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Estimation of Design Model Constants for a Constructed Wetland with Palm Kernel Shell as Substrate for Slaughterhouse Wastewater Treatment

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ABSTRACT

Design of horizontal subsurface flow constructed wetlands using the state of the art *k*-*C** first order model requires the use of correct model constants to ensure that the design systems meets the required treatment standards. The aim of the study was to estimate the model constants for the design of a field scale horizontal subsurface flow constructed wetland to treat slaughterhouse wastewater using palm kernel shell as substrate. A 40 days column incubation was conducted and the model was fitted to experimental data. Rate constant (k_{20}) values of 0.604/day, 0.623/day, 0.278/day, 0.323/day and 0.306/day were obtained for BOD, TSS, NH_4-N, NO_3-N and PO_4^{3-}. Estimated model constants were compared to the universal values in the literature which revealed very significant variations in the obtained wetland surface area.

***Keywords*:** Constructed Wetland, Palm Kernel Shell, Slaughterhouse Wastewater, Physicochemical Parameters, *k*-*C** Model, *Thalia geniculate*, *Eichhornia crassipes*

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1. INTRODUCTION

The growing need for low-cost and environmentally sustainable wastewater treatment systems has led to a growing interest in on-site and decentralized wastewater treatment technologies, especially in developing countries, where a combination of factors reduces the use of centralized systems (Mara, 2004). Constructed wetland (CW), which are engineered systems designed to mimic and use ecological processes found in natural wetland ecosystems to remove pollutants, meets most of the criteria necessary for a wastewater treatment technology to be considered suitable for developing countries. It has also been reported that they are efficient in the removal of organic substances, pathogens and nutrients, as well as other contaminants (Konnerup *et al*., 2009).

In Nigeria, there is a lack of rigorous field data on actual process performance under a variety of operating conditions, and with different native plant species.

Denny (1997) described the spread of constructed wetland technology in developing countries as "depressingly slow". Although there are a number of cases where CWs (mainly surface flow planted with water hyacinth, *Eichhornia crassipes* spp.) are used as secondary treatment units for domestic wastewater in the country, the technology so far is not yet common for the same purpose and the few that are operational perform below the required standards (Adeniran *et al*., 2012). The feasibility of CWs varies with waste characteristics and climate (Cronk, 1996). Design of CWs using the *k-C** model of Kadlec and Knight (1996), which is one of the most widely accepted models, has been proven effective. However, the model constants are dependent on a number of variables including influent concentrations, weather and the type of wetland.

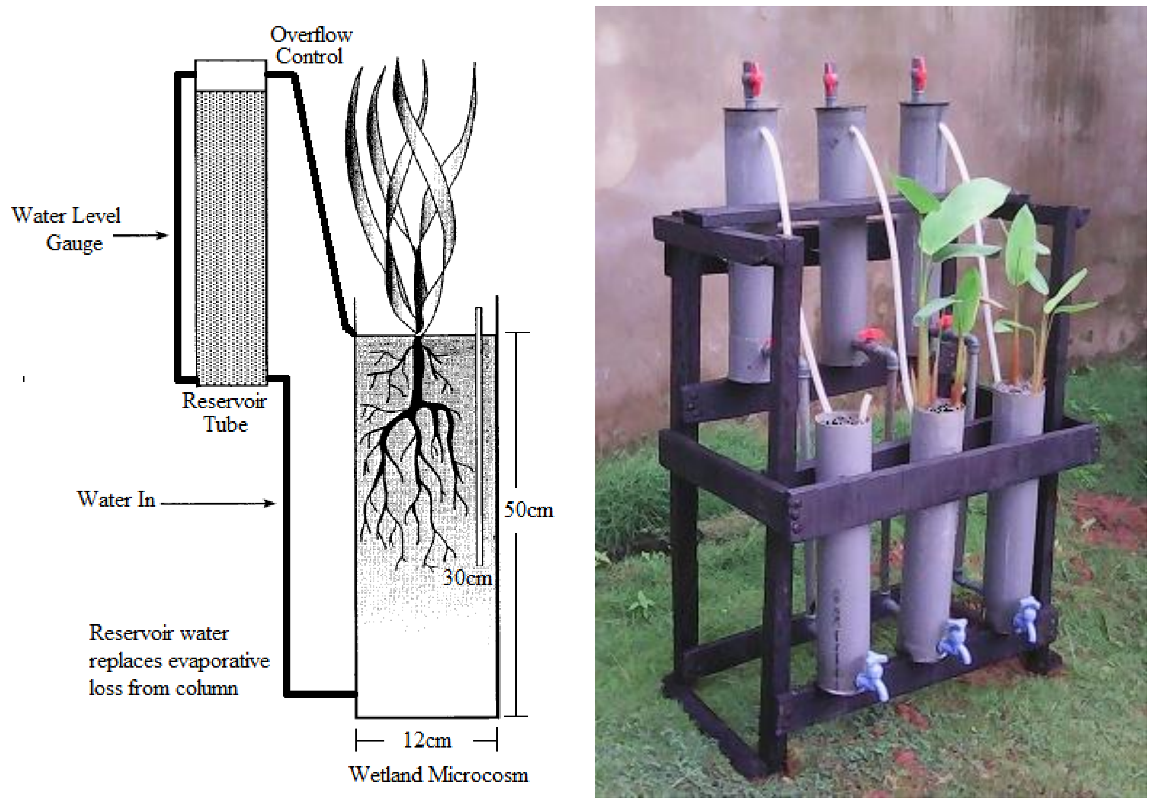
Kadlec and Knight (1996) advocate the use of the "global" parameters they determined from the analysis of performance data available on the North American Data Base, for the design of pilot systems, but stated that specific parameters should be locally determined prior to investment in a full-scale system, in order to ensure suitability of design. Thus, It is important to use appropriate model constants. Little or no research work has been carried out focusing on parameter estimation for horizontal subsurface flow CW treating slaughterhouse wastewater in Nigeria.

Sizing of CWs for slaughterhouse wastewater treatment using coefficients specific to this type of wastewater, rather than relying on values determined for other types of wastewater, in other regions of the world, will ensure a more effective and efficient system. Therefore the aim of the study is to estimate the design model constants for CW with palm kernel shell as substrate for slaughterhouse effluent remediation.

2. MATERIALS AND METHODS

2. 1. Experimental Setup

Three Horizontal Subsurface Flow (HSSF) CW columns were used for the study. The columns were constructed according to the procedures of Allen *et al*., (2002). They were made of polyvinyl chloride (PVC) pipe (60 cm in height × 12 cm in diameter) and filled to a depth of 50 cm as shown in Figure 1.



(a) **(b)**

Figure 1. (a) Schematic diagram of column design and water delivery system (Adapted from Allen et al., 2002), **(b)** Experimental setup

Two columns were filled with PKS and planted with *Thalia geniculata,* while the third was filled with PKS and left unplanted to serve as control. Access tubes (1.1 cm diameter) were installed to a depth of 30 cm for sampling. Plastic taps were fitted on the floor of each cell for washout. Water level was automatically maintained at the media surface by replacing evaporative losses with tap water added to the bottom of the columns. To ensure no overflow and washout of the wastewater, a plastic tap was fitted at the inlet of the microcosm and was always closed prior to filling the reservoir from the top. Each column functioned as an independent batch reactor. After planting, the columns were also filled with stream water to enable the plants acclimatise for 2 weeks, after which the plants were left to establish in wastewater. A 40 days batch incubation was conducted using the HSSF wetland columns from January 2017 to February 2017.

The dry season experimental run was to allow for accurate sampling because there was no dilution effect through rainwater mixing with the samples. Columns were gravity drained a day prior to the incubation. During the incubation the columns were filled with pre-settled wastewater. The reservoirs were intermittently refilled from the top with tap water to compensate for evaporative losses. Wastewater samples were collected from the HSSF CW columns at days 0, 2, 5, 8, 12, 21, 30 and 40. The samples were analyzed for BOD, TSS, NH_4-N, NO_3-N and PO_4^{3-} according to standard methods (APHA, 1988).

2. 2. Calibration of Wetland Design Model

The *k-C** model of Kadlec and Knight, (1996) is given below.

$$\frac{(C_e - C^*)}{(C_i - C^*)} = exp^{-kt} \qquad (1)$$

where C_e is the effluent concentration (mg/l); C_i is the influent concentration (mg/l); C^* is background pollutant concentration (mg/l); k is the volumetric first-order removal rate constant (d^{-1}); t is time (d).

The rate constant (k), an important term in the design models is dependent on temperature. The effect of temperature on the rate constant is modelled using the modified Arrhenius relationship given as:

$$k = k_{20}(\theta)^{(T-20°)} \qquad (2)$$

where k is the rate constant at temperature T, (d^{-1}), K_{20} is the rate constant at 20 ºC, (d^{-1}), Θ is the dimensionless temperature coefficient.

Rate constant at 20 ºC reference temperature (k_{20}), temperature coefficients (θ) and background concentration (C^*) were found by fitting the model predictions to the measured concentrations in the HSSF CW columns, and minimizing the sum of squared error (SSQE). BOD, TSS, NH_4-N, NO_3-N and PO_4^{3-} concentrations obtained during the 40 days incubation were used to obtain the best fit estimates of the model constants. Parameter optimization was performed in Microsoft Excel® using Solver®. The procedure assumes that the solution to the inverse problem, the best fit, is obtained when the values of the adjusted parameters yield the minimum value of the sum of squared error between the measured data and model predictions as given below:

$$SSQE = \sum_{i=1}^{N}(C_{eff} - C_{predicted})^2 \qquad (3)$$

3. RESULTS AND DISCUSSIONS

Figures 2 and 3 respectively illustrate the mean observed and calibrated BOD and TSS dynamics in the HSSF CW column. The input BOD and TSS concentration were 636.23 mg/l and 483 mg/l, respectively. In the figures, the X-axis represents the hydraulic retention time (HRT) in days and the Y-axis the concentration of the pollutant. As can be seen from the figure, the BOD reduction followed exponential trends and the modified first order kinetic model with a rate constant (k_{20}) of 0.604/day (32.63 m/year), temperature coefficient (θ) of 0.995 and a background concentration (C^*) of 43.23 mg/l matched the data of the experimental run (coefficient of determination for regression $R^2 = 0.897$). BOD decreased rapidly in the first five days of incubation and approached residual levels on day 12. Also the TSS reduction followed exponential trends and the modified first order kinetic model with a k_{20} of 0.623/day (33.65 m/y), θ of 1.093 and C^* of 33.77 mg/l matched the data of the experimental run ($R^2 = 0.525$).

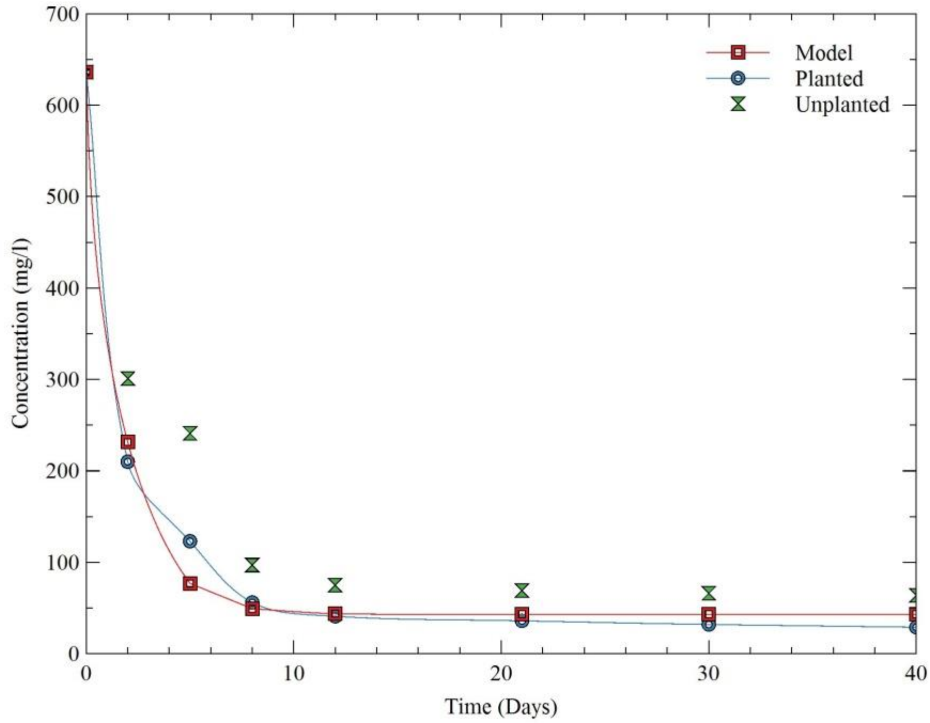


Figure 2. Measured and calibrated BOD dynamics in the HSSF-CW column.

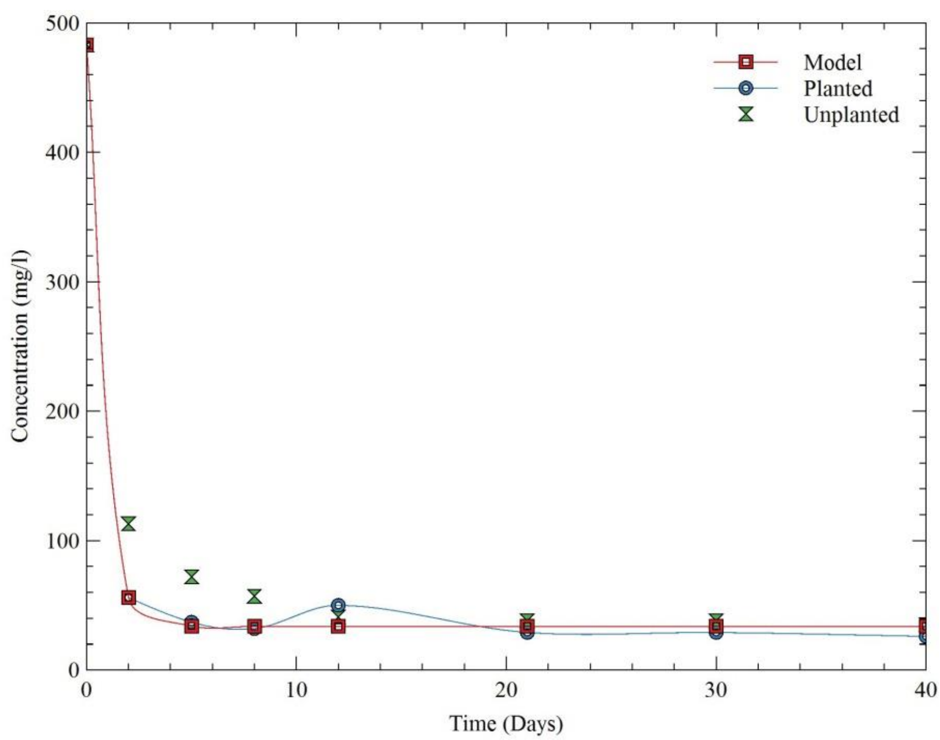


Figure 3. Measured and calibrated TSS dynamics in the HSSF-CW column.

There are no removal rates reported in literature for BOD and TSS in CWs using PKS as media. However, the rate constant of 0.604/day (32.63 m/yr) obtained for BOD in this study was within ranges of 0.17/day to 6.11/day previously reported for different types of CW (0.17/day by Tanner *et al*., 1995; 0.3 - 6.11/day by Kadlec and Knight, 1996; 0.87/day by Lin *et al*., 2002; 1.104/day by Reed and Brown, 1995; 0.86/day by Liu *et al*., 2000) and the rate constant of 0.623/day (33.65m/yr) for TSS also falls within the ranges of 0.27/day to 4.11/day previously reported (0.20/day by Cosmos, 2006; 4.11/day by Wong *et al*., 2006).

θ describes the temperature dependency and a value of 1.000 indicates that the temperature does not influence the treatment, while values below or above 1.000 have a negative or positive effect on the treatment (Kadlec and Wallace, 2009). The estimated θ values for BOD and TSS were comparable to those reported by Kadlec and Knight (1996).

The slightly less than unit value obtained for BOD suggested a slightly lower removal rate at higher temperatures. This is not consistent with concepts of microbial degradation and must therefore be viewed with scepticism. Possible explanations are the relatively short duration of the column experiments, which may have occurred in a grow-in period for plants and microbes.

The C^* values for BOD in this study were higher than the values recommended by Kadlec and Knight (1996) for system design. Possible explanations are the very short duration of column experiments. In the literature, a range of $1.7 < C^* \leq 18.2$mg/l with an average of 9.9 mg/l was reported by Stein *et al*., (2006). The lower values in the literature can be attributed to the fact that their values were long-term averages of residual values obtained from different systems and it is a known fact that the values of k and C^* vary from one wetland to another, depending on site-specific factors such as type of vegetation, age of the wetland, strength of influent wastewater, temperature and hydraulic variables (Frazer-Williams, 2010).

The planted HSSF-CW column showed better BOD and TSS reduction compared to the unplanted. The results show that the activity of microorganisms in the root systems of the planted columns was greater than in the unplanted column. The reduced efficiency can therefore be due to the lack of the root system in the column.

Figure 4 - 6 respectively shows the mean observed and calibrated NH_4-N, NO_3-N and PO_4^{3-} dynamics in the HSSF CW columns. The input NH_4-N, NO_3-N and PO_4^{3-} concentrations were 63 mg/l, 34mg/l and 11mg/l respectively. As can be seen from the figure, the nutrient reduction followed exponential trends.

For NH_4-N, the values of k_{20}, θ and C^* that minimized the sum of error squared between the observed concentrations and the prediction of the modified first order kinetic model were 0.278/day (15.01m/yr), 1.050 and 38mg/l respectively with a coefficient of determination for regression $R^2 = 0.792$.

For NO_3-N, the values of k_{20}, θ and C^* were 0.323/day (17.44 m/yr), 1.015 and 0.36 mg/l respectively with a coefficient of determination for regression $R^2 = 0.957$. For PO_4^{3-}, the values of k_{20}, θ and C^* were 0.306/day (16.53m/yr), 0.953 and 0.42 mg/l respectively with a coefficient of determination for regression $R^2 = 0.919$.

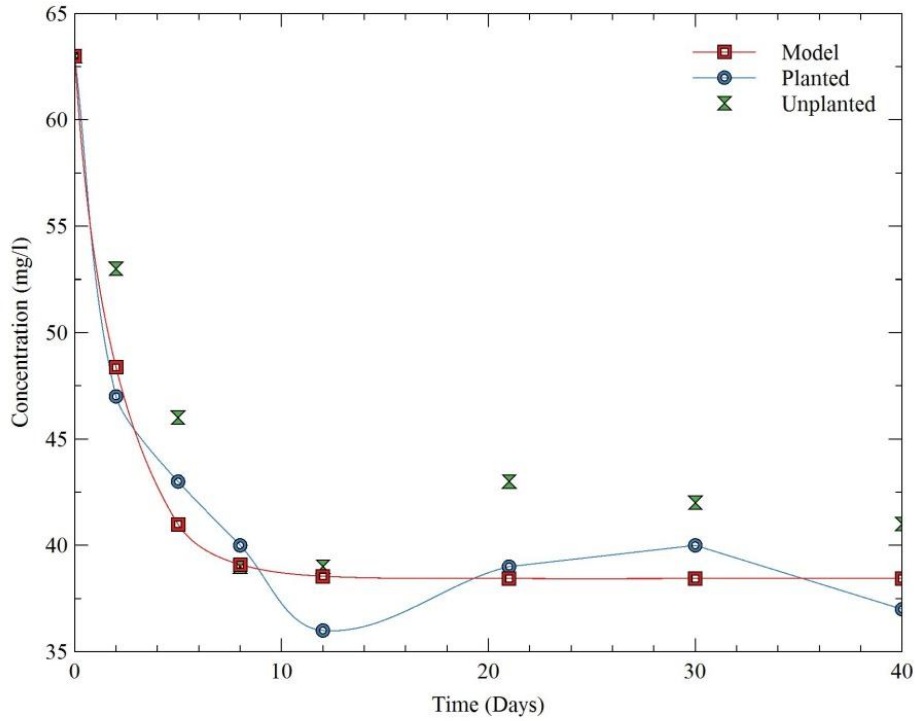


Figure 4. Measured and calibrated NH_4-N dynamics in the HSSF CW column.

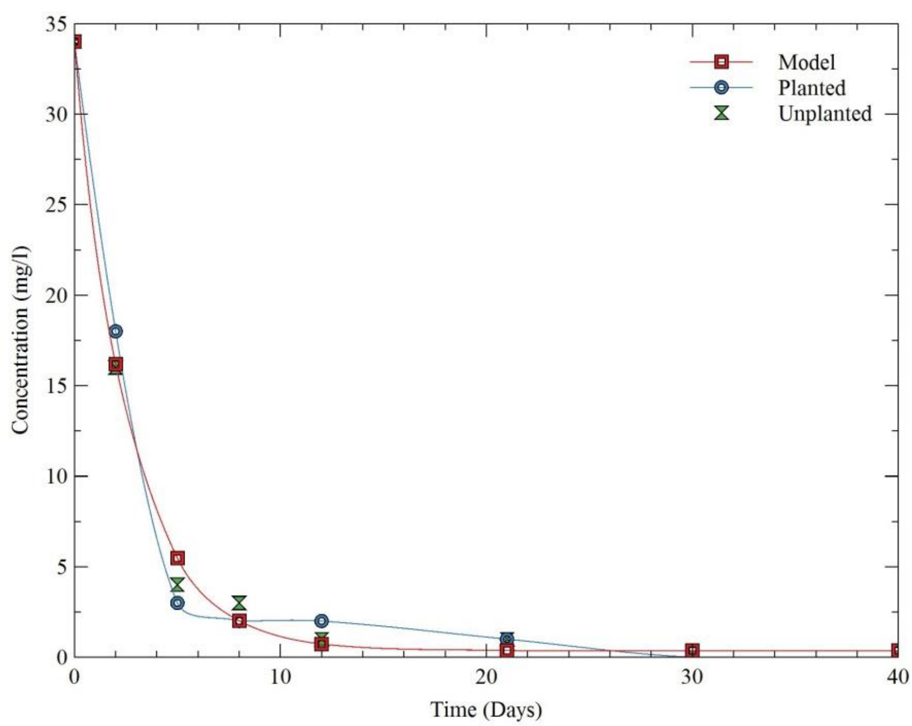


Figure 5. Measured and calibrated NO_3-N dynamics in the HSSF CW column.

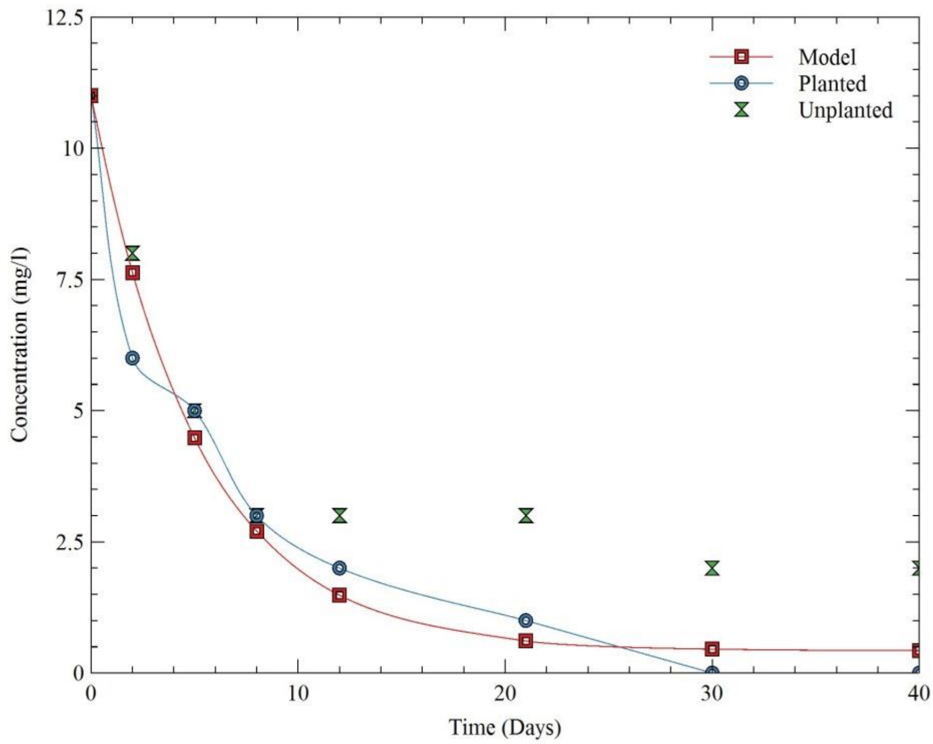


Figure 6. Measured and calibrated PO_4^{3-} dynamics in the HSSF CW column.

Also, there are no removal rates reported in literature for nutrient removal in CWs using PKS as substrate. However, the k_{20} and θ obtained in this study do not differ significantly from the values reported in the literature. According to Kadlec and Knight (1996), the preliminary model parameters developed from the North American Wetland System Database were 18m/yr and 35m/yr for NH_4-N and NO_3-N respectively for k_{20} and θ of 1.05 for both NH_4-N and NO_3-N. Cui *et al*., (2016) in their study on nitrogen removal in a HSSF CW reported k_{20} of 27.01±26.49 m/year and 16.63±10.58 m/year for NO_3-N and NH_4-N respectively and θ of 1.0042 and 0.9604 for NO_3-N and NH_4-N respectively. Dzakpasu *et al*., (2014) in their assessment of an integrated constructed wetland for decentralized wastewater treatment in a rural community in Ireland reported k_{20} of 15.4m/year and 5.1m/year for NH_4-N and NO_3-N respectively. The mean effects of temperature on the N removal rate constants were estimated to be 1.064 for NH_4-N and 1.004 for NO_3-N. This finding of this study was consistent with previous reports that N removal in CWs is significantly influenced by temperature (Kadlec and Reddy, 2001). The very high residual concentration for NH_4-N is not consistent with the zero N residual concentrations in the literature. Kadlec and Wallace (2009) stated that treatment wetland systems can be assumed to have a theoretical background of zero for NH_4-N. Therefore, the residual concentration obtained must also be viewed with scepticism. Rate coefficient for PO_4^{3-} in the literature is scarce. Most design guidelines gave values for total phosphorus such as 0.11 - 0.18/day by Trang *et al*., (2010), 0.14/day by Tanner *et al*., (1995). Stone *et al*., (2002) reported that K_{20} values for TP ranged from 1.04 to 1.79 m/year. The somewhat negative effect of the temperature on the PO_4^{3-} treatment was surprising because it is well documented that phosphorus processes are not influenced by temperature (Stone *et al*., 2002; Kadlec and

Wallace, 2009). To examine the implications of the estimated design parameters on the sizing of a HSSF CW to treat slaughterhouse wastewater, the estimated parameters from the calibration and the universal values in the literature were used to predict the size of a field-scale system for Eke-Awka Etiti slaughterhouse, in Anambra State, Nigeria.

A mean temperature, depth and porosity of 28.9 ºC, 0.5m and 0.4 respectively were assumed and the input and output concentrations and flow parameter are as shown in the Table 1.

Table 1. Constructed wetland areas using calibrated values and "universal" values.

	Q_{in} (m^3/d)	C_{in} (mg/l)	C_{out} (mg/l)	K_{20} (d^{-1})	θ	C* (mg/l)	Area (m^2)	Diff (%)
BOD								
Calibration	2.0	622	50	0.604	0.995	23.0	53.65	-
Reed *et al.*, (1995)	2.0	622	50	1.104	1.06	6.0	14.23	-73
Kadlec and Knight (1996)	2.0	622	50	2.166	1.057	36.67	10.63	-80
TSS								
Calibration	2.0	457	65	0.623	1.093	25.6	17.40	-
Kadlec and Knight (1996)	2.0	457	65	0.801	1.0	36.60	33.64	48
NH_4-N								
Calibration	2.0	77	10	0.278	1.05	0	47.56	-
Reed *et al.*, (1995)	2.0	77	10	0.2187	1.04	0.2	65.82	28
Kadlec and Knight (1996)	2.0	77	10	0.648	1.05	0	20.41	-57
NO_3-N								
Calibration	2.0	42	20	0.323	1.015	0.36	20.38	-
Reed *et al.*, (1995)	2.0	42	20	1.0	1.15	0.2	2.01	-90
Kadlec and Knight (1996)	2.0	42	20	0.926	1.05	0	5.19	-75
PO_4^{3-}								
Calibration	2.0	13	5	0.306	0.953	0.42	137.7	-
Kadlec and Knight (1996)	2.0	13	5	0.168	1.097	0.02	68.04	-51

Using the parameters obtained for BOD during the model calibration in this study, the CW size was $53.65m^2$, 73% and 80% higher than the calculated areas using the values of Reed *et al.,* (1995) and Kadlec and Knight (1996) respectively. For TSS, the predicted area of the wetland based on the calibrated values of model constants was 48% lower than the predicted area using the value of Kadlec and Knight (1996). For NH_4-N, the area based on the constants of this study was lower than the values calculated using the values Reed *et al.,* (1995) by 28%, but was higher than the area calculated using the values of Kadlec and Knight (1996) by 57%. A very high difference was obtained between the calculated areas for NO_3-N. The calculated area from this study was lower than that of Reed *et al.,* (1995) by 90% and that of Kadlec and Knight (1996) by 75%. The predicted area for PO_4^{3-} based on the calibrated constants was 51% higher than the predicted area based on the constants of Kadlec and Knight (1996).

4. CONCLUSION

This study has estimated model constants that can be used in the design of HSSF CW for treatment of slaughterhouse wastewater in Nigeria. The findings of this study has established the fact that “universal” values of rate constants, as offered in many literature sources, does not exist as parameter values obtained from various operating wetland systems vary widely. The very significant variations in the predicted CW sizes exposed the great risk in extrapolation beyond the calibration conditions. Kadlec and Wallace (2009) stated that "extrapolation from a wetland of one type to another is clearly not a reasonable step because the microbial communities, as well as the character and magnitude of the biogeochemical cycles, may differ markedly". Also, Kadlec (1999) stated that difficulties arise when the model extrapolates outside of the calibrated concentration ranges, or for comparing design configurations. Therefore, it is prudent to determine the model parameters before using them for design calculations.

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