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Nitrogen and Phosphorus Removal of Wastewater via Constructed Wetlands Approach

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ABSTRACT: This study aimed to determine the efficiency of media pollutant removal from municipal wastewater with high concentrations of ammonia and phosphorus in constructed wetlands (CWs). The study utilized secondary data from previous studies that were published in credible sources. The removal efficiencies of the five media used in the constructed wetland, namely, peat-cattails, cattails, peat, *Viteveria zizanioides*, and Phragmite karka, were compared. The results showed that CWs with *Viteveria zizaniode* exhibited the best performance on average, removing 84% nitrogen and 86% phosphorus. Peat was also effective in attenuating pH. Humic and fulvic acids in peat moss can be released quickly in an aqueous environment under alkaline conditions, effectively lowering the pH value. The combination of *Viteveria zizaniode* and peat significantly improved pollutant removal efficiency in municipal wastewater with high concentrations of ammonia and phosphorus.

KEYWORDS: Constructed wetlands; wastewater treatment; phytoremediation; nutrient removal; plant-based treatment

1. Introduction

The release of domestic wastewater into the environment without proper treatment has a significant impact on the environment. Releasing untreated wastewater into rivers can result in the spread of disease and death among humans in the short or long term. In developing countries, the wastewater issue has not been effectively addressed, resulting in irreparable environmental harm [1]. Ammonia and phosphorus are the nutrients commonly found in wastewater. The presence of ammonia and phosphorus in the receiving streams and estuaries leads to algal blooms, excessive growth of nuisance aquatic plants, aesthetic issues, deoxygenation, and problems related to water purification for potable use [2, 3]. The most common methods used to remove these pollutants are treatment-based biological nitrification and denitrification processes. Despite its extensive use, aeration is associated with considerable maintenance costs when treating ammonia and phosphorus levels [4, 5]. Some circumstances result in effluent quality that did not meet the standards owing to inadequate maintenance [6]. Alternatively, CWs construction is a tertiary method for treating wastewater with high nutrients. It is an engineering system designed to use natural processes involving wetland vegetation, soil, and microorganisms to degrade pollutants in wastewater. CWs have been widely used throughout the world and have been proven to effectively solve water quality problems and treat a wide range of wastewaters [7, 8]. The treatment method is economical and technically feasible if built according to proper design to remove pollutants from all types of sewage [9, 10]. CWs have been investigated for more than four decades for the removal of organics, suspended solids, phosphorus, bacteria, and nitrogen from wastewater [11, 12].

In CWs, systems are classified according to the types of plants planted, which are roughly divided into submerged plants, floating plants, and emergent plants. Submerged plants are primarily used for primary and secondary wastewater treatments [7, 13]. However, these systems are still being investigated [14, 15]. A floating plant system is used to treat nitrogen and phosphorus pollutants and increase the efficiency of traditional stabilization ponds by removing these pollutants [16, 17]. Emergent plants are most commonly used in CWs [18, 19]. Emergent plant systems can be divided into three main categories in terms of wastewater flow mode [20, 21]: surface flow wetlands, subsurface flow wetlands, and vertical flow wetlands. Surface flow wetlands usually consist of shallow reservoirs planted with emergent plants, with a layer of impervious material filled with gravel substrate or soil. The water level is set above the surface of the substrate to allow wastewater to penetrate through dense vegetation and flow over it. The residence time of the wastewater in the system is approximately 10 days. There are five steps in the purification process: sedimentation of suspended solid particles, diffusion of dissolved nutrients and deposition of organic matter, mineralization of organic matter, absorption and transformation of nutrients by microorganisms and plants, decomposition of microorganisms into organic matter and conversion into gas components, and physicochemical absorption and precipitation. The advantages of surface flow systems include low investment, ease of operation, and affordability [22]. However, its disadvantages include the need for a large floor space, low organic pollution and hydraulic load, poor sanitary conditions, and a significant impact on the environment.

Subsurface wetlands are similar to surface wetlands, but they were designed with high soil porosity to allow wastewater to flow through the substrate. The water level is also lower than the surface of the substrate in the subsurface wetland. Gravel is widely used as a substrate in subsurface systems to replace the soil. As sewage flowed into the filler, it was treated by retention, adsorption, biochemical conversion of the filler, and the surface of the biofilm and plant roots. The treatment process in wetlands maintained the temperature of water flow and stabilized the climate [23, 24]. Owing to their large hydraulic and pollutant loads, as well as ideal sanitary conditions, these systems were widely promoted. However, it was difficult to meet the oxygen demands of microorganisms in the filler, owing to the limited oxygen supply of aquatic plants [25]. Most of the fillers were in the anoxic and anaerobic states. Therefore, subsurface wetlands experienced strong denitrification and nitrification processes. Vertical-flow wetlands combined a few of the characteristics of surface and subsurface flow wetlands. However, denitrification was less effective owing to the relatively complex operation controls. In these systems, mosquitoes and flies could easily reproduce and were expensive to construct. In addition, organic matter could not be easily removed.

The presence of nutrients in discharged wastewater may contribute to eutrophication. This could adversely affect fish populations, reduce the level of dissolved oxygen in water, and promote the growth of algae and aquatic plants. To improve the quality of water in streams, the use of CWs was an alternative approach. However, CWs had drawbacks for wider applications in wastewater treatment. Their efficiency could vary seasonally depending on the weather, as opposed to conventional wastewater treatment plants [26, 27]. The purpose of this study was to understand the efficacy of plants planted in CWs in the treatment of wastewater containing ammonia and phosphorus pollutants.

2. Materials and Methods

2.1. Research paper collection and screening.

In this study, secondary data were obtained by conducting online searches of relevant journal publications using sites such as ScienceDirect (https://www.sciencedirect.com/), PubMed (https://pubmed.ncbi.nlm.nih.gov/), Elsevier (https://www.elsevier.com/en-in/), and others. The data found in the literature were compiled using keywords to form meaningful inferences to evaluate the performance of CWs: "Constructed wetlands", "Domestic wastewater", "Ammonia", and "Phosphorus" and their possible combinations. Next, the collected research papers were screened to identify and extract relevant information necessary to attain the aim of the study. Further screening for data collection was conducted considering the following points: (1) papers involving only those CWs for domestic wastewater treatment and not equipped with any additional technology; (2) papers utilizing CWs for the removal of ammonia and phosphorus were selected for this study.

2.2. Parameter selection.

Both quantitative and qualitative analyses of the experimental conditions and physicochemical parameters of CWs were essential for reaching a meaningful conclusion in this study. All relevant parameters, including influent and effluent levels of pH, Dissolved Oxygen (DO), phosphate (PO_4-P), ammonium (NH_4-N), Total Nitrogen (TN), nitrate (NO_3-N), and Total Suspended Solids (TSS), were meticulously collected for comparison and assessment.

2.3. Statistical analysis.

Microsoft Excel was used for statistical analysis, quantification, and trend assessment, as well as plotting curves and trends.

3. Results and Discussion

3.1. Characterization of influent and effluent wastewater.

Table 1 illustrates the influent and effluent water quality for the two-set experiment based on available data. The influent of Set A differed from Set B because it was directly pumped out of the wastewater stabilization pond. Set B was the influent after passing through the sedimentation tank. There was a high pH of 7.7 for the CWs planted with peat, cattails, and peat-cattails. In the wastewater stabilization pond, algae were very active during the summer, depleting inorganic dissolved carbon and negatively affecting the pH balance [28, 29]. The NO_3-N level was significantly higher at 7.93 mg/l, due to the lower ambient temperature in the fall season. The nitrification process was less effective, which reduced the activity of nitrifying bacteria [30, 31]. The concentration of PO_4-P was considerably higher after the purification process, indicating that phosphorus was removed less effectively.

Table 1. Characterization of wastewater in CWs.

Parameter	**Unit**	**Set A**				**Set B**		
		Influent	**Peat-Cattails Effluent**	**Cattails Effluent**	**Peat Effluent**	**Influent**	***V. zizanioide* Effluent**	***P. karka* Effluent**
pH		7.7	6.4	6.5	6.5	7	7.8	7.8
DO	mg/l	6.10	6.44	5.92	6.32	0.33	6.2	6.4
TSS	mg/l	4.10	9.80	6.40	17.60	346.8	27	30.6
NH_4-N	mg/l	0.20	0.97	0.47	1.69	29	4.9	4.1
NO_3-N	mg/l	7.93	1.08	0.64	1.43	3	0.58	0.56
TN	mg/l	8.29	2.19	2.04	2.68	NA	NA	Na
PO_4-P	mg/l	0.75	0.31	0.67	0.38	12.2	1.5	1.7

In Set B, most parameters treated with *V. zizanioides* and *P. karka* were substantially reduced. The concentration of nutrients in effluents was much lower compared to Set A, indicating that the plants were effective at absorbing nutrients. The TSS concentration of 346.8 mg/l was reduced by 27 mg/l and 30.6 mg/l with *V. zizanioides* and *P. karka*, respectively. In both plants, the DO levels in the effluent increased by 0.33 mg/l to 6.2 mg/l for *V. zizanioides* and 6.4 mg/l for *P. karka*. These results showed an improvement in water quality.

3.2. Attenuation of pH.

Figure 1 shows the pH trend over time during wastewater treatment in CWs with peat-cattails, cattails, and peat, which were available in literature. At the beginning of the operating period, the initial pH values of CWs with peat-cattails and CWs with peat were similar, both measuring pH 6.8. The dropping of the initial pH was the short-term effect of peat which released the acid compound. The pH value for peat-cattails increased to about 9 in 2-4 weeks, but then dropped to about 7 in week 7 due to the heavy rain season, and the pH was neutralized by runoff. CWs with peat maintained a relatively stable pH value throughout the operation period. The pH value for cattails at the beginning of the operation period was similar to the influent. However, at the end of the operation period, the pH value gradually decreased from 9 to 6.5. It is worth noting that precipitation greatly affected the pH value of influent water [32, 33]. After heavy rains, neutral pH rainwater runoff usually entered the stabilization pond and helped to neutralize the high pH wastewater.

In the previous summer, algae blooms were discovered in the wastewater stabilization pond, causing the influent pH to become very high, and these pH values usually exceeded the legal discharge limit allowed by the system [34]. To effectively address the pH problem, the introduction of Surface Flow CWs (SFCW) was considered feasible. This study notes that the treatment wetland reduced the pH to a level below the prescribed emission limit throughout the experiment. Nevertheless, the increase in algal activity in the wastewater stabilization pond caused by increased ambient temperatures and strong sunlight irradiation resulted in an overall rise in pH. To effectively lower the average pH value, the peat substrate played an important role. The release of humic acid and fulvic acid from peat moss in an aqueous environment under alkaline conditions was confirmed to effectively lower the pH value [35]. Previous benchmark-scale studies also confirmed this immediate impact [36, 37]. *V. zizaniodes* and *P.*

karka recorded similar final pH values, which were 7.8, and there was a slight increase in pH values from 7.1 to 8.2 for influent and effluent, respectively. It was found that the temperature of effluent in both CWs ranged between 22.4 and 26.7°C. The temperature range of 25°C to 35°C and the pH range of 6.5-7.5 provide suitable conditions for microbial activity. The Pearson correlation indicated that NH_4-N and PO_4-P removal efficiencies were related to pH at 0.964 and 0.978, respectively.

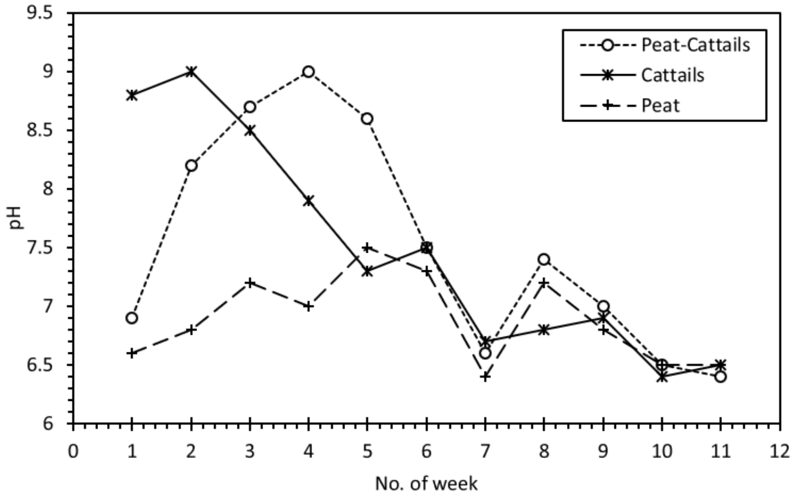

Figure 1. pH variations in CWs with peat-cattails, cattails and peat.

3.3. Nitrogen removal.

The available evidence in the literature exhibits in Figure 2, which showed the NH_4-N removal efficiencies of different CWs. The CWs with cattails achieved the highest removal efficiency among the other plants (92.7%), while with peat only had the lowest removal efficiency of 81.7%. Peat-cattails, *P. karka*, and *V. zaizaniodes* achieved 86.9, 85, and 84% removal of NH4-N, respectively. The NO3-N removal efficiencies of CWs with peat-cattails, cattails, peat, *V. zaizaniodes*, and *P. karka* also reached 86.4%, 91.9%, 81.9%, 80.67%, and 81.33%, respectively. Because NH_4-N is easily oxidized and converted into NO_3-N, the concentration of NH_4-N in the wastewater decreased, which proved that it had a certain relationship with the nature of the shallow water wastewater stabilization pond (usually in which aerobic conditions existed) in the results [38, 39]. Another reason to further reduce the level of NH_4-N was that the increased pH in the stabilization pool could promote the volatilization of NH_3 into the atmosphere [40, 41]. This also resulted in a low concentration of NH_4-N in the effluent throughout the experimental period. It was not expected that NH_4-N would be removed during subsequent treatment. The NH_4-N concentration of the influent during the operation periods was 0.20 mg/l. In all other cases, the effluent NH_4-N concentration increased during the treatment period. The relationship between low NH_4-N removal efficiency and low influent concentration has also been reported in other studies [42, 43]. A study of surface flow wetlands showed that when the influent concentration was 0.88 mg/l, only 11.8% NH_4-N removal efficiency could be achieved. Another study also observed that when the influent NH_4-N content was less than 0.41 mg/l, NH_3-N was not positively removed [44]. Because of the dissimilatory reduction of nitrate to ammonia, NO_2-N and NO_3-N could be reduced to NH_4-N in an anoxic/reducing environment to increase the concentration of NH_4-N [45, 46]. High NH_3-N effluent concentrations may also have been caused by the nitrogen released by peat [47, 48]. Although the ability to remove NH_4-N from the secondary effluent was limited, NO_3-N and

TN were removed during the treatment period. Cattails reached 92.7% and 75.0%, respectively, while NO_3-N accounted for the majority of TN removal in all CWs.

The decontamination capacity of *P. karka* (85%) was significantly higher than that of *V. zizanioides* (84%). Nitrification/denitrification was the main nitrogen removal mechanism in CWs [49]. With an increase in the age of the wetlands, the nutrient removal performances of the two wetlands increased. This was related to the growth of the microorganisms. The ability of plants to absorb nutrients gradually improved over time. Thus, the increase could be related to the gradual increase in plants and their biomass [50]. In CWs, the influence of the substrate on the development of microbial communities was based on the morphology and development of plant roots [51, 52]. Dhanya and Jaya reported that in wetlands planted with *V. zizanioides*, the removal of NH_4-N (81.4%) and NO_3-N was 55.5%, which was lower than that reported in this study [53]. The mechanisms of nitrogen removal include ammonization, denitrification, nitrification, adsorption, volatilization, plant absorption, and microbial degradation [53]. When the pH value was higher than 11, NH_4-N could be removed through volatilization. However, the measured pH value in this study was between 7.1 and 8.2; therefore, this mechanism was excluded.

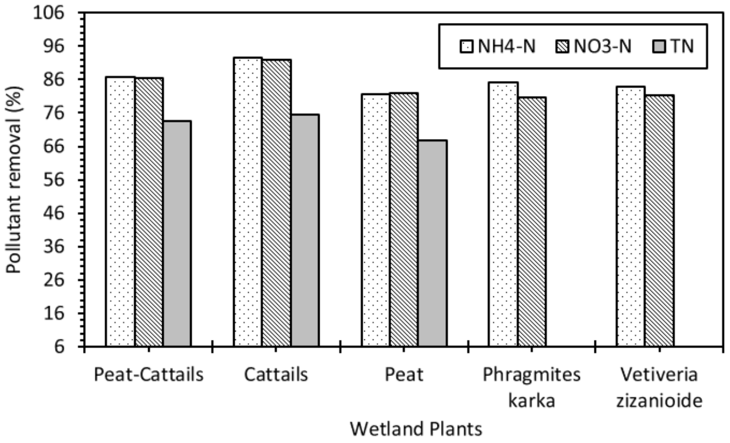

Figure 2. Nitrogen removal efficiency with different wetland plants.

3.4. Phosphorus removal.

Based on Figure 3, it can be observed that the reduction in PO_4-P concentrations in CWs with peat-cattails and peat was superior compared to those with cattails alone. The maximum PO_4-P removal efficiency achieved was 58.7%. In CWs with *V. zizanioides* and *P. karka*, PO_4-P removal efficiencies of 86% and 84% were respectively attained. The substrate constitutes the primary component of phosphorus storage and plays a crucial role in the overall phosphorus retention in CWs. Several studies have reported that the substrate accounts for over 50% of phosphorus removal, compared to other components such as water, perennial plants, and macrophytes [54, 55]. Peat possesses robust phosphorus retention capabilities, making it an exceptional phosphorus absorbent [56]. PO_4-P is a critical nutrient in surface water, commonly utilized by bacteria, plants, and algae, and is also referred to as reactive phosphorus. A study has established that, in comparison to other phosphorus forms such as organic phosphate and particulate phosphorus, CWs can effectively remove PO_4-P [57].

The results obtained from CWs with *V. zizanioides* and *P. karka* were relatively close. Adsorption, precipitation, and plant uptake, which are crucial for plant growth, are the most commonly used methods for phosphorus removal in CWs. Depending on the climate, plants, and wastewater types, the phosphorus removal rate achieved through plant growth can reach up to 10%. Dhanya and Jaya have reported that the PO_4-P removal rate of raw sewage treated in vetiver wetlands was 70.3%, lower than that of this study [53]. The nutrient processing performance of plants varies across species. Due to the relatively higher absorption capacity of *V. zizanioides*, the removal efficiency of PO_4-P was more significant compared to CWs grown by *P. karka*. This is due to the larger root system that aids the plant's nutrient absorption [58].

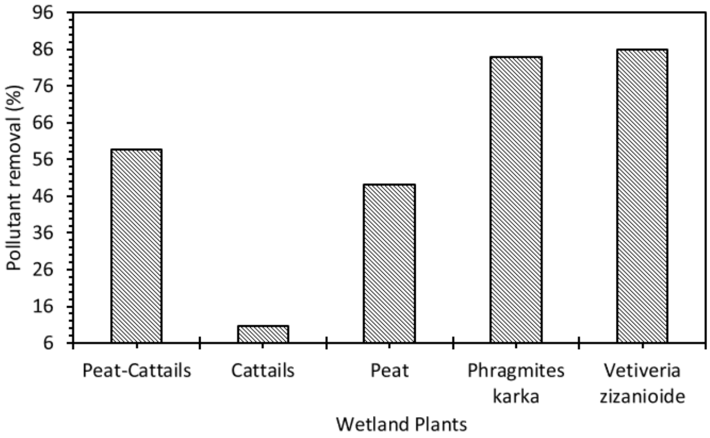

Figure 3. Phosphorus removal efficiency with different wetland plants.

3.5. Wetland plant.

The present study investigated the efficacy of wetland plants, specifically *V. zizanioides* and *P. karka*, in removing phosphorus and nitrogen from wastewater in constructed wetlands. The findings indicate that plants with extensive root systems and large biomass can be appropriately aerated in CWs to effectively remove pollutants. *V. zizanioides* demonstrated higher removal efficiency for PO_4-P (86%) and NO_3-N (84%) than *P. karka.* As a result, the treated water pollutants meet the standards set by the EEPA and WHO (pH = 6-9, NO3-N = 10 mg/l, NH_4-N = 30 mg/l) and can be discharged directly into surface waters or used for irrigation. The study further revealed that a well-developed root system is crucial for the successful selection of constructed wetland plants. This is because plants with developed root systems secrete more root exudates, which create favorable conditions for the survival of microorganisms, promote rhizosphere biodegradation, and improve the purification capacity of the constructed wetland [59]. Moreover, the root systems of plants play a vital role in fixing the surface of the bed, enveloping the soil, maintaining the vigorous vitality of plants and microorganisms, and ensuring the stability of the wetland ecosystem. Therefore, large aquatic plants, such as *V. zizanioides* and *P. karka*, with strong root systems and many developed adventitious roots are better suited for water purification in constructed wetlands, while small species, such as *P. stratiotes*, with less developed root systems, may have less effective purification capacity [60].

Anderson demonstrated that plant rhizosphere exudates promote microbial transformation and accelerate the biodegradation of pollutants [61]. Additionally, Liang et al. found that urease activity in wetland soil is positively correlated with soil microbes, organic matter, and total nitrogen, and is also positively correlated with the removal rate of TN from constructed wetland sewage [62]. The study revealed a positive correlation between urease activity and the removal rate of TN from constructed wetland sewage. Therefore, the urease activity in the root zone soil of CWs can serve as a primary indicator of their effectiveness in eliminating nitrogen-containing pollutants from sewage. Furthermore, this finding highlights the possibility of utilizing enzyme activity as a criterion for selecting suitable wetland plants. In addition to the role of plants in removing pollutants, their root systems are also vital in stabilizing the wetland ecosystem by anchoring the bed surface, enveloping the soil, and maintaining the vigorous vitality of plants and microorganisms. Adcock noted that aquatic plants such as *V. zizaniodes* and *P. karka*, which have strong root systems and well-developed adventitious roots, are better suited for water purification, while small species like P. stratiotes have less developed root systems and are, therefore, less effective in purifying water [63].

4. Conclusions

CWs containing peat and cattails have the capacity to effectively treat wastewater and meet municipal regulatory discharge standards. The experimental results indicated that maintaining pH levels below 7.5 resulted in improved removal of NO_3–N, TN, and PO_4-P. Peat introduction had a more significant impact on the wetland system compared to cattails. The physical and chemical properties of peat make it an effective pH reducing agent, which greatly enhances phosphorus removal efficiency. However, the presence of peat leads to a decrease in the ability of cattails to remove nitrogen compounds. Despite this, the introduction of cattails contributes to increased nitrogen removal efficiency, providing additional removal pathways. Among the plants analyzed, *V. zizaniodes* and *P. karka* exhibited high pollutant removal performance in all parameter analyses. The choice of plants plays a significant role in determining the treatment efficiency of CWs with regard to organic pollutants, nutrients, and microorganisms.

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Competing Interest

The authors declare no conflict of interest.

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