Journal of Environmental Sciences and Sustainability
ISSN: 3106-7883 | 3106-7875
Volume 2, Issue 3, 2025

# EVALUATING THE EFFICIENCY OF A CONSTRUCTED WETLAND SYSTEM FOR INDUSTRIAL AND DOMESTIC WASTEWATER TREATMENT IN SOUTHERN PUNJAB, PAKISTAN

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**Keywords**
*Constructed wetlands; wastewater treatment; bioremediation; heavy metal removal; sustainable sanitation; water scarcity*

**Article History**
*Received: 12 July 2025*
*Accepted: 22 August 2025*
*Published: 30 September 2025*


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## Abstract
*Water scarcity has become an increasingly urgent global issue, fueled by rapid population growth, industrialization, and inefficient water management. The World Water Assessment Programme predicts that nearly two-thirds of the world's population could face severe water shortages by 2025, with almost half affected by 2030. In Pakistan, per capita water availability has plummeted from 5000 $m^3$ $year^{-1}$ in 1951 to roughly 1100 $m^3$ $year^{-1}$, placing the country under critical water stress.Constructed wetlands (CWs) have emerged as cost-effective, nature-based solutions for wastewater treatment, particularly in areas challenged by pollution and freshwater scarcity. This study was conducted at C-Block, MNS-University of Agriculture, Multan, where a surface flow constructed wetland system was established to treat wastewater from the Wali Muhammad Distributary—a canal contaminated with untreated domestic and industrial effluents. The wetland consisted of a series of vegetated ponds designed to promote natural filtration processes. Wastewater samples were collected weekly over a three-week period and analyzed for key physico-chemical parameters. Statistical analyses were performed using R software, with significance assessed via t-test at $p < 0.05$.The system achieved substantial reductions in various parameters: pH (16%), electrical conductivity (93.30%), carbonate (82%), bicarbonate (66%), total dissolved solids (75%), total solids (84.43%), total suspended solids (75%), biological oxygen demand (84.23%), chemical oxygen demand (39%), potassium (53%), sodium (75%), and calcium (68%). These findings underscore the high pollutant removal efficiency of constructed wetlands and highlight their potential as a sustainable strategy for wastewater treatment and water resource management.*

## INTRODUCTION
Water scarcity represents one of the most pressing global challenges of the 21st century, affecting multiple sectors including industry, agriculture, power generation, household and environmental systems - competing to meet their water requirements. The severity of this challenge is projected to intensify dramatically, with two-thirds of the world's population facing drastic water shortages by 2025 (Ingrao *et al.*, 2023). Furthermore, water scarcity is expected to affect half of the world's population by 2030 (Scheierling *et al.*, 2011; Biswas *et al.*, 2025).

According to comprehensive assessments by the World Water Assessment Program (UN, 2025) all production sectors will experience increased water demand, more than one-third of the global population facing water stress by 2030. The primary drivers of water scarcity include exponential population growth, expanding agricultural and industrial sectors, climate change, and global warming. Additionally, limited water resources and inequitable access to these resources contribute significantly to regional water scarcity challenges (Biswas *et al.*, 2025).

The current global water crisis stems primarily from the dual pressures of population growth and economic sector expansion (Lu *et al.,* 2022). This situation is particularly acute in countries with weak economies and ineffective wastewater management systems (Onu *et al.,* 2023). As the population continues to grow, water and food requirements will increase proportionally, creating a scenario where water use exceeds available resources and reduces agricultural productivity (Omohwovo, 2024).

Population-driven demand results in substantially increased wastewater discharge containing various pollutants, including biological oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, biodegradable organics, ammonia-nitrogen, nitrate- nitrogen, fuel hydrocarbons, agrochemicals, heavy metals and pathogenic microorganisms. Freshwater contamination poses a significant global challenge, particularly in countries like Pakistan, where industrial and municipal waste is discharged with minimal or no treatment directly into water bodies (Lacalamita *et al.,* 2024).

These pollutant compounds severely compromise water quality in receiving systems, rendering water unsuitable for domestic use, agricultural irrigation, and aquatic ecosystem health. The organization for Economic Co-operation and Development (OECD) reported a 45% increase in wastewater production in 2020 compared to 1995 levels (Barath *et al.,* 2025). However, comprehensive risk assessments are essential, as wastewater sources vary significantly in chemical and organic composition, and potentially impact the natural ecosystems (Omohwovo, 2024).

Keeping in view the global nature of water scarcity, planning for non-traditional water sources has become imperative to meet increasing freshwater demands. Multiple researchers have identified wastewater as a viable alternative for addressing water scarcity challenges resulting from population expansion and other factors (Ndeketeya and Dundu, 2022). However, the uncontrolled use of untreated wastewater for agricultural irrigation and water body discharge poses significant risks to aquatic life and human health (Ahmad *et al.*, 2023).

Constructed Wetlands (CWs) represent cost effective and energy efficient engineered systems that utilize natural processes involving wetland vegetation, soil, and associated micro biota for treating various types of wastewaters (Addo- Bankas *et al.*,2024). These systems offer significant potential for wastewater treatment that can subsequently substitute freshwater in agricultural irrigation, addressing global water deficits while providing economic benefits to households by reducing disease related costs from wastewater exposure.

Constructed wetlands operate through nature-based materials and processes, utilizing minimal steel and concrete infrastructure. The primary system components - soil, gravels, and plants – contribute to high local content value, making these systems particularly suitable for developing regions (Waly *et al.,* 2022). Key operational parameters, including retention time, loading rate, and plant growth, significantly influence trace element removal efficiency (Waqas *et al.,* 2023). Optimal retention time is critical for effective COD and heavy metal removal (Afsar *et al.,* 2025). Hydrological parameters such as evapotranspiration, infiltration capacity, retention time, hydraulic conductivity, and loading rate are crucial for different constructed wetland types (UN, 2025). Recent studies have emphasized the importance of hydraulic retention time in constructed wetland performance (Afsar *et al.,* 2025). These systems demonstrate resilience to high fluctuation in loading rates
while maintaining treatment efficacy (Cai *et al.,* 2025).

Constructed wetlands have shown superior performance in wastewater treatment applications globally, particularly benefiting rural localities and small towns. These systems typically exhibit optimal removal efficiency for organic compounds including COD, BOD and suspended materials, while nitrogen removal effectiveness varies with wetland type (Dominguez-Solis *et al.,* 2025). The integration of soil, vegetation and microbiota in constructed wetlands enhance water pollutant removal capabilities (Huang *et al.,* 2019). Keeping in view the above discussion, this study was planned to evaluate the performance of newly constructed wetland.

## Materials and Methods

### Study area

The study was conducted in C-block of MNS-University of Agriculture, Multan, Pakistan (Figure 1a). The water source was Wali Muhammad Distributary canal, which receives untreated industrial and domestics wastewater discharge from the Water and Sanitation Agency (WASA). This direct discharge of

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ISSN: 3106-7883 | 3106-7875
Volume 2, Issue 3, 2025

wastewater into the canal system without treatment poses significant environmental pollution risks to soil, surface water, and groundwater resources in the local area.

**Figure 1a: Wetland ponds at C-block of MNS University of Agriculture, Multan**

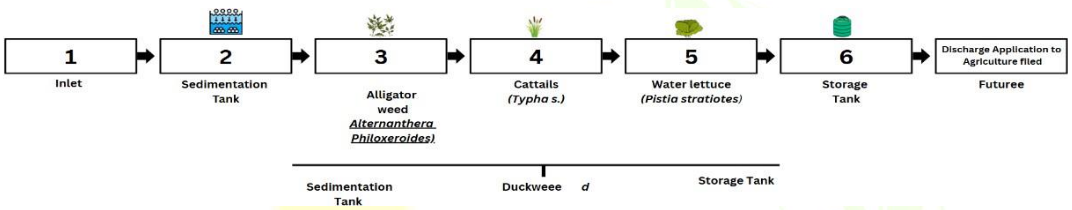


**Figure1b. A schematic process diagram of a constructed wetland wastewater treatment system**

**Constructed Wetland Design**

A constructed wetland system consisting of six earthen ponds in series was established at the MNSUAM Research Farm, Multan (Figure 1b). The wetland covered a total area of 854 $m^2$ with an overall storage capacity of 1,554 $m^3$. Each pond was designed with a seven-day hydraulic retention time (HRT), which was optimized based on preliminary analysis of biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS) in samples collected weekly.

**Pond construction and preparation**

The base of each pond was compacted using an automatic roller compactor to ensure structural integrity. Following compaction, infiltration tests were conducted by filling each pond to a depth of 0.3 m and covering it with polyethylene sheets to prevent evaporation. To minimize groundwater contamination, the pond bases and walls were lined with polyethylene sheets.

The substrate configuration consisted of a bottom layer of gravel (20-40 mm diameter) covered by a layer of fine sand (0.10-0.25 mm diameter). Wastewater entered the first pond and flowed sequentially through the remaining ponds, with a retention time of seven days per pond. Plant species were selected based on their rapid growth characteristics, heavy metal hyperaccumulation capacity, and tolerance to heavy metal contamination.

**Water Quality Parameters and Analytical Methods**

**Biochemical Oxygen Demand (BOD)**

$BOD_5$ was determined using the electrode method according to the USEPA (1998) standard procedure. Appropriate dilutions were prepared to ensure residual dissolved oxygen (DO) remained above 1 mg $L^{-1}$ with at least 2 mg $L^{-1}$ Do after five days of incubation. Diluted samples were transferred to parallel glass BOD bottles and incubated at 20 ± 1°C for five days. Initial and final DO concentrations were measured using a DO meter and electrode.

**Chemical Oxygen Demand (COD)**

COD was determined using the open reflux method (USEPA, 1998). A 50 mL sample was placed in a 500 mL refluxing flask containing glass beads. Mercury sulfate (1 g $HgSO_4$) and sulfuric acid (5 mL $H_2SO_4$) were added, followed by potassium dichromate solution (25 mL, 0.5 M $K_2Cr_2O_7$). An additional 70 mL of sulfuric acid was added with continuous swirling. The mixture was refluxed for two hours, then cooled and diluted with distilled water. The samples determined by the color change from bluish green to reddish-brown.

**Total Solids (TS)**

Pre-weighed crucibles were used to analyse 50 mL wastewater samples. Samples were dried in an oven at 103- 105°C until constant weight was achieved. After cooling, the final weight was recorded using the following formula as:

$$TS\ (mg\ L^{-1}) = \frac{(Final\ weight - Initial\ weight) \times 1000}{Sample\ volume\ (mL)}$$

Total Dissolved Solids (TDS)

A 50 mL filtered wastewater sample was placed in pre-weighed crucibles and dried at 103-105°C. The dried residue was cooled and weighed using the following formula as:

$$TDS\ (mg\ L^{-1}) = \frac{(Final\ weight - Initial\ weight) \times 1000}{Sample\ volume\ (mL)}$$

**Total Suspended Solids (TSS)**

TSS was calculated as the difference between TS and TDS using the following formula as:

$$TSS\ (mg\ L^{-1}) = TS - TDS$$

**Cation Analysis ($Na^+$, $K^+$, $Ca^{2+}$)**

Sodium, potassium, and calcium concentrations were determined using flame photometry. Standard solutions ranging from 0-100 mg $L^{-1}$ were prepared for calibration. Then the concentration of each was determined by the following formula:

*$Na^+$ (mg $L^{-1}$) = ($Na^+$ concentration in solution) × Dilution factor $K^+$ (mg $L^{-1}$) = ($K^+$ concentration in solution) × Dilution factor $Ca^{2+}$ (mg $L^{-1}$) = $Ca^{2+}$concentration in solution) × Dilution factor*

**Calcium and Magnesium Hardness**

A 10 mL wastewater sample was placed in a conical flask. Buffer solution (10 drops of $NH_4Cl$-$NH_4OH$) and Eriochrome Black T indicator (3-4 drops) were added. The samples were titrated with 0.5 M EDTA were titrated against ferrous ammonium sulfate using ferroin indicator (0.15 mL), with the endpoint Carbonate ($CO_3^{2-}$) and bicarbonate ($HCO_3^-$) concentrations were determined by titration of a 10 mL water sample against 0.01 N $H_2SO_4$ using phenolphthalein and methyl orange indicators sequentially (Estefan et al., 2017). Then the concentration was calculated by the following formula:

$$HCO_3^-\ (meq\ L^{-1}) = (T - 2Y) \times N \times 1000 / V$$

$$CO_3^{2-}\ (meq\ L^{-1}) = (2Y \times N \times 1000) / V$$

Where: V = sample volume (mL), Y = titration volume with phenolphthalein (mL), T = titration volume with methyl

orange (mL), N = normality of $H_2SO_4$

pH and Electrical Conductivity

pH was measured using a digital pH meter (MW804, ROMANA), and electrical conductivity (EC) was determined using a conductivity meter (MW804, ROMANA) both in field and laboratory conditions.

**Removal Efficiency:**

The removal efficiency was calculated using the until the color changed from fine red to bluish green. Then the concentration was calculated using the following formula:

$$Ca^{2+} + Mg^{2+}\ (mg\ L^{-1}) = \frac{(mL\ EDTA\ for\ sample - mL\ EDTA\ for\ blank) \times N \times 1000}{Sample\ volume\ (mL)}$$

$$Mg^{2+} (mg\ L^{-1}) = (Ca^{2+} + Mg^{2+}) - Ca^{2+}$$

**Carbonate and Bicarbonate Analysis**

following formula:

$$Removal\ Efficiency\ (\%) = [Cin - Cout) / Cin] \times 100$$

Where Cin is the influent concentration and Cout is the effluent concentration of the respective parameters.

**Statistical Analysis**

Data was statistically analyzed using R software (R Core Team, 2023). Statistical significance was determined using t-tests at $P < 0.05$. The removal efficiency of the constructed wetland systems was

Journal of Environmental Sciences and Sustainability
ISSN: 3106-7883 | 3106-7875
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calculated using the retention equation described by Solano et al. (2004).

## Results

### pH Removal Efficiency

pH concentrations in both influent and effluent samples from the constructed wetland system were monitored across ten sampling times during the three-week study period (June 21 to July 5, 2021), as presented in Figures 2a, b, and c. Statistical analysis revealed a significant difference between influent and effluent pH values across all sampling data ($p < 0.05$). The maximum pH reduction was consistently observed in pond-6 across all three-sampling data, while the minimum (9.1) occurred during the second sampling data. The weekly pH removal efficiencies were 11%, 16%, and 9% for weeks 1, 2, and 3, respectively.

### Electrical Conductivity (EC) Removal Efficiency

The EC measurements for influent and effluent samples across the three sampling periods are illustrated in Figures 3a, b, and c. T-test analysis confirmed statistically significant differences between initial and final EC values for each sampling data ($p < 0.05$). The constructed wetland demonstrated consistent EC reduction capabilities, with

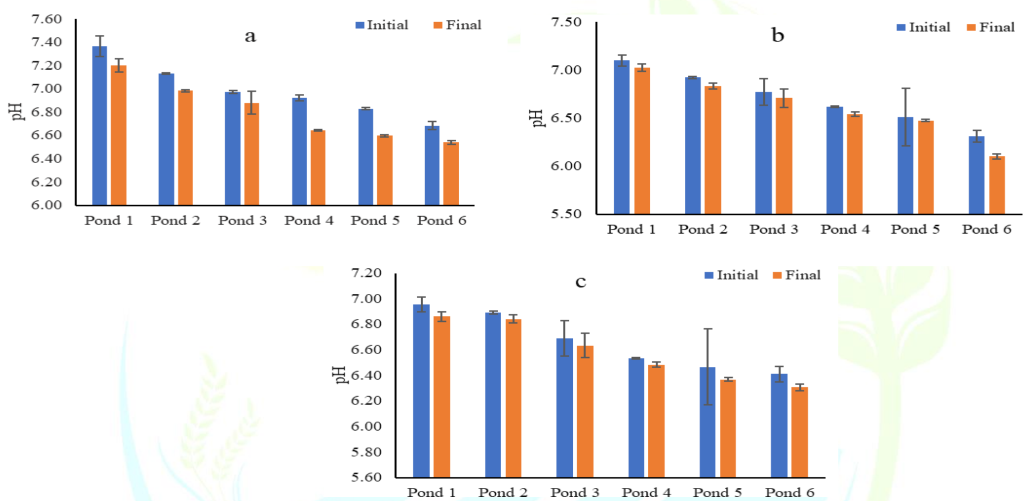


**Figure 2. Removal Efficiency of wetland on pH of wastewater a) after 1st week, b) after 2nd week and c) after 3rd week**

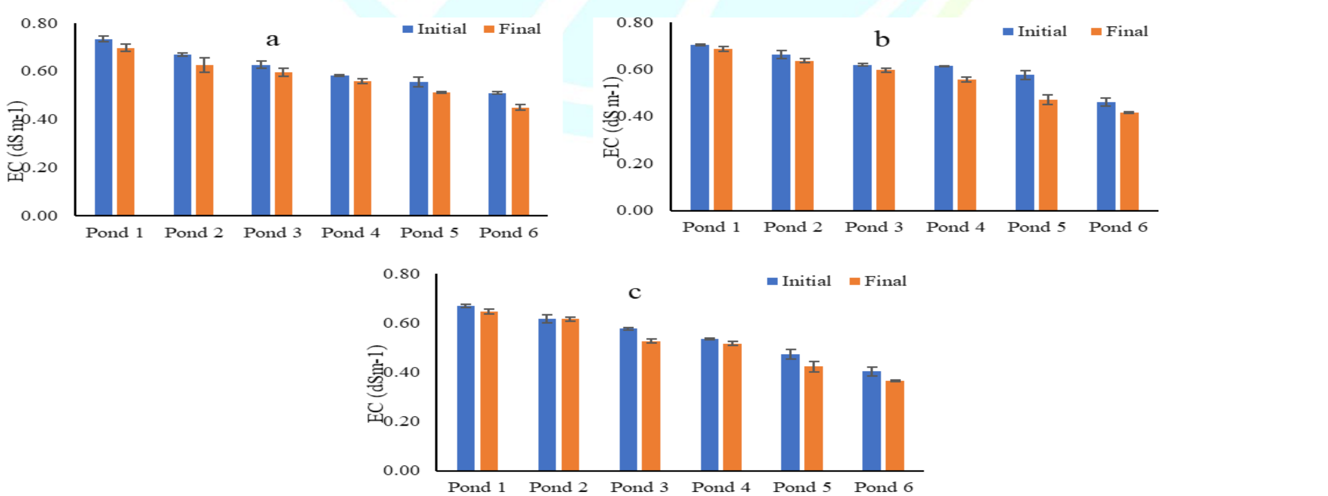


**Figure 3. Removal Efficiency of wetland on electrical conductivity of wastewater a) after 1st week, b) after 2nd week andc) after 3rd week**

values decreasing from 0.47 to 0.42 dS $m^{-1}$ during the second sampling period, particularly in ponds 5 and 6. However, statistical analysis indicated no significant variation in EC reduction efficiency between different sampling dates.

**Carbonate Removal Efficiency**

Figures 4a, b, and c present the carbonate concentrations in influent and effluent samples throughout the study periods. Significant differences between initial and final carbonate concentrations were observed across all sampling data ($p < 0.05$). Ponds-6 consistently demonstrated the highest carbon removal efficiency across the three sampling periods, while the minimum reduction (65 mg $L^{-1}$) was recorded during the first sampling period. The carbonate removal efficiency showed progressive improvement over time: 65% in week 1, 76% in week 2, and
82% in week 3.

**Bicarbonate Removal Efficiency**

The bicarbonate removal performances are presented in Figures 5a, b, and c. Statistical analysis revealed significant differences between influent and effluent bicarbonate concentration across all sampling data ($p < 0.05$). Pond-6 exhibited the highest bicarbonate removal efficiency throughout the study period, with the minimum reduction occurring during the first sampling data. The bicarbonate removal efficiency demonstrated a progressive increase of 55% in week 1, 58% in week 2, and 66% in week 3.

**Chemical Oxygen Demand (COD) Removal Efficiency**

The COD removal performance is illustrated in Figures 6a, b, and c. Significant differences between influence and effluent COD concentration were observed across all sampling data ($p < 0.05$). Pond-6 consistently achieved the maximum COD removal efficiency, while the minimum reduction (9.1 mg $L^{-1}$) was recorded during the second sampling data. The COD removal efficiency varied considerably throughout the study period: 28% in week 1 and 4% in week 2.

**Biochemical oxygen demand (BOD) removal Efficiency**

The constructed wetland system achieved substantial BOD reduction throughout the study period (Figure 7a-7c). Statistical analysis revealed a significant difference ($p < 0.05$) between influent and effluent BOD concentrations across all sampling data. The system demonstrated progressive improvement in BOD removal efficiency: 77% in the first week, 84% in the second week, and 84.23% in the third week. Pond-6 consistently exhibited the highest BOD removal efficiency across all three-sampling data, while the minimum reduction was observed during the second period.

**Total Suspended Solids (TSS) Removal Efficiency**

TSS removal efficiency was evaluated through weekly monitoring (Figure 8 (a-c), showing a significant difference between influent and effluent concentrations ($p < 0.05$). The system achieved TSS reduction rates of 75% in the first week, 74% in the second week, and 71% in the third week. Pond-6 demonstrated maximum TSS reduction across all sampling dates, while the minimum reduction occurred during the third sampling event.

**Sodium (Na) Removal Efficiency**

Sodium removal performance showed significant differences between influent and effluent concentrations across all sampling data (Figures 9 (a-c)). The system maintained consistent Na removal efficiency: 75% in the first week, 74% in the second week, and 75% in the third week. Pond-6 achieved maximum Na reduction across all sampling dates, while minimum reduction was observed in the sixth pond during the second and third sampling events.

**Calcium (Ca) Removal Efficiency**

Calcium removal showed significant treatment efficiency across all monitoring periods (Figures 10 (a-c)).
The system achieved Ca removal rates of 66% in the first week, 68% in the second week, and 66% in the third
week. pond 6, while minimum reduction occurred in the sixth pond during the second sampling date. Maximum calcium reduction was consistently observed in pond 6, while minimum reduction

occurred in the sixth pond during the second sampling date.

**Potassium (K) Removal Efficiency**

Potassium removal efficiency showed a significant difference between influent and effluent concentration (Figures 11 (a-c)). The system demonstrated progressive improvement in K removal: 34% in the first week, 38% in the second week, and 53% in the third week. Pond-6 consistently achieved maximum potassium reduction, while minimum reduction was observed during the third sampling date.

**Total Dissolved Solids (TDS) Removal Efficiency**

TDS removal performance demonstrated significant treatment efficiency (Figures 12 (a-c)), with removal rates of 75% in the first week, 74% in the second week, and 75% in the third week. Maximum TDS reduction was observed in pond-6 across all sampling dates, while minimum reduction occurred during the third sampling event.

**Total Solids (TS) Removal Efficiency**

Total solids removal showed significant treatment efficiency across all monitoring periods (Figures 13 (a-c)). The systems achieved remarkable improvement in TS removal: 64% in the first week, 84% in the second week, and 84.43% in the third week. Pond-6 consistently exhibited maximum TS reduction, while minimum reduction was observed during the first sampling date.

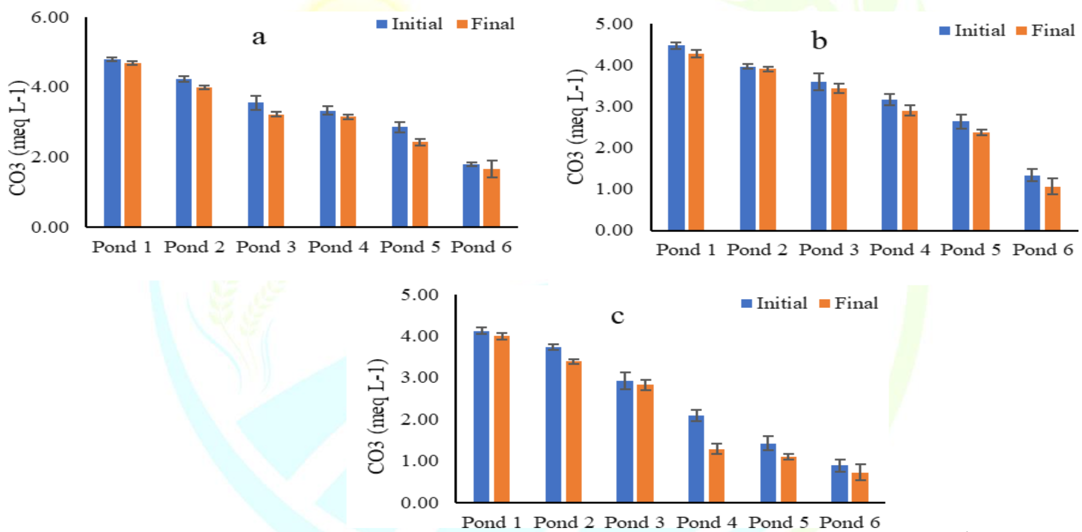


**Figure 4.** Removal Efficiency of wetland on carbonate of wastewater a) after 1st week, b) after 2nd week and c) after 3rd

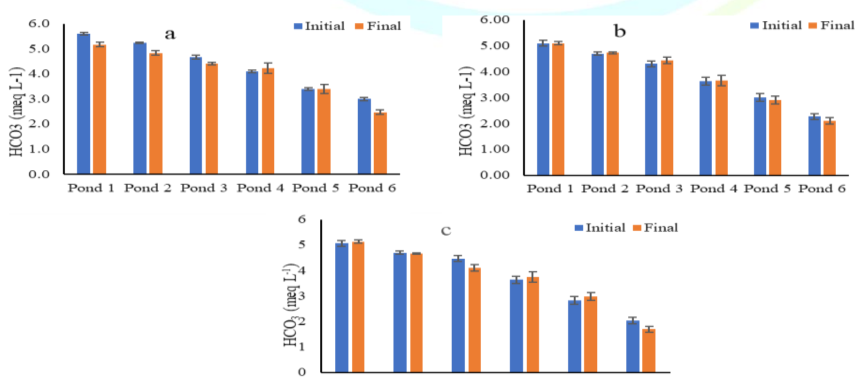


**Figure 5. Removal Efficiency of wetland on bicarbonate of wastewater a) after 1st week, b) after 2nd week and c) after 3rd week**

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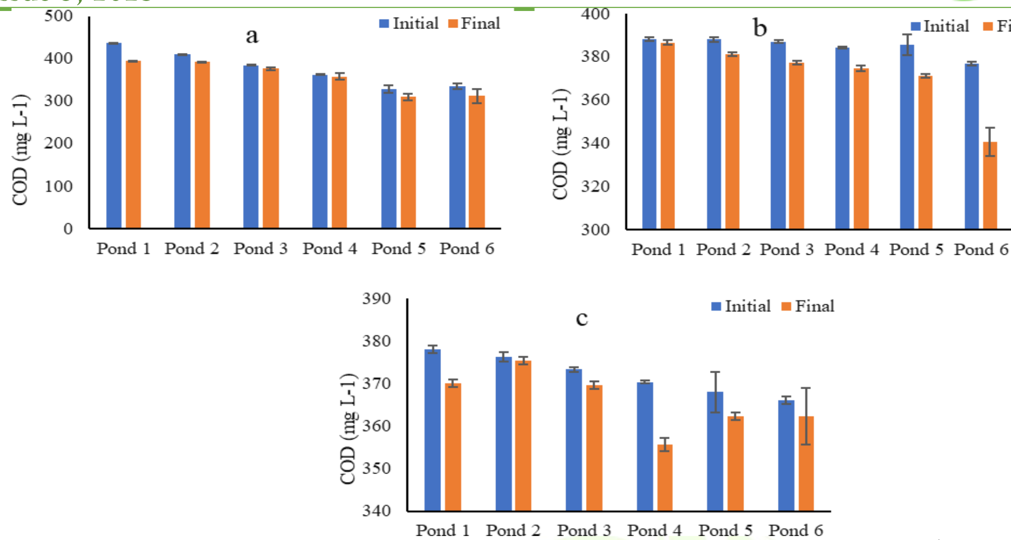


**Figure 6. Removal Efficiency of wetland on COD of wastewater a) after 1st week, b) after 2nd week and c) after 3rd week**

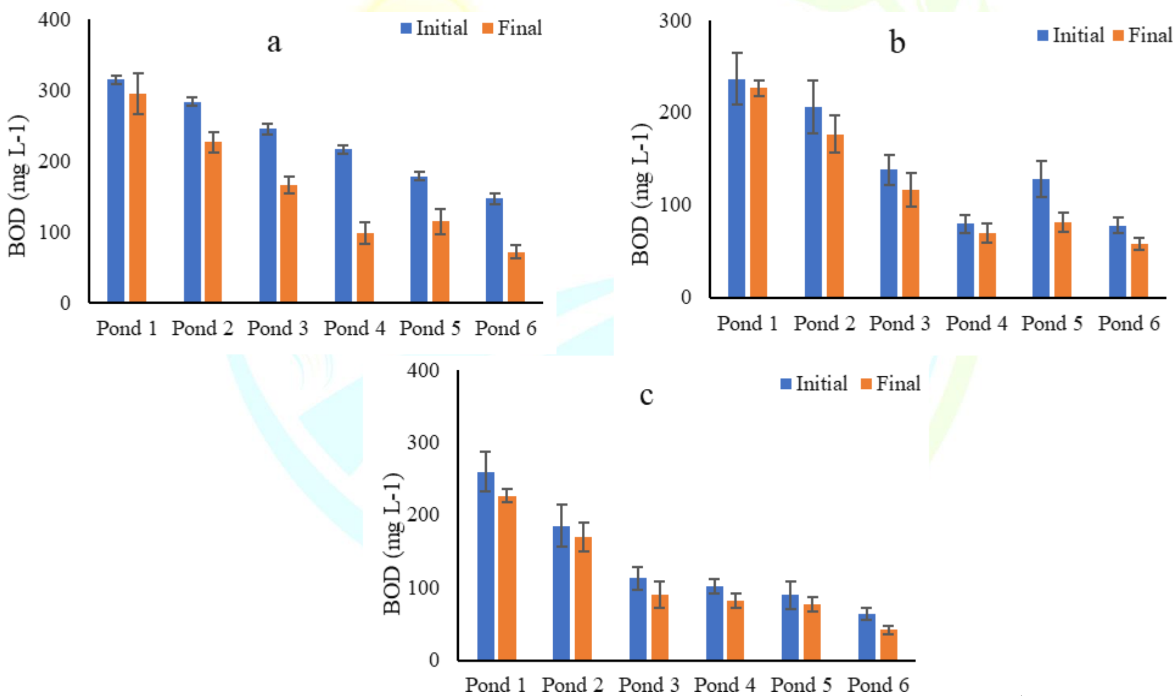


**Figure 7. Removal Efficiency of wetland on BOD of wastewater a) after 1st week, b) after 2nd week and c) after 3rd week**

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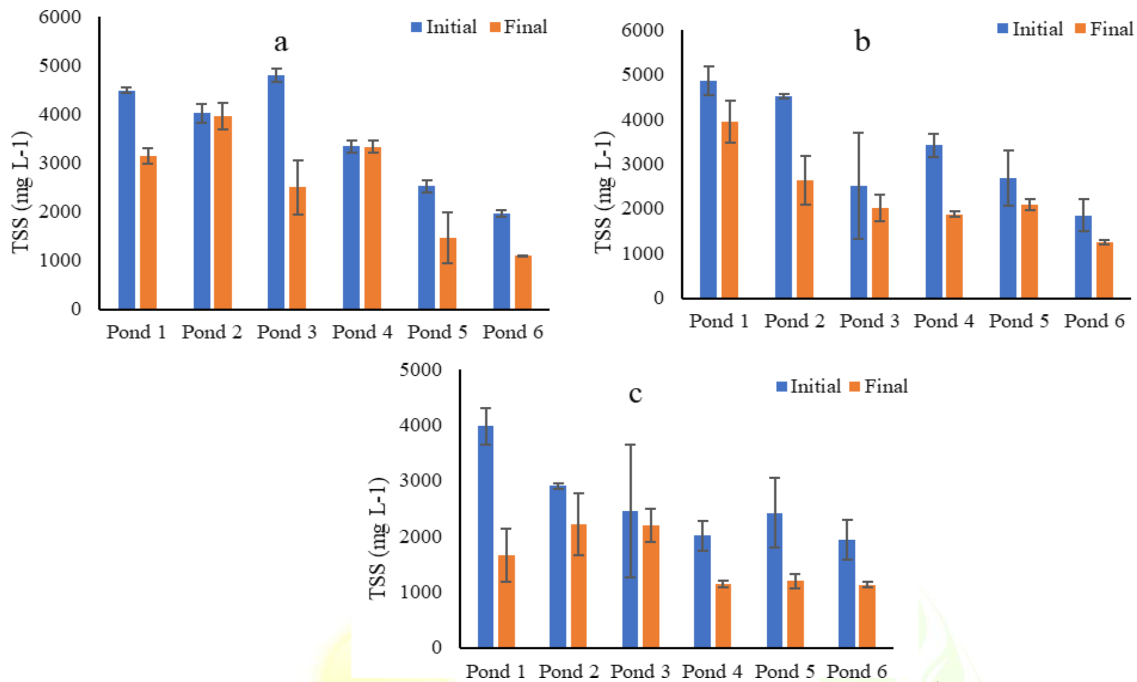


Figure 8. Removal Efficiency of wetland on TSS of wastewater a) after 1st week, b) after 2nd week and c) after 3rd week

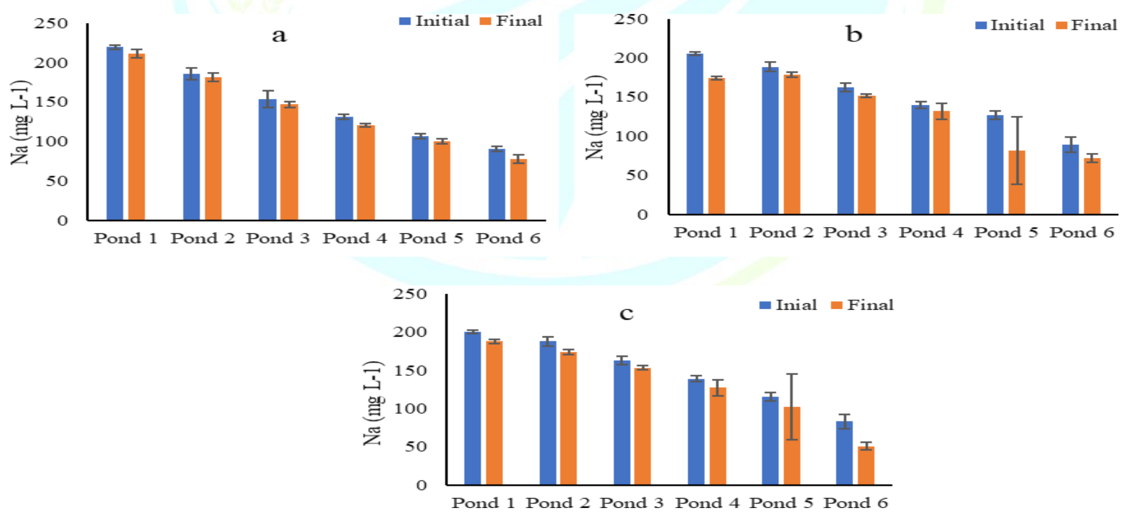


**Figure 9. Removal Efficiency of wetland on Na of wastewater a) after 1st week, b) after 2nd week and c) after 3rd week**

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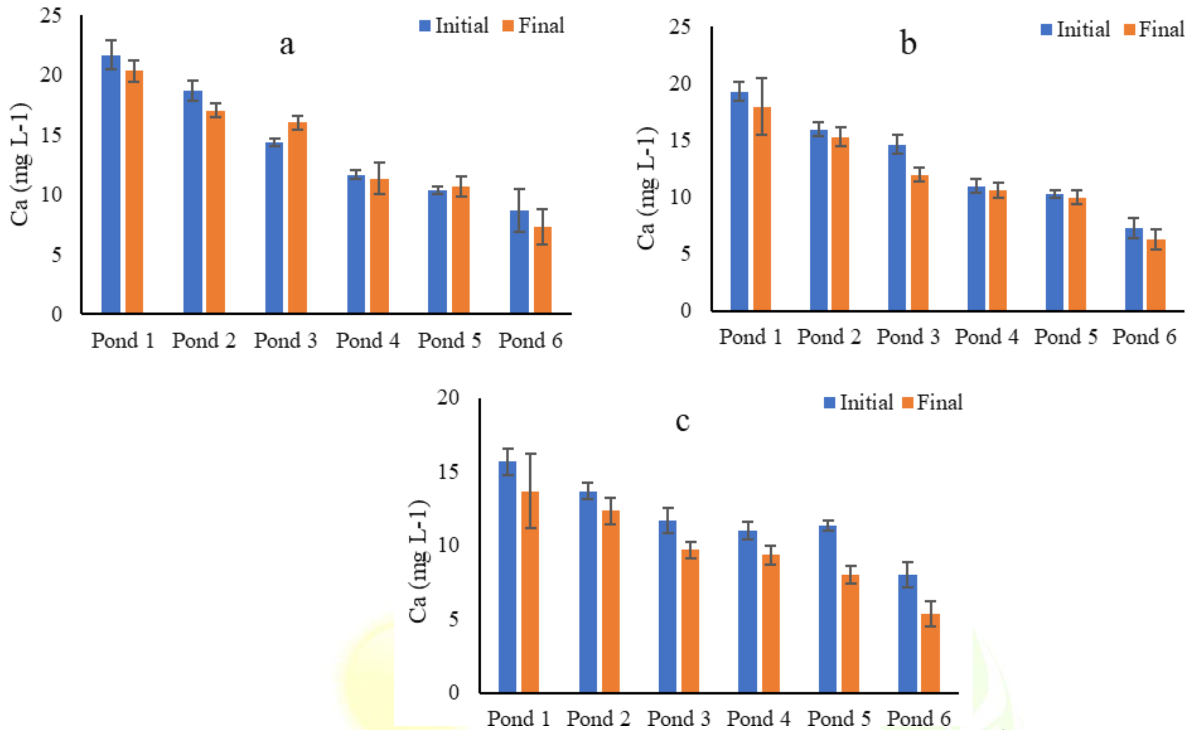


**Figure 10.** Removal Efficiency of wetland on Ca of wastewater a) after 1st week, b) after 2nd week and c) after 3rd week

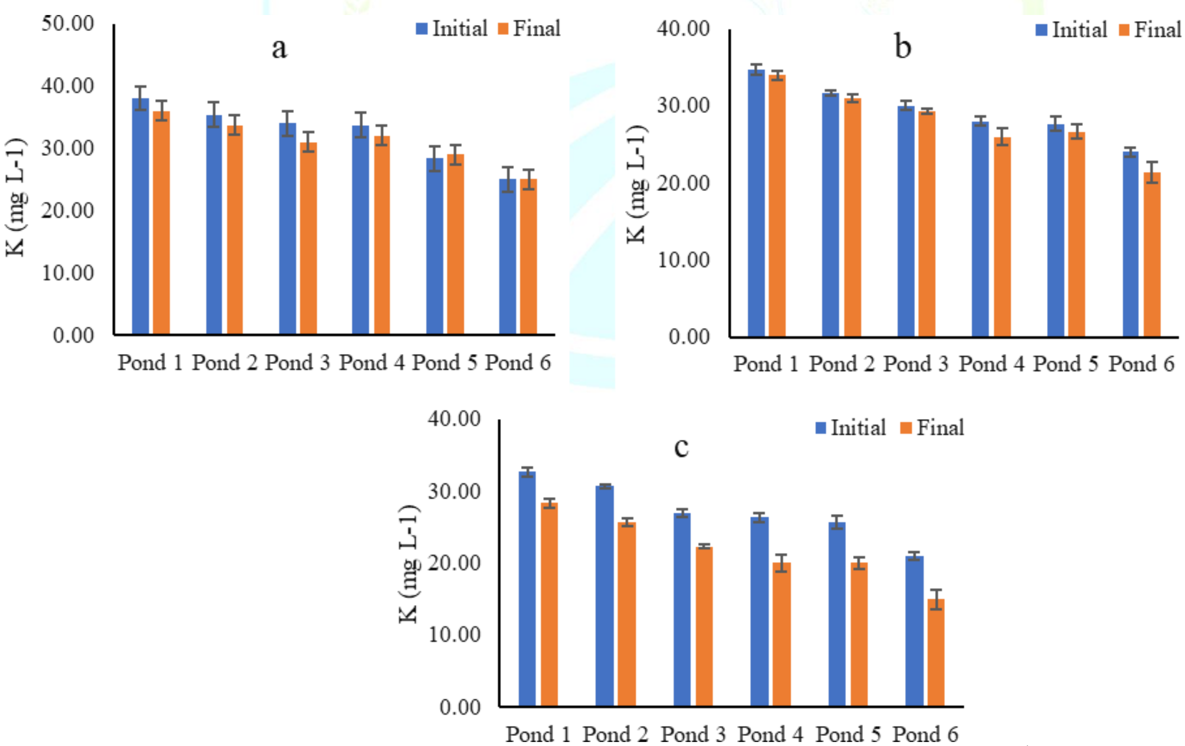


**Figure 11.** Removal Efficiency of wetland on K of wastewater a) after 1st week, b) after 2nd week and c) after 3rd week

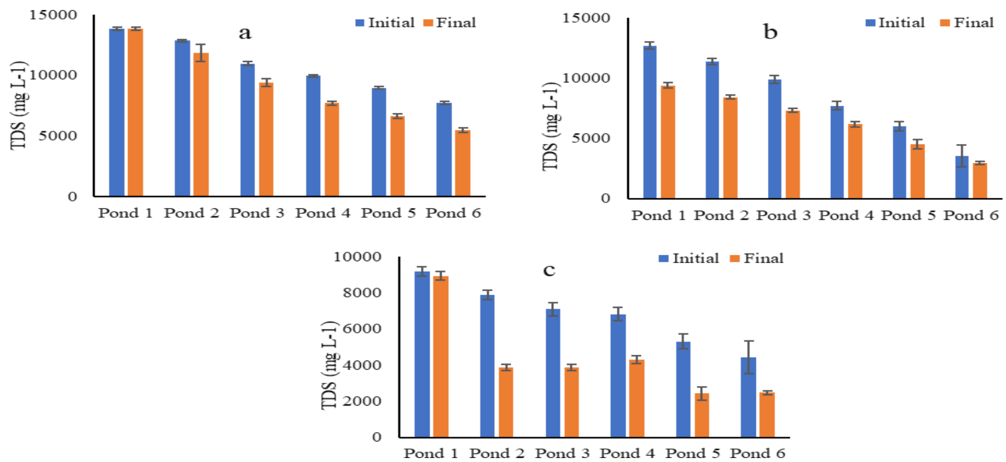


**Figure 12. Removal Efficiency of wetland on TDS of wastewater a) after 1st week, b) after 2nd week and c) after 3rd week**

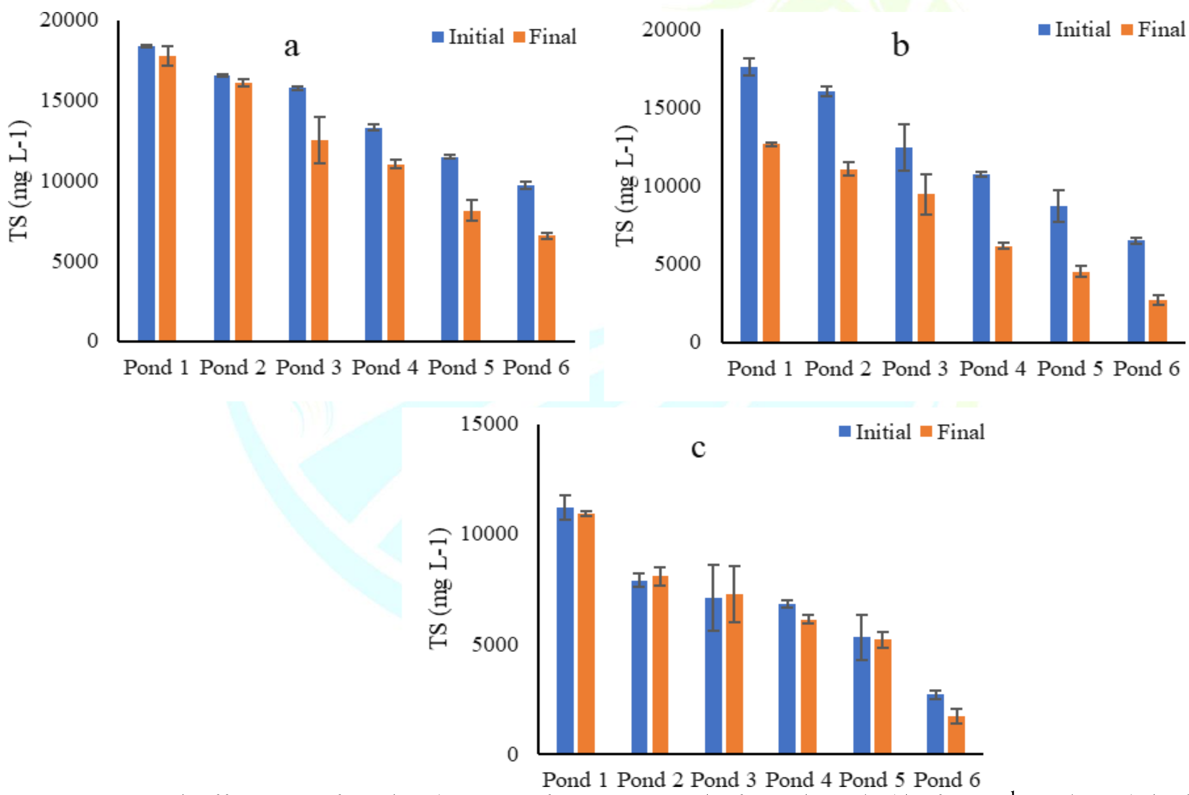


**Figure 13. Removal Efficiency of wetland on TS of wastewater a) after 1st week, b) after 2nd week and c) after 3rd week**

**Principal component analysis of water quality parameters**

Principal component analysis revealed (Figure 13) substantial variance explanation of 86.4% across the first two dimensions (PC1:78.1%, PC2: 8.3%). The first principal component delineates a pronounced salinity gradient, characterized by strong positive loadings of electrical conductivity (EC), total dissolved solids (TDS), total solids (TS), Sodium ($Na^+$), and magnesium ($Mg^+$). Spatial ordination of sampling sites revealed distinct hydro chemical differentiation, with Pond 6 exhibiting elevated salinity parameters along the positive PC1 axis, 1 demonstrated association with elevated pH and reduced mineralization along the negative PC1 axis. The second principal component accounted for secondary variance through loadings associated with organic pollution indicators (COD and BOD) and particulate dynamics (total suspended solids).

**Treatment systems performance and implications**

The constructed wetland system demonstrated effective wastewater treatment across all monitored parameters, with pond-6 consistently showing optimal performance. The system achieved high removal efficiencies for organic matter (BOD: 77-84%), suspended solids (TSS: 71-75%), and dissolved constituents (TDS: 74-75%). The removal efficiencies for carbonates (65-82%) and bicarbonates (55- 66%) demonstrated effectiveness in treating inorganic constituents. However, the variable pH adjustment (9-16%) and declining COD removal (28% to 4%) were observed. Progressive improvement was observed in several parameters, while slight decreases in TSS and COD removal efficiency over time.

**Discussion**

The constructed wetland demonstrated variable pH adjustment efficiency throughout the treatment period. The moderate pH reduction during the initial week can be attributed to the establishment phase of microbial communities within the wetland systems. The improved performance in the second week (16% reduction) indicates the stabilization of biological processes, while the slight decline in the third week suggests the need for system optimization or maintenance. These findings align with Chen et al. (2024), who reported stable pH conditions in a constructed wetland due to the buffering capacity provided by periodic microbial activity. Recent research has emphasized the critical role of pH management in constructed wetlands, particularly regarding its impact on organic matter removal (Rani *et al.*, 2024). The fluctuations in pH removal efficiency likely result from the intermittent influent loading and the dynamic nature of biogeochemical processes within the wetland ecosystem. pH values below 6 are generally unfavorable for wetland performances as they inhibit nitrification processes and promote ammonium formation, potentially compromising treatment efficiency.

The reduction in EC values can be attributed to the uptake of soluble ions by aquatic vegetation and adsorption processes within the wetland substrate. These results are consistent with Ali, *et al.* (2024), who reported EC reductions of up to 93.30% in constructed wetland systems. The observed EC decrease is also associated with the reduction of total suspended solids in the effluent, indicating a comprehensive pollutant removal mechanism operating within the system. Contemporary studies demonstrate that small-scale constructed wetlands achieve consistent removal efficiencies across multiple pollutant types, with organic matter and nutrient removal reaching 68.8-84.0% in global assessments (Chen *et al.*, 2024).

The temporal trend in carbonate removal efficiency indicates the maturation of treatment processes within the wetland system. The enhanced removal efficiency over time can be attributed to the establishment of stable biogeochemical conditions and increased plant biomass, which facilitate greater ion uptake and precipitation processes. The initial lower removal efficiency during the first week reflects the adaptation period required for optimal wetland functioning. The results support the findings of Chen et al. (2024), who noted the importance of stable salt concentrations for maintaining consistent carbonate removal in the wetland system. The periodic nature of treatment efficiency corresponds to the intermittent influent loading pattern and the subsequent biological responses within the ecosystem.

This upward trend in bicarbonate removal efficiency indicates the gradual optimization of treatment processes and the establishment of mature biogeochemical conditions within the wetland. The improved performance over time can be attributed to enhanced plant root development, increased microbial activity, and stabilized substrate conditions. The results corroborate the findings of Chen et al. (2024), who emphasized the role of periodic biological activity in maintaining stable bicarbonate levels in constructed wetlands. The observed removal efficiency suggests effective operation of multiple treatment mechanisms, including biological uptake, chemical precipitation, and adsorption processes.

The substantial decrease in removal efficiency from week 1 to week 2 requires further investigation and may indicate system operational challenges or changes in influent characteristics.

The initial higher removal efficiency (28%) suggests effective organic matter degradation during the establishment phase, potentially due to readily available dissolved oxygen and active microbial populations.

Journal of Environmental Sciences and Sustainability
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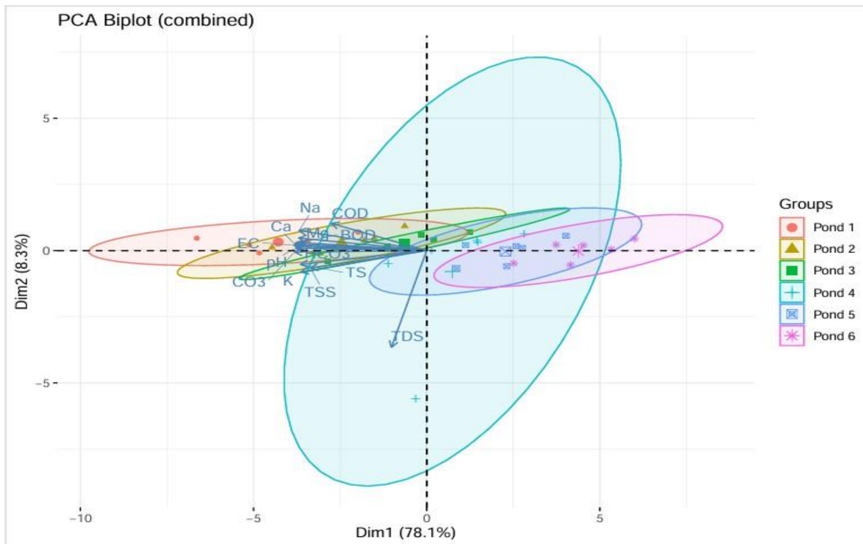


**Figure 14. Principal component analysis of water quality parameters**

The significant decline in week 2's performance may result from oxygen depletion, changes in microbial community structure, or substrate saturation. These findings partially align with Chen et al. (2024), who noted the importance of stable microbial communities for consistent COD removal in wetland systems. Recent research by Ali et al. (2024) demonstrated that constructed wetlands can achieve substantial organic matter removal with 82% BOD and 81% COD reduction over extended hydraulic retention times, suggesting that longer retention periods may improve our observed COD removal efficiency.

The high dissolved oxygen level at the wetland inlet promotes aerobic decomposition of organic matter. The microbial community within the wetland plays a crucial role in organic matter decomposition, with activity patterns correlating with the periodic influent loading cycles. These findings align with Cheng et al. (2010), who reported stable BOD performance in constructed wetlands due to the periodic activity of microbial communities. The periodic nature of microbial activity corresponds to intermittent influent flow patterns, which are characteristic of constructed wetland systems. According to Bianchi *et al.* (2011), BOD values below 6 mg/L in wetland effluent are considered favorable for environmental discharge,

indicating the system's effectiveness in organic pollution control. Current research indicates that constructed wetlands with vegetation obtain approximately 22.22% more dissolved oxygen than unvegetated systems, enhancing aerobic treatment processes (Yang *et al.*, 2024).

The effective TSS removal mechanisms include physical filtration through plant root systems, sedimentation due to reduced flow velocity, and bio-flocculation processes. The increased retention time within the wetland system enhances particle settling and root zone filtration. Plant root adhesion and sedimentation processes are the primary mechanisms for TSS removal, as supported by the findings of Dai et al. (2025). The authors emphasized that wetland stability depends on periodic microbial activity, which correlates with influent loading patterns. The slight decrease in TSS removal efficiency over time may be attributed to the accumulation of settled particles, which could reduce the effective filtration capacity of the systems. Recent comparative studies show that effective TDS and TSS removal can be achieved with hydraulic retention times as short as 7 days in optimized constructed wetland systems (Ali et al. (2024).

Plant uptake represents the primary mechanism for sodium, calcium, and potassium removal, with uptake rates

varying according to plant physiological cycles and influent loading patterns. The periodic nature of plant uptake activity correlates with the intermittent influent flow into the wetland system. According to Ali *et al.* (2024), sodium concentration below 6 mg/L in wetland effluent is considered favorable for environmental discharges and potential reuse applications. The consistent removal efficiency observed suggests that wetland vegetation effectively assimilates sodium through normal metabolic processes.

The progressive improvement in potassium removal efficiency suggests adaptation of the plant community to the wastewater environment and enhanced nutrient uptake capacity over time. Chen et al. (2024) reported similar findings, attributing stable potassium levels to periodic microbial community activity and plant uptake processes. Contemporary research emphasizes the importance of substrate selection, with building debris and biochar emerging as commonly used materials in constructed wetlands for enhanced nutrient removal.

The stables' TDS removal efficiency indicates effective dissolved solids management through combined physical, chemical, and biological processes. Chen et al. (2024) attributed stable TDS performance to periodic microbial community activity, which corresponds to influent loading cycles in constructed wetland systems. The substantial improvement in TS removal Efficiency over time indicates system maturation and enhanced treatment capacity. Plant root adhesion and sedimentation processes contribute significantly to total solids removal, with retention time playing an important role in treatment efficiency (Huang et al., 2019). Recent innovations in constructed wetland design focus on addressing physical clogging issues through strategic modifications such as vertical baffles to maintain hydraulic efficiency (Ali et al., 2024).

The PCA results demonstrate robust dimensionality reduction for the multivariate water quality dataset, which is consistent with established hydro chemical theory where in EC exhibits strong correlation with dissolved ionic constituents (Hammoumi et al., 2024; Gautam et al., 2024). The spatial differentiation indicates enhanced mineralization potentially attributable to anthropogenic inputs or evaporative processes in pond 6, whereas pond 1 represents comparatively pristine conditions. This ordination pattern corroborates established paradigms of aquatic system classification based on hydro chemical composition (Chen et al., 2024), thereby providing a quantitative framework for environmental assessment where in Pond 6 represents a priority management concern due to salinity-induced stress, while Pond 1 constitutes a reference condition for potential restoration targets among
the intermediate-status Ponds (Ponds 2-5) (Hashmi *et al*., 2009).

The constructed wetland systems employed multiple synergistic treatment mechanisms, including physical filtration, biological uptake by aquatic plants, microbial degradation, adsorption onto substrate materials, and chemical precipitation processes. The superior performance of pond-6 across multiple parameters suggests optimal hydraulic and biological conditions in this treatment unit. These findings contribute to the understanding of constructed performance and provide valuable insights for designing optimization and operational management of similar treatment systems.

Contemporary research confirms that constructed wetlands consistently achieve substantial removal rates for total suspended solids, biochemical oxygen demand, chemical oxygen demand, emerging contaminants, and antimicrobial-resistant bacteria, supporting the viability of this technology for comprehensive wastewater treatment (Chen et al., 2024). Recent trends indicate growing global attention to constructed wetlands as green, efficient, and energy-saving wastewater treatment technologies, emphasizing their potential for sustainable water management solutions (Ali et al., 2024).

## Conclusions

The constructed wetland system demonstrated variable but generally promising treatment performance for the parameters studied. The most effective treatments were observed for carbonate removal (up to 82%), followed by bicarbonate removal (up to 66%). The system showed potential for pH adjustment and EC reduction, though with moderate efficiency. The declining COD removal efficiency requires attention and system optimization. These findings suggest that constructed wetlands can serve as effective treatment systems for specific wastewater constituents but require careful design and operation management for optimal performance.

## Funding

The funding was provided by HEC under HEC Award letter NO. 21-2327/SRGP/R&D/HEC/2018.

**Acknowledgment**
The authors want to acknowledge the Department of Soil and Environmental Sciences, MNS-University of Agriculture, Multan. We also acknowledge Maxim Agri Pvt., Multan, for supporting this study.

**SDGs Addressed**
This study contributes to SDGs 3, 6, 9, 11, 12, 13, and
15 by showing that constructed wetlands can effectively reduce pollutants (e.g., BOD 84.23%, COD 39%, TDS 75%), improve wastewater reuse, support sustainable urban management, lower health risks, and enhance environmental resilience in water-stressed regions of Pakistan.

**Conflict of interest**
The authors declare no conflict of interest.

## REFERENCES

Addo-Bankas, O., Zhao, Y., Wei, T., & Stefanakis, A. (2024). From past to present: Tracing the evolution of treatment wetlands and prospects ahead. In *Journal of Water Process Engineering* (Vol. 60). https://doi.org/10.1016/j.jwpe.2024.105151.

Afsar, E., Nejaei, A., & Mosaferi, M. (2025). Experimental and numerical study of efficient sulfate reduction and heavy metal elimination from real acid mine drainage. *Chemical Engineering Communications*, *212*(8), 1198–1212.
https://doi.org/10.1080/00986445.2025.2450701.

Ahmad, S., Jia, H., Ashraf, A., Yin, D., Chen, Z., Xu, C., Chenyang, W., Jia, Q., Xiaoyue, Z., Israr, M., & Ahmed, R. (2023). Water resources and their management in Pakistan: A critical analysis on challenges and implications. In *Water-Energy Nexus* (Vol. 6). https://doi.org/10.1016/j.wen.2023.10.001.

Barath, A., Selvakumar, S., Ravikumar, V., Sivakumar, U., & Boomiraj, K. (2025). Integrating traditional and emerging technologies for enhanced water quality monitoring and sustainable resource management. *PlantScienceToday*. https://doi.org/10.14719/pst.9412.

Bianchi, V., Peruzzi, E., Masciandaro, G., Ceccanti, B., Ravelo, S. M., & Iannelli, R. (2011). Efficiency assessment of a reed bed pilot plant (Phragmites australis) for sludge stabilisation in Tuscany (Italy). *Ecological Engineering*, *37*(5). https://doi.org/10.1016/j.ecoleng.2010.05.008.

Biswas, A., Sarkar, S., Das, S., Dutta, S., Roy Choudhury, M., Giri, A., Bera, B., Bag, K., Mukherjee, B., Banerjee, K., and Paul, D. (2025). Water scarcity: A
global hindrance to sustainable development and agricultural production – A critical review of the impacts and adaptation strategies. *Cambridge Prisms: Water*, *3*, e4. doi:10.1017/wat.2024.16.

Cai, C., Shang, Z., Guo, Y., Huang, X., Peng, K., Guo, R., & Liu, J. (2025). *Resilience and Stability of Wastewater Treatment Plant under Stochastic Influent: A Novel Pollutant-Carbon Synergy Framework*. https://doi.org/10.21203/rs.3.rs-5854184/v1.

Chen, G., Mo, Y., Gu, X., Jeppesen, E., Xie, T., Ning, Z.,
Li, Y., Li, D., Chen, C., Cui, B., & Wu, H. (2024).
Sustainability of global small-scale constructed wetlands for multiple pollutant control. *Npj Clean Water*, 7(1). https://doi.org/10.1038/s41545-024-
00336-3.

Dai, S., Wang, R., Lin, J., Zhang, G., Chen, Z., Li, L., & Shi, Q. (2025). Study on physical clogging process and practical application of horizontal subsurface flow constructed wetland. *Scientific Reports*, *15*(1). https://doi.org/10.1038/s41598-024-84159-9.

Domínguez-Solís, D., Martínez-Rodríguez, M. C., Ramírez-Escamilla, H. G., Campos-Villegas, L. E., & Domínguez-Solís, R. (2025). Constructed Wetlands as a Decentralized Treatment Option for Domestic Wastewater: A Systematic Review (2015–2024). In *Water (Switzerland)* (Vol. 17, Issue 10). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/w17101451.

Gautam, V. K., Kothari, M., Al-Ramadan, B., Singh, P. K., Upadhyay, H., Pande, C. B., Alshehri, F., & Yaseen, Z.

M. (2024). Groundwater quality characterization using an integrated water quality index and multivariate statistical techniques. *PLoS ONE*, *19*(2 February). https://doi.org/10.1371/journal.pone.0294533.

Hammoumi, D., Al-Aizari, H. S., Alaraidh, I. A., Okla, M. K., Assal, M. E., Al-Aizari, A. R., Moshab, M. S., Chakiri, S., & Bejjaji, Z. (2024). Seasonal Variations and Assessment of Surface Water Quality Using Water Quality Index (WQI) and Principal Component Analysis (PCA): A Case Study. *Sustainability (Switzerland)*, *16*(13). https://doi.org/10.3390/su16135644.

Hashmi, I., Farooq, S., & Qaiser, S. (2009). Chlorination and water quality monitoring within a public drinking water supply in Rawalpindi Cantt (Westridge and Tench) area, Pakistan. *Environmental Monitoring and Assessment*, *158*(1–4). https://doi.org/10.1007/s10661- 008-0592-z.

Huang, X. feng, Ye, G. yu, Yi, N. kang, Lu, L. jun, Zhang, L., Yang, L. yan, Xiao, L., & Liu, J. (2019). Effect of plant physiological characteristics on the removal of conventional and emerging pollutants from aquaculture

wastewater by constructed wetlands. *Ecological Engineering*, *135*. https://doi.org/10.1016/j.ecoleng.2019.05.017.

Ingrao, C., Strippoli, R., Lagioia, G., & Huisingh, D. (2023). Water scarcity in agriculture: An overview of causes, impacts and approaches for reducing the risks. In *Heliyon* (Vol. 9, Issue 8). https://doi.org/10.1016/j.heliyon 2023.e18507.

Lacalamita, D., Mongioví, C., & Crini, G. (2024). Chemical oxygen demand and biochemical oxygen demand analysis of discharge waters from laundry industry: monitoring, temporal variability, and biodegradability. *Frontiers in Environmental Science*, *12*. https://doi.org/10.3389/fenvs.2024.1387041.

Lu, N., Zhu, J., Tang, Z., Zhang, J., & Chi, H. (2022).

Decreasing water dependency for economic growth in water-scarce regions by focusing on water footprint and physical water: A case study of Xi'an, China. *Sustainable Cities and Society*, *85*. https://doi.org/10.1016/j.scs.2022.104092.

Ndeketeya, A., & Dundu, M. (2022). Alternative water sources as a pragmatic approach to improving water security. *Resources, Conservation and Recycling Advances*, *13*. https://doi.org/10.1016/j.rcradv.2022.200071.

Omohwovo E. J. (2024). Wastewater Management in Africa: Challenges and Recommendations. *Environmental Health Insights*.;18. doi:10.1177/11786302241289681.

Onu, M. A., Ayeleru, O. O., Oboirien, B., & Olubambi, P.

A. (2023). Challenges of wastewater generation and management in sub-Saharan Africa: A Review. *Environmental Challenges*, *11*, 100686.

Rani, A., Chauhan, M., Kumar Sharma, P., Kumari, M., Mitra, D., & Joshi, S. (2024). Microbiological dimensions and functions in constructed wetlands: A review. In *Current Research in Microbial Sciences* (Vol. 7). Elsevier

Scheierling, S. M., Bartone, C. R., Mara, D. D., & Drechsel,

P. (2011). Towards an agenda for improving wastewater use in agriculture. *Water International*, *36*(4). https://doi.org/10.1080/02508060.2011.594527.

United Nations. (2025). *The United Nations World Water Development Report 2025 – Mountains and glaciers: Water towers*. https://doi.org/10.54679/LHPJ5153.

United States Environmental Protection Agency (USEPA). (1998). Guidelines for Ecological Risk Assessment. *EPA/630/R-95/002F*, *63*(April).

Waly, M. M., Ahmed, T., Abunada, Z., Mickovski, S. B., & Thomson, C. (2022). Constructed Wetland for Sustainable and Low-Cost Wastewater Treatment: Review Article. In *Land* (Vol. 11, Issue 9). https://doi.org/10.3390/land11091388.

Waqas, S., Harun, N. Y., Sambudi, N. S., Abioye, K. J., Zeeshan, M. H., Ali, A., Abdulrahman, A., Alkhattabi, L., & Alsaadi, A. S. (2023). Effect of Operating Parameters on the Performance of Integrated Fixed-Film Activated Sludge for Wastewater Treatment. In *Membranes* (Vol. 13, Issue 8). https://doi.org/10.3390/membranes1308070.

Yang, L., Jin, X., Hu, Y., Zhang, M., Wang, H., Jia, Q., & Yang, Y. (2024). Technical structure and influencing factors of nitrogen and phosphorus removal in constructed wetlands. *Water Science and Technology*,*89*(2),271–289. https://doi.org/10.2166/wst.2023.414.