

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

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Abstract

Efficiency wastewater management is a critical environmental challenge, particularly in industrial region like Delhi, Mumbai, where untreated textile effluents contribute to severe water pollution. This study evaluates the potential of bioremediation using floating Aquatic plants like: - (water hyacinth {*Eichhornia crassipes*}, water lettuce {*Pistia stratiotes*} & *lemna minor* {common duckweed}- for the treatment of industrial textile wastewater. A controlled laboratory scale experiments was conducted to assess pollutant removal efficiency over a 10-day retention period. The result demonstrated that *Eichhornia crassipes* exhibited the highest removal efficiency, achieving reduction of TDS (37.12%), Electronic Conductivity (36.12%), Salinity (40.20%), PH (5.12%), Total Hardness (38.2%) & Chlorides (50.52%), *pistia stratiotes* or *lemna minor* were particularly removal of different types of impurities or effective into removing Nitrate (98.76%), Ammonium (52%) and Sodium Absorption ratio(48.29%), indicating species specific bioremediation potential. These findings highlight the variety of a low-cost, ecofriendly and sustainable nature-based solutions for wastewater treatment in industrial cluster, offering a practical alternative to conventional treatment technologies wastewater treatment uses a phytoremediation strategy that sets significant trends according to recent research from 2019-2021 period, being of the most efficient strategies regarding the removal of pollutants using artificial wetlands with aquatic plants.

Keywords; Water Pollution, Biological Wastewater Treatment, Physiochemical Parameters, Wastewater Reuse, Phytoremediation, Floating Aquatic Plants.

INTRODUCTION

Water is a one of the precious natural resources of this planet and it is a basic need for survival of life. Quantity of portable water is slowly reducing, and it becomes major problems in the world. Wastewater treatment is an encouraging proposal to restore the initial condition after industrial, domestic or municipal use, with phytoremediation being the treatment with the highest demand for use in the last two decades therefore, this review aims to find the most effective aquatic plants in waste water treatment through an exhaustive analysis of current trends considering phytoremediation as a biological treatment that can be achieved through phytoextraction, Hypofiltration, Phyto stabilization and Phyto transformation (Phytodegradation) enhancing the photosynthetic activity & growth rate of the species used to adapt them to the contained environment have the advantages of their low-cost, the main element is the aquatic plants & it is shown in the literature that about 30 are used for the treatment of industrial wastewater & 24 for agricultural and domestic waters.

According to the latest united nations report, approximately 2.2 billion people worldwide have limited or no access to safe drinking water, a crisis exacerbated by population growth, urbanization and industrialization. Recognising this issue, the United Nations sustainable development goals (SDG 6) aim to reduce untreated wastewater by 50% & enhance its safe recycling and reduce by 2030-2032.



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Despite these global commitments, a significant portion of wastewater, particularly in developing countries, is used for irrigation without adequate treatment. In many regions, including our study area, there are no specific guidelines or national standards for wastewater irrigation apart from general environmental quality standards for municipal and industrial effluents. Phytoremediation, a subset of biological treatment methods, utilizes plants and associated microbial communities to remove contaminants from wastewater through mechanism such as Phytoaccumulation, Phytodegradation & Hypofiltration. Various macrophytes including floating plants like water hyacinth (*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*), duckweed (*Lemna major*) has demonstrated remarkable potential in removing pollutants, including Nitrogen, Phosphorus, Heavy Metals. For instance, water hyacinth has been effectively employed to remove heavy metals from electroplating wastewater, while water lettuce has shown efficiency in nutrients & pollutant uptake through phytoaccumulation and hypofiltration.

Similarly, *Lemna minor* has been reported to effectively remove Nitrogen and phosphorus from wastewater. However, the effectiveness of these plants depends on several factors, including growth conditions, plants density, pollutant concentration and retention time. The main element is the aquatic plants, and it is shown in the literature that about 30 are used for the treatment of industrial wastewater and 24 for agricultural and domestic wasters. The main operational properties and characteristics are based in Degradation, Extraction and Transformation or Detoxification using well or pond systems with depths ranging from 0.4 to 1.5 meters where strategies are implemented in the form of wetlands by the load of growth activity of the aquatic plants.

Despite extensive research on phytoremediation, several critical knowledge gaps remain. First, there is limited understanding of low these aquatic plants perform under varying wastewater compositions, particularly in mixed industrial effluents. Second, the existing literature lacks comprehensive comparisons of different macrophytes under controlled experimental conditions to determine the most effective species for wastewater treatment. Third, while previous studies have assessed pollutant removal efficiency, they often do not examine the long-term sustainability and practical implementation of phytoremediation at larger scales. The Present study aims to bridge these gaps by evaluating the efficiency of selected aquatic plants (*hyacinth*, *lemna major*, *duckweed*) in treating mixed industrial wastewater. Unlike, previous studies, which

primarily focused on single industry effluents, this research investigates phytoremediation applicability to complex wastewater Mixters. Additionally, we examine key treatment parameters, including retention time, plant biomass growth & pollutant removal efficiency. The goal of this study is to develop an environmentally sustainable & cost- effective phytoremediation strategy that meets both regional & international wastewater treatment standards, facilitating safe disposal & potential agricultural reuse. There are many treatments available for purification the wastewater like primary treatment, secondary treatment and tertiary treatment. Some of the suitable wastewater treatment processes for domestic wastewater include biological treatment processes such as activated sludge, tricking filter, and rotating biological contractor systems. However, these treatment systems have high operation, investment costs, difficult to operate and maintain with stable removal efficiencies. These limitations can be overcome by the application of non-conventional eco-friendly approaches of wastewater treatment like Phytoremediation. It is economical and environment friendly (Brix et.al. 1989, Valipour et. Al. 2011, Lakshmi et. Al. 2017, Kumar et.al.2015).

PHYTOREMEDIATION

Phytoremediation is a biological process which is used to eliminate pollutants from wastewater by using plants. Its combination of two Latin words plants and remedy gave rise to the term phytoremediation. These are used to clean up industrial waste sites, abandoned mines, pesticides-contaminated areas, and to remove heavy metals like Copper, Zinc, Radioactive materials from soil and groundwater. The phytoremediation mechanism is based up on in which plants uptake pollutants through their roots and concentrate them, degrade them, or stabilize them in the rhizosphere.

It is a clean, inexpensive and efficient technology. It is a non- invasive alternative technology for engineering-based remediation methods. The term PHYTOREMEDIATION Technique includes the life interactions of bacteria, the roots of the wetland's plants, soil, air, water, and sun. This type of treatment is an engineered methods of purifying wastewater as it passes through artificially constructed wetland area. This treatment is most effective with constructed friendly technology for water purification (Yuli Nath et al.2008). The principle of phytoremediation process is to clean up contaminated water by growing aquatic plants which have a capacity to absorb pollutants. This technology has been used in industrial and domestic effluent and wastewater treatment

in removing of nutrients, Organic chemicals, pesticides, oils, explosives, heavy metals and sewage pollutants. Phytoremediation includes several processes like, Phytoextraction, Phytodegradation, hypofiltration, Rhizostabilization and phytovolatilization (Gupta et.al. 2012, Lakshmi et al.2017). Phytoremediation technique is highly effective to treat different types of wastewaters. Many different types of plants have been used variously in phytoremediation. Aquatic plants absorb elements through roots and shoots. Much interest in *Typha august folia*, Duckweed, Water hyacinth, water lettuce and vetiver grass recently have indicated that the plants have potential for removal of a wide range of pollutants such as total suspended solids, dissolved solids, electrical conductivity, hardens, biochemical oxygen demand, chemical oxygen demand, Nitrogen, Phosphorus, Heavy Metals and many other contaminants related to wastewater (Gupta et al.2012).

MACROPHYTES AND ITS ROLE

The Three Types of macrophytes are emergent, free-floating and submerged which have been discussed above. Macrophytes play a major role in red beds, influencing biological, chemical and physical treatment processes. Physical effects include Filtration of suspended materials, protection against erosion by reducing turbulence and flow velocities, stabilisation of sediments and providing the surface area for micro organism. Metabolic functions of macrophytes include nutrient uptake and o₂ release from roots into the rhizosphere. Macrophytes have adapted to anaerobic conditions by developing internal air spaces which transport o₂ to the root zone. These air space from an extensive system throughout the plants and can occupy 60% of the total tissue volume. Many research studies differ on the potential for macrophytes to release O₂ from roots to the surrounding rhizosphere, thus providing aerobic conditions for plant nitrification to occur.

A study concluded that internal O₂ from roots to the surrounding rhizosphere, thus providing aerobic conditions for plant nitrification to occur. A study concluded that internal O₂ movement not only supplied to buried plant tissues but also leaked O₂ into the rhizosphere. Macrophytes can also provide habitat for flora and fauna and increase aesthetic appeal (Guo et. al.2003, Klomjek et al. 2005, Demarien et. al. 2014, Hamizah et al.2015). The primary motivation behind the development of phytoremediation technologies is the potential for low- cost remediation. It is the use of green plant-based system to remediate contaminated soils, sediments, and water. Such plants are known as pollution mitigators. The key factors for the

success of the remediation process depend on characteristics of mine water, environmental climatic conditions, type of amendment used and selection of plant species (Rezaian et al. 2015). The most important factor in the successful implementation of phytoremediation is the selection of an appropriate plant that should have high uptake of both organic and inorganic pollutants, grow well in polluted environments and be easily controlled (Lemna et al. 2014). In this study four aquatic plants (*Typha August folia* and *Eichhornia Crassipes*) are used for the treatment of domestic wastewater.

MATERIALS AND METHODOLOGY

Phytoremediation of municipal, industrial & domestic wastewater, aquatic plants for wastewater treatment. In this way, a considerable list of recent articles for the periods 2019-2021 was obtained, through a systematic mapping, the collected information was synthesised in order not to exclude any of the critical positions of the researchers, & comparison were made through the tables that highlight the dimensions & indicates of each variable under study.

Sampling Site

A total of 200 L of mixed industrial textile effluent was collected from a sub-tributary of the Pharang Drain in Punjab, Mumbai (31.4504 ° N, 73.1350 ° E), a region known for its dense textile industry and significant wastewater discharge. Sampling was conducted using pre cleaned, high-density polyethene (HDPE) bottles with a 30L capacity to ensure sample integrity.

Effluent was collected at a single point over a 2h period during peak discharge, mixed thoroughly, & immediately transported to the laboratory. Samples were preserved at 4 ° c in a refrigerated unit until the experiments commenced within 48 h of collection to minimise physicochemical changes. The experiment was carried out using 20 L tubs.

Collection of aquatic plants & establishment of nursery: -

Locally available aquatic plants, namely. Water hyacinth, duckweed and water lettuce were collected from the sewage treatment plant & then analysed in the experimental setup. Wastewater is collected from the unit inlet chamber. The parameters involved are PH, BOD, COD, water hyacinth and water lettuce, which were collected randomly from nearby me, these macrophytes were selected based on local availability.

A nursery was established after rinsing the plants and placing them into large tubs filled with the help of tap water under ambient conditions. (figure: -1). To ensure effective

removal efficiency against mixed industrial textile effluent, plants were acclimatised in gradually increasing concentrations of textile effluent (0:100, 25:75, 60:60, 76:26, 100:01) to enhance tolerance. The nursery was maintained in plastic tubs, ensuring proper growth before

experimentation. These plants are known for their high growth rate and adaptability to local climate conditions. Previous studies by the National Institute of Bioremediation (NIB) and NARC have confirmed the suitability of these aquatic plants for wastewater treatment.



Figure 1. Collection and establishment of laboratory-based aquatic plants.

Bech Scale Experiment: -

The experiment was conducted in 20 L plastic tubs, each tub filled with the help of raw textile effluent. Three aquatic plants named water hyacinth, water lettuce and duckweed with an equal number of leaves, were thoroughly washed with deionised water to remove residual nutrients from roots or fronds before transfer from the nursery to the plastic tubs.

Experimental Treatments:

Four treatments with three replications were used to compare treated and untreated mixed 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: -

Samples were collected at 0, 5, and 10-day intervals in plastic bottles pre-washed with distilled water. Now we can measure the water quality parameters that were analysed: -

- pH, TDS (Total Dissolved Solids), EC (Electrical Conductivity), Salinity, Temperature, Chloride,

Nitrate and Ammonia using SEBA Hydrometer MPS-16.

- Total hardness determined by titration with EDTA using Eriochrome Black T as an indicator.
- Sodium Concentration measured using a flame photometer (JENWAY PFP7).

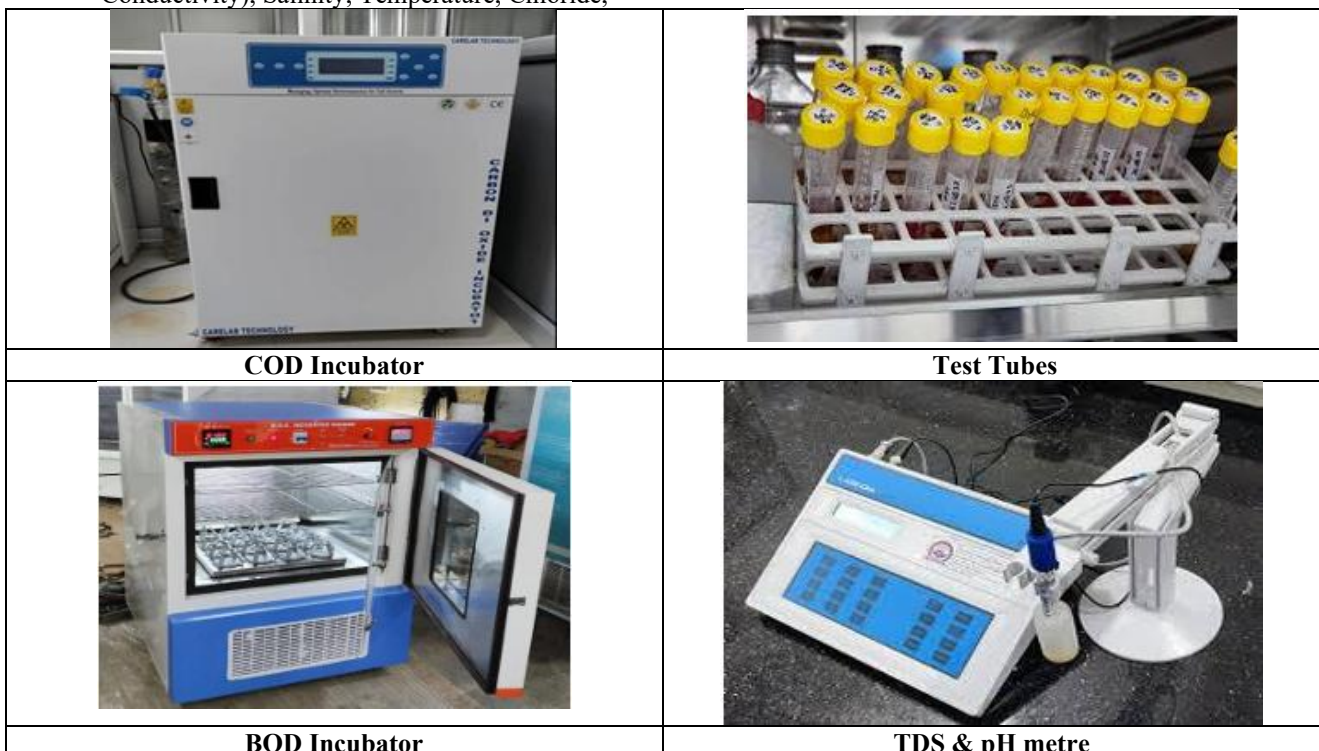


Figure 6. Instrument Used

Potential of Hydrogen:-It is a logarithmic scale from 0 to 14 that measures the concentration of Hydrogen ions. The p H, an abbreviation of the potential of Hydrogen, refers to the concentration of hydrogen ions (H⁺) and hydroxyl ions (OH⁻) in the water or wastewater. The pH of a solution represents the basic, acidic, or neutral nature of the water. It is expressed as a logarithmic reciprocal of hydrogen ion activity.

Total Dissolved Solids (TDS)-Total dissolved solids are basically minerals that are present in water and properly dissolved in water. TDS contains positively charged ions and negatively charged ions. These types of minerals or solids cannot be seen with the naked eye because they are neither suspended nor on the surface. TDS is the main cause of colour change in the water. TDS does not contain any colloids, and any type of gas is directly proportional to EC, as given in the equation.

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

Where, K = 640, K = 735 for mixed water or, K = 800 for EC >5 ds/m. The EC of water is directly proportional to the total amount of solids dissolved in it.

EC also measures the ability of water to conduct an electrical current.The minerals dissolved in water include Carbonate, Bicarbonate, Phosphate, Chloride, Sulphate, Nitrates, Sodium, Magnesium and Calcium, etc. It is also affected by the temperature as the higher the temperature as the higher the temperature, the higher the EC.

The concentration of salt in the water defines salinity. These Values are also within the same limits. Salinity and conductivity are interrelated. High salinity of the water is toxic to plants.

Salinity: -Salinity is a major environmental issue affecting freshwater resources, agricultural productivity, and ecosystem stability. Increasing salinisation of water bodies occurs due to industrial discharge, irrigation return flow, and climate change-induced seawater intrusion. Conventional methods for salinity removal, such as reverse osmosis and ion exchange, are often expensive and energy-intensive.

Temperature: -The degree of hotness or Coldness of any substance is said to be the temperature of that body. The temperature of water directly influences the water properties and biological activities. Temperature can be measured in C and Kelvin. Instruments that are normally used for measurement are a thermometer and a thermistor. Temperature plays an important role in the efficiency of the

treatment system. The removal rate of almost all the pollutants is dependent on the temperature of the water and the ambient air. In addition to the temperature, plant uptake and microbial activity play a major role in removing pollutants. At lower temperatures, usually below 10 °C, the removal efficiency decreases significantly. Microorganisms perform optimally at temperatures of more than 15.c.

Chloride:Chloride is formed when chlorine in its gaseous form reacts with any metal. The action of water by weathering helps chlorides to leach down from different rocks. Chlorides are versatile and move close to basins and oceans. The presence of chloride also indicates the water hardness because it breaks down from calcium chloride (CaCl₂). The high concentration of chloride in irrigation water makes it toxic.

Nitrate: - Nitrate naturally occurs in water bodies. A specified amount is always present in the water sample, but if contamination occurs, then the number of nitrates also increases. When nitrates exceed their limits, this is very detrimental to young children or young livestock. Unnecessary nitrates can result in the restriction of oxygen transport in the bloodstream.

Ammonia:Ammonium Ions in water or unionised ammonia (NH⁴⁺) are commonly non toxic and behave like predominates when the pH is low. As pH increases, toxicity due to ammonium ions also increases.

Total Hardness:

Magnesium (Mg²⁺) and Calcium (Ca²⁺) ions present in the water sample determine the water hardness. Any water sample can be said to be hard water if it does not make a lather with soap. There are two types of hardness: temporary hardness and permanent hardness. The first type of hardness is due to the presence of carbonates (CO₃²⁻), bicarbonates (HCO₃⁻), and OH⁻ with (Ca²⁺) and (Mg²⁺). Permanent hardness is due to the existence of chlorides (Cl⁻), Sulphate (SO₄²⁻), and any ion except alkaline ions with (Ca²⁺) and (Mg²⁺).

Calcium: Calcium is one of the most abundant elements in rocks. Calcium is present in water due to the concentration of mineral salts in water bodies through rocks. The high concentration of calcium is not worthwhile because it represses the formation of a lather with soap. The calcium was determined by SEBA.

Sodium Adsorption Ratio (SAR): The sodium adsorption ratio is an important water quality irrigation parameter that is used in managing soils troubled with sodium. It describes

the suitability of water use for irrigation. It can be calculated from the concentration of alkaline and cations present 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: - The collected data were analysed statistically to determine the overall significance, and the least significance difference (LSD) test with a 95% confidence interval was used to compare the difference between the treatment means. The experiment was arranged under a completely randomised design (CRD) with three replications. For all statistical data analyses, Microsoft Excel and R Studio were used.

Results: - In this study, a total of nine wastewater quality parameters were considered to determine the efficiency of three aquatic plants in a laboratory-scale experiment for the treatment of mixed industrial wastewater. Table 2 shows that in the initial days, the removal efficiency of all aquatic plants in their unfamiliar environment. The samples were taken for analysis on days 0, 5 and 10. The experiment was conducted over a 10 – day period.

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
To	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
T1	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
T2	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
T3	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

Effects on chemical parameters of mixed industrial wastewater: Present experiment the percentage reduction of total dissolved solid for old treatment was 90.2%, 30.3%,

15.85% and 13.83% for T0, T1, T2, T3, respectively, at the 5-day retention time. Similarly, TDS was reduced by all the applied treatment 30.81%, 36.12%, 19.43%, 16.43% for

T0, T1, T2, T3, respectively, at a 10-day retention period. Figure no. 7(A) shows that the maximum reduction was

shown by Eichhornia crassipes (T1), which reduced the TDS of industrial water to 38.12% at a 10-day retention time.

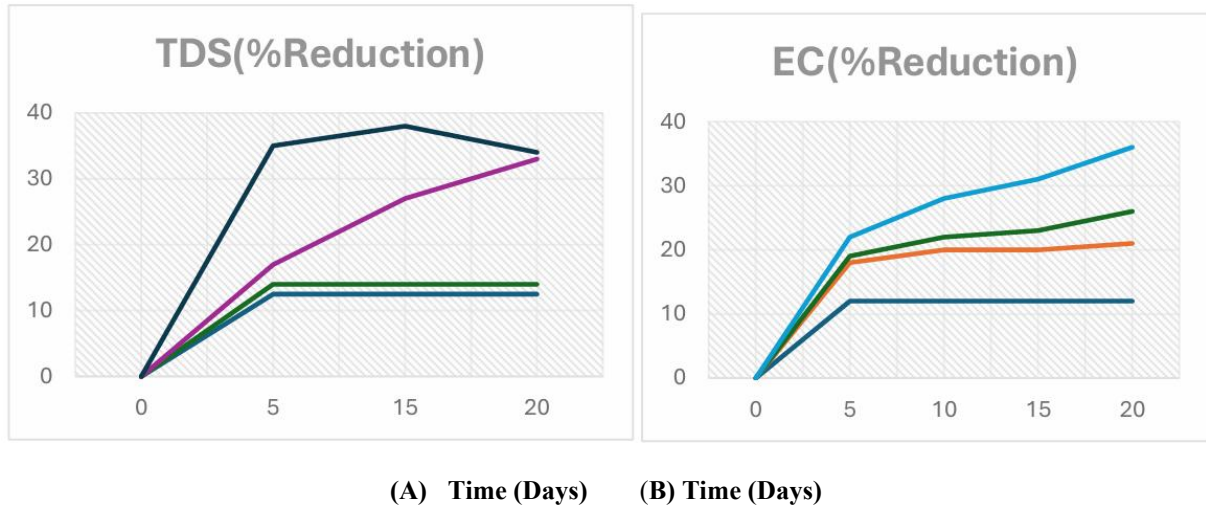
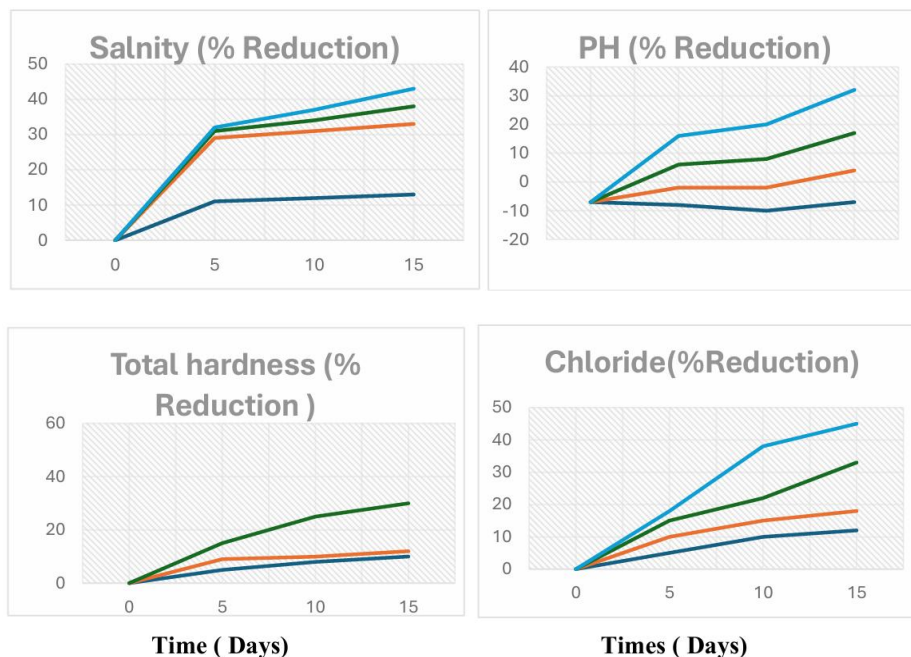


Figure 7. Comparison of the Induction in total dissolved solids (TDS) and electrical conductivity (EC) across four different treatments, showing the variation in treatment efficiency.

Apply treatment was found to reduce EC to 18.62%, 34.30%, 17.63%, and 14% for To, T1, T2, T3, respectively, at a 5-day retention time. The percentage reduction of EC for all the treatments was 33.96%, 37.13%, 21.45%, and 14.56% for To, T1, T2, and T3, respectively, at a 10-day retention time (Figure 7b). All the above results show that Eichhornia crassipes T1 significantly reduced the EC of mixed industrial wastewater to 36.14% at a 10-day retention time, making it superior to the other treatments.

Effects on physical parameters of mixed industrial wastewater: - Salinity was reduced by 17.43%, 34.34%, and 16.32% for TO, T1, T2, T3, respectively, at a 5-day retention time. On the 10th day, it was found that all treatments reduced salinity to 30.78%, 29.90%, 21.05%, and 14.56% for T0, T1, T2, and T3, respectively (Figure 8a). The result showed that Eichhornia crassipes T1 significantly reduced the salinity of mixed industrial wastewater to 34.30% at a 10-day retention time.



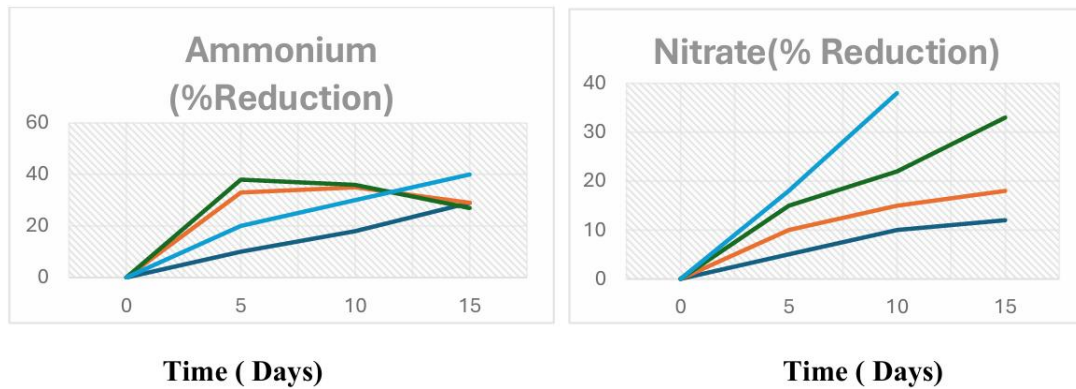


Figure 8. Comparison of the reduction in key wastewater quality parameters, including salinity(a), pH (b), Total Hardness(c), Chloride (d) and ammonia €, across four different treatment approaches, highlighting the variation in treatment efficiency.

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

Treatment reduced total hardness up to 15.22%, 17.45%,1.09%, 8.70% for T₀,T₁,T₂,T₃ respectively,at a 5-days retention time. It was found to be 17.17%, 34.30%, 14.15% and 11.98% for T₀,T₁,T₂,T₃, respectively, at a 10-days retention time(Figure 8(c)). All of the above results show that Eichhornia crassipes T₁ significantly reduced the total Hardness of mixed industrial wastewater to 34.30%, at a 10-day retention time.

The chloride for all treatments was reduced to 3.15%, 29.60%, 17.45% and 0.78% for T₀, T₁, T₂, T₃, respectively,

at a 5-day retention time. It was further reduced to 12.56%, 45.45%, 33.34% and 6.56% for T₀, T₁, T₂, T₃, respectively, at a 10- day retention time Figure 8(d). Eichhornia crassipes (T₁) significantly reduced the chloride in mixed industrial wastewater to 44.34% at a 10- day retention time.

The ammonium was reduced by 18.45%,33.56%, 35.45% and 33.45% for T₀, T₁,T₂, T₃, respectively, at a 5-day retention time. The percentage reduction for all treatments was found to be 23.45%,

Effects on Agricultural Parameters of Mixed Industrial Wastewater: -

The percentage reduction of nitrate for all treatments was 32.45%, 34.30%, 85.67% and 43.30%, for T₀, T₁, T₂, and T₃, respectively, at a 5-day retention time. The nitrate was reduced to 98.78%, 99.79% and 99% for T₀,T₁,T₂,T₃ respectively, at a 10- day retention time(Figure 9 (a)). T₁ significantly reduced the nitrate in mixed industrial wastewater to 99.24% at a 10- day retention time.

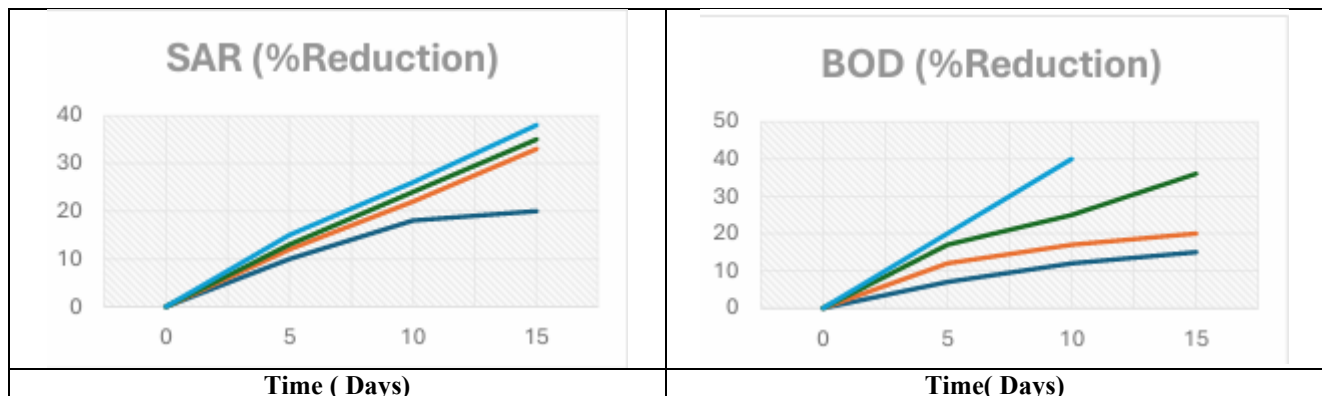


Figure 9. Evaluation of the Nitrate (a) and Sodium Adsorption Ratio(SAR) (b) removal across four different treatment approaches, highlighting the variation in treatment efficiency.

SAR was reduced to 27.46%, 33%, 25.67% and 13.80% for T₀, T₁, T₂, and T₃, respectively, at a 5-day retention time. It was further reduced to 42.45%, 46.23%, 45.23% and 32.31% for T₀, T₁, T₂, T₃, respectively, at a 10- days retention time (Figure 9b). The result showed that T₁ significantly reduced the SAR of mixed industrial wastewater to 45.29% at a 10- day retention time.

Statistical Evaluation of Results: -

Figure 10 shows bar graphs comparing the mean values of different water quality parameters across treatments and

the least significant difference values. The data regarding the comparison of individual mean values of TDS, EC, salinity, PH, Total hardness, Chloride, nitrate, SAR, BOD, and COD of industrial effluent under various treatments were significant. The grand LSD values across the data were as follows: 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%.

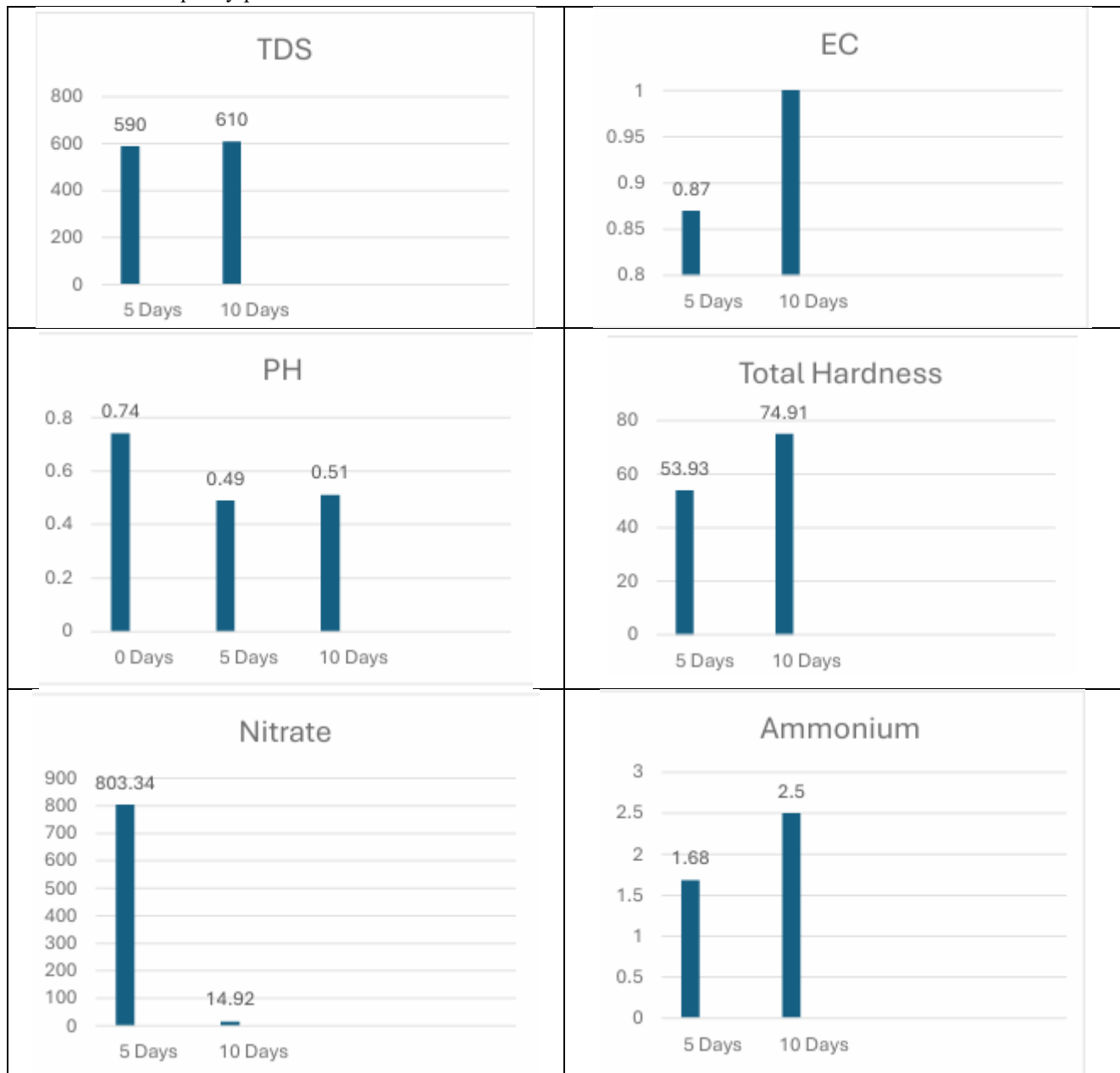




Figure 10. bar graphs comparison

The analysis of variance for regression indicates that all treatments had significant effects ($\alpha = 0.05$) on the TDS, EC, salinity, total hardness, nitrate, ammonium, and SAR of the mixed industrial wastewater (Fcal. Is greater than Fcri. ($p > 0.05$)). The ANOVA for regression indicates that all treatments had non-significant effects ($\alpha = 0.05$) on the pH and chloride of the mixed industrial wastewater as Fcal. Is less than Fcri. ($p > 0.05$)).

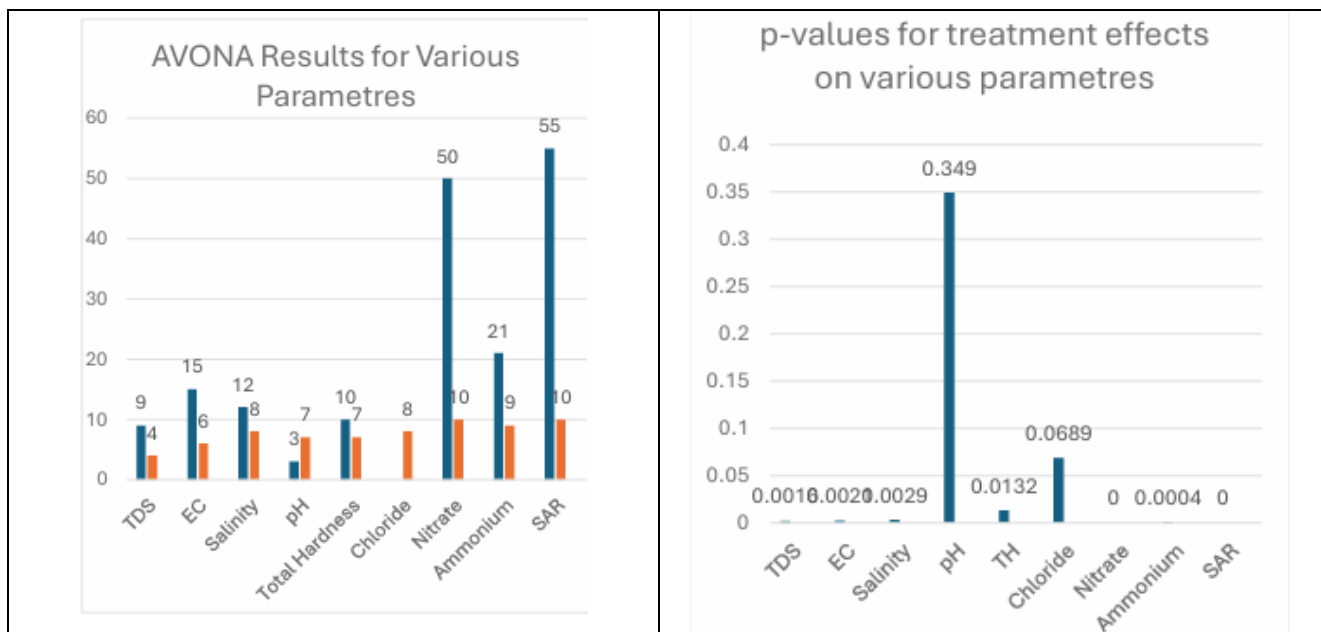


Figure 11. Statistical significance (p-value) of treatment effects on various parameters.

DISCUSSION

The Findings of this study demonstrate the efficiency of aquatic plants, particularly *Eichhornia crassipes*, in reducing various pollutants in industrial wastewater. While previous studies have acknowledged the phytoremediation potential of *Eichhornia crassipes*, *Pistia stratiotes*, and *Lemna Major*, this study provides a comparative analysis of their pollutant removal efficiencies. 9 15 12 3 10 50 21 55 4 6 8 7 7 8 10 9 10 0 10 20 30 40 50 60 AVONA Results for Various Parametres under controlled retention times. The Mechanisms underlying the differential performances of these plants warrant further discussion.

Superior Pollutant Removal By *Eichhornia crassipes*:

- The Superior Performance of *Eichhornia crassipes* compared to *Pista stratiotes* and *Lemna minor* can be attributed to multiple factors. First, *Eichhornia crassipes* possesses an extensive root system with a high surface area, providing more sites for pollutants attachment, absorption, and microbial colonisation. This allows for the increased bioaccumulation of dissolved solids and the enhanced microbial-mediated degradation of organic and inorganic contaminants. Second, its higher biomass accumulation rate contributes to greater pollutant uptake, as previously reported in phytoremediation studies. Furthermore, economies support diverse microbial community debt faculties key to biogeochemical processes, including nitrification, denitrification and organic matter decomposition, enhancing the overall treatment efficiency.

Nitrate Removal Efficiency: - The exceptionally high nitrate removal efficiency (up to 99%) observed in this study is likely due to multiple removal mechanisms. Plant uptake played a significant role, as *Eichhornia crassipes* is known for its high nitrogen assimilation capacity. Additionally, microbial processes, particularly nitrification and denitrification, contributed significantly to nitrate reduction. The root zone of *Eichhornia crassipes* fosters an oxygen gradient that supports both aerobic nitrification (conversion of ammonium to nitrate gas). The formation of biofilms on the root surface further enhances microbial activity, accelerating the removal of nitrates from the wastewater. The possible precipitation of nitrate-containing compounds could also contribute to the high removal rates, as observed in previous studies.

Comparison with Previous Literature: - While this study aligns with previous research demonstrating the phytoremediation potential of *Eichhornia Crassipes*, a critical comparison highlights both consistencies and discrepancies. Studies have also reported significant reductions in pH in wastewater treated with *Eichhornia crassipes*, consistent with the findings of this study. The mechanism behind pH reduction is primarily due to the formation of carbonic acid (H_2CO_3) from microbial degradation of organic pollutants. However, variations in removal efficiencies across studies may arise due to differences in wastewater composition, retention time, and environmental conditions. A Comparative summary of removal efficiencies in different studies is presented in Table No.3.

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Table No.3: Comparison of removal efficiencies with previous studies.

Pollutant	<i>Eichhornia crassipes</i> (This study)	<i>Eichhornia crassipes</i> previous studies)	<i>Pistia stratiotes</i>	<i>Lemna Minor</i>
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

Challenges and Real- world Implementation

Considerations: - While phytoremediation using *Eichhornia crassipes* shows great potential, real- world application presents several challenges that must be addressed:

- ❖ **Seasonal Variations:** Plant growth rates and pollutant uptake efficiency may vary with seasonal changes in temperature, light availability and nutrient levels. Cold seasons may reduce metabolic activity, impacting remediation efficiency.
- ❖ **Retention time constraints:** Industrial wastewater treatment requires large- scale implementation, where prolonged retention times may not be feasible. Optimisation of hydraulic retention time (HRT) to balance treatment efficiency and operational feasibility in vertical flow constructed wetlands can enhance contaminant removal by optimising water distribution and retention dynamics. Additionally, the strategic incorporation of specialised microbial consortia within these wetlands can significantly improve biodegradation processes, further augmenting treatment efficiency through biological mechanisms.
- ❖ **Plant Disposal and Biomass Management:** Accumulated pollutants in plant tissue pose disposal challenges. Safe disposal or valorisation strategies, such as bioenergy production or composting, need to be considered. Incineration of contaminated biomass presents an effective approach to prevent the release of toxic compounds into open water systems, thereby mitigating environmental risks. This controlled thermal degradation not only ensures the safe removal of hazardous substances but can also facilitate energy recovery, aligning with sustainable waste management principles.
- ❖ **Variability in wastewater composition:** Different industries discharge wastewater with diverse compositions. The effectiveness of phytoremediation

may vary depending on the type and concentration of contaminants present.

Economic Feasibility: The cost- effectiveness of phytoremediation must be critically evaluated for large-scale adoption. While *Eichhornia crassipes* offers a low- cost, Eco- friendly alternative to conventional treatment methods, factors such as land requirements, maintenance costs and plant harvesting expenses must be considered. Previous studies suggest that phytoremediation can be a cost- effective method when integrated with existing wastewater treatment facilities, reducing operational costs compared to chemical or mechanical treatment methods. However, further economic analysis is required to establish its financial viability at an industrial scale.

CONCLUSION

The present 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. Among the tested species, *Eichhornia crassipes* exhibited the highest pollutant removal efficiency, significantly reducing key irrigation quality parameters such as total dissolved solids (TDS), electrical conductivity (EC), Salinity, pH, Total Hardness, and sodium adsorption ratio (SAR), BOD, and COD within a 10-day retention time. These findings highlight the potential of plant-based phytoremediation as an eco-friendly, chemical-free, and cost-effective alternative to conventional wastewater treatment methods.

Beyond laboratory conditions, this study holds importance real- world implications. Textile industrial clusters, particularly in Shamli and similar industrial hubs, could integrate this phytoremediation technology into wastewater treatment frameworks to mitigate environmental pollution and improve compliance with regulatory requirements and standards.

Wastewater treatment with aquatic plants is a phytoremediation strategy that sets significant trends for the year 2021 and requires low treatment costs. In addition, the efficiency of pollutant removal is independent of the origin of the discharge, whether it is industrial, domestic, or municipal. From the research collected, it was obtained that plants have a better location if the environment is adapted to their living conditions in horizontal or vertical flow, which will motivate the plant to imminent development for the most marked removal as is the case of *Eichhornia crassipes*, an aquatic weed that has an effective removal and nitrate up to 90% for industrial wastewater, *Pista stratiotes*, which removed Turbidity 98.0%, Total phosphate 99% and COD 80.16% in 60 days for domestic wastewater. The scalability if this method could be explored in wastewater treatment plants, either as a standalone solution for small-scale industries or as a supplementary treatment in larger facilities.

Additionally, the aesthetic appeal and sustainable of this nature-based Approach make it a webel long term strategy for industrial effluent management while the laboratory results are promising further research is necessary to validate the facing ability of this technology in field scale applications further studies should focus on optimising retention time evaluating plant performance in real wastewater treatment settings and conducting comprehensive economics analysed to determine the cost benefit ratio of large scale implementation.

Moreover, assessing the long-Term survival regeneration capacity and potential reuse of this aquatic plant in different environmental conditions would enhance the practical applicability of these approaches. These plant species are commonly imported from other reason of medicinal or ornamental purposes. However, they gradually evade human Control and establish a self-sustaining population in the world. Aquatic plants are frequently used in wastewater due to their significantly reduced cost and superior efficiency. They are utilised in the treatment process to diminish or restrict the presence of pollutant-laden wastewater. The quality of the treated wastewater met the worldwide effluent criteria for irrigation.

Supplemental materials:-The following supporting information can be downloaded from <https://www.mdpi.com/artical/10.3390/w17071080/s1>, Table S1 Percentages% reduction in wastewater quality parameters, Table S2 ANOVA for TDS: Table S3. Comparison of TDS values: Table S4. ANOVA for EC: Table S5. Comparison of EC values: Table S6. ANOVA for Salinity: Table S7.

Comparison of salinity values: Table S8. ANOVA for pH: Table S9. Comparison of pH values. Table S10 ANOVA for Total Hardness: Table S11: Comparison of Total Hardness values: Table S12 ANOVA for Chloride: Table S13. Comparison of Chloride Values: Table S14 ANOVA for Nitrate: Table S15. Comparison of Nitrate values: Table S16. ANOVA for Ammonium: Table S17. Comparison of Ammonium values S18. Anova for SAR: Table S19. Comparison of SAR values.

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Data Availability Statement: - The supplementary data supporting the findings of this study are available on request from the corresponding author and have been provided as part of the submission. Please refer to the Supplementary Materials for further details.

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