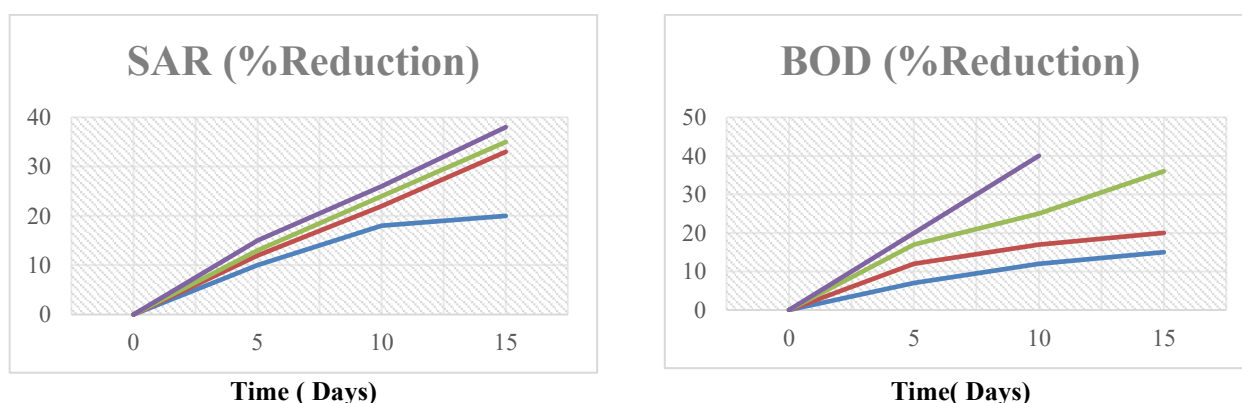


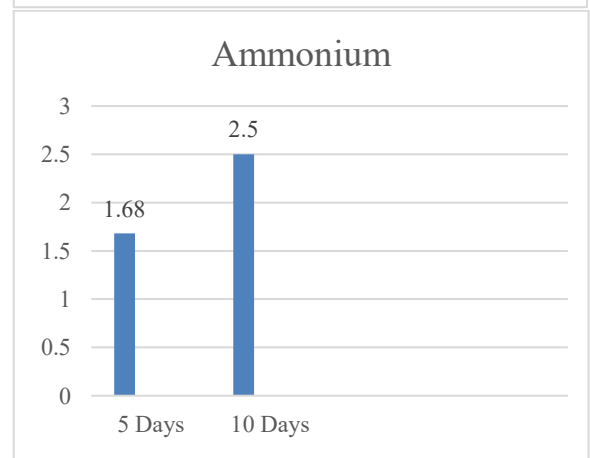
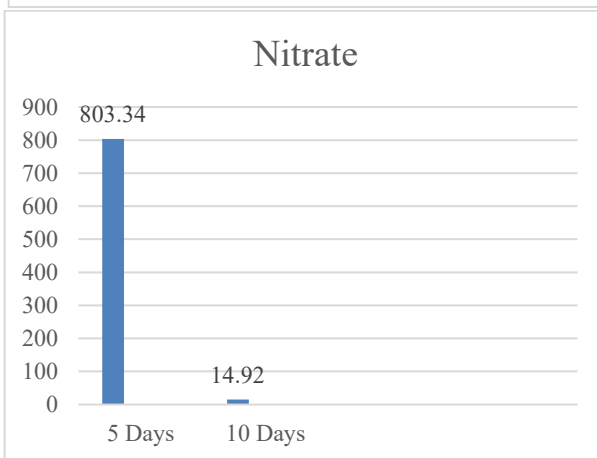
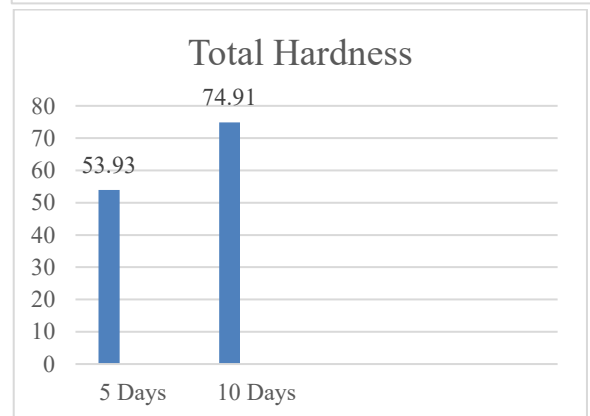
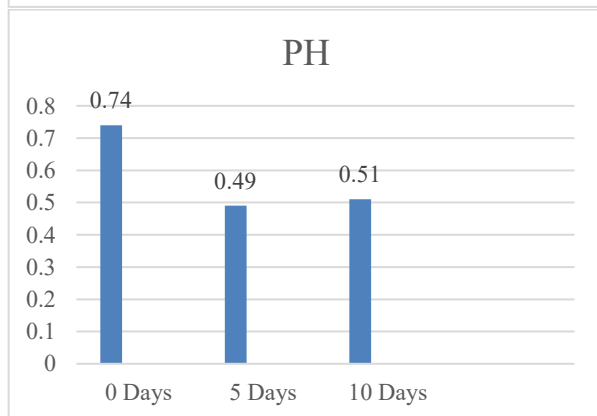
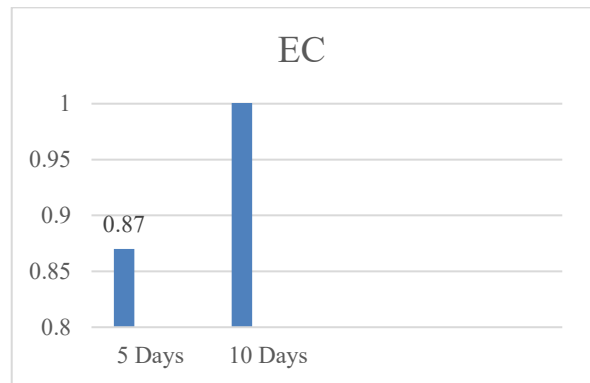
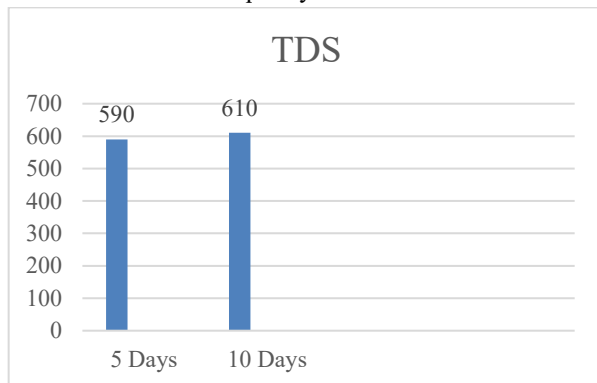
Figure 9: Evaluation of "Nitrate (a)" and "Sodium Adsorption Ratio (SAR) (b)" removal using four different treatment approaches, illustrating the disparities in treatment effectiveness.

Following a 5-day retention period, the SAR reduced to 27.46% for T₀, 33% for T₁, 25.67% for T₂, and 13.80% for T₃. The results were then lowered to 42.45%, 46.23%, 45.23%, & 32.31% for T₀, T₁, T₂, and T₃ after a 10-day retention period (Figure 9b). The results showed that T₁ considerably reduced the SAR of the mixed industrial wastewater to 45.29% during a 10-day retention period.

Statistical Evaluation of Results

Figure 10 presents bar graphs that compare the mean values of several water quality measures across treatments

with the least significant difference values. The statistics comparing the individual mean values of TDS, EC, salinity, pH, total hardness, chloride, nitrate, SAR, BOD, and COD of industrial effluent across different treatments were significant. The comprehensive LSD values in the dataset were: TDS 518.29%, EC 1.75%, pH 1.51%, salinity 1.38%, total hardness 50.56%, chloride 416.34%, nitrate 463.34%, ammonium 1.51%, and SAR 3.12%.



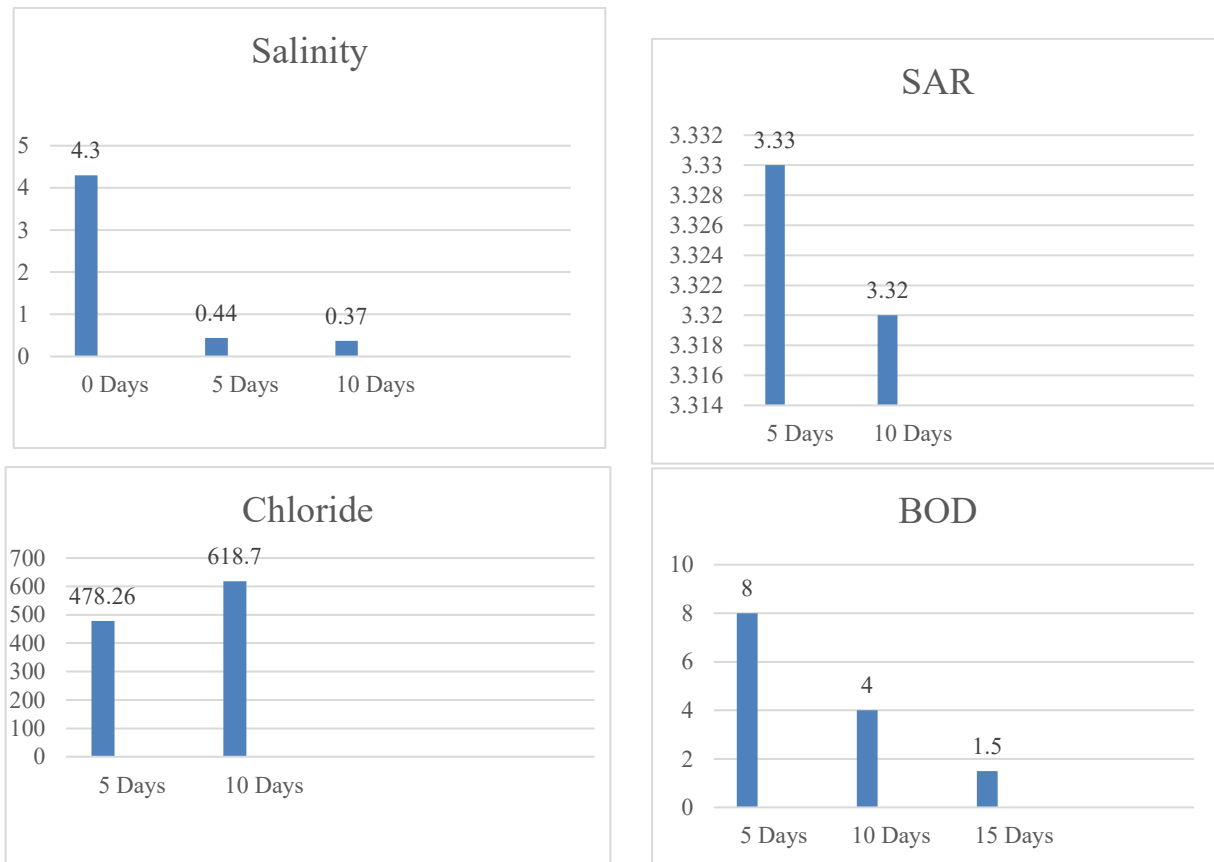


Figure 10: Bar graphs comparison

Figures 10 and 11 illustrate that the analysis of variance for regression indicates all treatments exerted significant effects ($\alpha = 0.05$) on the TDS, EC, salinity, total hardness, nitrate, ammonium, and SAR of the mixed industrial wastewater (F_{cal}). Surpasses F_{cri} . ($p > 0.05$). The ANOVA

for regression indicates that all treatments exerted non-significant effects ($\alpha = 0.05$) on the pH and chloride concentrations of the mixed industrial wastewater, as evidenced by F_{cal} . Is inferior than F_{cri} . ($p > 0.05$).

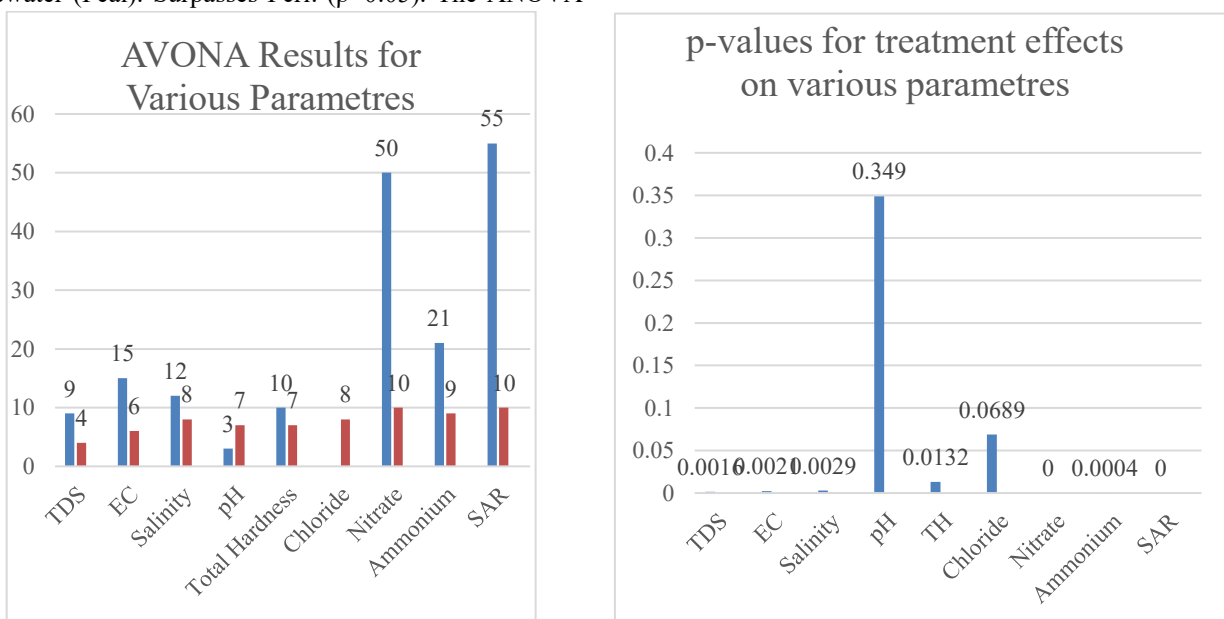


Figure 11: illustrates the statistical significance (p-value) of treatment effects across multiple parameters.

DISCUSSION

This study's findings illustrate the efficacy of the aquatic plants, especially "Eichhornia crassipes", in diminishing numerous contaminants in industrial effluent. This work offers a comparative investigation of the pollutant removal efficiency of Pistia stratiotes, Eichhornia crassipes, & Lemna major, despite earlier studies recognizing their phytoremediation capabilities under regulated retention durations. The mechanisms responsible for the varying performances of these plants need more examination.

Superior

Eichhornia crassipes has higher pollutant removal effectiveness than Pistia stratiotes & Lemna minor due to a variety of variables. Eichhornia crassipes has a large root system with a high surface area, which increases the likelihood of pollutant adhesion, absorption, & microbial colonization. This leads to increased biological accumulation of the dissolved solids and microbial-mediated breakdown of organic and inorganic pollutants. Furthermore, increasing biomass accumulation rate promotes pollutant absorption, as established in previous phytoremediation experiments. Furthermore, economies improve several microbial community activities that are essential for biogeochemical processes, which include, denitrification, nitrification, and breakdown of organic matter, hence increasing total treatment efficiency.

Nitrate Removal Efficiency

The exceptional nitrate removal effectiveness (up to 99%) demonstrated in this study is likely due to many removal mechanisms. Plant absorption was essential, as Eichhornia crassipes is noted for its significant nitrogen uptake capacity. Furthermore, microbial activities like as denitrification and nitrification played an important role in nitrate reduction. The root zone of "Eichhornia crassipes" forms an oxygen gradient, which promotes aerobic nitrification. The growth of biofilms on the surface of the roots increases microbial activity, which speeds up the removal of nitrates from effluent. Previous research has shown that precipitation of nitrate-containing molecular compounds may increase removal rates.

Comparison with Prior Literature

This work corroborates prior studies on the phytoremediation capabilities of Eichhornia Crassipes, revealing both similarities and differences upon close examination. Research has revealed significant pH level decreases in wastewater treated by utilizing Eichhornia crassipes, which are in alignment with the findings of this study. The pH-lowering process is predominantly due to the creation of "carbonic acid (H₂CO₃)" generated by the microbial breakdown of organic pollutants. Nonetheless, discrepancies in removal efficiency across studies may result from changes in effluent composition, retention period, and environmental variables. A comparative assessment of removal efficiencies across several experiments is provided in Table 3.

Table 3 Comparison of removal efficiencies with previous studies

Pollutant	Eichhornia crassipes (This study)	Eichhornia crassipes previous studies)	Pistia stratiotes	Lemna Minor
TDS (%)	83.4	80-86	75.6	-
EC (%)	Significant reduction	Reduction with increased HRT	Moderate Reduction	Low Reduction
Chloride (%)	933.1	54.4	Low absorption	Minimal impact
Nitrate (%)	99	90-96	Moderate Removal	Moderate Removal

Obstacles and Practical Implementation Considerations: Although phytoremediation of Eichhornia crassipes has significant promise, actual implementation entails certain obstacles that need resolution.

Seasonal Variations The rates of pollutant absorption efficiency and plant growth may vary with seasonal fluctuations in temperature, light availability, and nutrient concentrations. Cold seasons may diminish metabolic activity, hence impacting cleaning efficiency.

Retention time constraints Industrial water waste treatment requires extensive execution, since longer retention durations may be unfeasible. Increasing hydraulic retention time (HRT) in vertically flowing constructed wetlands to balance treatment effectiveness and operational feasibility may increase pollutant removal by optimising water distribution and retention dynamics. The purposeful incorporation of certain microbial consortia into these

wetlands may improve biodegradation processes, hence enhancing treatment efficiency through the use of biological mechanisms

Plant Disposal and Biomass Management

The accumulation of contaminants in plant tissue presents disposal issues. Strategies for safe disposal or valorization, including bioenergy generation and composting, must be taken into account. The burning of polluted biomass is an effective strategy for limiting the discharge of dangerous compounds into aquatic ecosystems hence alleviating environmental problems. This controlled thermal degradation ensures the safe removal of hazardous items while also allowing for energy recovery, in conformity with "sustainable waste management standards".

Variability in wastewater composition

Various industries produce wastewater with different compositions. The efficiency of phytoremediation may vary depending on the kind and quantity of pollutants that are present in the water.

The economic viability of phytoremediation requires thorough assessment for widespread implementation. *Eichhornia crassipes* is a cost-effective and environmentally sustainable alternative to traditional treatment techniques; nevertheless, considerations must include land needs, maintenance costs, and expenditures associated with plant harvesting. Prior research indicates that phytoremediation may serve as a cost-effective approach when combined with current wastewater treatment systems, hence decreasing operating expenses relative to chemical or mechanical treatment approaches. Nonetheless, more economic study is necessary to determine its economical feasibility at an industrial scale.

CONCLUSION

This study demonstrated the effectiveness of free-floating aquatic plants (*Eichhornia crassipes*, *Pistia stratiotes*, and *Lemna minor*) in treating industrial textile wastewater through a controlled laboratory-scale experiment. *Eichhornia crassipes* exhibited the greatest pollutant removal efficacy among the evaluated species, significantly reducing critical irrigation quality metrics such as total dissolved solids (TDS), electrical conductivity (EC), salinity, pH, total hardness, sodium adsorption ratio (SAR), biochemical oxygen demand (BOD), and chemical oxygen demand (COD) over a 10-day retention period. These findings highlight the potential of plant-based phytoremediation as an environmentally sustainable,

chemical-free, and economically feasible alternative to conventional wastewater treatment methods.

This research has substantial real-world ramifications outside experimental settings. Textile industry clusters, particularly in Shamli and similar industrial hubs, ought to integrate this phytoremediation method into wastewater treatment systems to mitigate environmental pollution and improve compliance with regulatory standards and requirements.

Aquatic plant-based wastewater treatment is a phytoremediation method that gained prominence in 2021 and requires little treatment costs. The effectiveness of pollution treatment is independent of the discharge source, be it industrial, residential, or municipal. Studies demonstrate that plants flourish best when their surroundings are customized to their specific living conditions, regardless of horizontal or vertical movement. This adaptation promotes substantial growth, as demonstrated by *Eichhornia crassipes*, an aquatic weed that can eliminate up to 90% of nitrates from industrial wastewater, and *Pistia stratiotes*, which removes 98.0% of turbidity, 99% of total phosphates, and 80.16% of COD within 60 days in domestic wastewater. The scalability of this technique can be examined in wastewater treatment plants, either as a standalone solution for small enterprises or as a supplementary treatment in larger facilities.

Furthermore, the visual appeal and sustainable nature of this natural technology make it a viable long-term option for industrial wastewater treatment. Although the laboratory findings are encouraging, further study is needed to validate the usefulness of this technique in large-scale applications. Future study should concentrate on increasing retention length, assessing plant performance in real-world wastewater treatment circumstances, and performing comprehensive economic analyses to evaluate the cost-benefit ratio of large-scale use.

Furthermore, evaluating the long-term survivability, regeneration capability, and possible repurposing of this aquatic plant in a variety of climatic settings will improve the practical use of these strategies. These species of plants are commonly imported from various areas for medicinal or decorative reasons. Nonetheless, they progressively elude human control and develop a self-sufficient global population. Aquatic plants are widely used in wastewater treatment owing to their low cost and high efficiency. They are used in the treatment process to reduce or eliminate

polluted wastewater. The treated wastewater passed international effluent standards for irrigation.

Supplemental materials The subsequent supporting material can be downloaded from <https://www.mdpi.com/article/10.3390/w17071080/s1>, which includes Table S1: Percentages of reduction in wastewater quality parameters, Table S2: ANOVA for Total Dissolved Solids (TDS), and Table S3. Comparison of TDS values: Table S4. ANOVA for Electrical Conductivity: Table S5. Comparison of Electrical Conductivity values: See Table S6. ANOVA for Salinity: Refer to Table S7. Comparison of salinity values: Table S8. ANOVA for pH: Please consult Table S9. Analysis of pH values. Table S10: Analysis of Variance for Total Hardness Table S11: Comparative Assessment of Total Hardness Table S12 displays the ANOVA findings for Chloride, succeeded by Table S13. Comparison of Chloride Concentrations: Table S14 presents ANOVA results for Nitrate; refer to Table S15. Comparison of Nitrate Concentrations: See Table S16. ANOVA for Ammonium: Consult Table S17. Comparison of Ammonium Values S18. ANOVA for SAR: Table S19. Comparison of SAR Results.

Author Contributions Author conceptualization: S.N.K; methodology: S.N.K; validation: S.N.K; formal analysis: S.N.K and A.A; investigations: S.N.K; resources: S.N.K and L.A; data curation: L.A and A.N; supervision: S.N.K, S.A, and M.A; project administration: A.N; funding acquisition: A.N; contributions: S.N.K, L.A, and S.A. All authors have reviewed and consented to the published version of the work.

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Data Availability Statement The extract data that underlies the findings of this study may be received upon a request from the corresponding author and is attached with the submission. Please refer to the Supplementary Materials for further details.

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