International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 8, 2025
https://theaspd.com/index.php

Integrated Efficacy Assessment of Constructed Wetland for Nutrients and Organics Removal in Piggery Wastewater Under Tropical Conditions

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Abstract
Piggery effluent is composed of a large percentage of water which makes it a target for exploitation such as in reuse for agriculture but its disposal without treatment leads to contamination of both surface and subsurface water resources. The study investigated the treatment of piggery wastewater in constructed wetlands under selected hydraulic retention times (HRTs). Two HRTs (3 and 5 days) were used to monitor the contaminant reduction efficiencies (CREs) of the CW at the outlet of the treated effluents. Standard methods were used to analyse the contaminants (nutrients and organics) for the characterization of the effluent quality. The data collected were analysed using one-way ANOVA for the CREs at P < 0.05. The CRE values for the 3- and 5-day HRTs were found to be 62.50 and 58.33%, 51.70 and 51.91%, -2.07 and 9.01%, -20.46 and -12.48%, 84.76 and 86.84%, 61.87 and 60.43% and 77.60 and 74.90% for TN, TP, Ca, Mg, Na, COD and BOD respectively. As expected, the wastewater injected into the constructed wetland system was treated, and for both HRTs, a sizable amount of the nutrients present in the wastewater were retained by the substrate. Furthermore, the macrophytes absorbed a portion of the wastewater nutrients. The results of the study gave insight into the effectiveness of Coix lacryma J. CWs at the chosen HRTs.
Keywords: *Constructed wetland, piggery wastewater, hydraulic retention time, nutrients, organics, efficacy.*

1. INTRODUCTION

Availability of water is an essential requirement for crop production with about 70% of available global freshwater being reported to be utilized in Agriculture especially in areas with significant irrigation needs for crop production (UNESCO, 2024). This figure underscores the strain on freshwater resources, particularly in regions facing water scarcity due to climate change and population growth. According to the World Water Development Report, agriculture remains the largest consumer of the world's freshwater resources, with the trend expected to continue as food demand increases with global population growth (UN-Water, 2023). The recent rise in population and global warming due to climate change give rise to a strict competition for the available freshwater among the different consuming sectors of the world (UN-Water, 2023).

High-strength wastewater with noticeable seasonal variations in both quantity and quality can be produced by agro-food operations, particularly intensive livestock husbandry (UN-Water, 2023). Although swine slurry's composition varies widely, nitrogen is its primary constituent of concern. In particular, untreated swine slurry has high ammonium concentrations, depending on the farm's features, and significant volumes of non-stabilized organic matter (Raphael et al., 2020). According to (Armrnegol & Salgot, 2013), spreading too much slurry over croplands can primarily lead to nitrate pollution of groundwater and eutrophication of surface waters because of the phosphorous content. Excessive nitrogen intake from swine slurry can build up in soils, causing an overabundance of nitrates that subsequently seep and percolate. At saturation, as reported by Wang, Li, and Zhang (2018), nutrients are lost by leaching exponentially to either surface or ground waters at saturation. Around the world, large volumes of swine slurry are currently produced. A maximum of roughly 50 heads of slurry can be accommodated on 1 acre of land in sensitive locations when discharge limits are applied. In regions with heavy production, there are occasionally more over 1,000 heads per hectare of land.

Under such conditions, there is an excess of manure that cannot be used in agriculture without first being pre-treated (De Medina-Salas et al., 2021).
Many treatment methods for treating wastewater have been evaluated with many physical, chemical and biological treatment technologies developed, tested and adopted successfully (Raphael et al, 2019). Most of these sophisticated technologies are expensive and therefore not sustainable in developing country like Nigeria high production cost, skilled labour and high-power supply requirement for operation and maintenance (Fernández Ramírez et al., 2023). Constructed wetlands (CWs) which are engineered systems designed to use natural wetland functions to improve wastewater quality ((EPA, 2020). They have proven to reduce the amount of nutrients in the liquid fraction of the wastewater (Zheng et al., 2024; Water Environment Federation, 2017). Treatment efficiency of CW for piggery effluent varies for different pollutants and changes considerably in space and time, depending mostly on the type of CW used, its design, age of the system, feeding mode (how wastewater is applied), hydraulic load (HL) and hydraulic retention time (HRT) as recorded by (Ramos et al., 2022). This study developed a coix seed plant-covered Horizontal Sub-Surface Flow Constructed Wetland (HSSFCW) system for treating piggery feedlot wastewater and characterizes the pre and post treated effluent in the constructed wetland to assess the reduction efficiencies of the nutrients and organics.

2. MATERIALS AND METHODS

2.1Description of the study location

This study was conducted in a screen-house located at the Research and Demonstration Farm of the Department of Agricultural and Bio-Environmental Engineering at The Oke-Ogun Polytechnic, Saki (TOPS) in Oyo State, South Western Nigeria. The institution's coordinates are 3.40491008225 Easting and 8.63801057654 Northing. It is located close to the beginning of the Ofiki River, the main branch of the Ogun River, approximately 60 km (40 miles) from the Republic of Benin border (Geodatos, 2024). In Saki, the wet season is oppressive and overcast, the dry season is humid and partly cloudy, and it is hot year-round. Saki experiences year-round temperatures of 26.3°C. March is often the warmest month, with an average temperature of 28.9°C. August is typically the coolest month, with an average temperature of 24.2°C (Weather Spark, 2024).

2.2Wastewater collection and characterization

The wastewater was collected from Sunday Otunla Farms Limited, a local piggery farm in Saki West Local Government Area of Oyo State, Nigeria. A typical piggery pen for the collection of the wastewater was as shown in Figure 1. The wastewater samples were taken with two litre polyethylene bottles and were preserved and taken for pre-treatment analysis to ascertain the extent of contamination at the National Soil and Water Laboratory, Ibadan, Oyo State. To minimize changes in the parameters, all sampling bottles were washed, rinsed with distilled water and filled the wastewater to capacity leaving no air above the sample and then kept in an ice box before being transported to the laboratory for analysis. The samples were transported for analyses within few hours of sampling. The sampling and pre-treatment characterization were repeated at a regular interval during the experiment as new piggery effluent are being added to the inflow reservoir of the constructed wetlands so as to cater for the variations in the parameters of the wastewater from the farm. The mean value was determined and considered as the pre-treatment pollution status of the wastewater. The parameters determined include organics such as Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD); Macro nutrients – Total Nitrogen (TN) and Total Phosphorus (TP); and micro nutrients such as Iron (Fe), Zinc (Zn), Calcium (Ca), sodium (Na) and Magnesium (Mg).
Both the raw and treated effluents were subjected to laboratory analysis to determine the performance of the CW treatment system. The variations obtained in the concentrations of the selected parameters of the inflow wastewater before treatment and the outflow wastewater after the treatment were used to calculate the Contaminant Reduction Efficiency (CRE).

2.3Description of the CW

A Pilot-scale type of horizontal sub-surface flow CW (HSSFCW) was adopted for this study using 1000 litres reinforced portable plastic tank. Each tank was cut into two and the height was also reduced to slightly above the root zones of the selected macrophyte to create the pilot-scale CWs. The reduction of the height to slightly above the root zone was to achieve roots contact with the wastewater during the treatment. Job Tears (*Coix lacryma-jobi*), an aquatic plant was used as the macrophyte. Inflow and outflow pipes of the CWs have ball valves were installed in them as control gates for proper management of flow and draining of the of the treated effluent from the wetlands.

Figure 1 A typical piggery pen for the wastewater collection

The HRT which is the effluent detention time (days) for the introduced wastewater into the CWs was varied at two levels of 3 and 5 days.

2.4Piggery wastewater pre-treatment

The collected piggery wastewater was taken through a screening cloth bag to remove floating and suspended particles to serve as a form of pre-treatment before introduction into the pilot-scale CWs. The cloth bag was rinsed in clean water after each batch of pre-treatment operation before the introduction of another batch of wastewater.

2.5Performance of the CW

The performance of the CW under specific operational conditions was typically evaluated by calculating the percentage reduction of contaminants, referred to as the CRE. This metric depends on the concentrations of contaminants in the inflow and outflow of the wetland. CRE is calculated using equation 1, adapted from Abdelhakeem, Aboulroos, and Kamel (2016):

$$\mathrm{CRE} = \frac{(\mathrm{Cinflow} - \mathrm{Coutflow})\,.100}{\mathrm{C\ inflow}} \qquad (1)$$

Here, C_{inflow} and $C_{outflow}$ represent the contaminant concentrations in the inflow and outflow of the wetland, measured in mg/L. This formula calculates the percentage reduction of contaminants as they pass through the system, offering a clear indicator of wetland performance.

2.6Data Analysis

The variations in the characteristics of the treated and untreated wastewater were assessed and also the calculated values of the contaminant reduction efficiency statistically tested for using a one-way ANOVA also at 5% significant level using IBM SPSS 23 as the statistical package (IBM Corp. 2015).

3. RESULTS AND DISCUSSION

3.1Characterization of the untreated piggery pen wastewater

The average values of the selected parameters analysed for in the untreated piggery pen wastewater were shown in Table 1. The parameters are selected organics - COD and BOD; macro nutrients - TN and TP and micro nutrients - Mg, Na and Ca. For the organics, the COD and BOD_5 average values were 1112$\pm$356.05 mg/l and 586.8$\pm$142.40 mg/l respectively, macro nutrients, TN and TP had values of 0.024$\pm$0.40 mg/l and 0.942$\pm$2.36 mg/l respectively while micro nutrients, Mg, Na and Ca had average values of 53.21$\pm$11.42 mg/l, 289.50$\pm$9.25 mg/l and 316.71$\pm$55.93 mg/l respectively.

The analysis results of the untreated piggery pen wastewater revealed significantly high levels of both organic and nutrient pollutants, confirming its strong contamination potential and environmental impact if discharged untreated. The average COD and BOD values observed are characteristic of concentrated animal waste and exceed permissible discharge limits by regulatory agencies such as NESREA and WHO (Ogunbanwo et al., 2023). These elevated values indicate a high organic load, with COD levels representing the total oxidizable material and BOD reflecting the biodegradable fraction. The high BOD/COD ratio (approximately 0.53) also suggests that the wastewater contains a significant portion of readily biodegradable organic matter, supporting the potential for biological treatment (Saleh et al., 2022).

Table 1: Average values of untreated wastewater characteristics

Parameters	**NT**
Total Phosphorus (mg/l)	0.942
Total Nitrogen (mg/l)	0.024
COD (mg/l)	1112
Calcium (mg/l)	316.711
Magnesium (mg/l)	53.211
Sodium (mg/l)	289.50
BOD (mg/l)	586.80

Legend:
NT – Raw wastewater

In terms of macronutrients, TN and TP concentrations were measured and presented as above. The low TN level is likely influenced by the form and state of nitrogen present, particularly losses due to volatilization of ammonia or conversion to other forms prior to sampling. On the other hand, TP concentration is comparatively higher and may pose a risk of eutrophication if discharged into surface water bodies (Ahmed et al., 2023). Phosphorus in piggery waste is often associated with undigested feed and faecal matter, and its presence at nearly 1 mg/L aligns with findings in similar studies on untreated livestock effluents (Chen et al., 2022).

Micronutrient analysis showed elevated levels of cations which are consistent with the mineral content of pig diets and the use of hard water in piggery operations (Kebede et al., 2020). High concentrations of Na and Ca may impact soil permeability and structure if such wastewater is used for irrigation without proper treatment or dilution, potentially leading to sodicity issues (Adelani et al., 2020).

Generally, the data indicates that untreated piggery wastewater poses a serious threat to the environment due to its high organic load, nutrient richness, and mineral content. The findings underscore the urgent need for appropriate treatment methods such as constructed wetlands, anaerobic digestion, or integrated bio-physical treatment systems before any reuse or discharge (Li et al., 2023; Kumar et al., 2023).

3.2Characterization of the CW

The constructed wetland characterization in terms of variations in the mean laboratory analysis values of both the raw and treated effluents at the two HRTs which is the effluent retention time (in days) for the introduced wastewater into the CWs were revealed in Figures 2 and 3. The mean values for the 3- and 5-day HRTs are 0.46±0.05 and 0.43±0.04 mg/l, 0.009±0.05 and 0.012±0.05 mg/l, 424±130.87 and 528±116.54 mg/l, 131.30±52.35 and 147.30±46.62 mg/l, 323.25±54.85 and 288.17±43.97 mg/l, 64.10±9.96 and 59.85±8.42 mg/l, 44.11±10.27 and 38.11±8.76 mg/l, for TP, TN, COD, BOD, Ca, Mg and Na respectively.

TP concentrations were reduced at both the 3- and 5-day HRTs, suggesting effective phosphate uptake and retention in the wetland substrate and by plant uptake mechanisms. The slightly improved reduction at 5-day HRT is consistent with the trend that longer HRTs allow for increased sedimentation, adsorption, and plant uptake of phosphorus (Vymazal & Březinová, 2021). The reduced values fall within acceptable discharge limits for surface water discharge in many regulatory frameworks. TN values were similarly low for both selected HRTs. While the 3-day HRT showed a marginally lower TN, the values at both retention times indicate nearly complete nitrogen removal. This could be attributed to combined nitrification–denitrification processes occurring within the aerobic and anaerobic zones of the CW, as well as potential plant uptake and microbial assimilation (Leng et al., 2023).

The analysed micronutrients also demonstrated moderate noticeable reductions at the two selected HRTs. These reductions are attributed to sedimentation, cation exchange in the wetland substrate, and possible uptake by wetland plants (Akratos & Tsihrintzis, 2021; Adelani et al., 2020). Notably, a longer retention time generally improved the removal efficiency of these ions, supporting existing findings on HRT's critical role in cation mobility within wetland matrices.

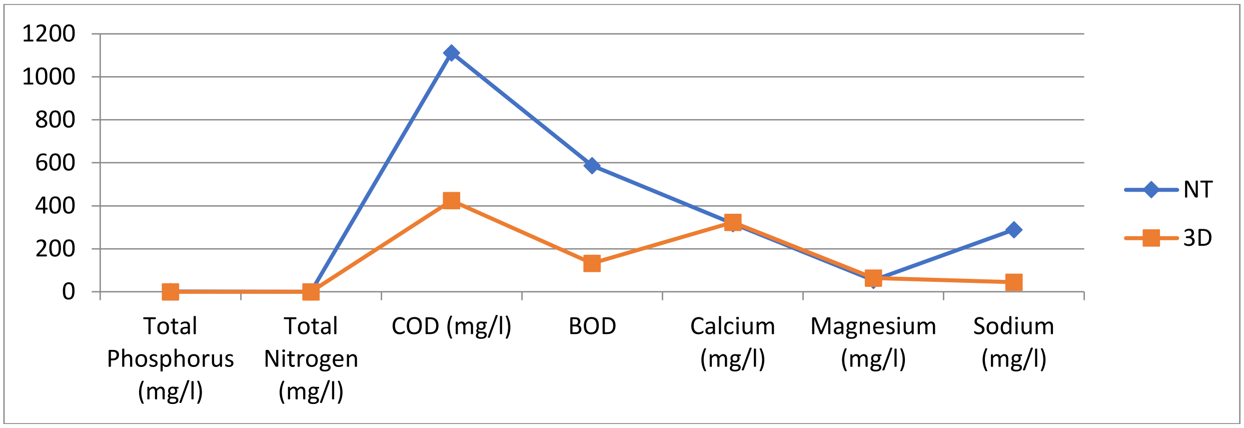

Figure 2: Variations in the wastewater parameters at 5-day HRT
Legend: 3D – 3-day HRT effluent

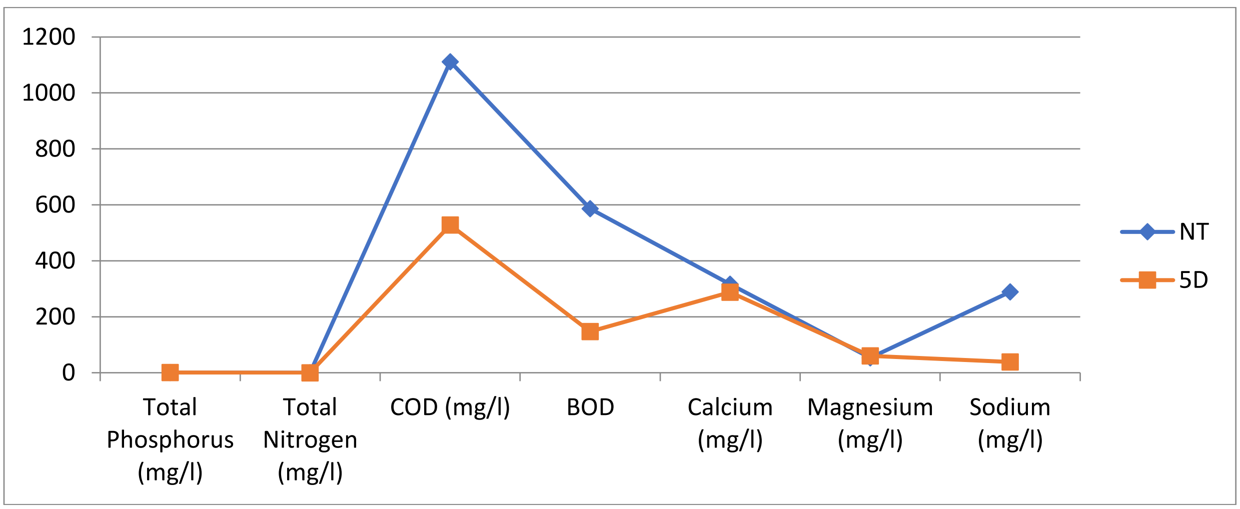

Figure 3: Variations in the wastewater parameters at 5 days HRT
Legend:5D – 5-day HRT effluent

For organic pollutants at the 3- and 5-day HRTs, a lower COD and BOD was observed at the 3-day HRT. This counterintuitive result may reflect episodic system dynamics such as variable loading rates or higher microbial activity at shorter retention times (Gaballah et al., 2021). Nonetheless, both HRTs achieved significant reductions compared to raw wastewater, validating the CW's capability for degrading organic matter (Li et al., 2023).
The CW conclusively demonstrated efficient pollutant removal across both retention times, with slightly better performance for nutrients (both macro and micro) contaminants at the 5-day HRT, while 3-day HRT showed better or equivalent removal of the organics, likely due to dynamic microbial responses. These findings are consistent with previous studies highlighting the influence of HRT on treatment performance and affirm the potential of CWs as a sustainable wastewater treatment option for high-strength piggery effluent (Leng et al., 2023; Kumar et al., 2023).

3.3Performance of the developed CWs planted with C*oix lacryma-jobi*

The constructed wetland system, as expected, treated the wastewater introduced into the system, and the substrates also absorbed a large part of the nutrients in the piggery wastewater as also observed by Olawale et al., (2021). The performance of the CW in terms of the contaminant reduction efficiency (CRE) in percentage at the two HRTs was determined, and the relationship was shown in Figure 4. The CRE values for the 3- and 5-day HRTs were found to be 62.50 and 58.33%, 51.70 and 51.91%, -2.07 and 9.01%, -20.46 and -12.48%, 84.76 and 86.84%, 61.87 and 60.43% and 77.60 and 74.90% for TN, TP, Ca, Mg, Na, COD and BOD respectively.

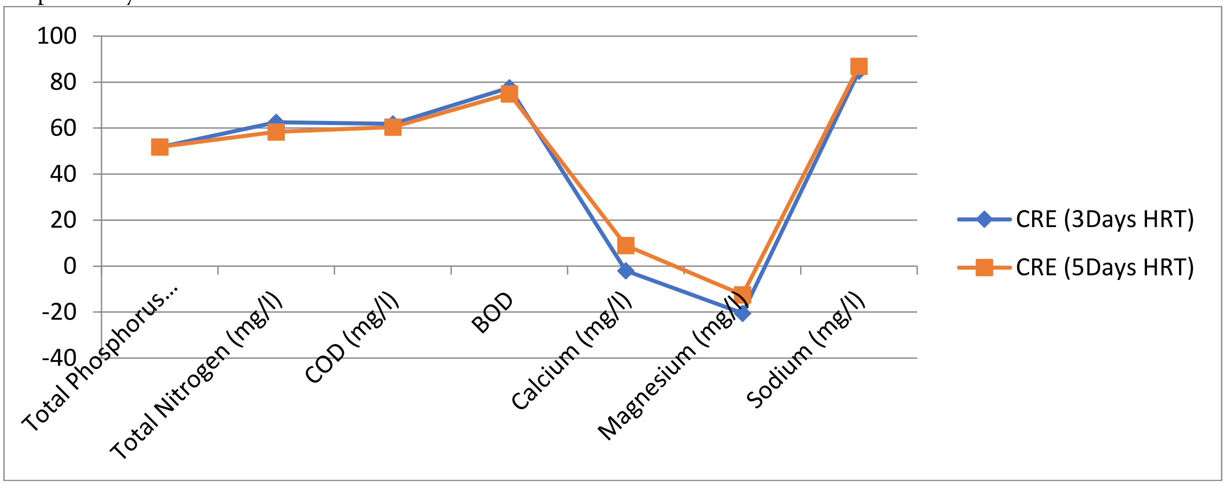

Figure 4: CW performances in terms of the CREs

The constructed wetland (CW) system effectively reduced most contaminants in the piggery wastewater, with notable removal efficiencies observed for BOD, COD, TN and TP at both 3- and 5-day HRTs. These results are in tandem with previous studies that reported efficient removal of organic matter and nutrients in CWs treating livestock effluent (Li et al., 2023; Leng et al., 2023). The substrates contributed significantly to nutrient absorption, particularly for Na which is consistent with findings on cation exchange and adsorption processes in wetland media (Akratos & Tsihrintzis, 2021). The macrophyte also absorbed a portion of the wastewater nutrients. However, the negative CRE values for Ca and Mg suggest either solubilization, potential ion leaching or limited substrate retention capacity, as similarly observed in other systems handling mineral-rich wastewater (Adelani et al., 2020). Generally, the system revealed high efficiency in reducing organic pollutants and nitrogen, supporting the applicability of CWs for sustainable livestock wastewater management.

4. CONCLUSION

The results of this study show that the effectiveness of reducing contaminants in the HSSFCW planted with *Coix lacryma-jobi* for the treated piggery effluent varied depending on the selected HRTs. The TN as a macro nutrient and all micro nutrients such as Ca and Mg, showed improved reduction efficiencies with longer HRT of 5-day while the organics, TP and Na showed higher values of CREs at 3-day HRT. The CREs showed a statistically significant difference at the 5% significance level (P < 0.5) between the raw wastewater and treated effluent (Table 3). However, it is important to note that not all parameters saw decreased values with longer HRTs, underscoring the need to fine-tune these conditions for optimal results. The characterization of treated effluents at the selected two HRTs also showed improvement compared to the raw wastewater.

As expected, the wastewater injected into the constructed wetland system was treated, and for both HRTs, a sizable amount of the nutrients present in the wastewater were retained by the substrate. Furthermore, the macrophyte absorbed a portion of the wastewater nutrients. In general, this research emphasized the efficacy of utilizing HSSFCW, especially with *Coix lacryma-jobi*, as a practical phyto-filtration and rhizo-filtration approach for addressing agricultural wastewater.

5. Acknowledgements

I would like to express my deepest gratitude to my supervisor for the PhD, Prof. J.O. Ojediran, for your invaluable guidance, encouragement, and unwavering support. Your mentoring has been instrumental in shaping both this journal article and my academic growth, and for that, I am forever grateful. I also express a heartfelt thank you to the co-supervisor, Dr. O.D. Raphael. Your expertise, thoughtful insights, and continuous encouragement have been vital in the development of this paper.

6. Author's Contributions

Adeyolanu, A.S. – conceptualization, investigation, reviewing, methodology, writing an original draft, funding acquisition.
Ojediran, J.O. – project administration.
Raphael, O.D. – writing-reviewing and editing.

7. **Conflict of Interests:** The authors declare no conflict of interest.

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