



PARTITIONING NUTRIENTS CYCLING IN A CONSTRUCTED SUBSURFACE WETLAND TREATING PIGGERY WASTEWATER FOR POLLUTION CONTROL

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ABSTRACT

Piggery wastewater management is an environmental concern due to the risk of nutrient pollution on surface and groundwaters. In surface and subsurface flow constructed wetlands, nutrient removal show inconsistency, and the contributions of their various partitions remain unclear; making the optimization of Constructed Wetlands (CW) systems difficult. *Pennisetum clandestinum* plants and sediment in constructed wetlands play important roles in nutrient polishing and reduction but their capacities have not been partitioned. An experimental constructed Horizontal Sub-Surface Flow Wetland (HSSFW) planted with *Pennisetum clandestinum* was fed from a piggery wastewater source at Akwa Ibom State University (AKSU). Samples of piggery wastewater were collected before and after each six respective days of detention in the wetlands. Nutrient mass balances and effluent qualities of the partitions were evaluated based on World Health Organization (WHO) and Nigeria Environmental Standards Regulation Enforcement Agency (NESREA) benchmarks. Nitrogen detention by sediment, plant uptake, denitrification and water column partitions in planted HSSFCW varied between 4.32-18.3, 8.71- 40.3, 6.6-17.4 and 24-80.37% respectively, while the unplanted HSSFCW nitrogen detention varied between 5.3-24.3, 6.3-16, 59.7- 88.4% respectively. Phosphorus detention in planted HSSFCW varied between 7.2-45.2, 3.5-28.6 and 26.2-89.3% for sediment, plant and water column concentrations respectively, while the unplanted HSSFCW phosphorus equilibrium between sediment and water column fluctuated between 9.8-55.6% and 44.4-90.2% respectively. NESREA benchmarks was generally attained in three days. The result outlined the importance of plant uptake and sediment storage as major nutrient removal pathways in wastewater polishing and improving pollution control. Increasing the proficiency of these compartments would also improve removal efficiency and reduce nutrient impact on land and water.

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1.0 Introduction

Intensive piggeries constitute point sources of nutrient loaded waste waters which is the primary cause of algal bloom in the Akwa Ibom State University (AKSU) tributary of the Obio Akpa river. Reduction of the nutrient concentrations in the wastewater to required standard for discharge to land and surface water is necessary (Mariet et al., 2013). One economical way to do this is to optimize the efficiency of agricultural wastewater treatment technologies to cope with the continuous intensification of waste generation and pollution of land and water resources particularly in developing countries (Adeyi et al., 2014). According to Schilling (2021) the best economical approach to decrease wastewater nutrient and sediment loads to streams and rivers is to create wetlands along water courses to intercept and process approaching wastewater loads.

Constructed wetland (CW) treatment of agricultural wastewater has been proven (Wetzel, 2001) as a technology that substitute centralized physical infrastructures with lower cost community scale systems, environmental sustainability and efficiency in removing nutrient from agricultural waste waters (Ghrabi *et al.*, 2011; Waly *et al.*, 2022). The ability of CW to treat piggery wastewater for discharge to land and surface water in the study area was demonstrated by Udom *et al.* (2018). However, the ability of CW to remove nitrogen and phosphorus varies (Udom *et al.*, 2023) and an understanding of the removal mechanisms is necessary to explain the role each of the CW compartments play in the nutrient recycling and removal (Kurzbaum *et al.*, 2012).

This is important following the observation of El-Sheikh *et al.* (2010) and Kurzbaum *et al.* (2012) admitting that the difficulty of optimizing CW systems could be abated by addressing observed inconsistencies in nutrient removal and vagueness in the contributions of the various partitions in nutrient cycling

2. Materials and Methods

2.1 Study Area

The study was carried out at the Obio Akpa river watershed on the campus of the Akwa Ibom State University. The location of Obio Akpa is shown in Figure 1.



Figure 1: Site map of Obio Akpa Source (<https://goo.gl/maps>)

Obio Akpa campus is located between longitudes $07^{\circ} 3''$ E and $07^{\circ} 3''$ E and latitude $04^{\circ} 45''$ N and $04^{\circ} 55''$ N in the humid tropics. The minimum and maximum temperatures range between $18-27^{\circ}\text{C}$ and $24^{\circ}\text{C}-36^{\circ}\text{C}$ respectively. Relative humidity ranges between 55-86%. Rainfall has a bimodal distribution lasting from April to October with a short break in August. Average rainfall values range from 2050 to 2450 mm (Udom *et al.*, 2018)

2.2 Wetland Design

Three concrete horizontal subsurface flow (HSSF) wetland basins sized 7 m x 1.75 m x 0.60 m and lined with a 2.5 mm thick polythene soil liner were constructed within Akwa Ibom State University, Obio Akpa campus, in immediacy with the piggery building for the experimental purpose. Both the wastewater inlet and outlet sections of the wetland basins were filled up to 0.60 m depth with 30 mm crushed granite rock extending one meter from the walls into the treatment area. The wetland basin was filled up to 0.60 m depth with the coarse floodplain soil.

Two of the wetland cells were then planted with *Pennisetum clandestinum* (PC) and the control (C) was not planted. Thereafter, the wetland was left for three months to stabilize before delivery of wastewater (Kostel, 2019).

2.3 Operating Method

The inflow rates of the secondary effluent in the three cells were constant at 9.6 m³/day. The water levels were maintained at 10 cm just below the surface of the treatment cells. Each cell was sampled daily from days 1–6. The flow of 3 m³/day was delivered by gravity flow through a system of pipes to each of the CW treatment cells. The area, porosity and theoretical hydraulic retention time HRT estimated by Kostel (2019) as:

$$HRT = LW \frac{yn}{Q} = \frac{\text{wetland volume } (V)}{\sum \text{inflows } (Q)} \quad (1)$$

Where,

L = Length of the wetland cell (m); W = Width of the wetland cell (m); y = depth of water in the wetland cell (m), n = porosity or the space available for water to flow through the wetland (a percent expressed as a decimal) ; Q = Ayp = average flow rate through the wetland (m³/d); A (m²) is the mean surface area of the system; V (m³) is the system volume; y (m) is the flow depth; p is the porosity, which is the existing space for the water to flow through the media, roots and other solids in the HSSF system.

2.4 Wastewater Sampling

Seven-months data of secondary piggery wastewater taken twice monthly, were collected before and after six days' detention in the wetland. The collection points were at the inlet to the wetland (0 m), the middle of the wetland (3.5 m) and at the outflow point (7.0 m) of each unit cell. Clean, labelled one-liter plastic bottles duly washed with detergent, rinsed and dried were used for wastewater collection. The bottles were then rinsed with effluent water samples three times before filling with water samples. The effluent samples were collected by tipping the outflow pipe for the wastewater to spill into a container after recording the rise of wastewater in the pipe which indicates the depth of effluent wastewater in the wetland basin for every sampling regime and retention time.

To assess the changes in nitrogen and phosphorus contained in the sediments, samples were collected from 0.25 cm and 0.50 cm depths using hand trowel since soil auger was not appropriate in order not to damage the liner on the CW floor. The samples were properly labelled and submitted to the laboratory for analysis. Samples from the sampling depths were mixed, ground to pass through a 40 mesh sieve, wet digested and analyzed for TN and TP using a 3-AA3 Auto Analyzer (Bran-Luebbe, Inc., Germany). This was done at the beginning and at the end of the sampling period. The difference between the initial and final nutrient values explained the amount of nutrient retained in the interval.

Plants (above and below ground) were tested destructively to appraise plant nutrient uptake from the soil in the beginning and at the end of the experimental period. Each entire plant was harvested, washed and rinsed with pure water and blotted with absorbent paper. It was easy to uproot whole plants because the roots only proliferated in the shallow depth above the plastic liner. The harvested plants were oven dried at 80 °C for a minimum of 48 hours until constant weight was achieved (Ademoroti, 1996). All dried plant samples were powdered separately in a micro plant grinding machine to less than 1 mm, wet digested and analyzed for total nitrogen and phosphorus using spectrophotometric method according to Ademoroti (1996).

2.5 Nitrogen Removal Mass Balance

Nutrient mass balances evaluated by computing the nutrient content of the various compartments in the wetland system before and after the retention time were compared with the Nigerian standard (NESREA, 2009). The complete equations of the various sinks involved in the nutrient transformations are stated in the following equations.

$$N_{influent} = \frac{C_i V_i}{A} \quad (2)$$

Where,

$N_{influent}$ = influent nitrogen (mg/l); C_i = influent nitrogen concentration (mg/l)

V_i = volume of the influent fed to the wetland (m³/d); A = constructed wetland area (m²)

$$N_{input} = N_{effluent} + N_{plant} + N_{media} + N_{others} \quad (3)$$

Where,

N_{input} = total nitrogen input to the wetland system (mg/l)

$N_{effluent}$ = nitrogen content in effluent (mg)

N_{plant} = nitrogen content in plant biomass (mg)

N_{media} = nitrogen in wetland media (mg)

N_{others} = nitrogen loss from wetland by other processes (mg)

$$N_{effluent} = \frac{C_e V_e}{A} \quad (4)$$

Where,

C_e = effluent nitrogen concentrations (mg/l); V_e = volume of the influent (litres)

A = constructed wetland area (m²)

$$N_{plant} = M_{final} N_{final} - M_{initial} N_{initial} \quad (5)$$

Where,

M_{final} = average dry biomass per wetland at the end of the study period (mg)

$M_{initial}$ = average dry biomass per wetland at the beginning of the study period (mg)

$N_{initial}$ = average N concentration in plants as percentage of dry weight at the beginning of the study period (mg/l).

N_{final} = average N concentration in plants as percentage of dry weight at the end of the study period (mg/l).

$$N_{media} = W_{media} \times N_{media} \text{ at the end per unit area and days of operation} \quad (6)$$

Where,

W_{media} = dry mass of the media (mg)

N_{media} = mean N concentration in the wetland media (mg)

$$N_{others} = N_{input} - [N_{effluent} + N_{plant} + N_{media}] \quad (7)$$

Other losses involve the uptake by micro biota (bacteria, fungi, algae), dead leaves loss, denitrification, and ammonia volatilization.

2.6 Phosphorus Removal Mass Balance

Phosphorus mass balances calculated by computing the values of each of the compartments concentrations (Udom, 2018) are shown in Equations 8 - 13 below

$$P_{influent} = \frac{C_i V_i}{A} \quad (8)$$

Where,

C_i = influent concentration (mg/l).

V_i = volume of the influent fed to the wetland (litres)

A = constructed wetland area (m^2).

$$P_{input} = P_{effluent} + P_{plant} + P_{media} + P_{others} \quad (9)$$

$$P_{effluent} = C_e V_e \quad (10)$$

Where,

C_e = effluent concentrations (mg/l); V_e = volume of the influent (litres)

$$P_{plant} = M_{final} P_{final} - M_{initial} P_{initial} \quad (11)$$

Where,

M_{final} = average dry biomass per wetland at the end (mg/m^2)

$M_{initial}$ = average dry biomass per wetland at the beginning (mg/m^2)

$P_{initial}$ = average P concentration in plants as percentage of dry weight at beginning (mg/l)

P_{final} = average P concentration in plants as percentage of dry weight at the end (mg/l)

$$P_{media} = V_{media} \times \rho_{media} \quad (12)$$

Where,

W_{media} = dry mass of the media (mg)

ρ_{media} = density of the dry mass of the media (mg/l)

P_{media} = mean P concentration in the wetland media (mg/l)

$$P_{other} = P_{input} - (P_{effluent} + P_{plant} + P_{media}) \quad (13)$$

2.7 Analysis

Wetland treatment performance was evaluated in terms of reduction in concentration of targeted nutrients. Nutrient retention was calculated as the difference between input and output of N and P concentrations transport and presented in percent as changes in specific retention. Differences between compartments means evaluated by a one-way Analysis of Variance (ANOVA) was used to determine the significant differences in variations of nitrogen and phosphorus concentrations in the CW compartments.

3. Results and Discussion

The study evaluated nutrient uptake by plants, retention in the wetland sediment, water column and the effluent. The difference between the wastewater input and output and accumulation

accounted for other losses (denitrification). Phosphorus removal model included uptake by plants, retention in water column and sediment. Nutrient distribution in the constructed wetland (CW) compartments after six hydraulic retention days are shown in Tables I – 4.

3.1 Nitrogen Distributions

Table I show that Nitrogen concentration in planted wetland was partitioned among sediment, plants, water column and others specifically denitrification. The distribution of nitrogen in the planted wetland compartments for detention times ranging from one to six days are shown.

Table I: Mean nitrogen concentrations in planted cells

Wetland compartment	Pollutants concentrations (mgL ⁻¹)						
	0 HDT	1 HDT	2 HDT	3 HDT	4 HDT	5 HDT	6 HDT
Inflow	28.02						
Sediment		1.21±0.111	2.50±0.229	4.53±0.412	4.97±0.458	4.82±0.443	5.12±0.460
Plants		2.44±0.219	5.57±0.514	9.63±4.374	9.775±0.629	10.90±1.627	11.30±0.337
Water column		22.52±2.62	15.86±1.457	8.87±0.815	8.63±0.789	8.12±0.743	6.73±0.615
Others*		1.85±0.173	4.09±0.376	4.99±0.458	4.90±0.448	4.18±.382	4.87±0.448

HDT = Hydraulic detention time (days) *Denitrification

The distribution of nutrients among the wetland compartments progressively reduced the pollutant concentration in the water column as the compartments continue to strip off nutrients from the water column. After one day retention, the sediment compartment of the planted CW absorbed 1.21 ± 0.11 mg/l (4.32%) of the inflow nitrogen. From the second to the sixth day, nitrogen storage in sediment increased to 2.5 ± 0.21 mg/l (8.92%), 4.53 ± 0.41 mg/l (16.17%), 4.97 mg/l (17.74%), and 5.12 ± 0.46 mg/l (18.27%). Sediment deposition in wetlands benefits downstream water quality by retaining nitrogen that is sorbed to the sediments retained. This can have an important cumulative effect on water quality at the watershed scale. Plants storage also increased with number of days that wastewater was detained in the wetland. After initial value of 2.44 ± 0.22 mg/l (2.44%), plants uptake increased to 5.57 ± 0.51 mg/l (19.88%), 6.63 ± 4.37 mg/l (34.37%), 9.75 ± 0.63 (34.37%), 10.26 ± 1.63 m/l (35.69%) and 10.72 ± 0.34 mg/l (4.32%). Other losses, principally volatilization, increased from 1.85 ± 0.17 mg/l (6.60%) in first day of detention to 4.87 ± 0.45 mg/l (17.38%) at six days after wastewater detention. The water column concentration of 28.02 mg/l nitrogen received from the piggery facility changed markedly in the long run, losing 76% of its concentration to the wetland compartment and finally delivered 6.73 ± 0.62 mg/l effluent after six days of retention in the CW. The absorption of the nitrogen by the wetland media was the main path for nitrogen reduction in the water column, while denitrification played a complementary role both at the sediment-water boundary and in the overlying water (Shen, 2020.)

Table 2 shows how the nitrogen concentration in non-planted wetland was partitioned among sediment, water column and others specifically denitrification. The distribution of the concentrations in the non-planted wetland compartments reflects the effect of detention for times ranging from one to six days

Table 2: Mean nitrogen concentrations in non-planted cells

Pollutants concentrations (mgL ⁻¹)	0 HDT	1 HDT	2 HDT	3 HDT	4 HDT	5 HDT	6 HDT
Inflow	28.02						
Sediment		1.49±0.137	3.06±0.285	5.03±0.458	6.51±0.596	7.20±0.661	6.81±0.662
Water Column		24.78±2.272	20.87±1.915	18.00±1.650	17.56±1.609	17.59±1.614	16.93±1.548
Others*		1.78±0.164	3.89±0.358	4.99±0.463	4.95±0.453	4.37±0.401	4.66±0.428

HDT = Hydraulic detention time (days).

In the non-planted CW cells, (Table 2 column 3), nitrogen retention in the sediment increased from 1.49±0.14mg/l (5.22%) at 1HDT to 3.06±0.29 (28.77), 5.03±0.46mg/l (17.95%), 6.51±0.60mg/l (23.23%), 7.2±0.66 (25.70%) and 6.81±0.62mg/l (24.3%) at six days of retention respectively. CW water column concentration changed correspondingly from 24.78 ±2.27 mg/l to 20.87±1.92mg/l, 18.0±1.65mg/l, 17.56±1.61mg/l, 17.59±1.61 and 16.93±1.55mg/l respectively, after six days of retention in the CW. Other loses accounted for 6.35%, 13.88%, 17.81%, 17.67%, 15.60% and 16.63% for one to six days of retention respectively.

Nitrogen retention in sediment provides the process sites for reduction of nitrogen concentrations in CW. As particulates accumulate and settle on the wetland floor with their nitrogen loads from decomposed materials, they are used by microorganisms and plants (if available). If the rate of consumption is less than the rate of accumulation, there will be net increase in nitrogen retention in the CW sediment (Lee et al., 2009).

3.1.1 Sediment

Figures 2 and 3 shows nitrogen concentrations in CW compartments for planted and unplanted wetland conditions.

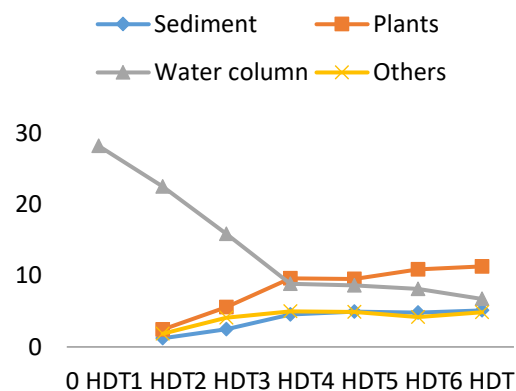


Figure 2: Nitrogen concentrations in planted wetland cells

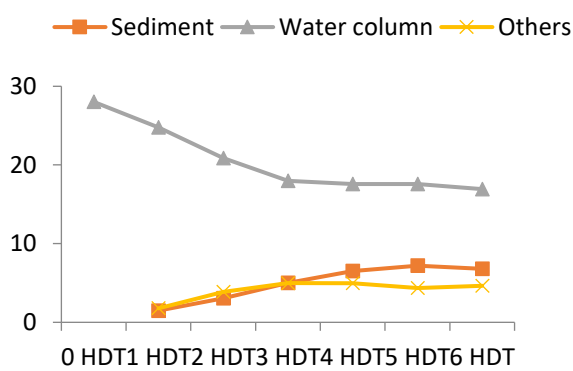


Figure 3: Nitrogen concentrations in non-planted Cells

Wetland soils constitute the single largest pool of N in wetland environments and the quantity of N amassed in CW soils is contingent on the balance between allochthonous import and particulate export.

Nitrogen partitioning to intact sediment is chiefly by adsorption, absorption, or precipitation (Thompson and Goyne, 2012). Sorptive concentration is the most significant influence on the accumulation of nutrients in wetland sediment. Figure 2 shows nitrogen concentration variations in the sediment. Nitrogen concentration in the sediment gradually built up linearly from 1HDT up to 3HDT followed by a near constant increase up to 6HDT. At the introduction of the wastewater, the increase in the nitrogen concentration resulted in an increase in the amount of sediment sorbed by the wetland sediment. Increased absorption of nitrogen by the sediment continued to drive the strip-off of nitrogen from the wastewater (the rising limb of Figure 2) towards nonlinearity. At higher concentrations, a maximum sorption plateau was reached at 3HDT after which subsequent (availability of nitrogen) increases in nitrogen concentration do not result in further sorption of nitrogen to the wetland sediment. This is the case in Figure 2 from 3HDT to 6HDT. This equilibrium condition continued until there was a change in any of the conditions in the wetland such as physicochemical and physical properties, properties of the pollutants, or environmental factors such as temperature and wetland moisture fluctuations.

Sediment retained 4.32% of available nitrogen concentration within 1HDT, 8.9%, 16.1%, 17.7%, 17.2% and 18.3% in 2,3,4,5 and 6 HDT respectively. A study by El-Sheikh *et al.* (2010) recorded initial increase in holding of pollutants in treatment bed followed by a decrease with distance along the bed. In the present study, there was an increase of 4.6% retention between 1 and 2 HDT, 7.2% between 2 and 3 HDT, 1.6% between 3 and 4 HDT, - 0.4% between 4 and 5 HDT and finally 1.1% between 5 and 6 HDT. The work of Xu *et al.* (2016) showed that an HDT of 12 h, gave an average total nitrogen (TN) removal efficiency of 91% and 41% when HDT increased to 24 h. There is an indication here of an optimal HDT and capacity beyond which efficiency increases negatively and storage capacity fluctuates.

3.1.2 Plants

Plants perform various key roles in constructed wetlands in wastewater treatment. Nutrient uptake by wetland plants contributes to the wetland removal process. Wetland plants require nutrients for growth and reproduction, and take up nutrients primarily through their root system (Vymazal, 2011).

As HSSFCWs do not efficiently remove nitrogen due to the low oxygenation of the filtration bed and thus low nitrification, plant uptake may be responsible for the removal of reasonable amount of nitrogen (Vymazal, 2020).

Nitrogen accumulation in the entire plant compartment is shown in Figure 2. At the onset (1HDT), the plant stored 8.71% of incoming nitrogen load. The amount of nitrogen stored by the plant compartment increased up to 40.3% in 6HDT. A rapid uptake in the first three HDTs was followed by a gradual accumulation of nitrogen in the plant compartment. Plant nutrient

concentrations are the highest in the beginning of the growing season and decrease gradually throughout the growing season as plants mature and senesce. Plants can only store finite amounts of nutrient at a particular time no matter the abundance in the water column. According to (Vymazal, 2020), nutrient standing stocks in wetland macrophytes are usually limited and do not increase linearly with available nutrients. The increase in nutrient concentration in the water column will not cause an increase of nutrient concentrations in the biomass but can result in higher above ground biomass. Generally, the removal of nitrogen in HSSFCWs is usually low or medium and the percentage of nitrogen removed by plant uptake increases with decreasing inflow load. (Vymazal, 2020), observed that in combination with low inflow loadings, the amount of nitrogen removed through above ground biomass harvesting in constructed wetlands treating municipal wastewater amounted to 62% of removed nitrogen. These results have a slight dissimilarity to a certain range as N removal transformations may be affected by plant species, media, wastewater type, retention times, loading rates, environmental climate (Vymazal, 2020). These results revealed that plants can actually play an important direct role in nutrients removal in lightly loaded systems.

3.1.3 Water column

CW water column serves as temporary storage for incoming wastewater to the wetland basin before distribution to other compartments for processing and retention.

The trend of nitrogen variation in wastewater column in both the planted and unplanted CW are shown in Figures 2 and 3. Beyond 3HDT, the concentration line of nitrogen in the unplanted CW appeared to be parallel to the sediment line indicating water column equilibrium with the sediment whereas that of the planted wetland continued to show a decrease in concentration. Nitrogen storage in water column varied from 80.37% in 1HDT to 56.60, 31.7, 29.9, 29.0 and 24.0% in 2,3,4,5, and 6 HDT respectively in the planted CW. In the unplanted CW, the water column held more nutrient in concentration compared to the planted CW. In the 1HDT, the unplanted CW held 10.10% more nitrogen in storage than the planted CW. From 2HDT to 6HDT, the unplanted CW held 22.54, 40.47, 40.83, 40.35 and 44.45% more nitrogen in storage than the planted wetland. This difference explains the role of the wetland plant in the CW nitrogen storage. A study by Wetzel (2001) showed that wastewater quality in the water column is not static but fluctuates with dynamic processes in the wetland sinks that extract pollutants from the wastewater either by direct assimilation or physiologically mediated alteration of absorption sites on sediment and plants.

The quality of wastewater column at the end of the HDT is the excess of the saturation of the sinks (temporary capacities) or interim extractions of nutrients by the wetland sinks. The residual wastewater is left behind in the wetland basin after the effluent is discharged or collected. As nutrients are added to the water column, the equilibrium is temporarily shifted and will rapidly return to the steady state as the nutrients are taken up by the various fractions of the solid phase. Thus, after reestablishment of equilibrium, there would be more nutrient in the system but not necessarily in the water column.

The main N removal pathway in the planted (Figure 2) and unplanted (Figure 4) wetlands had differences in nutrient storage in this present study. Differences recorded in storage in sediment compartment include 28%, 22.4%, 11.04%, 31%, 49% and 33% for 1 HDT to 6 HDT respectively. Similarly, differences in water column include 10%, 31.6%, 102%, 103%, 116.6% and 151.6% respectively for 1 HDT to 6 HDT. Losses due to denitrification decreased in the unplanted wetland from 1 HDT (-3.7%), 2 HDT (-4.9%), to 3 HDT (0%), increased from 4 HDT to 5 HDT (1.02% to 4.54%) and decreased again to -4.3%. Although the ANOVA values of $p \cong 1$ at 0.05 probability level for both the planted and non-planted HSSFCWs suggested that there was no difference between the compartments. The per cent differences obtained in this study indicates that plant uptake and sediment storage might be the key factors in wetland N removal.

The rapidly declining N removal efficiency with increasing loading rates as seen in Figure 3 may be because of limits on the rate of denitrification, nitrification, oxygen availability, or NH_3 or NO_3 diffusion.

3.2 Phosphorus Distribution

Table 3: Phosphorus concentrations in planted cells

Pollutants concentrations (mgL ⁻¹)	0 HDT	1 HDT	2 HDT	3 HDT	4 HDT	5 HDT	6 HDT
Inflow	10.42						
Sediment		0.76±0.071	2.03±0.183	4.36±0.403	4.49±0.412	4.63±0.420	4.71±0.432
Plants		0.36±0.036	1.08±0.101	1.46±0.137	1.63±0.147	2.52±.230	2.98±0.275
Water column		9.30±0.851	7.31±0.668	4.58±.422	4.30±0.376	3.27±0.301	2.73±0.249

Phosphorus concentration in the planted CWs varied through detention days with progressive increments in retention in the various compartments except the water column which concentration was decreasing.

Phosphorus in the sediment sink progressively increased from 0.76±0.07mg/l (7.29%) after the first day of detention to 2.03±0.60 (19.48%), 4.36±0.40 (41.84%), 4.49±0.41 (43.09%), 4.63±0.42 (44.43%), and 4.71±0.43 (45.20%) respectively, after the sixth day of detention. The wetland plants extracted phosphorus from the water column pool of nutrients. Plants phosphorus content progressively increased from 0.36±0.04 (3.45%) after one day to 1.08±0.10 (10.36%), 1.48±0.14 (14.2%), 1.63±0.15 (15.64%), 2.52±0.23 (24.18%) and 2.98±0.28 (28.60%) mg/l respectively from day two to six. There was continuous reduction of phosphorus concentration in the water column from 9.30±0.851 (89.25%), 7.31±0.668 (70.15%), 4.58±.422 (43.95%), 4.30±0.376 (41.27%), 3.27±0.301 (31.38) to 2.73±0.249 (26.20%) concentration from one to six days respectively.

Sedimentation follows once phosphorus attached to particles and aggregates in wastewater arrive a CW and, as the velocity of the water is reduced, the phosphorus particle can settle on the bottom. As reported by Braskerud (2002), sedimentation of particulate phosphorus is the main retention process in small CW in receipt of wastewater rich in suspended matter. One more

factor affecting the retention capacity is residence time. The longer time wastewater stays in a CW, the more phosphorus can be removed and retained through the different mechanisms in Table 3. The different compartments also will have the opportunity to take their full available supply from the pool. Increased phosphorus demand associated with plant and microorganism growth will deplete the water column phosphorus concentration to satisfy these needs if incoming supply is less than storage.

Table 4: Phosphorus concentrations in non-planted cells

Pollutants concentrations (mgL ⁻¹)	0 HDT	1 HDT	2 HDT	3 HDT	4 HDT	5 HDT	6 HDT
Inflow	10.42						
Sediment		1.02±0.092	2.18±0.199	5.63±0.514	5.68±0.520	5.68±0.520	5.79±0.306
Water column		9.40±4.585	8.24±0.753	4.79±0.439	4.74±0.432	4.74±0.432	4.48±0.453

The non-planted CW sediment sink phosphorus retention increased from 1.02±0.09 (9.79%) to 2.18±0.20 (20.92%), 5.63±0.51 (54.03%), 5.68±0.52 (54.51%) and 5.79±0.31 (55.57%) at the end of six days. The water column concentration gradually decreased from 9.40±4.59 (90.21%) to 8.24±0.75 (79.08%), 4.79±0.44 (45.97%), 4.74±0.43 (45.49%) and 4.48±0.45 (42.99) mg/l at the end of six days respectively. This is due to stripping of nutrients from the water column by the sediment to fill its empty sites and thus establish equilibrium within the CW system. As nutrients are added to the water column, the equilibrium is temporarily shifted and will rapidly return to the steady state as the nutrients are taken up by the sediment. Thus, after reestablishment of equilibrium, there would be more nutrient in the system but not necessarily in the water column (Braskerud, 2002).

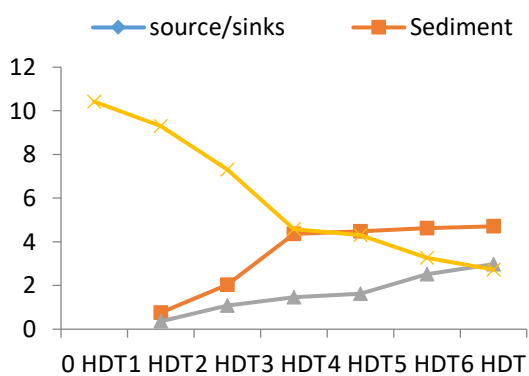


Figure 4: Phosphorus concentrations in planted cells

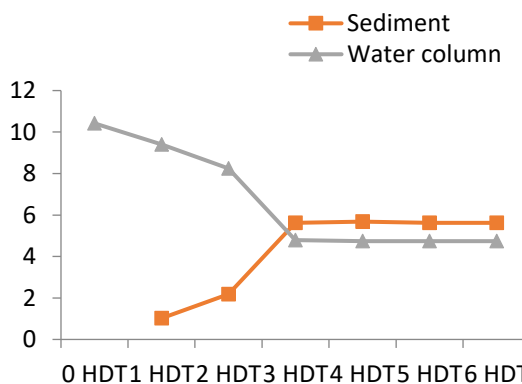


Figure 5: Phosphorus concentrations in non-planted cells

In Figures 4 and 5 show the trend of P storage in CW compartments. Maximum P retention capacity of soil/sediment was generally reached following saturation of all sorption sites. Sorption of P onto CW sediment and uptake by plants increased rapidly and initially as phosphorus that was stripped-off the water column was stored in the sediment and up taken by plants. After

3HDT, phosphorus storage in both sediment and plants reduced with sediment storage tending towards equilibrium and plant storage showing only minimal increase perhaps in response to plant growth. Zurayk et al. (1997) observed that P removal in the soil-based systems is rapid, and an equilibrium value may be reached beyond which no further removal is possible or negligible. Baldovi et al. (2020) deduced from phosphorus removal studies in a pilot scale free water surface constructed wetland that increasing the detention time of wastewater in the system will allow for more time for plant uptake of P, possibly resulting in higher removal rates. In the unplanted CW, incoming phosphorus stream supplied sediment storage up to the 3HDT when both the water column and sediment storage were in balance. The non-significant difference ($p=0.05$) between the planted and non-planted wetlands suggest no difference between the compartments, but the per cent differences obtained in this study indicate that sediment storage might be the key factors in wetland p removal. Hence, there is indication that from 1HDT to 3HDT, the increase is linear and from 4HDT to 6HDT, the increase is nearly constant. The main removal pathway in P was accumulation in the sediment.

3.3 Nutrient Balances with HDTs

Over the range of the HDTs, there were disparities in the concentration of nutrients in the wetland compartments. The accrual of concentration of nutrients in the compartments increased with increase in HDTs except for the water column which reduced as nutrients remained extracted toward the compartments. In Figure 2, the linearity of water column retention of nutrients approached a balance after 3HDT to a much less rate of decrease determined by the growing plant compartment. This trend was also observed in the non-planted cells (Figure 3). Although the capacities of the “others” compartment for nitrogen appeared to have been satisfied after 3HDT, the major exchange of nutrient remained between the sediment and water column as the balance between them keep shifting probably due to changes in environmental conditions particularly temperature. Obviously, higher HDTs improve the quality of the effluent by allowing more interaction time for nutrient removal processes in HSSFCW compartments to be maximized. In this study, nitrogen and phosphorus levels required by the Nigerian standard for wastewater quality for discharge to land and surface water was met in the 3HDT and subsequent increases in the HDTs resulted in marginal increases in nutrient removal. These increases, particularly for nitrogen, could be attributed to increased removal of NO_3 associated with denitrification predominant in planted HSSFCWs.

3.3.1 Nitrogen Balance

Figures 6 and 7 summarized the percentage of nitrogen detentions in the entire compartments in the planted and unplanted CWs. Plant uptake process was the major removal route of nitrogen from the water phase, accounting for 34.4% of the inflow nitrogen load, followed by retention in wetland water column (31.7%), denitrification (others) process accounted for 17.8% and lastly, sediment retention in wetland accounted for 16.1% all in the 3HDT. Saunders and Kalff (2001) identified denitrification as more operative than nitrogen sedimentation in inhibiting nitrogen from being transferred downstream. Plants escalate nitrogen retention through vegetative uptake

and offer favorable conditions for sedimentation and denitrification by increasing the supply of potentially limiting organic carbon and nitrate to denitrifying bacteria.

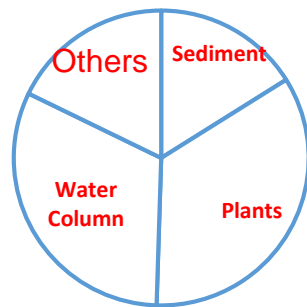


Figure 6: Nitrogen removal in planted wetland

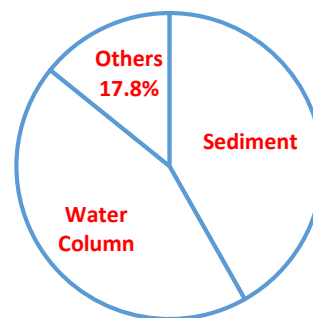


Figure 7: Nitrogen removal in non-planted wetland

In the non-planted CWs, the water column continuously held the nutrient in dynamic storage as high as 64.2% in 3HDT. Sediment retained 18% nitrogen while others (specifically denitrification) accounted for 17.8%. The amount removed by denitrification was the same with that of the planted wetland. This observation suggests non-fluctuation in temperature since denitrification is affected by temperature.

Szogi *et al.* (2003) and Hunt *et al.* (1997) observed that CW media adsorption and plant uptake are significant components of CW N cycling when they receive relatively low loading of N resulting in very significant denitrification occurring in the constructed wetland.

3.3.2 Phosphorus Balance

Figures 8 and 9 illustrate the trends in phosphorus removal in both planted and unplanted wetlands.

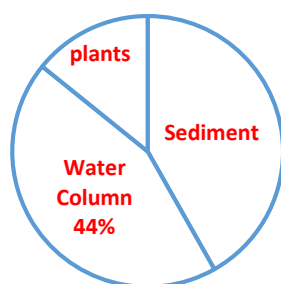


Figure 8: Phosphorus removal in planted wetland

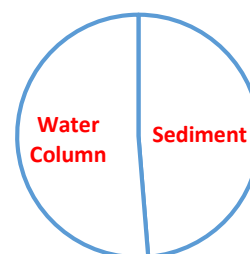


Figure 9: Phosphorus removal in non-planted wetland

Phosphorus detention in water column of planted wetland was 44%. Plant uptake contributed 14.20% and detention in the wetland sediment contributed 41.8%. Phosphorus retention in water column of unplanted wetland was 54% and retention in wetland sediment was 46% respectively.

Besides chemical adsorption by ligand exchange, the physical adsorption becomes operational as the chemical adsorption sites approach saturation at higher equilibrium concentrations of phosphorus in the water column. The chemical and physical adsorption of phosphate onto the surface of soil minerals is a rapid process. Slower reactions continue to remove phosphorus from the water column for periods of from several days to several months.

Adsorption by wetland sediment is not necessarily a permanent sink for wastewater P; it is at least partially reversible. A reduction in the phosphorus concentration in the water column in contact with the sediment, by plant uptake or by flushing or dilution with low phosphorus water, will release some P into solution. The wetland sediment functions to some extent as a "phosphorus buffer" in regulating the concentration of phosphate in solution. Soils that adsorb P the least readily typically release P the most easily.

It is not known how long a wetland can continue to remove P from wastewater. It is known that if sufficient P is added, the P adsorption capacity of a wetland soil can be saturated. In addition to becoming saturated and losing the capacity to retain any more phosphorus, a wetland soil can release some of the P that it has previously absorbed if the P concentration in the water in contact with the soil is reduced (Dunne *et al.*, 2005).

4. Conclusion

Nitrogen and phosphorus removal in CW involves a complex of physical, chemical and biological processes. The mechanisms that remove these nutrients include: sorption on wetland sediments, storage in plants biomass, and denitrification. Based on this study, nutrient retention in compartments of HSSF constructed wetland with and without *Pennisetum clandestinum* treating piggery wastewater in southern Nigeria varied. N removal by sediment, plant uptake, denitrification and water column concentration in planted CW varied between 4.32-18.3, 8.71-40.3, 6.6-17.4 and 80.37-24.0% respectively. In the unplanted CW, nitrogen detention among the sediment, denitrification and water column compartments varied between 5.3-24.3, 6.3-16, 88.4-59.7% respectively. Similarly, phosphorus detention in planted CW compartments varied between 7.2-45.2, 3.5-28.6 and 89.3-26.2% for sediment, plant and water column concentration respectively for 1-6HDT. In the unplanted CW, phosphorus detention equilibrium between sediment and water column shifted between 9.8-55.6% and 90.2-44.4% in the sediment and water column respectively. By considering the 3HDT which quality conformed with the Nigerian standard for discharge to land and surface water, plants, denitrification and sediment in the planted CW detained 34.4, 17.8 and 16.1% of nitrogen respectively and 14.2 and 41.8% of phosphorus in the plant and sediment compartments respectively. The result obtained in this study indicate that plant uptake and sediment storage contributed more than other compartments in N and P removal in the HSSF wetlands treating piggery wastewater. Improving these partitions could also improve removal efficiency at shorter HDT and reduce the pollution on land and water resources.

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