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Significance of constructed wetlands in combating pollutants from wastewater: A sustainable development perspective

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Abstract:
Water contamination is the greatest hazard to public health. Addressing water scarcity and protecting accessible water sources necessitates the effective treatment of wastewater. This makes the use of sustainable solutions such as constructed wetlands (CWs) essential. CWs leverage natural processes involving wetland vegetation, soils, and microbial communities. This study evaluates the efficiency of a horizontal sub-surface flow CW, established with local plants at Hudiara drain, in removing pollutants such as Biochemical Oxygen Demand (BOD), Turbidity, Nitrates, Phosphates, and pH, across different months. The study reveals that while temperature and precipitation rates influence the CW's efficacy, the linear regression model indicates a strong correlation between phosphorus and BOD levels with precipitation. However, nitrates are sensitive to temperature, and turbidity is influenced by both temperature and precipitation within certain limits. Additional factors impacting CW performance include wastewater characteristics, design flow, and wetland location. When compared with Pakistan Environmental Quality Standards (PEQS), it is concluded that CWs are effective in wastewater treatment. By constructing CWs along the banks of wastewater drains, treated water from the outlet chamber can be collected and redirected, offering a viable solution to water scarcity challenges.

Keywords:
constructed wetland; pollutant's removal; Hudiara drain; sustainable water; treatment of wastewater

1 Introduction

Globally, many countries, due to their geographical location, are experiencing water shortages and are likely to encounter more severe water availability issues in the future. Additionally, the introduction of untreated sewage and industrial wastewater into existing water sources exacerbates pollution. This not only degrades water quality but also adversely impacts irrigation, fish production, and recreational activities [1]. Despite significant efforts and advancements in the past decade, the continual mismanagement of wastewater and excretions remains a critical threat to environmental integrity and public health [2].

Pakistan's annual per capita water accessibility decreased from 5260 cubic meters in 1951 to 1038 cubic meters in 2010. In 2015, this reduction was 900 cubic meters per annum. Additionally, water bodies are being polluted due to the introduction of wastewater. River Ravi is the most polluted river in the country. It collects untreated domestic and industrial wastewater through five outfalls and two natural surface drains that are placed 98 km from Ravi Siphon and Balloki Headwork. Estimates indicate that approximately 4.847.040 m^3/day of wastewater are discharged into the Ravi River daily [3].

Water contamination is one of the greatest health risks in emerging nations. Consequently, it is crucial to clean wastewater from human activities and reuse it to fight water scarcity and protect accessible water sources [3, 4]. The extensive use of traditional treatment systems has raised concerns about their sustainability, particularly for small settlements, owing to their high construction and operating maintenance costs and tremendous energy demand [5]. Implementing the technologies, i.e., sustainable technologies, is important for effectively treating wastewater in the long run. Developing countries are still making efforts to manage macropollutants, whereas urbanised countries are motivated to manage micropollutants. CWs have shown high efficiencies in the removal of organic materials, nutrients, and pathogens [4]. The major feature distinguishing wetlands from other landforms or watercourses is the presence of macrophytes that are adapted to their environment and are unique to hydric soils. Wetlands are special ecosystems that are entirely or occasionally submerged underwater, where oxygen-free processes predominate [6].

The CW technology is a feasible choice because it reduces nutrients and disinfects wastewater. CWs are engineered systems that are created to utilise organic processes in wetland vegetation, soils, and the corresponding microbial communities [7, 8]. It is an economical and energy-efficient technique for treating various forms of wastewater originating from different sources, such as agricultural, domestic, municipal, mine drainage, and stormwater runoff. Treated effluent from CWs can be used in amenities and natural habitats [7]. Water purification, water storage, processing, and recycling of carbon and other micro- and macronutrients, shoreline stability, and support for plants and animals are just a few of the roles performed [9, 10]. The two primary types of constructed wetland systems are surface and subsurface flow. A constructed wetland system uses physical, chemical, biological, and biochemical processes to remove toxins from wastewater [8].

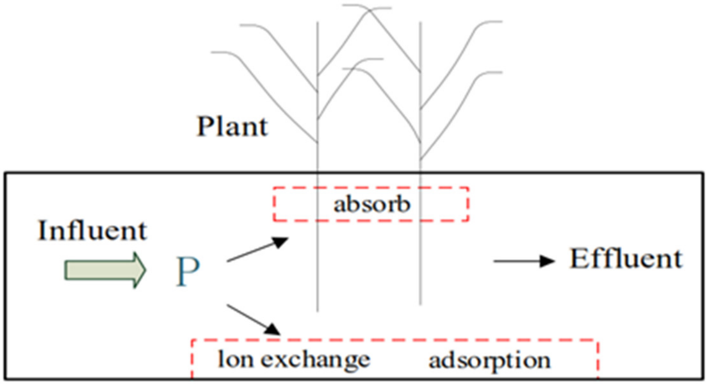

Figure 1. Schematic diagram of CW [11]

The treated wastewater can also be used to irrigate crops, gardens, or golf courses. In both developed and developing worlds, CWs are important active and low-cost substitutes for wastewater treatment [5]. Construction of a wetland downstream of Hudiara drain will receive wastewater from five major pumping stations, situated on the left bank of Ravi, namely NE District Outfall (399 cusecs), Main Outfall (236 cusecs), Gulshan Ravi Outfall (194 cusecs), Multan Road Outfall (123 cusecs), and Hudiara Drain (618 cusecs). The total discharge of wastewater from these five outfalls was 1572 cusecs [3].

Vast investments, intrinsic process complications, and energy extensiveness of conventional wastewater treatment technologies are the main obstacles in treating wastewater. Hence, there is a need to examine alternative low-cost treatment methods [12]. CW systems include a biofilm, emerging macrophytes above the water's surface, and a recreated substrate bed for plants to conduct processes, such as ion exchange and adsorption, as shown in Figure 1. Sand and gravel are widely used as substrates. Algae, fungi, and bacteria cover the substrate and plant stem surfaces of the biofilm [13]. The macrophyte microbial community in wetlands is a source of carbon and organic nitrogen [11]. They also contribute to the development of aerated rhizospheres that support oxidative reactions [13].

The soil media in constructed wetlands, which include soil, sand, gravel, and rocks, play a crucial role in facilitating biological and chemical processes. These components are commonly used in CWs to provide an increased surface area, aiding in the removal of solids and other pollutants [13]. Water within these wetlands is vital for biochemical reactions, serving as a transport medium for organic solids, nutrients, and gases [14]. Additionally, living organisms, particularly bacteria, are instrumental in the wastewater treatment process [14].

In surface flow constructed wetlands, microbial activity predominantly occurs within the stems of wetland plants and the upper soil layer, as well as in the wastewater itself [11, 12, 15, 16]. Subsurface flow-constructed wetlands (SSFCWs) are designed to prevent direct contact between wastewater and the air-exposed layer by incorporating a gravel or aggregate layer above the water level. SSFCWs typically employ two main design types: vertical and horizontal flows, as illustrated in Figure 2 [15,11].

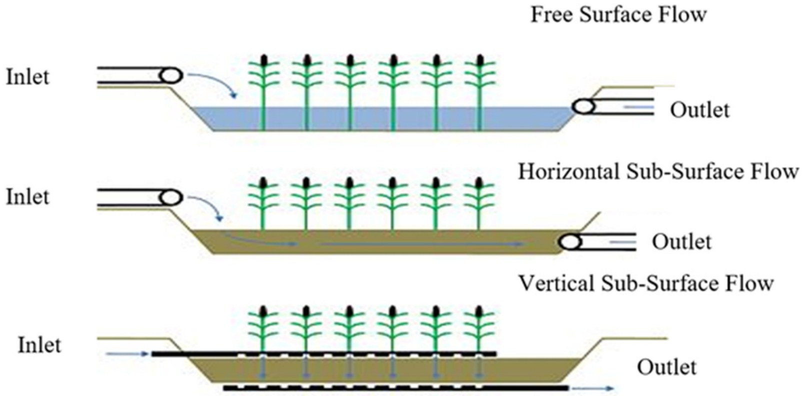

Figure 2. Types of wetlands according to the water flow [16,12]

CWs are designed to remove contaminants, including nutrients, organic matter, faecal bacteria, and suspended solids [15]. While designing and building municipal wastewater treatment systems, pollutants, such as heavy metals, surfactants, medicines, and personal care items are eliminated; however, they are often not prioritised [17, 18]. The main mechanisms of nitrogen removal from wastewater in constructed wetlands involve microbial activities, such as nitrification and denitrification, and physicochemical processes such as absorption and precipitation. Additionally, heavy metals and nutrients are absorbed by plants [19]. The primary mechanisms for removing heavy metals from wastewater include flocculation, sedimentation, and filtration. Physical processes are conducted through interactions between substrates containing wastewater and plant root systems. By harvesting plant shoots, CWs enable the permanent removal of heavy metals because plants can biologically absorb heavy metals through their root systems, transport them, and deposit them in other plant tissues in a process termed as phytoaccumulation. Moreover, some microbes found in CWs can remove heavy metals through metabolism and biosorption during their microbial activities. Chemical adsorption, ion exchange, and oxidation are a few chemical methods that can eliminate heavy metals from CWs [20, 21]. Typically referred to as macrophytes, larger aquatic plants grow in wetlands. These include large algae, aquatic mosses, and aquatic vascular plants [22]. Macrophytes stabilise the surface of beds, provide good conditions for physical filtration, prevent vertical flow systems from clogging, insulate against frost during winter, and provide a large surface area for microbial growth [23].

Table 1. Role of macrophytes in constructed wetlands [22] [8]

Macrophytes property	Role in the treatment process
Aerial plant tissue	Light attenuation → reduced growth of phytoplankton Influence on microclimate → insulation during winter Reduced wind velocity → reduced risk of re-suspension The aesthetic pleasing appearance of the system Storage of nutrients
Plant tissue in water	Filtering effect → filter large debris Reduce current velocity → increase rate of sedimentation, reduce the risk of re-suspension Excretion of photosynthetic oxygen → increases aerobic degradation Uptake of nutrients
Roots and rhizomes in the sediment	Stabilizing the sediment surface → less erosion Prevents the medium from clogging in vertical flow systems Release of oxygen increases degradation Uptake of nutrients

Table 2. Plant types used for specific pollutions [24]

Pollutant type	Plant used	Comments	Reference
Hydrocarbons	Phragmites spp.	Petrochemical wastewater application	[25, 26]
	Typha spp.	Laboratory tests of straight-chain alkanes in the range of c10 to c26	[27]
	Scirpus californicus	Refinery effluent was used in the comparison of three species. Scirpus showed the highest densities.	[28]
Oil and grease	Typha spp.	Dairy effluent application, study involving comparison of three species of oils, etc.	[29]
Mineral oils	Phragmites spp.	Treatment of heavy-oil-produced water	[30]
Chlorinated volatiles	Typha latifolia	Schilling farm for removal of trichloroethylene from the groundwater plume	[24]
Aromatics	Phragmites spp.	For the removal of aniline, nitrobenzene, nitrophenols, and sulphonic acid	[24]
	Rumex hydrolapatum	Sulphonated anthraquinones	[24]
	Schoenoplectus spp. & salix spp.	Casper phytoremediation project to remove btex, mtbe, and hydrocarbons	[24]
Glycols	Phragmites spp.	Used in the latter stage of the airport-run-off treatment system	[27]

Table 3. Main removing mechanisms for pollutant and pathogen in CWs [20, 21]

Parameter	Main Removal Mechanisms
Suspended solids (SS)	Sedimentation, filtration
Organic matter (OM)	Sedimentation and filtration for the removal of particulate organic matter, and biological degradation (aerobic and/or anaerobic) for the removal of dissolved organic matter
Nitrogen (N)	Ammonification and subsequent nitrification and denitrification, plant uptake and export through biomass harvesting
Phosphorus (P)	Adsorption-precipitation reactions driven by filter media properties, plant uptake, and export through biomass harvesting
Pathogens	Sedimentation, filtration, natural die-off, and predation (carried out by protozoa and metazoa)
Heavy metals	Sedimentation, filtration, adsorption, ion exchange, precipitation, and biological degradation through plants and microbiological metabolism

The roles of macrohytes in CW wetlands are listed in Table 1, and the types of plants used for various types of water pollution are listed in Table 2; the main contaminants and pathogens found in wastewater are suspended particles, pathogens, nitrogen, phosphorus, and heavy metals. Table 3 lists the removal processes for each of these pollutants and pathogens [20] [21]. The initial influent level, microbial biofilm, detention period, plant species, and configuration are the most important variables that directly determine the removal rates in the CW method for wastewater treatment, and they are efficient and environmentally friendly [31]. In CWs, reeds and vegetation, when opposed to open water systems, such as lagoons, play a significant role in the treatment of wastewater because their roots and rhizomes offer a suitable environment for the development of microbial biofilms. This results in a higher level of biological activity per unit area. Small amounts of oxygen and organic carbon molecules are released into the environment and can be utilised in both aerobic and anoxic microbial processes. Furthermore, they spread the flow, and thereby, decrease the hydraulic shortload [32]. Sedimentation and filtration occurs in the substrate materials. Sedimentation of suspended particles in wastewater results in contaminant removal [32]. Besides removing coliform bacteria, the sedimentation process significantly minimises the amount of organic waste [32, 33]. As particles accumulate within the substrates of the treatment bed, they produce dissolved organic compounds that are broken down through hydrolysis processes. In most constructed wetlands (CWs), a range of nitrogen removal mechanisms are actively involved. These include ammonification, nitrification, denitrification, absorption by plants and microbes, nitrogen fixation, nitrate reduction, anaerobic ammonia oxidation, as well as adsorption, desorption, burial, and leaching [34, 35]. Figure 3 provides a detailed illustration of key considerations in CW design.

Exploring a cost-effective treatment method like constructed wetlands (CWs) is advisable in Lahore. Notably, CWs do not require energy for operation, making them especially beneficial in light of the country's significant power shortages [7].

The specific objectives of the study are as follows:

- Removal of pollutants from wastewater by CW based on horizontal subsurface flow beds (HSSFBs)
- To check the effectiveness of a horizontal subsurface flow CW using reed plants across the Hudiara drain.

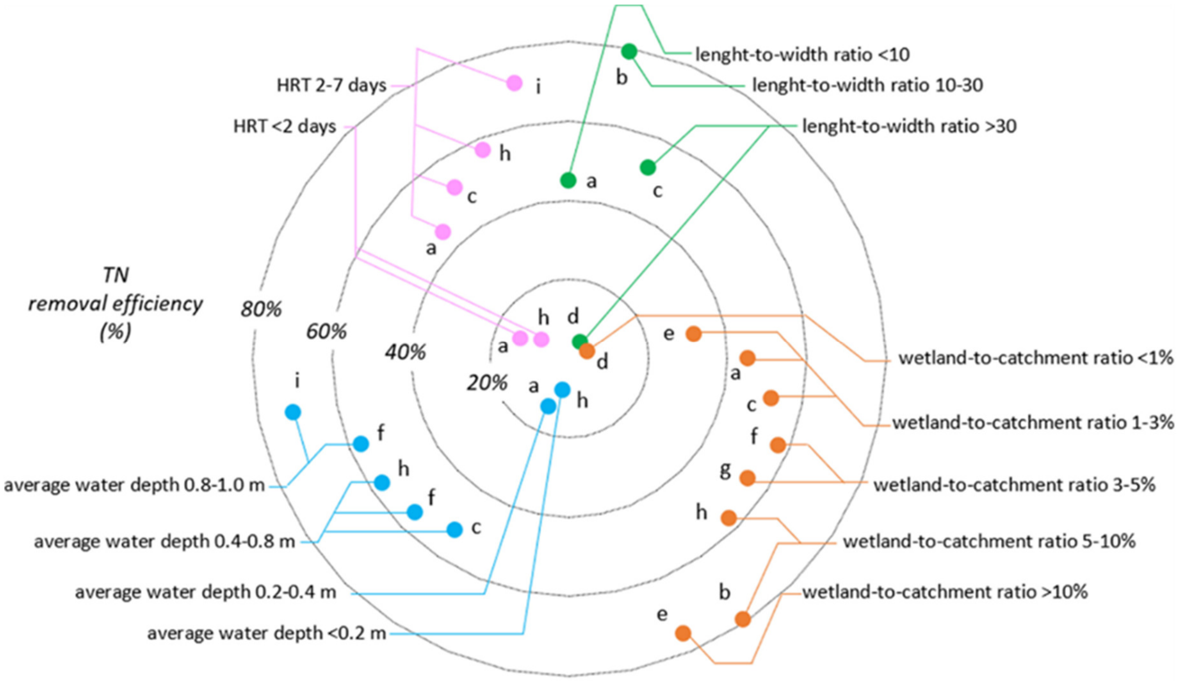

Figure 3. Design considerations for removal of pollutants [36]

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2 Methodology

A CW model was constructed to understand the structural behaviour and removal efficiency of different impurities present in the Hudiara Drain and check its efficiency for compliance with the PEQS. Sampling, preservation, and analysis of the samples were performed according to standard methods.
The site selected for the study was the Hudiara Drain, located in Lahore, Pakistan. It is near Bhobtiyan Chowk on Raiwind Road, as depicted in Figure 4. This site, situated about 11.3 km from The University of Lahore (Old Campus), was chosen for its suitability for wetland development. Factors such as the availability of raw materials and plants for wastewater treatment were crucial in the site selection process. The Hudiara drain discharges approximately 178 cusecs of water annually. Given the well-documented high levels of pollution in the Ravi River, this drain has become a significant concern for numerous environmental protection organizations in both Pakistan and India.

Figure 4. Site map of Hudiara Drain

The average daily maximum temperature of Punjab, one of Asia's hottest regions, is only 30 °C. Several months of the year are warm to hot, with daytime highs consistently exceeding 25 °C, sometimes up to 39 °C [37].

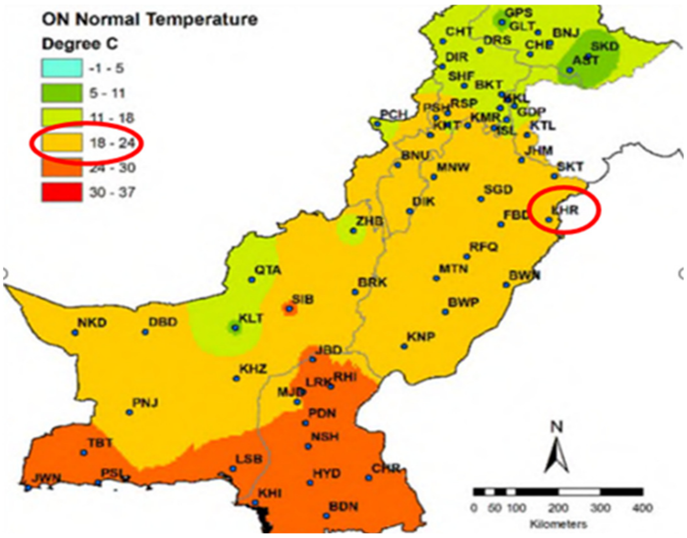

Figure 5. Temperature zone of Pakistan [37]

Punjab's capital city, Lahore, is located in Pakistan at a latitude 31,5204° N and longitude of 74,3587°. Figure 5 illustrates that from April 23 to July 20, the average daily high temperature consistently exceeds 95 °F. Conversely, from December 6 to February 21, the average daily high temperature remains below 73 °F [37].

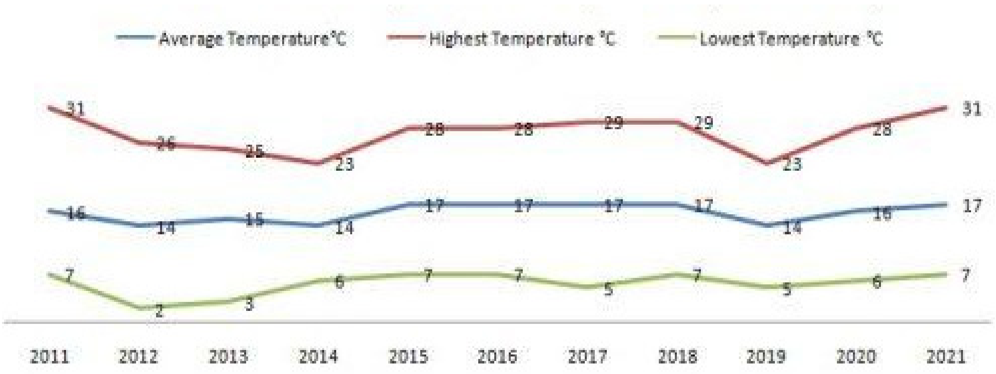

Figure 6. Climate graph of Lahore in February (2011–2021) [38]

Figure 6 presents an analysis of Lahore's climate data over the years, sourced from meteorological records. The city's climate graph reveals fluctuations in average temperatures between 2011 and 2021. In 2011, the maximum temperature recorded was 31 °C, a high that seemingly recurred in 2021. The lowest temperature of 2 °C was experienced in 2012. Compared to the last two years, this year's highest temperature has risen to 8 °C. These changes, potentially indicative of shifting weather patterns, have led to a shorter spring season nationwide [37].

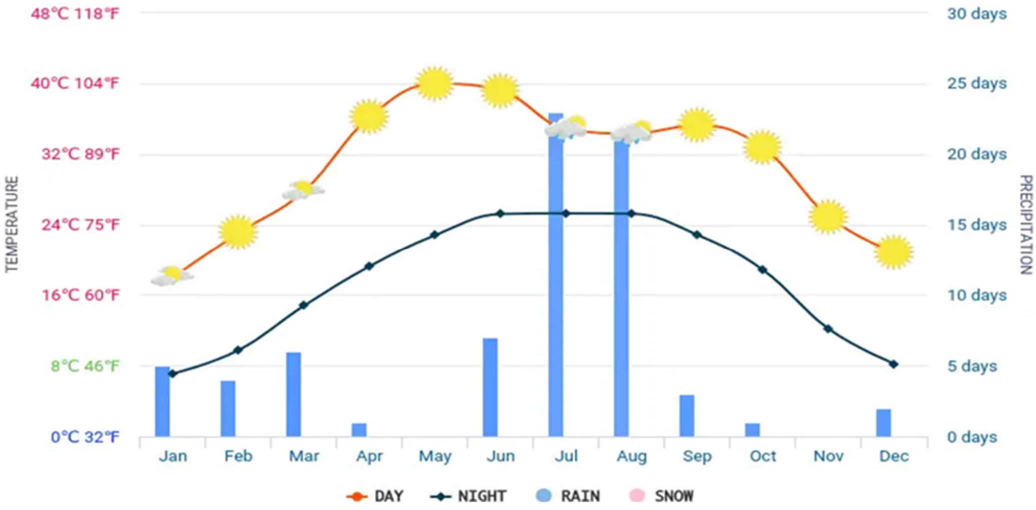

Figure 7. Average monthly temperature and precipitation in Lahore, Pakistan [39]

Figure 7 shows that the summer season in this area is from March to October, whereas the winter season is from November to February. The time frame selected for sample collection was from May to December to determine the impact of weather conditions on the efficiency of wetlands, particularly during the summer.

A day was categorised as having sufficient measurable precipitation if the recorded rainfall reached at least 0,0254 cm. In Lahore, the months of January, February, March, April, September, October, and December experienced lower precipitation, averaging 4 days. May and November typically experiences 0 days of precipitation. In contrast, June, July, and August were characterised by higher precipitation, averaging 18 days. For the study, a horizontal subsurface flow wetland was constructed. Phragmites australis (Reed), a plant species found near the site, was chosen due to its effectiveness in similar applications and its local availability. The retention time in the wetland was fixed to 9 h (from 8:00 am to 5:00 pm).

The basic design parameters included wetland area, loading rate, retention time, plant type, and temperature. Each parameter was significant in the system.

Table 4. Parameters and their measurement methods

Parameter	Unit	Measurement method	Standard
pH	-	Ion exchange	WHO
Phosphorous	Mg/l	Photometric method	WHO
Biological oxygen demand	Mg/l	Incubator dilution and inoculation	WHO
Nitrates	Mg/l	Photometric method	WHO
Turbidity	NTU	Nephelometry	WHO

Table 4 lists some of the parameters selected for testing, along with their respective treatment methods. A primary tank, with an approximate water storage capacity of 93 L, was used to supply water to a secondary tank for wastewater treatment. The secondary tank was then excavated. The bed was also prepared to prevent seepage, and an additional concrete crush was used on the weak soil surface of both the primary and secondary tanks. The surface soil at our site was very weak. Therefore, to improve the soil strength, a layer of concrete was laid. Brick curing is necessary for constructing wetland tanks. After the excavation, a secondary tank made of bricks and mortar was constructed. The primary sedimentation tank was also constructed according to the same design as the secondary tank. An outlet tank was used to collect treated wastewater for sample testing. Pipe connections and valves were installed to collect and control the wastewater and treated wastewater samples from the Hudiara drain. Wastewater samples were collected monthly, from May to December.

3 Results and Discussion

For all treated samples, acquired monthly from May to December, the results of various tests, including pH, BOD, turbidity, nitrates, and phosphates, were noted. These findings were within permitted limits of the PEQS for treated wastewater.

3.1 pH and BOD

The pH of the Hudiara drain ranged from a maximum of 10,98 to a minimum of 3,68 as observed in Figure 8. The pH of the treated wastewater decreased. The maximum pH of the treated wastewater was 8,91 and minimum pH was 6,15. However, the nature of the wastewater in most months was basic. According to PEQS recommendations, the pH range for treated water is 6 to 9.

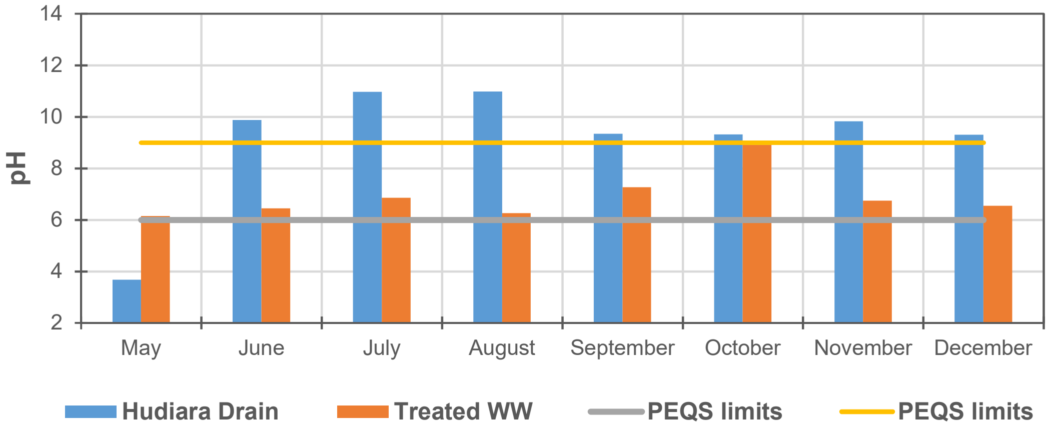

Figure 8. Effect of wetland on the pH of wastewater

As shown in Figure 9, max and min BOD_5 values correspond to 550 mg/l and 3, respectively. However, the maximum BOD_5 of the treated wastewater was 40 mg/l and minimum was 30 mg/l. Hence, BOD_5 treated wastewater was within the range of 80 mg/l (PEQS guidelines).

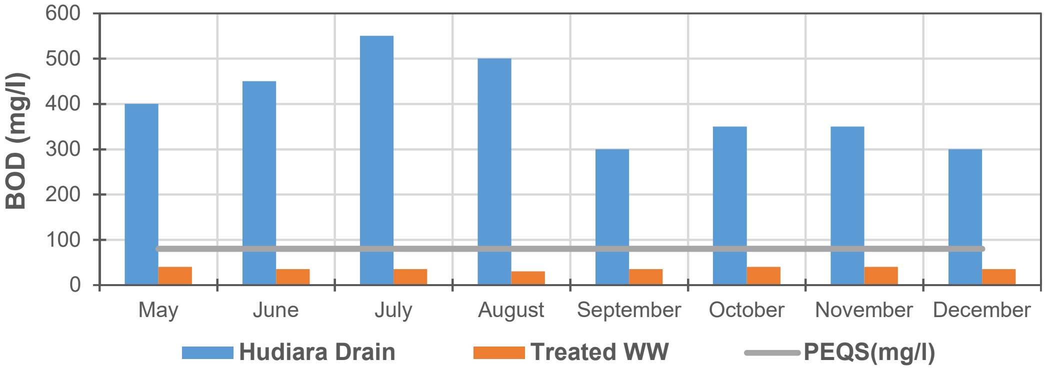

Figure 9. Effect of wetland on BOD of wastewater

Figure 10 shows that the maximum BOD removal is 94,00 %, which can be achieved in August, and the minimum BOD removal is 90,00 % in May, October, and November. The average removal of BOD from the treated wastewater samples was 90,25 %. The removal efficiency increased with increasing temperature until August; however, owing to the decrease in temperature, the % removal efficiency decreased.

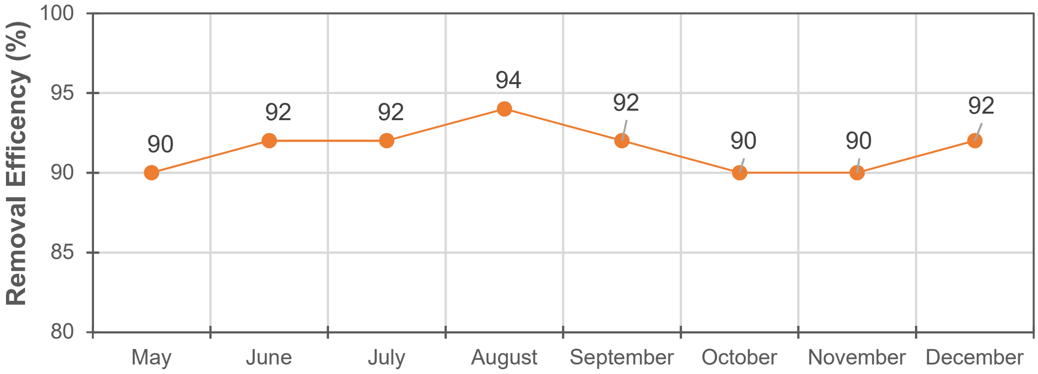

Figure 10. % Removal efficiency of BOD in treated wastewater

The BOD removal rate increased when the temperature increased from 20 °C to 30 °C, but it decreased when the temperature increased from 50 °C to 60 °C or temperature decreased below 20 °C. Higher temperatures enhanced the endogenous respiration of microbes. Therefore, increased water temperatures accelerate bacterial decomposition, resulting in higher BOD levels. Temperature also influences the survival of aquatic organisms [40]. However, the precipitation was at its minimum in May and November and at its maximum in July and August. The minimum removal efficiency was 90 % as precipitation decreased (0-days) and an increase was observed as precipitation increased.

3.2 Turbidity

Figure 11 demonstrates that the treated wastewater has a maximum turbidity of 9,4 NTU and a minimum turbidity of 2 NTU. Furthermore, the maximum turbidity of the Hudiara drain was 188 NTU and minimum turbidity was 22,9 NTU. The turbidity of the treated wastewater was within the allowable limit of 10 NTU.

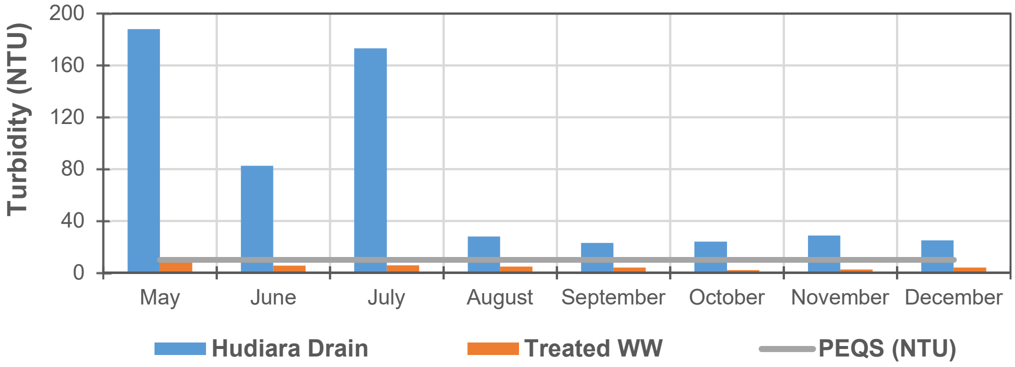

Figure 11. Effect of wetland on the turbidity of wastewater

In Figure 12, the maximum percentage reduction in turbidity (96,0 %) was attained in July, and the minimum percentage removal (82,0 %) was attained in August. The total turbidity removed from the treated wastewater samples was 89,5 %. The results also show that the turbidity removal efficiency is significantly affected by temperature. The turbidity and removal efficiency of the wastewater were higher in summer than those in winter.

There is an inverse relationship between the turbidity removal efficiency and precipitation. When the precipitation is 0-day, the removal efficiency increased by 95 % and 91 %, respectively, and increasing precipitation decreased the removal efficiency by up to 82 %. except in July, when high removal efficiency was perceived in the presence of high precipitation for 23 days. The same relationship was observed between the precipitation and turbidity of the wastewater.

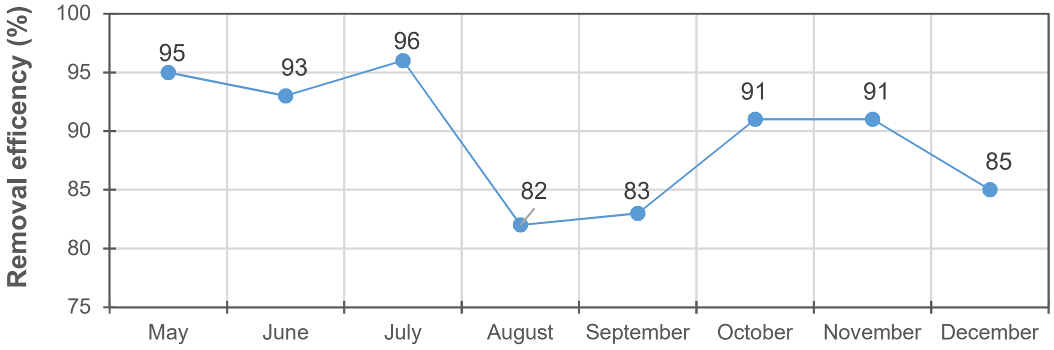

Figure 12. % Removal efficiency of turbidity in treated wastewater

3.3 Nitrates

The results in Figure 13 show that the maximum nitrate concentration in untreated water is 18,4 mg/l and the minimum concentration is 7,9 mg/l. However, the maximum nitrate concentration in treated wastewater was 4,4 mg/l and minimum was 1,3 mg/l. According to the PEQS recommendations, the nitrate levels in treated wastewater are in the range of 30 mg/l.

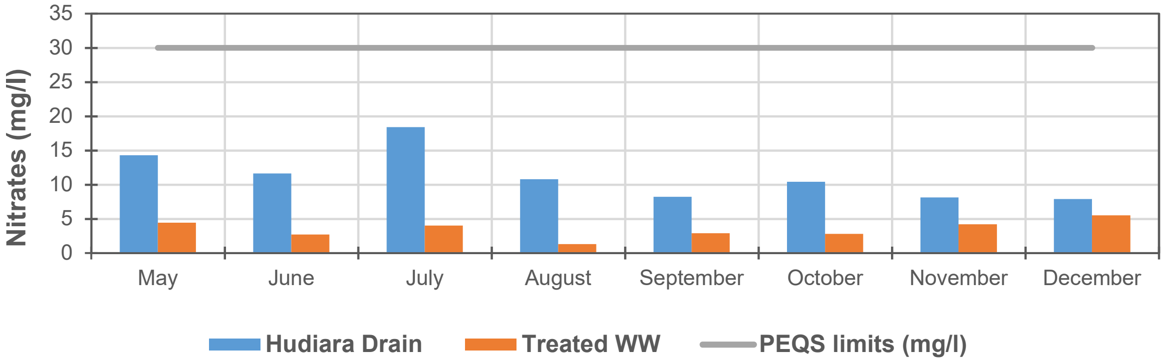

Figure 13. Effect of Wetland on Nitrates of Wastewater

The removal efficiency at seasonal temperatures was determined and found to be sensitive to the temperature. The removal efficiency in the constructed wetland is significantly influenced by temperature: it increases with rising temperatures but decreases when the temperature drops, though it should ideally remain below 40 °C. Precipitation rate is another dominant factor. For instance, in August, the peak nitrate removal rate reached 90 %, as depicted in Figure 14. Conversely, the lowest elimination rate, at 30%, was recorded in December.

It is evident from Figure 14 that the removal efficiency increases as precipitation increases. However, a decline was observed when precipitation was low. However, a change in the trend was observed in December owing to the temperature effect. Overall, 67 % of the nitrate was removed from the treated wastewater samples used in this study.

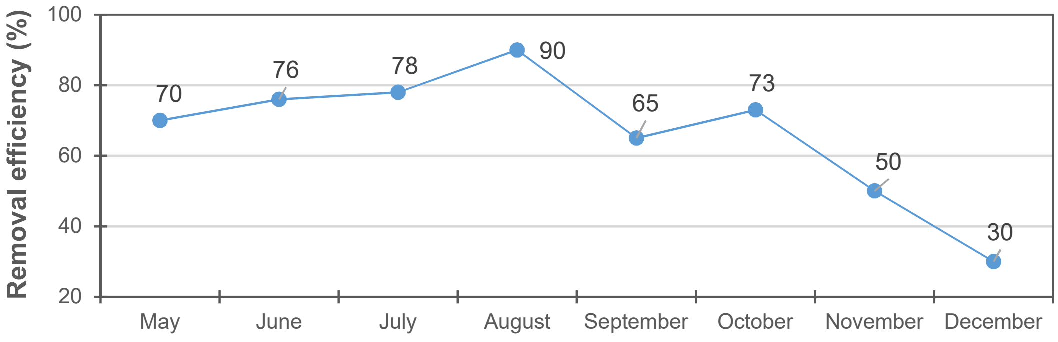

Figure 14. % Removal efficiency of nitrates in treated wastewater

3.4 Phosphates

The maximum phosphorus level in the Hudiara drain is 250 mg/l, with a minimum of 50 mg/l as shown in Figure 15. The maximum phosphorus level in the treated wastewater was 25 mg/l, whereas the minimum level was 10 mg/l. According to the PEQS regulations, this is within the allowable range of 30 mg/l.

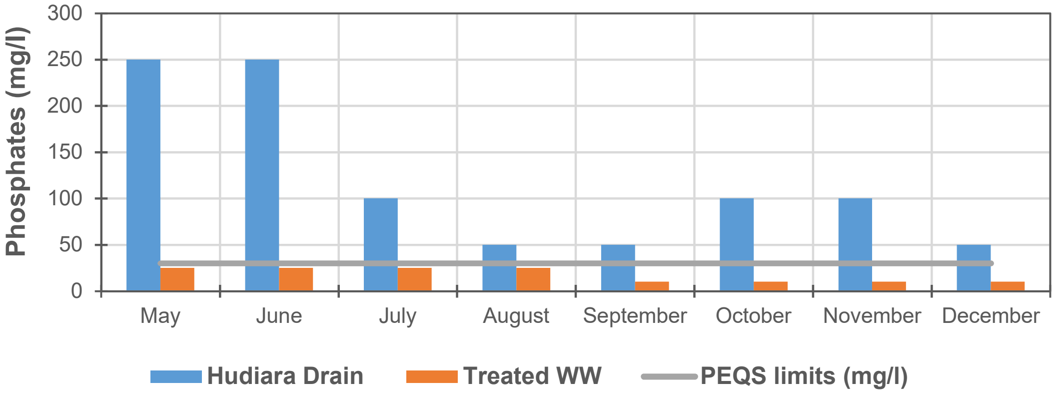

Figure 15. Effect of wetland on phosphorous of wastewater

Phosphate can be removed to a maximum of 99,00 % in October and November and to a minimum of 50,00 % in August. In this study, 82,88% of the phosphates are removed from the treated wastewater samples, as shown in Figure 16. There is an inverse relationship between phosphate removal efficiency and precipitation. With zero days of precipitation, the efficiency increased to 90,00 % and 99,00 %. Conversely, as precipitation increased, the efficiency decreased, dropping to as low as 52,00 %. An exception occurred in July, a month of high precipitation, where phosphate removal efficiency still reached 75,00 %. This inverse correlation was also noted between precipitation levels and phosphate concentrations in the wastewater.

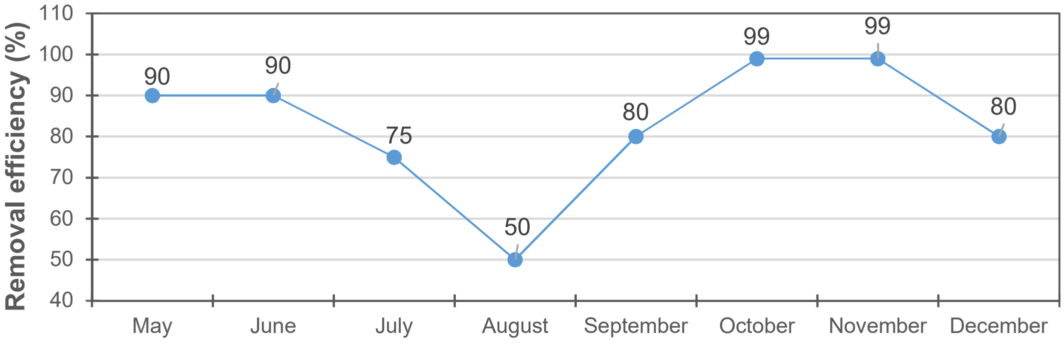

Figure 16. % Removal efficiency of phosphates in treated wastewater

4 Correlation and Regression Analyses

As shown in Figure 17, a linear trend between the temperature and percentage removal efficiency of several containments was developed through regression analysis. The regression analysis results provided insights into the relationship between temperature and the removal efficiency of different contaminants. For BOD, the quadratic equation suggests that the relationship is complex, and the low R^2 value of 0,02 indicates that only a minor 2% of the variability in BOD removal efficiency can be attributed to temperature changes. The turbidity linear equation demonstrates a relatively stronger correlation, with an R^2 value of 0,0775; implying that approximately 7,75 % of the turbidity removal efficiency variation aligns with temperature fluctuations.

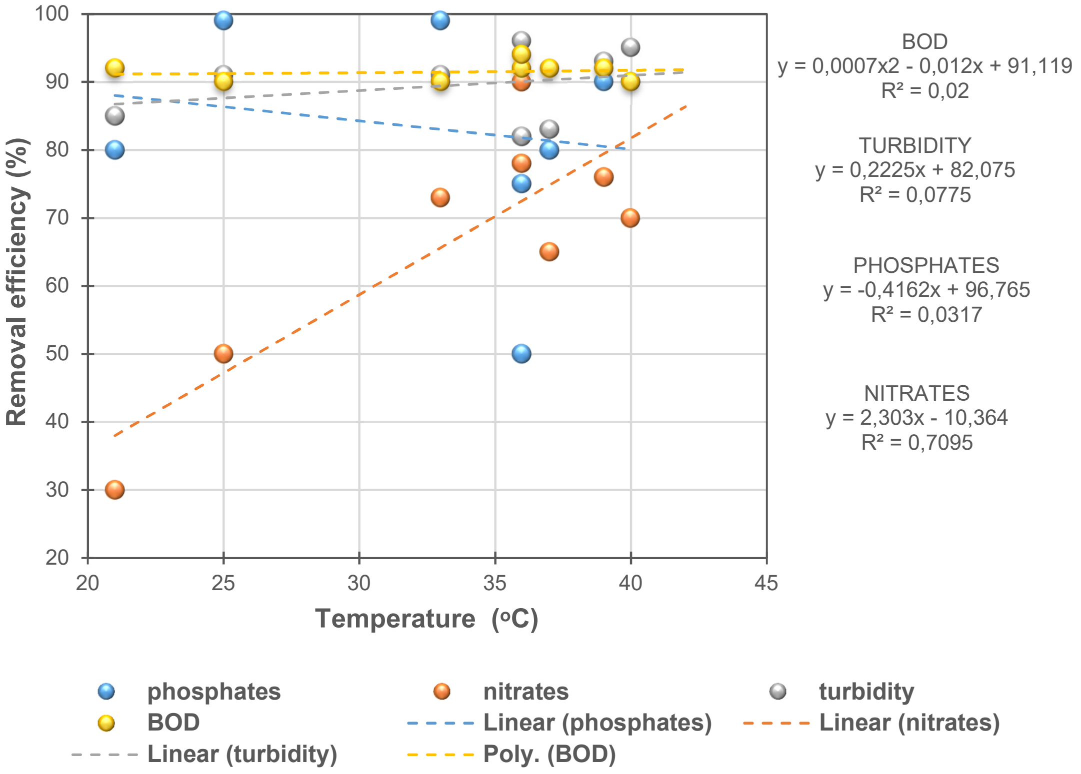

Figure 17. % Removal of phosphates, nitrates, turbidity, and BOD in CW at different temperatures

Phosphates showed a negative linear trend, with an R^2 value of 0,0317; indicating that temperature shifts explain about 3,17 % of the variability in phosphate removal efficiency. In contrast, nitrates demonstrated a strong linear correlation with temperature. The high R^2 value of 0,7095 suggests that temperature changes account for a significant 70,95 % of the variability in nitrate removal efficiency. These results emphasize that among the contaminants studied, nitrates have the most direct relationship with temperature. Meanwhile, factors affecting BOD, turbidity, and phosphates appear more complex, involving a variety of factors beyond temperature.

For BOD, $y = 0,\ 0007\times2–0,012x+91,119$ is applicable for temperatures in the range of 50 –20 °C. For turbidity, $y = 0,2225x + 82,075$. For nitrates, $y = 2,303x – 10,364$ is applicable up to 40 °C. For phosphates $y = –0,4162x + 96,765$. Temperature determines the rate of metabolic activity and affects microbial populations, and there was a significant ($p < 0,05$) positive impact of temperature on the rate of organic matter degradation, nitrification, and denitrification processes in less time. The success of treatment in CW often declines at cold temperatures, mostly because of decreased biotic activity [41].

Therefore, the removal efficiency of CW is not only affected by temperature, but also by other external factors such as precipitation and humidity, as well as the characteristics of wastewater, design flow, and location of the wetland. However, internal parameters, such as substrate selection, crop selection, water depth, HRT, HLR, and feeding status, drive the pathways for establishing a sustainable CW system and achieving sustainable treatment performance [42], as mentioned above. Phosphates, nitrates, turbidity, biological oxygen demand (BOD), and pH can be controlled by constructed wetlands.

Table 5 validates the experimental results by comparing them with values derived from linear regression. This comparison reveals that variations in the percentage removal efficiency of contaminants at different temperatures are within acceptable limits for BOD and turbidity, with maximum variations of –12 % for BOD and –9 % for turbidity. However, for nitrate and phosphate, the removal efficiencies varied more significantly, at –15 % and –64 %, respectively.

Table 5. Percentage variation between temperature and % removal efficiency of pollutants

Temperature (°C)	BOD			Turbidity			Nitrates			Phosphates		
	Exp	Predicted	% Variation	Exp	Predicted	% Variation	Exp	Predicted	% Variation	Exp	Predicted	% Variation
40	90	102	-12	95	91	4	70	82	-17	90	80	11
39	92	101	-9	93	91	2	76	79	-5	90	81	11
36	92	100	-8	96	90	7	78	73	7	75	82	-9
36	94	100	-6	82	90	-9	90	73	19	50	82	-64
37	92	100	-8	83	90	-8	65	75	-15	80	81	-2
33	90	98	-8	91	89	2	73	66	10	99	83	16
25	90	95	-5	91	88	4	50	47	6	99	86	13
21	92	94	-2	85	87	-2	30	38	-27	80	88	-10

Figure 18 features a linear regression analysis between precipitation and the percentage removal efficiency of various contaminants, providing insights into their complex interplay. Specifically, phosphate removal efficiency showed a moderate negative correlation with precipitation. The linear regression equation and the R^2 value of 0,6229 suggest that about 62,29 % of the variability in phosphate removal efficiency can be explained by precipitation levels. Conversely, the linear model for nitrates demonstrated a positive correlation with precipitation, but with a lower R^2 value of 0,3781. This indicates that about 37,81 % of nitrate removal efficiency variability is due to changes in precipitation. Turbidity's relationship with precipitation was more complex, as evidenced by a negligible R^2 value of 0,0024; suggesting that the linear model does not adequately capture their interaction. For BOD, a quadratic model was used, highlighting its complex relationship with precipitation and suggesting an optimal range for its removal efficiency. The use of a quadratic model for BOD highlights its complex dependence on precipitation, indicating a potential optimal range for its removal efficiency. The significant R^2 value of 0,7324 implies that this model accounts for approximately 73,24% of the variability in BOD removal efficiency. This observation, along with the diverse responses of other contaminants, underscores the nuanced impact of precipitation on removal efficiency. Phosphates and nitrates exhibit clearer correlations with precipitation, while turbidity shows a less distinct pattern, and BOD demonstrates intricate quadratic dependencies. The R^2 values also suggest that additional factors beyond precipitation play a substantial role in the variability of removal efficiencies, highlighting the complexity and multifaceted aspects of wetland treatment processes.

The relatively lower R^2 value for nitrates may result from the complex nature of nitrate removal, which is affected by various factors including microbial activity, vegetation uptake, and water chemistry, with precipitation being just one of these elements. Conversely, the minimal impact on turbidity could be due to its sensitivity to a range of factors such as sedimentation, organic content, and biological processes. In this complex scenario, precipitation plays a limited direct role in influencing turbidity removal efficiency.

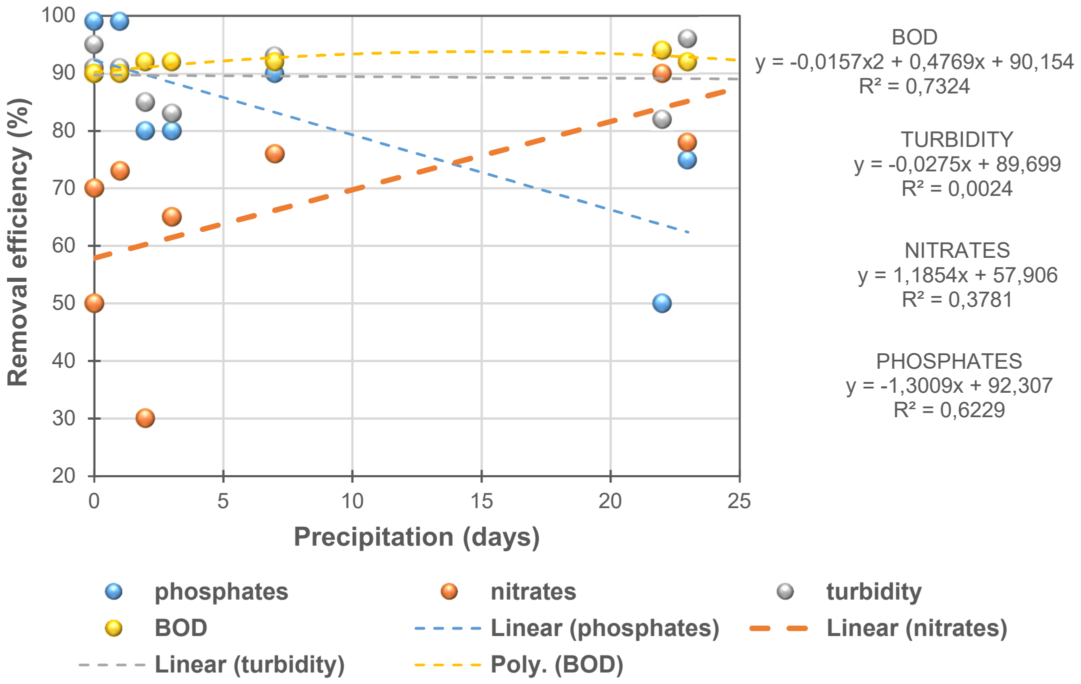

Figure 18. % Removal of phosphates, nitrates, turbidity, and BOD in CW at different precipitation levels

Table 6 shows the % variation between the regression analysis's predicted values and experimental results. The maximum differences for BOD, turbidity, and phosphates were 3%, –8 %, and –27 %, respectively.

Table 6. Percentage variation between precipitation and % removal efficiency of pollutants

Precipitation (days)	**BOD**			**Turbidity**			**Nitrates**			**Phosphates**		
	Exp	**Predicted**	**% Variation**	**Exp**	**Predicted**	**% Variation**	**Exp**	**Predicted**	**% Variation**	**Exp**	**Predicted**	**% Variation**
0	90	93	-3	95	90	6	70	58	17	90	92	-3
7	92	93	-1	93	89	4	76	66	13	90	83	8
23	92	93	-1	96	89	8	78	85	-9	75	62	17
22	94	91	3	82	90	-8	90	84	7	50	64	-27
3	92	91	2	83	90	-7	65	61	5	80	88	-11
1	90	90	0	91	90	1	73	59	19	99	91	8
0	90	91	-1	91	90	2	50	58	-16	99	92	7
2	92	90	2	85	90	-5	30	60	-101	80	90	-12

Nitrates exhibited a notably high maximum variation following two days of precipitation. The average removal efficiencies for BOD, turbidity, nitrate, and phosphate were 90,25 %, 89,50 %, 67,00 %, and 82,88 % respectively, and the pH of the treated wastewater was successfully reduced to within the 6 – 9 range. During May–August, high removal efficiencies were recorded for several contaminants including BOD, turbidity, nitrate, and phosphate, with average summer values for treated wastewater being 92,00 %, 91,50 %, 78,50 %, and 76,25 % respectively. In contrast, winter experiences less effective removal of contaminants, except for phosphate, with average values for treated wastewater of BOD, turbidity, nitrate, and phosphate at 91,0 %, 87,5 %, 54,0 %, and 89,5 % respectively. This is attributed to the influence of increased water temperatures in summer, which accelerate bacterial decomposition and impact the survival of aquatic organisms.

5 Conclusions and recommendations

The primary tank in constructed wetlands, essential for settling solids, supports the horizontal subsurface flow system in efficiently removing contaminants. Locally sourced plant reeds, such as Phragmites, are effective in filtering pollutants such as BOD, nitrate, phosphate, and turbidity. The average removal efficiencies for these contaminants were 90,25 %, 89,50 %, 67,00 %, and 82,88 %, respectively, with a pH of treated wastewater maintained within the 6 – 9 range. High removal efficiencies for turbidity, BOD, nitrate, and phosphate were noted from May to August, with summer averages for treated wastewater at 92,00 %, 91,50 %, 78,50 %, and 76,25 %, respectively. In contrast, winter averages were 91,0 %, 87,5 %, 54,0 %, and 89,5 %, respectively. In winter, the wastewater removal efficiency was generally lower, except for phosphorus, which exhibited less sensitivity to temperature changes. Nitrates demonstrated a strong and positive correlation with temperature, with the percentage of removal efficiency increasing as temperatures rose. However, this trend altered when temperatures exceeded 40 °C. In contrast, phosphate, turbidity, and BOD showed weaker correlations between temperature and removal efficiency. CW are influenced by temperature, but the role of precipitation is also significant. During the summer, particularly in the monsoon months of June, July, and August, high precipitation levels further impact the removal efficiency.

Linear regression analysis revealed that precipitation significantly influences the percentage removal efficiency of CW. A strong correlation exists between phosphorous and BOD with precipitation, while nitrates, being temperature-sensitive, and turbidity, affected by both temperature and precipitation within certain limits, behave differently. Additionally, factors such as the characteristics of wastewater, design flow, and wetland location also play a role. Given that the Hudiara drain is a significant source of pollution with industrial waste, employing CW to remove heavy metals is recommended. Exploring the use of treated wastewater for amenities and services, including public park irrigation, horticulture, and road water sprinkling, is advisable. Future experiments should vary plants, filter media, times, locations, and discharges to further assess CW effectiveness.

Abbreviations

CW	Constructed wetland
NTU	Nephelometric turbidity unit
Mg/l	Milligram/litre
PEQS	Pakistan environmental quality standards
BOD	Biochemical oxygen demand
pH	Potential hydrogen

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