Wastewater Treatment Using Constructed Wetland and Sustainable Climate Change Mitigation

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Introduction/Importance of Study: Addressing wastewater treatment and sanitation challenges is particularly crucial in rural areas experiencing environmental stress. As interest in recycling wastewater grows and water scarcity becomes more pressing, constructed wetlands emerge as a cost-effective solution, especially in arid regions.

Novelty Statement: This study examines a constructed wetland at Mehran UET that effectively treats wastewater while promoting sustainable water reuse. By reusing water and functioning as a carbon sink, this approach addresses water scarcity and helps mitigate climate change effects.

Material and Methods: Water samples were collected from selected locations within the constructed wetland, chosen for their effectiveness in contaminant removal. Key wastewater parameters—total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD), and biological oxygen demand (BOD)—were measured for these samples.

Results and Discussion: The removal of total suspended solids was observed to decrease from an average of 31 mg/l in the influent to 21 mg/l in the effluent. BOD and COD concentrations decreased from 137 mg/l to 99 mg/l and from 212 mg/l to 131 mg/l, respectively. Nitrogen concentrations in the influent were 20 mg/l, with removal to 11 mg/l in the effluent. Phosphorus removal was observed to reduce from 23 mg/l to 12 mg/l.

Concluding Remarks: Constructed wetlands enhance community resilience to climate change by offering decentralized, flexible water management solutions tailored to local conditions and climate scenarios. They diversify water sources and reduce dependence on traditional supplies.

Keywords: Wastewater treatment, Constructed wetland, Climate change mitigation

Introduction:

Water scarcity results from climate conditions such as severe droughts, rising temperatures, and increased pressure on both available water supplies and demand [1]. The primary drivers of the intense strain on water resources are the growing global population, the expansion of irrigated agriculture, economic development, and climate change [2]. The current supply of clean water is increasingly insufficient to meet the rising consumer demand [3]. However, treated wastewater presents a viable alternative resource for various uses. Beyond conventional wastewater treatment methods, nature-based solutions (NBSs) offer environmentally friendly alternatives. One effective NBS is engineered ecological systems, or constructed wetlands (CWs), which treat wastewater through natural processes involving aquatic plants, soils, and microorganisms [2]. Constructed wetlands are favored over traditional systems due to their numerous advantages, especially for small communities. These benefits include reduced construction and operational costs, ease of use, and high efficiency in pollutant removal [4]. The effluents from CWs can be repurposed for public and industrial uses such as irrigation, gardening, toilet flushing, and groundwater replenishment [2]. Constructed wetlands have also been successfully employed to treat wastewater, stormwater, and landfill leachate [5].

Carbon Sequestration in Constructed Wetlands:

Constructed wetlands utilize a combination of plant and microbial activity within their physical and chemical environments to treat wastewater. A notable process within these systems is carbon sequestration, where wetlands absorb carbon dioxide (CO2) from the atmosphere and convert it into organic carbon stored in the soil, mudflats, or plant biomass. This process is facilitated by the wetland's high-water levels, anaerobic conditions, and slow decomposition of organic matter [6].

Study Initiative and Objectives:

An initiative has been undertaken to construct a small-scale wetland designed to treat municipal wastewater at the Center for Advanced Studies in Water, MUET. This wetland aims to promote sustainable water management by recycling water for various activities, particularly for gardening and planting within the facility. The study seeks to evaluate the performance of the wetland in pollutant removal, assess the significance of treated water reuse, and highlight the role of CWs in climate change mitigation.

Objectives:

The main objectives of this study are:

- To analyze the physicochemical properties of wastewater before and after treatment.
- To assess the treatment efficiency of constructed wetlands.

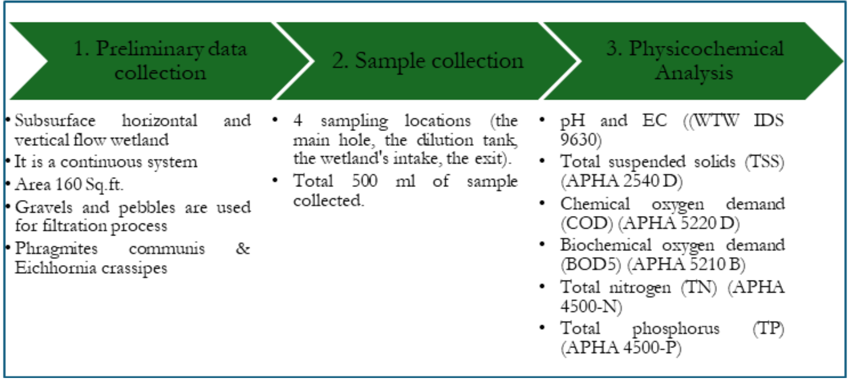
Materials and Methods:

Sample Collection and Water Quality Analysis:

The wetland in question is a subsurface horizontal and vertical flow system with an area of 160 square feet, designed to operate continuously. Sampling was conducted at four locations: the main hole, the dilution tank, the wetland's intake, and the exit. Each compartment is filled with gravels and pebbles to enhance natural filtration. The plants used for nutrient removal are *Phragmites communis* and *Eichhornia crassipes*, commonly known as common reed and water hyacinth, respectively. These plants are fixed and submerged in the wetland, with roots growing fully submerged in the water. In developing countries, *Eichhornia crassipes* is favored for water treatment due to its low operational cost and effectiveness [7]. Figure 1 illustrates the flow of the methodology.

The sample was collected in a 500 ml plastic bottle that had been pre-washed with distilled water [8]. After collection, the samples were transferred to the laboratory and preserved at 4°C. Three rounds of sampling were conducted. All tests were performed in the laboratory, with pH and electrical conductivity (EC) measured using a multiprobe equipment

(WTW IDS 9630). The total solids in wastewater include both suspended and dissolved solids. Sedimentation is one method for removing settleable solids [9], analyzed following the APHA 2540 D method. The Chemical Oxygen Demand (COD), which indicates the amount of oxygen required to oxidize organic molecules by strong oxidizing agents such as dichromate or permanganate, was determined using the APHA 5220 D method [9]. The Biochemical Oxygen Demand (BOD), reflecting the amount of dissolved oxygen required by aerobic organisms to decompose organic materials in a water sample, was measured in mg/L [9], with the 5-day BOD test conducted using the APHA 5210 B method. Nitrogen in wastewater can exist in both organic and inorganic forms. Key mechanisms for nitrogen removal include ammonification (conversion of organic nitrogen to NH3 by bacteria), nitrification-denitrification processes, plant absorption (utilization of nitrogen mostly as nitrates and NH3 by plants), and ammonium nitrogen volatilization [10]. Total nitrogen (TN) was analyzed using the APHA 4500-N method. Wastewater contains both organic and inorganic phosphorus, with ortho-phosphates (PO_4^{3-}) being the most common type. Phosphorus is typically removed through chemical precipitation, microbial absorption, or plant uptake [10]. The total phosphorus (TP) in the collected samples was analyzed following the APHA 4500-P method. All parameters were examined in accordance with APHA Standards [11].



1. Preliminary data collection

- Subsurface horizontal and vertical flow wetland
- It is a continuous system
- Area 160 Sq.ft.
- Gravels and pebbles are used for filtration process
- Phragmites communis & Eichhornia crassipes

2. Sample collection

- 4 sampling locations (the main hole, the dilution tank, the wetland's intake, the exit).
- Total 500 ml of sample collected.

3. Physicochemical Analysis

- pH and EC ((WTW IDS 9630)
- Total suspended solids (TSS) (APHA 2540 D)
- Chemical oxygen demand (COD) (APHA 5220 D)
- Biochemical oxygen demand (BOD5) (APHA 5210 B)
- Total nitrogen (TN) (APHA 4500-N)
- Total phosphorus (TP) (APHA 4500-P)

Figure 1: Flow diagram of Methodology followed in this study

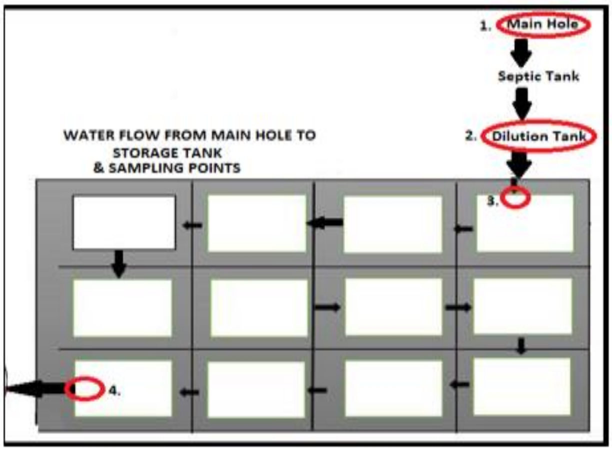


Figure 2: Water flow pattern and sampling points

Composition of Raw Wastewater and Diluted Wastewater:

The primary source of influent water is raw wastewater collected from the main hole (septic tank). In the septic tank, some degradation of organic matter occurs, and suspended and organic materials settle, effectively serving as a pre-treatment stage for the wastewater. This water is then mixed with grey water to create a combined wastewater stream, which helps reduce the pollution load to some extent. The composition of both types of wastewaters is detailed in Table 1.

Table 1: Composition of Raw and Mixed wastewater used in CW

Parameters	Raw Wastewater	Mixed Wastewater
pH	7.1	6.3
EC (µS cm-1)	1338	810
TSS (mg/l)	307	70
COD (mg/l)	504	261
BOD5 (mg/l)	335	174
Total Nitrogen (mg/l)	18.6	18.3
Total Phosphorous (mg/l)	41.4	11.7

Results and Discussion:

pH and Electrical Conductivity:

An important factor affecting the performance of artificial wetlands, particularly in the removal of nitrogen and organic matter, is the pH level of the wastewater [8]. During the assessment period, the pH of the municipal wastewater influent ranged from 6.3 to 6.8, with an average of 6.5 ± 0.3. Samples were analyzed every 7 days, and the average pH of the effluent was 6.5 ± 0.2. The electrical conductivity (EC) values in the influent samples ranged from 142 to 1153 µS cm^{-1}, with an average of 876 µS cm^{-1}. In the effluent, the EC values decreased, averaging 773 µS cm^{-1}. Throughout the treatment process, all constructed wetland (CW) systems effectively removed dissolved particles, resulting in lower EC values in the final outputs [12].

Total Suspended Solids (TSS):

Suspended particles are removed from constructed wetlands (CWs) through sedimentation on the CW bed surface, where low TSS concentrations at the outlets are achieved due to the filtration of solid particles by the gravels. Research indicates that retention time influences TSS removal, which is primarily a physical process [12]. The TSS concentration in the influent ranged from 29 to 49 mg/l, with an average of 30 mg/l. Conversely, TSS values at the system outlet ranged from 17 to 41 mg/l, with an average of 21 mg/l, as illustrated in Figure 2.

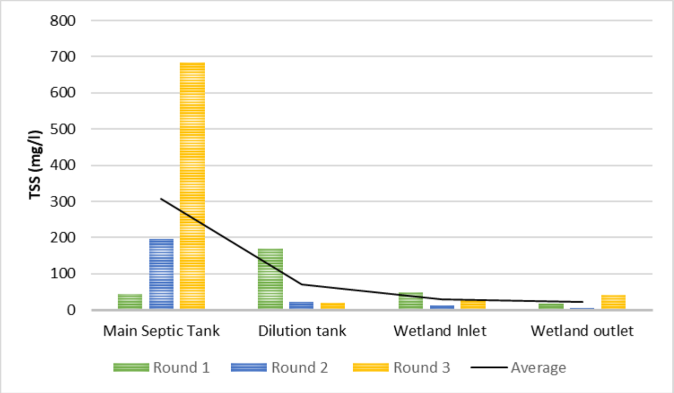


Figure 3: TSS Concertation at various points during the treatment.

COD and BOD_5:

In a constructed wetland, vegetation plays a crucial role in reducing Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand over 5 days (BOD_5). The heat generated by bacterial activity within the filter layer of the wetland mitigates the impact of air temperature on purification processes [8]. This increased temperature promotes higher organic matter breakdown due to elevated dissolved oxygen (DO) levels. Plants contribute significantly to the decomposition of organic compounds through their growing biomass, which fosters microbial development within the roots. This microbial growth encourages biofilm formation and enhances the breakdown of organic matter, thereby reducing the wastewater's organic load [12].

Figure 3 illustrates the inlet and outlet concentrations of BOD_5 and COD. The COD output concentration was 131 mg/L, compared to an input concentration of 212 mg/L at the inlet of the constructed wetland, indicating a high reduction efficiency. Similarly, BOD_5 removal followed a comparable trend [13]. Figure 4 shows an input concentration of 137 mg/L, with output concentrations reduced to 99 mg/L, as depicted in Figure 5. Effective removal of BOD_5 in constructed wetlands requires optimal aerobic conditions, suitable filter materials for microorganism growth, filtration of suspended organics, and sufficient contact time between the wastewater and wetland substrate [12], as illustrated in Figure 6. The system demonstrates effective organic matter removal. Figure 7 shows the reduction in Total Nitrogen (TN) and Total Phosphorus (TP) concentrations.

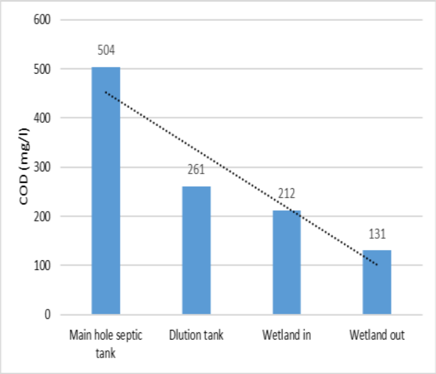


Figure 4: COD Concentrations in Influent and Effluent.

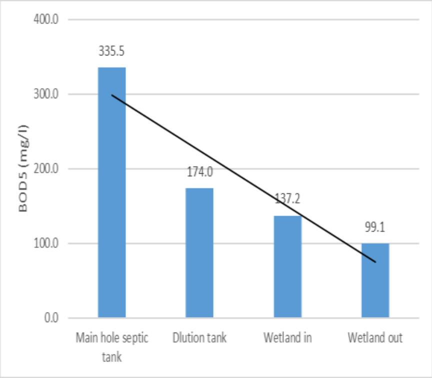


Figure 5: BOD Concentrations in Influent and Effluent.

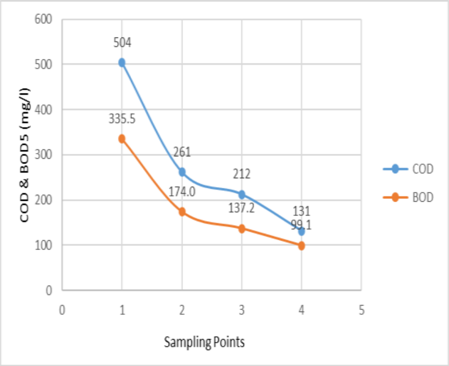


Figure 6: COD & BOD5 Reducing in Same Pattern.

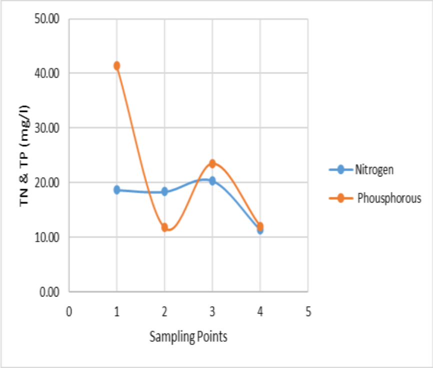


Figure 7: TN & TP Reducing Concentrations.

Nitrogen and Phosphorous Removal:

pH levels significantly affect both the chemistry and biology of wetland water. For instance, denitrification processes slow down at a pH of 5 and are minimal at pH values below 4. Denitrifying bacteria, however, thrive within a pH range of 6.5 to 7.5 [8]. Total phosphorus (TP) removal occurs through mechanisms such as plant absorption, precipitation, and adsorption onto porous media [12]. In this study, the average TP concentration in the influent of the constructed wetland was 23 mg/L, which decreased to 12 mg/L at the final outlet. A similar trend was observed for total nitrogen removal, with concentrations reducing from 20 mg/L in the influent to 11 mg/L in the effluent.

Pollutant Removal Rate (Efficiency):

To assess overall performance, the pollutant removal rate for each organic pollutant, nutrient, and suspended solid was calculated using the following formula:

$$\text{Removal rate } (\%) = (Ci-Co)*100/Ci \ [12]$$

Where Ci and Co represent the concentrations of contaminants in the inflow and outflow, respectively [14].

Table 2: Pollutant removal rate in CW

	BOD5	COD	TSS	TN	TP
Wetland Inlet and outlet	27%	38 %	43 %	45%	47%
Raw water to recycled water	38 %	62 %	43 %	79 %	96%

Table 2 defines the removal rates in two ways: first, by evaluating the performance of the wetland from inlet to outlet, which indicates the treatment efficiency of the system. Figure 2 illustrates that mixing raw water with grey water in the dilution tank reduces the load on the system. By comparing raw water concentrations to outlet concentrations, it is evident that the system demonstrates higher efficiency in removing total phosphorus (TP), total nitrogen (TN), BOD, and COD.

Constructed Wetland as a Sustainable Climate Change Mitigation:

Wetlands are among the most significant ecosystems for carbon sequestration (CS) in response to climate change. However, human activities are diminishing their CS capacity, and projections suggest that global population growth and climate change will further reduce this capacity. The literature highlights several strategies for enhancing CS in wetlands, enabling these ecosystems to continue playing a crucial role in maintaining the global carbon balance and mitigating climate change [15].

Conclusion:

The present study concludes that the continuously operated system for treating municipal wastewater demonstrates effective pollutant removal efficiency. This results in reduced concentrations of pollutants: TSS (31-21 mg/L), BOD (137-99 mg/L), COD (212-131 mg/L), TN (20-11 mg/L), and TP (23-12 mg/L). The plant species, along with the gravels and pebbles used in the system design, contribute significantly to reducing these concentrations. The system is particularly effective in lowering nutrient concentrations such as TP and TN, with reductions of 96% and 79%, respectively, due to nutrient uptake by plants. The treated water, now classified as recycled water, can be used for various purposes such as gardening, plantation, washing, and other non-potable uses. The main septic tank, used as a pre-treatment stage, effectively reduces the load on the treatment system. Grey water is also added before the main treatment, allowing both wastewater and greywater to be treated simultaneously without increasing the pollution load on the facility. Constructed wetlands (CWs) serve as long-term carbon sinks and emit fewer greenhouse gases (GHGs) compared to traditional wastewater treatment methods. However, without routine harvesting of wetland plants, decomposing organic matter can release carbon, diminishing purification effectiveness and exacerbating the greenhouse effect. Therefore, wetland plant-based solutions are essential for improving water purification, achieving carbon sequestration, and reducing greenhouse gas emissions [16].

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