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Hydraulic Modelling and Optimization of a Wastewater Treatment System for Developing Nations Using Computational Fluid Dynamics

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Abstract:

Waste stabilization pond (WSP) is globally one of the most popular wastewater treatment options because of its high efficiency and low cost. However, no rigorous assessment of WSPs that account for cost in addition to hydrodynamics and treatment efficiency has been performed. A study was conducted that utilized Computational Fluid Dynamics (CFD) coupled with an optimization program to optimize the selection of the best WSP configuration based on cost and treatment efficiency. Several designs generated by the CFD/optimization model showed that both shorter and longer baffles, alternative depths, and reactor length to width ratios could improve the hydraulic efficiency of the ponds at a reduced overall construction cost. In addition, a study was conducted on the optimized WSP which consisted of an anaerobic, facultative, and a maturation stage whose baffle orientation, length to width ratio, was specified by a CFD model prediction and was compared with a three stage WSP designed according to literature suggested reactor geometric configurations. Experimental tests were performed on a pilot scale version of the three-stage WSP where the removal performance was based on a number of parameters (Faecal coliform, pH, TDS, and Conductivity). Results showed that the significantly lower cost design based on the optimized CFD simulations displayed slightly better removal performance compared to the standard WSP design developed from literature data. The results of this study clearly showed that unit treatment process designs based on rigorous numerical optimization can aid in producing cost effective designs that make it more possible for developing nations to incorporate adequate and effective sanitation.

Key words: *Wastewater, Waste Stabilization Pond, CFD, Reactor design and Pond-configuration*

1. Introduction

The construction cost for a standard wastewater treatment plant has been a major barrier for the implementation of modern technologies by local authorities in many African nations (Agunwamba, 1994 and 2001b; Olukanni and Aremu, 2008; Olukanni and Ducoste, 2011). In addition, these technologies require considerable technical expertise, which is often not available in developing nations to successfully operate these treatment facilities. Consequently, developing nations are unable to incorporate these technologies as part of a wastewater treatment master plan. It is therefore imperative to develop treatment systems that are economical and sustainable.

Among the current processes used for wastewater treatment, WSP has been identified and consistently selected as the unit process choice for wastewater treatment in developing nations due to their low cost and efficient operation in tropical regions (Agunwamba, 2001a; Mara, 1997, 2004; Abbas et al., 2006; Kaya et al., 2007; Naddafi et al., 2009; Olukanni and Ducoste, 2011). Babu et al (2010) and Mara (2004) describe a WSP as a chemical reactor used for the reduction of solids, organic matter as well as pathogenic organisms. The WSP system usually consists of a series of continuous flow anaerobic, facultative, and maturation ponds. The anaerobic pond is designed for eliminating suspended solids and some of the soluble organic matter while the faclcultative pond is designed for further removal of the residual organic matter through the activity of algae and heterotrophic bacteria. The final stage of pathogens and nutrients removal takes place in the maturation pond (Olukanni and Ducoste, 2011; Mara, 2004; Babu, et al., 2010). WSPs are most suited for tropical and subtropical countries since the sunlight irradiance and ambient temperature are key factors for the WSP process efficiency (Mara, 2004; Mara 2001; Mara and Pearson, 1998). However, the application of WSP is limited by its large area requirement (Agunwamba, 1991 and 2001a). In addition, no rigorous experimental assessment of WSP that account for cost along with hydrodynamics and treatment efficiency has been performed (Olukanni and Ducoste, 2011). The goal of any WSP designer would be to optimize pond design by minimizing cost and land required while maintaining treatment effluent standards.

Previous studies have shown that the WSP treatment efficiency is often hydraulically compromised (Shilton and Mara, 2005; Shilton and Harrison, 2003a; Persson and Wittgren, 2003). Majority of the hydraulic studies on WSPs have been performed on full-scale field ponds, which have transient flows and large surface areas exposed to wind and temperature variations (Marecos and Mara, 1987; Moreno, 1990; Agunwamba, 1992; Fredrick and Lloyd, 1996). However, it was observed that operation and weather variations that occur during field experimental tests limit the study of reactor mixing characteristics only with lab-scale models studied under controlled conditions (Antonini et al., 1983; Shilton and Bailey, 2006), in which its results could be used to produce an optimal WSP design for field scale ponds performance.

The treatment of wastewater through WSPs has been an important research area over the past decades (Agunwamba, 1994; 2001a; Mara, 2004; Olukanni and Ducoste 2011). Oke, et al (2006) assessed the physical and engineering properties of a WSP system in Ahmadu Bello University (ABU), Zaria (Nigeria). The WSP system consisted of facultative and maturation ponds in series with hydraulic retention time of 24- and 6-days, hydraulic loading 15.34 and 10.2 ($m^3/m^2.d$) and BOD loading of 0.75 and 4.59 (kg/ha.d) respectively. Influent and effluent wastewater qualities were monitored from their system for one year. Oke et al.'s results revealed an average fecal coliform removal efficiency of 99% and an average reduction in suspended solids by 66%. The ammonia and phosphate concentrations of the raw influent were reduced on average by 88 and 81%, respectively, and an overall COD reduction of 96%. Oke et al (2006) confirmed that under tropical conditions, the WSPs are suitable compared to the modern and mechanized treatment systems such as trickling filters and activated sludge, because of the ease of operation and maintenance. Hodgson (2000) achieved similar results of a biological treatment plant at Akuse (Ghana) where the WSP system produced a 65% BOD reduction, 99.99% fecal removal, 46% reduction of suspended solids, and 92% and 94% of ammonia and phosphate removal, respectively.

Mohammed (2006) carried out the design and performance evaluation of a numerical model of a waste stabilization system that was comprised of one facultative pond, three maturation ponds, and a contact filtration unit all operated in series. The facultative and maturation ponds have hydraulic retention times of 11- and 4-days respectively. The numerically predicted microbial removal from each stage of the WSP system was greater than the experimentally measured percent removal. The numerical predicted removal of 62% and 91% was recorded for facultative and maturation ponds while experimental observed results were 45% and 84%, respectively. The deviation between the experimental and numerical results was likely due to the numerical assumptions, which assumed completely mixed reactors for the ponds. Other reasons for the deviation could be the values of the reaction coefficients used in the design.

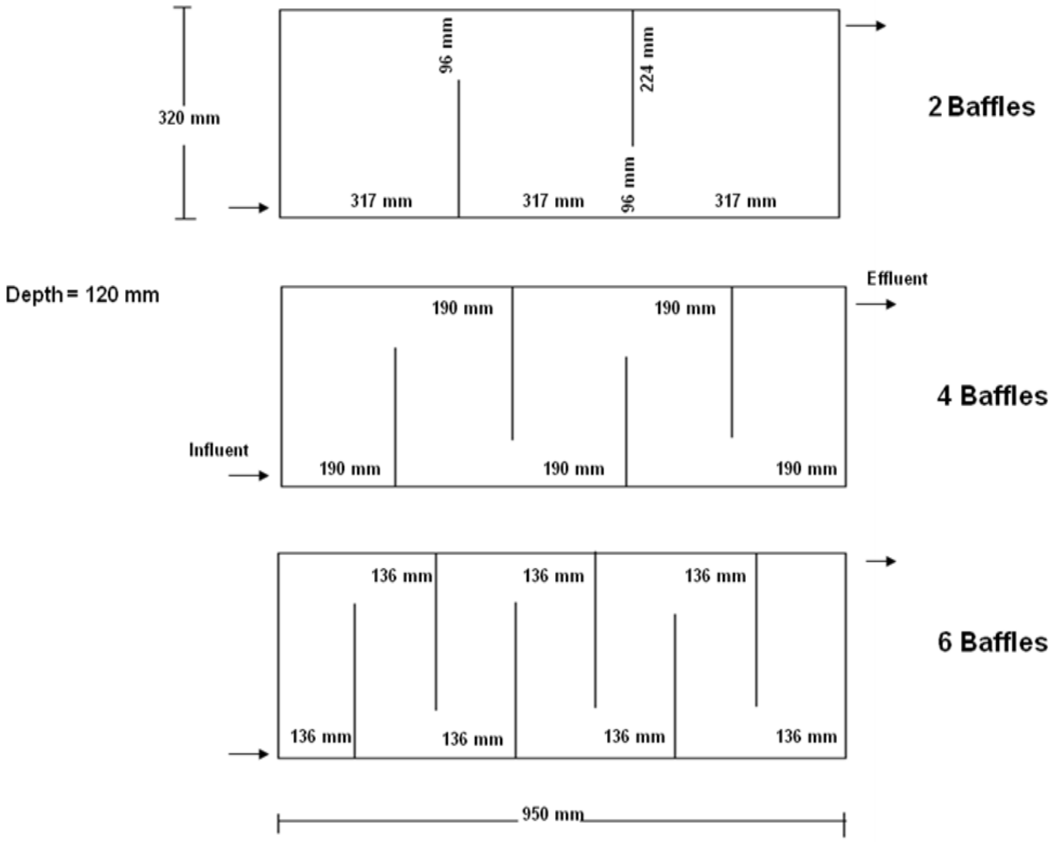
Recently, Olukanni and Ducoste (2011) performed a study that utilized computational fluid dynamics (CFD) coupled with an optimization program to optimize the selection of the best WSP configuration based on cost and treatment efficiency. The numerical results of monitoring the fecal coliform concentration at the reactor outlet showed that the conventional 70%

pond-width baffle pond design was not consistently the best pond configuration as previously reported in the literature. The study concluded that target effluent log reduction can be achieved by reducing the amount of construction material and tolerating some degree of fluid mixing within the pond. Several other designs generated by the CFD/optimization model showed that both shorter and longer baffles, alternative depths, and reactor length to width ratios could improve the hydraulic efficiency of the ponds at a reduced overall construction cost. Olukanni and Ducoste (2011), however, did not experimentally validate the CFD model predictions. Experimental validation in terms of microbial pollutant and nutrient removal of CFD generated WSP configurations are still scarce, especially for lab-scale ponds. The main focus of this study has been the need for a cost effective designs that will not jeopardize the treatment efficiency and to validate the predicted results of an optimized WSP discussed in Olukanni and Ducoste, 2011. In addition, a parameter sensitivity analysis was performed to determine the influence of the first order constant (k) and temperature (T) on the design configurations.

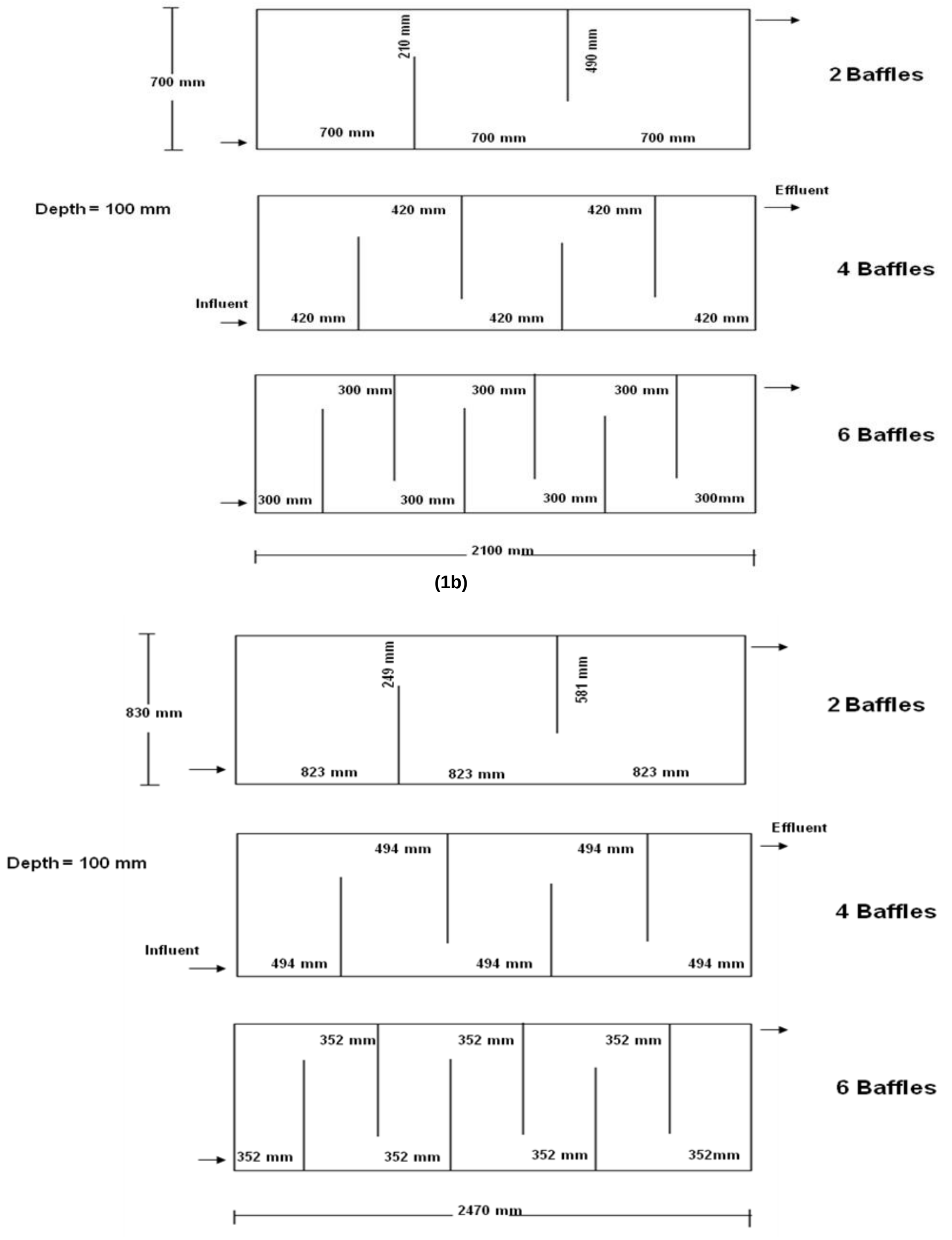
2. Materials and methods

2.1 Design and construction of a Laboratory-scale WSP

The initial length to width dimensions of the reactors are (950 mm × 320 mm) ($A_o = 0.3$ m^2), (2100 mm × 700 mm) ($A_o = 1.5$ m^2) and (2470 mm × 830 mm) ($A_o = 2.1$ m^2) for the anaerobic, facultative, and maturation ponds, respectively, as shown in Figure 1. The three sets of laboratory-scale reactors for WSP design configurations from Olukanni and Ducoste (2011) CFD model was compared with the Simplex and MOGA II design specifications. The SIMPLEX method was based on a modified single objective algorithm that takes into account discrete variables and constraints (mode-FRONTIER Manual, 2009). The Simplex solver produces an optimal result based on a single objective function while MOGA-II is a multi-objective genetic algorithm that uses a multi-search elitism (Silva, 2003; Olukanni and Ducoste, 2011). This elitism operator preserves some near optimal solutions without bringing premature convergence to a local-optimal (Fonseca and Fleming, 1993 and 1995). The five set of reactors had cost area ratio, wastewater depth, length, width, baffle length dimensions and number of baffles as presented in Table 1 (a-c) for the anaerobic, facultative, and maturation ponds, respectively. It was understood from practice that several other items make up for the construction costs of ponds which could have been incorporated into the design calculation, conversely, for the purpose of simplicity and in coupling computational fluid dynamics (CFD) with an optimization program to optimize the selection of the best WSP configuration based on cost and treatment efficiency, a 2 mm galvanized metal gauge plate was considered for the construction of the reactors including the baffle walls. Since the baffle walls were made with the same material as the reactor and matched the reactor depth, the cost of material per unit surface area was used as the only measure of the cost and excludes labor and other costs associated with the construction of the ponds.


320 mm
96 mm
224 mm
96 mm
317 mm
317 mm
317 mm
2 Baffles
Depth = 120 mm
Effluent
Influent
190 mm
190 mm
190 mm
190 mm
190 mm
4 Baffles
136 mm
136 mm
136 mm
136 mm
136 mm
136 mm
136 mm
6 Baffles
950 mm

(1a)



(1b)

(1c)

Figure 1 Different baffle arrangements with 70% pond width a) Anaerobic, b) facultative, c) maturation reactors

Table 1a. Anaerobic reactor configurations

	Six-baffle 70% pond-width transverse lab-scale reactor	Four-baffle 70% pond-width transverse lab-scale reactor	Four-baffle 70% pond-width longitudinal lab-scale reactor	Simplex transverse optimized designs	MOGA-II transverse optimized designs
Cost (N)	1, 669	1, 582	1, 926	1, 297	1, 234
Area ratio	3:1	3:1	3:1	3:1	2:1
Depth (m)	0.065	0.065	0.065	0.115	0.120
Length (m)	0.950	0.950	0.950	0.717	0.574
Width (m)	0.320	0.320	0.320	0.239	0.287
Baffle length (m)	0.224	0.224	0.665	0.117	0.166
Baffle ratio	70%	70%	70%	49%	58%
Number of baffles	6	4	4	3	2

Table 1b. Facultative reactor configurations

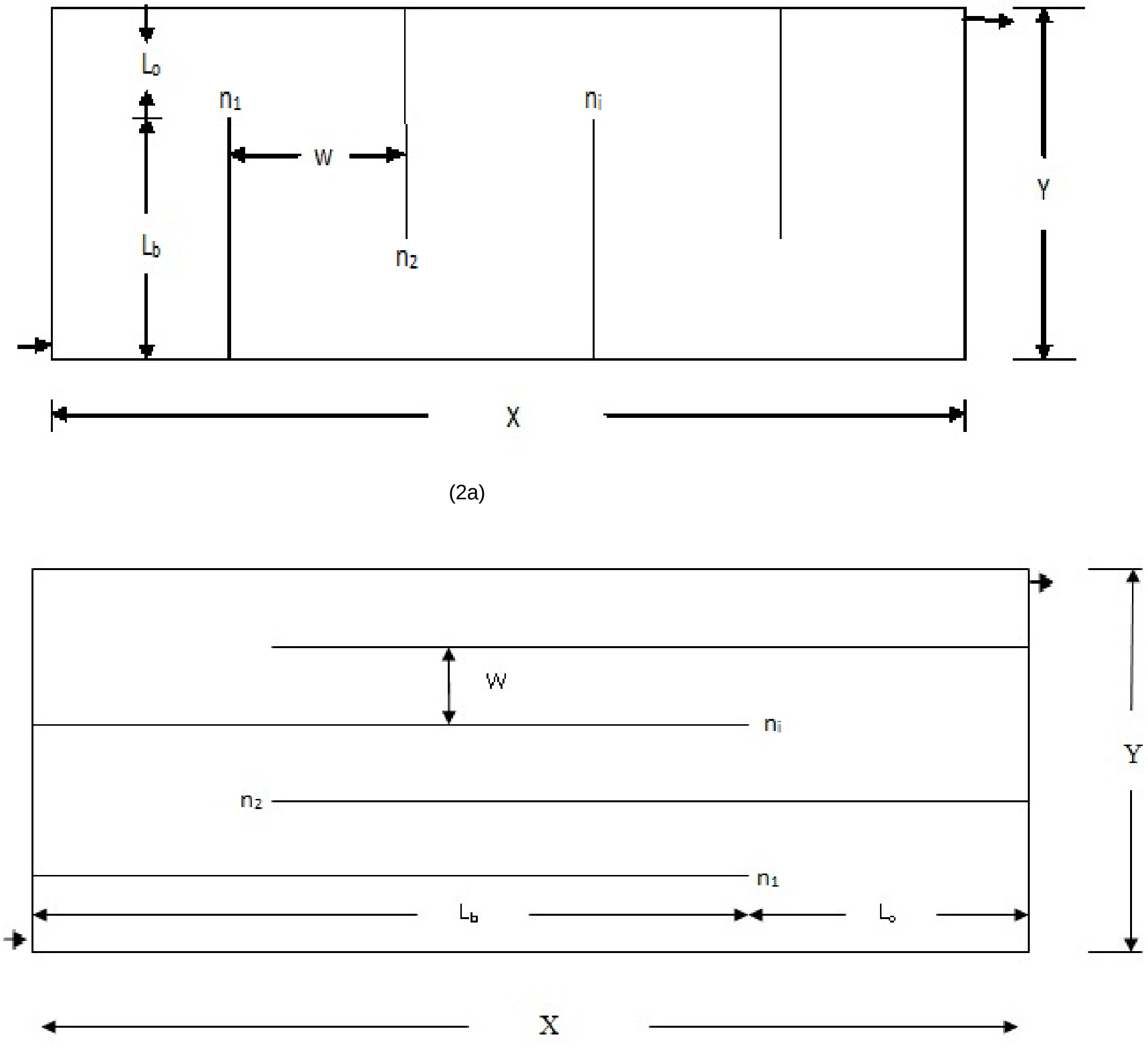
	Six-baffle 70% pond-width transverse lab-scale reactor	Four-baffle 70% pond-width transverse lab-scale reactor	Four-baffle 70% pond-width longitudinal lab-scale reactor	Simplex longitudinal optimized designs	MOGA-II transverse optimized designs
Cost (N)	5, 563	5, 431	5, 960	5, 091	4, 988
Area ratio	3:1	3:1	3:1	1:1	1:1
Depth (m)	0.045	0.045	0.045	0.048	0.048
Length (m)	2.10	2.10	2.10	1.17	1.17
Width (m)	0.70	0.70	0.70	1.17	1.17
Baffle length (m)	0.49	0.49	1.47	0.97	0.62
Baffle ratio	70%	70%	70%	83%	53%
Number of baffles	6	4	4	2	2

Table 1c Maturation reactor configurations

	Six-baffle 70% pond- width transverse lab-scale reactor	Four-baffle 70% pond-width transverse lab-scale reactor	Four-baffle 70% pond-width longitudinal lab-scale reactor	Simplex transverse optimized designs	MOGA-II transverse optimized designs
Cost (N)	7, 360	7, 221	7,772	7, 221	7, 221
Area ratio	3:1	3:1	3:1	3:1	3:1
Depth (m)	0.04	0.04	0.04	0.04	0.04
Length (m)	2.47	2.47	2.47	2.47	2.47
Width (m)	0.83	0.83	0.83	0.83	0.83
Baffle length (m)	0.58	0.58	1.73	0.58	0.58
Baffle ratio	70%	70%	70%	70%	70%
Number of baffles	6	4	4	4	4

2.2 Cost Estimation Model

As mentioned earlier, the impact of the water depth was included in the model simulation by adjusting the influent velocity while maintaining a constant flow rate through the WSP. In this study, initial water depths of 65mm, 45mm, and 40mm were used for the anaerobic, facultative, and maturation, respectively. Figure 2 shows the layout of the reactors as described in Olukanni and Ducoste, 2011 while Equations 1-6 describe the WSP optimization criteria used in estimating the cost for the model. The objective function was based on minimizing the cost of construction of the pilot scale WSP.



(2a)

(2b)

Figure 2 Geometric design parameters for the baffled lab-scale WSP

Minimize Cost = $3000 \times (2hX + 2hY + XY + bn \times L_b \times h)$ (1)

Subject to (Constraints)

$A \leq A_o$ (2)

where $A = XY$

$h_{min} \leq h \leq h_{max}$ (3)

$0 \leq bn \leq 8$ (4)

$\log (C_o/C) \geq 0.6$, 1.5 and 1.5 (5)

for anaerobic, facultative and maturation, respectively.

$1 \leq r \leq 4$ (6)

where $r = X/Y$

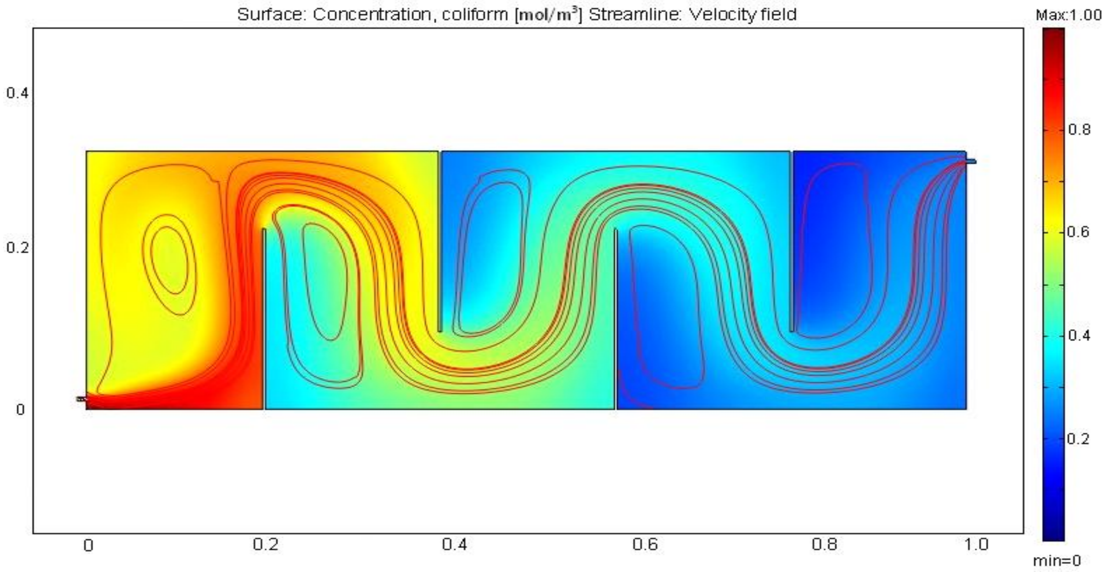
Table 1 Range of adjusted parameter values

Parameters	Anaerobic	Facultative	Maturation
Flow rate (constant)	1.39×10^{-6} m^3/s	1.39×10^{-6} m^3/s	1.39×10^{-6} m^3/s
Volume	0.0197 m^3	0.066 m^3	0.082 m^3
Depth (h)	0.048m – 0.12m	0.024m – 0.048m	0.024m – 0.04m
Reactor L/W ratio (r)	1:4	1:4	1:4
Baffle number (bn)	0 - 8	0 - 8	0 - 8
Baffle length ratio(L_b)	5% - 95%	5% - 95%	5% - 95%

In Equations 1-6, the cost function is in Naira (**N**); A is the surface area in (m^2); Co and C are the fecal coliform concentration at the pond inlet and outlet, respectively; X, Y, and h are the pond length, width, and depth, respectively; A, r, bn, and L_b are pond area, L/W ratio, baffle number, and baffle length, respectively. These values were specified in the optimization algorithm. The cost estimate was based solely on the construction material cost and excludes labor and other costs associated with the construction of the ponds. Equation (5) expresses the minimum required effluent log removal constraint that must be satisfied for each of the three reactors in series before the program is terminated. Details of the optimization set up and problem formulation for the optimization loop are expressed in Olukanni and Ducoste (2011).

3. CFD Model Application

A finite element-based commercial CFD code COMSOL Multiphysics was used in this study with the simulations performed under steady state conditions. The simulation of fecal coliform and fluid transport within the WSP requires the solution of the conservation of mass (continuity), momentum (Navier-Stokes) and convective-diffusion equations (Olukanni and Ducoste, 2011). Although a 2D model was used in this study, the impact of water depth was included in the model simulation by adjusting the influent velocity while maintaining a constant flow rate through the WSP. An unstructured mesh consisting of triangular elements was selected for the 2D geometry. The accuracy of the CFD solutions depends also on the quality of the grid. The grid size was determined through successive refinement in the grid and evaluating the impact of that size on the local fecal coliform concentration and mean velocity at selected points in the reactors. The final maximum grid size was specified as 5 percent of the width of each reactor, which was small enough to produce a grid-independent solution without significantly impacting the computational cost. The simulations were performed on a desktop computer (Intel ® Core(TM) 2 Duo CPU E6550 with 2048MB RAM). For the CFD optimization set up, ModeFRONTIER, an optimization tool was used to predict an optimal design using a single objective (SIMPLEX) and Multi-objective genetic algorithm (MOGA-II). Figure 3 describes the hydrodynamic result (Velocity streamlines and FC concentration maps) showing clear image of the CFD model before optimization. This range of baffle lengths were initially simulated to review the impact of baffle number, placement, and arrangement on the effluent log reduction as discussed in the literature without optimizing for cost. Details of the hydrodynamic result and the FC map of CFD model of the optimized designs are expressed in Olukanni and Ducoste, 2011.


Surface: Concentration, coliform [mol/m³] Streamline: Velocity field
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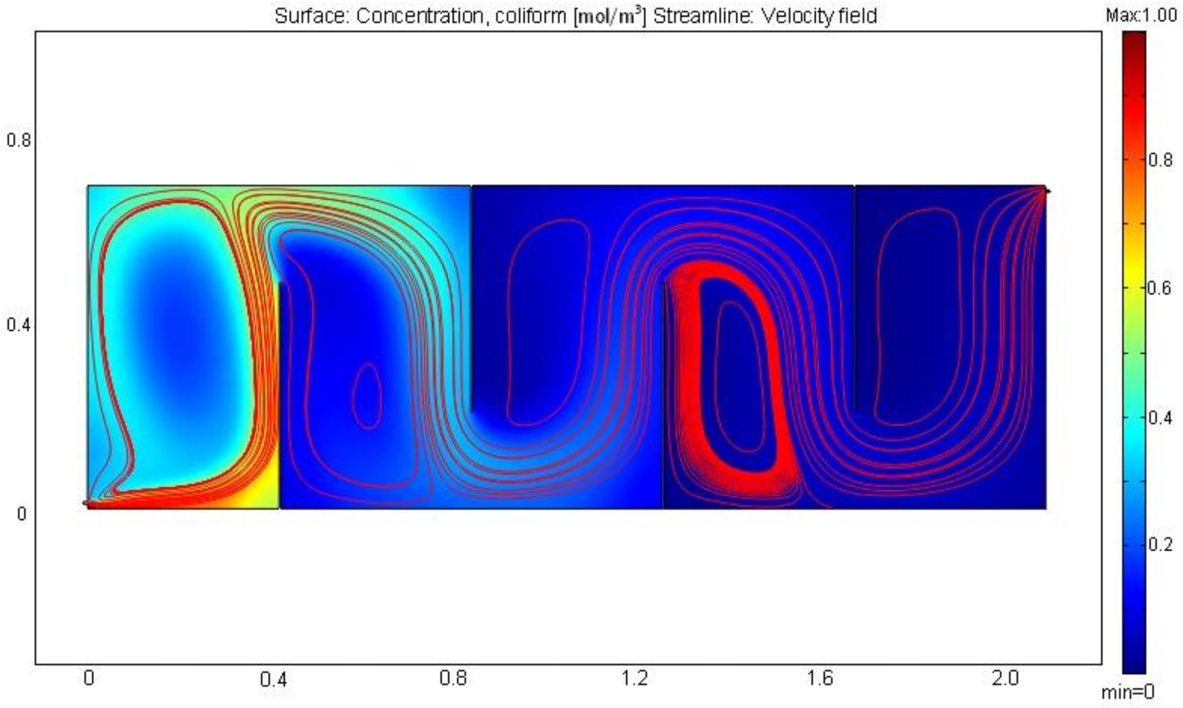
0.8
0.6
0.4
0.2
min=0
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1.0

(3a)


Surface: Concentration, coliform [mol/m³] Streamline: Velocity field
Max:1.00
0.8
0.6
0.4
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min=0
0.8
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0
0.4
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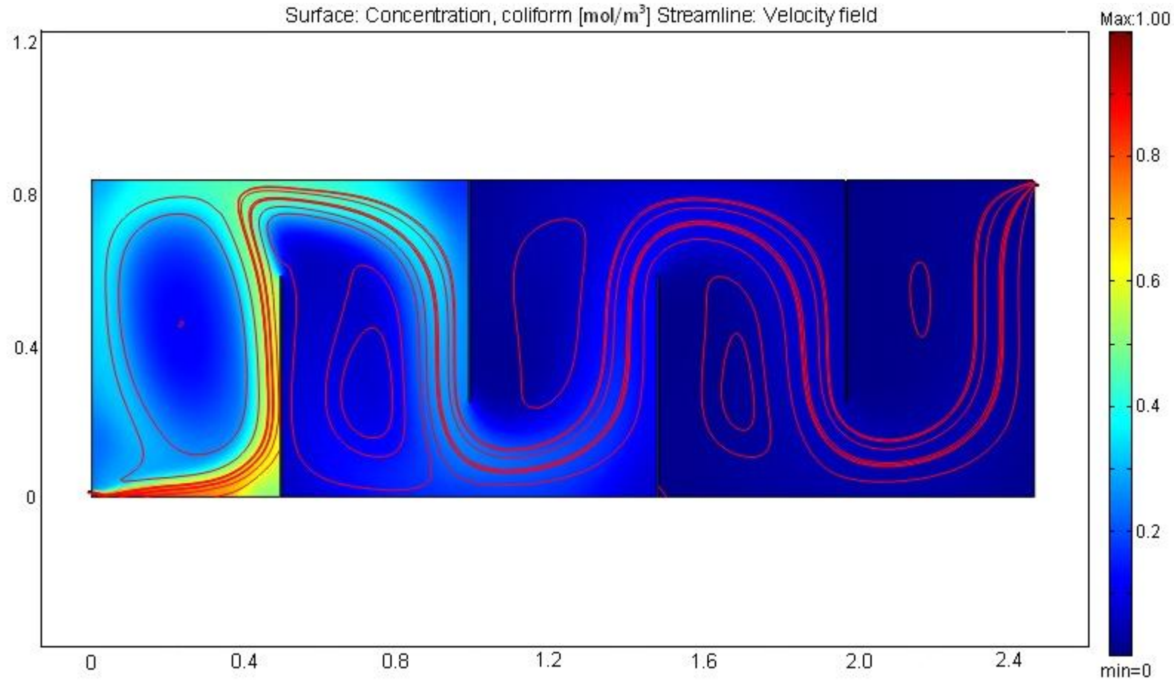
1.2
1.6
2.0

(3b)



(3c)

Figure 3 Velocity streamline and coliform inactivation for the 4 baffle 70% pond width baffle arrangement in a) anaerobic, b) facultaive, and c) maturation reactors.

3.1 Laboratory methods

Experimental tests were performed at the Civil Engineering hydraulics laboratory of Covenant University. Samples of the campus wastewater were collected at both the inlet and outlet position of each pond in series for the analysis of Fecal coliform, Total Dissolved Solids, Conductivity, and pH. The fecal coliform bacteria for the influent and effluent samples were determined by the membrane filter procedure (method no.: 9222D, APHA, 1998), which uses an enriched lactose medium and incubation temperature of 44.5 ± 0.2°C for selectivity. The total dissolved solid (TDS) and conductivity measurements were performed using the HANNA C99 Multiparameter Bench photometer. The pH was measured using the HANNA Instruments pH meter. The operating condition of the lab where the lab-scale pilot experiment was performed has a room temperature of 24^0C with the ponds hydraulic retention times of 0.165 day, 0.563 day, and 0.683 day for anaerobic, facultative and maturation ponds, respectively, that correspond to a flow rate of 0.12 m^3 per day. At this flow rate, the Re number for the three ponds was 304, which suggest that the WSP operates well within the laminar flow regime. The observed influent concentration into the three stage reactors were 59×10^3 per 100 ml for fecal coliform and a mean value of 342 (ppm), 695 (μS), and 7.47 for TDS, conductivity, and pH, respectively. Figure 4 displays the laboratory set up for the experiment that compares the initial design without cost and the optimized designs.

Figure 4 Different tested laboratory-scale reactor configurations during the experiment

3.2 SENSITIVITY ANALYSIS

A sensitivity analysis was performed with the optimization tool for the single objective (SIMPLEX) and Multi-objective genetic algorithm (MOGA-II) to determine the influence of the first order constant (k) and temperature (T) on the optimal design configurations. A 50 percent variation was made on the values of k proposed and adopted by Banda (2007). Equation 7 expresses the relationship k, in the convective-diffusion equation (Olukanni and Ducoste, 2011) as:

$$\rho\frac{\partial C}{\partial t}+\rho\sum_{j}\frac{\partial\left(U_{j}C\right)}{\partial x_{j}}=\rho\sum_{j}\frac{\partial}{\partial x_{j}}\left(\frac{\nu}{Sc_{l}}\frac{\partial C}{\partial x_{j}}\right)-kC \qquad (7)$$

where:

ρ = fluid density (kg/m^3)

U = mean velocity (m/s)

t = time (s)

υ = kinematic viscosity (m^2/s)

C = fecal coliform or tracer concentration (mol/m^3)

Sc = Schmidt number

k = first order decay of fecal coliform (d^{-1})

The simulations were performed at steady state and the reaction term in Equation 7 was used for characterizing the fecal coliform inactivation kinetics. Banda (2007) fecal coliform first-order decay rate constant was adopted in this study due to its reasonable goodness of fit for baffled WSPs. The goodness of fit as measured with R^2 between the predicted CFD fecal coliform counts and the measured effluent fecal coliform concentration from his baffled pilot-scale ponds was 0.83 when the following rate constant expression:

$$k = 4.55(1.19)^{T-20}\,day^{-1} \qquad (8)$$

$$k = k^{1}(1.19)^{T-20}\,day^{-1} \qquad (9)$$

where:

$k^1 = k^1_{old}$ (1 ± 0.5); (k^1 = 4.55 at T = 24^{0}C). Therefore, k = 6.825 (1.19)$^{24-20}$ = 13.686 (day^{-1}) at the upper bound and

k = 2.275 (1.19)$^{24-20}$ = 4.562 (day^{-1}) at the lower bound

For the sensitivity assessment on temperature, a 20 percent variation was evaluated based on the temperature range that may be possible in Nigeria. Equation 10 expresses how T value was varied while maintaining k^1 equal to 4.55.

$$k = k^{1}_{old}(1.19)^{T^{1}-20} \qquad (10)$$

where:

$$T^{1} = T^{1}_{old} \pm 4^{0}c$$

Therefore, k = 4.55(1.19)$^{28-20}$ = 18.297 (day^{-1}) at the upper bound and k = 4.55(1.19)$^{20-20}$ = 4.55 (day^{-1}) at the lower bound.

4.0 Results and Discussion

4.1 Evaluation of the Three-Stage WSP designs

Table 2 displays the comparison of the CFD predicted results and experimental data of the effluent fecal coliform log kill for the six-baffle 70% pond-width transverse, four-baffle 70% pond-width transverse, and longitudinal reactors with the CFD/optimized Simplex and MOGA II WSP designs. The CFD model reasonably predicts well the experimental fecal log kill for the anaerobic pond but over predicts the log kill for the facultative and maturation reactors. Possible reasons for these discrepancies include a slight difference in the experimental fecal 1st order rate constant, operating temperature, and the wastewater density (ρ) as compared to the values used in the model simulations. The literature reports that temperature and 1st order rate constant are factors that significantly affect experimental performance of WSPs (Shilton and Harrison, 2003a; Fredrick and Lloyd, 1996; Brissaud *et al.,* 2000, 2003).

It was recognized that the results in Table 2 are almost the same for the most part with little difference in the fecal coliform results for the different reactor configuration. Only that the model was able to show how to reduce the cost and still achieve similar effluent quality. The main prominent difference in the overall three-stage reactors in series is the cost for each of the different set of designs. For the anaerobic reactors, the simplex optimal design had the highest fecal log kill (0.35) as compared to other configurations followed by the four-baffle and Six-baffle 70% pond-width lab-scale reactors with 0.34 and 0.32, respectively. The MOGA II design configuration performed with a reduced fecal log kill as compared to the Simplex design (0.30 vs 0.35). For the facultative reactors, the same value of log removal was observed for Four-baffle 70% pond-width transverse reactor and the Simplex optimized design (0.81 log unit). The Simplex optimized design for the facultative reactor performed better than the remaining configurations with a log unit of 0.81 with an additional cost (N103) over the MOGA II design as compared to 0.74 and 0.75 in the six-baffle transverse and Four-baffle 70% pond-width longitudinal reactors, respectively. Surprisingly, there was no difference in the treatment performance for the six baffle transverse and four baffle longitudinal maturation reactors (0.70 fecal log kill). The same performance was observed in the four-baffle 70% pond-width transverse reactor, Simplex, and MOGA II optimized design with 0.60 fecal log kill.

While each design seemed to have produced similar log-kill removal results, the CFD optimized configuration led to designs that were cheaper in cost. A cost of N1, 297 and N1, 234 were achieved for the optimized designs for the anaerobic reactors as compared to N1, 669, N1, 582 and N1, 926 for the literature arranged designs. The same pattern of cost reduction was achieved for the facultative reactors except for the maturation reactor where the CFD/optimized designs (MOGA II and Simplex) have the same cost (N7, 221) with the four-baffle 70% pond-width transverse reactor configuration. This similar result confirms that the four baffle 70% pond-width maturation reactor could be considered a cost effective design that was suggested in the literature. However, the six-baffle 70% pond-width configuration displayed only a marginally higher cost (N7, 360) with a higher log reduction of 0.70 fecal log kill.

While the results of the simulated models in this study is expected to enhance the understanding of field-scale ponds and to aid in the estimation of some parameters that are useful in the design and evaluation of the performance of field-scale ponds, it is important to stress that most variables affecting ponds performance are very complex and may not be straightforwardly analyzed in which environmental, pond geometry and flow conditions are very paramount (Marcos do Monte and Mara, 1987; Agunwamba, 1992). Hence, the variation that could occur in performance between laboratory-scale model and field scale prototype of WSPs. This is because model ponds are often subjected to hydraulic flow, operating and boundary conditions that are not encountered in practice. Therefore, adequate consideration should then be given to these factors during the modeling phase in addition to the interpretation and application of the results of the models in the design and construction of field-scale ponds.

Table 2 Comparison of the CFD-predicted results and Experimental data of the effluents of fecal coliform log kill

Parameter Feacal coliform (FC/100ml) at k = 4.56 d^{-1}	**Six-baffle 70% pond-width lab-scale reactor**	**Four-baffle 70% pond-width transverse lab-scale reactor**	**Four-baffle 70% pond-width longitudinal lab-scale reactor**	**Simplex optimized designs**	**MOGA-II optimized designs**
		Anaerobic reactors			
Experimental Log-removal	0.32	0.34	0.31	0.35	0.30
CFD Simplex log-removal	-	-	-	0.32	-
CFD MOGA II log- removal	-	-	-	-	0.30
Cost of construction (N)	1, 669	1, 582	1, 926	1, 297	1, 234
		Facultative reactors			
Experimental Log-removal	0.74	0.81	0.75	0.81	0.76
CFD Simplex log-removal	-	-	-	1.01	-
CFD MOGA II lo-removal	-	-	-	-	0.71
Cost of construction (N)	5, 563	5, 431	5, 960	5, 091	4, 988
		Maturation reactors			
Experimental Log- removal	0.70	0.60	0.70	0.60	0.60
CFD Simplex log-removal	-	-	-	1.08	-
CFD MOGA II log-removal	-	-	-	-	0.81
Cost of construction (N)	7, 360	7, 221	7, 772	7, 221	7, 221

4.2 Results of sensitivity analysis for Simplex design at upper and lower boundary.

Tables 3-6 show WSP configurations that were generated due to changes in the fecal coliform 1st order rate constant and temperature. The results in Tables 3-6 displayed that changing these two parameters not only impacts the effluent fecal coliform concentration, which was expected, but also the WSP system configuration. In Tables 3-6, there are differences in the baffle length, area ratio, reactor depth, baffle orientation and baffle number. The result in Table 3 of the sensitivity analysis performed using the single objective simplex program at the higher k value displays a significant change in fecal coliform log removal with an appreciable difference in the associated cost at the higher disinfection rate constant.

Table 3 Simplex sensitivity analysis optimal design results for $k = 13.686\ d^{-1}$ at $T = 24^0C$

	Anaerobic Transverse SA1			**Facultative Longitudinal SA1**			**Maturation Transverse SA1**		
	Optimal design	Min. FC removal	Max FC removal	Optimal design	Min. FC removal	Max FC removal	Optimal design	Min. FC removal	Max FC removal
Cost (₦)	**1, 200**	1, 211	1, 767	**5, 184**	5, 184	5, 265	**7, 891**	7, 993	7, 992
Log removal	**0.82**	0.80	0.98	**2.32**	2.32	2.92	**2.34**	2.01	2.77
Area ratio	**3:1**	3:1	2:1	**2:1**	2:1	2:1	**2:1**	4:1	2:1
Depth (m)	**0.113**	0.113	0.062	**0.048**	**0.048**	**0.048**	**0.036**	0.035	0.036
Baffle ratio	**8%**	10%	71%	**70%**	70%	87%	**64%**	45%	68%
Number of baffles	**3**	4	7	**2**	2	2	**5**	4	6

Table 4 displays the results that were found at the lower bound of the k value used in the sensitivity analysis. The same order of optimal design solutions are recorded (Transverse-, Longitudinal- and Transverse-baffle arrangement). There is a significant change in FC log removal with little difference in the associated cost as compared to the simplex optimal design result in Table 3. This is due to the higher values of first order kinetic rate constant that was used in the simulation. A higher value of log removal also can be seen on the max FC removal columns for the three reactors. It can be said that the 8% pond-width baffle shown in anaerobic is as good as no baffles. An additional simulation was performed to verify the same configuration without the use of the 8% pond-width baffles and the results recorded were indeed the same. This is an indication that baffles may not be required in the anaerobic pond at that k value and it suggests that for efficient treatment, combinations in the order of transverse, longitudinal and transverse baffle arrangement may be a optimal solution for the anaerobic, facultative and maturation reactors respectively. The 14% baffle in the anaerobic pond was also evaluated and found to produce no significant difference compared to a no baffle configuration at the lower bound k value. The maturation reactors requires were found to require more number of baffles than both the anaerobic and facultative as shown in Tables 3 and 4. Also, only 2-baffles were achieved for the optimal solution in all the k values used in the facultative reactor. This may not be unconnected to the fact that the the final stage of pathogens and nutrients removal takes place in the maturation pond with wider surface area, shallow depth, and more number of baffles (Hamzeh and Ponze, 2007).

Table 4 Simplex sensitivity analysis optimal design results for k = 4.562 d^{-1} at T = 24^0C

	Anaerobic Transverse SA2			**Facultative Longitudinal SA2**			**Maturation Transverse SA2**		
	Optimal design	Min. FC removal	Max FC removal	Optimal design	Min. FC removal	Max FC removal	Optimal design	Min. FC removal	Max FC removal
Cost (₦)	**1, 192**	1, 237	1, 579	**5, 220**	5, 220	5, 750	**7, 991**	8, 698	8, 071
Log removal	**0.32**	0.30	0.33	**1.01**	1.01	1.16	**1.08**	1.02	1.30
Area ratio	**3:1**	3:1	4:1	**2:1**	2:1	3:1	**4:1**	3:1	4:1
Depth (m)	**0.12**	0.098	0.074	**0.048**	**0.048**	**0.048**	**0.036**	0.032	0.036
Baffle ratio	**14%**	16%	52%	**77%**	77%	95%	**70%**	49%	74%
Number of baffles	**2**	2	7	**2**	2	3	**6**	5	7

Table 5 displays the sensitivity analysis based on the multi-objective program at the upper bound value of k. Transverse, transverse and longitudinal baffle arrangements were obtained for the three reactors in series which is not the same as the configuration pattern predicted at the lower bound value of k = 4.562 d^{-1}. Table 6 shows that all configurations recorded transverse baffle arrangement for the three reactors in series. There is also a significant change in FC log removal with little difference in the associated cost. This same observation was made in the case of the simplex sensitivity analysis results in Tables 3 and 4. This observation is as a result of the higher values of 1st order kinetic rate constant that was used in the simulation. However, the number of baffles was significantly reduced for the MOGA II results as compared to the simplex sensitivity analysis results in both instances of higher and lower values of first order kinetic rate constants.

Table 5 MOGA-II Sensitivity Analysis Optimal Design Results k = 13.686 d^{-1}

	Anaerobic Transverse SA1			**Facultative Transverse SA1**			**Maturation Longitudinal SA1**		
	Optimal design	Min. FC removal	Max FC removal	Optimal design	Min. FC removal	Max FC removal	Optimal design	Min. FC removal	Max FC removal
Cost (₦)	**1, 219**	1, 369	1, 539	**4, 966**	4, 966	5, 235	**7, 727**	8, 457	7, 873
Log removal	**0.81**	0.80	1.00	**1.90**	1.90	2.48	**2.28**	2.01	2.98
Area ratio	**1:1**	1:1	1:1	**1:1**	1:1	1:1	**1:1**	4:1	2:1
Depth (m)	**0.115**	0.117	0.115	**0.048**	0.048	0.046	**0.036**	0.036	0.036
Baffle ratio	**46%**	66%	79%	**46%**	46%	68%	**74%**	62%	76%
Number of baffles	**2**	3	4	**2**	2	2	**2**	4	2

Table 6 MOGA-II Sensitivity Analysis Optimal Design Results k = 4.562 d^{-1}

	Anaerobic Transverse SA2			**Facultative Transverse SA2**			**Maturation Transverse SA2**		
	Optimal design	Min. FC removal	Max FC removal	Optimal design	Min. FC removal	Max FC removal	Optimal design	Min. FC removal	Max FC removal
Cost (₦)	**1, 188**	1, 476	1, 538	**4, 931**	4, 974	5, 385	**7, 623**	9, 566	9, 626
Log removal	**0.30**	0.30	0.35	**0.71**	0.71	1.1	**0.81**	0.80	1.42
Area ratio	**2:1**	3:1	1:1	**2:1**	3:1	1:1	**1:1**	3:1	1:1
Depth (m)	**0.11**	0.062	0.074	**0.048**	0.048	0.048	**0.036**	0.028	0.028
Baffle ratio	**29%**	33%	82%	**11%**	10%	85%	**42%**	90%	86%
Number of baffles	**2**	2	3	**6**	6	4	**2**	3	3

As presented in Table 2, even though the simplex and MOGA II designs produced similar fecal log reduction results, they achieved the results at a significantly reduced cost, which was the desired goal of this study. This observation suggests that the first order kinetic rate constant k for the laboratory experiment may perhaps be closer to the ones at lower range of k value and that the low end of the sensitivity analysis performed on the rate constant is actually quite good. While each design seemed to have produced similar results, the CFD optimized designs were cheaper in cost. Therefore, this approach to developing a cost effective design has been validated.

The experimental data of Physico-chemical (PH, conductivity and Total dissolved solids) parameters in the influent and effluent samples are presented in Tables 7-9 for anaerobic, facultative, and maturation laboratory scale WSPs, respectively.

The associated cost for each reactor configuration for nutrient removal performance is presented in Tables 7-9. Although the optimized design results and the standard configuration produced similar removal performance, the cost is vastly different. Table 7 displays the experimental pH that was measured in all the reactor configurations. The measured pH in all the reactor configurations compare well with the expected pH found in literature (Pearson et al, 1987; Parhad and Rao, 1974). Many chemical and biological reactions in wastewater treatment are pH dependent and rely on pH control. Table 7 shows that as the wastewater moves through the reactors in series, the pH of the effluent from the reactors increases from pH 7.5-7.9.

Table 8 shows that the experimental data of total dissolved solids in the influent was in the range of 340-343 (Avg = 341) ppm while the effluent concentration was in the range of 273-315 ppm, respectively. The CFD/optimized configuration performed well as compared to other configurations with TDS effluent of 275 ppm in Simplex and 293 ppm MOGA II optimized designs. The four-baffle 70% pond width transverse performed well as compared to the six-baffle transverse arrangement and the four baffle longitudinal arrangement.

Table 9 shows that the anaerobic reactor had minimal reduction in conductivity values as compared to the performance of the maturation reactors which gave a significant reduction in the conductivity of the effluents. The four-baffle 70% pond width transverse lab-scale reactor series gave the optimal conductivity reduction for the entire configuration (557 μS) followed by the simplex optimized design with a conductivity value of 562 μS. It is evident that the Simplex design is reasonably predicting more of pollutant reduction in the entire set of laboratory-scale WSPs. Continuous measuring systems are employed to monitor the salt load at the influent and effluent of wastewater treatment facilities. At present, the conductivity of wastewater is one of the important parameters used to determine the suitability of wastewater for irrigation (Crites and Tchobanoglous, 1998; Metcalf and Eddy 2003).

Table 7 Experimental data of PH variation for all the reactor configurations

Parameter pH	Six-baffle 70% pond width reactor	Four-baffle70% pond width transverse reactor	Four-baffle 70% pond width longitudinal reactor	Simplex optimized design	MOGA-II optimized design
Influent pH	7.43	7.47	7.47	7.50	7.50
Anaerobic Effluent pH	7.69	7.54	7.53	7.62	7.58
Facultative Effluent pH	7.81	7.86	7.81	7.80	7.84
Maturation Effluent pH	7.88	7.89	7.85	7.82	7.89
Cumulative cost (N)	14, 592	14, 234	15,658	13,609	13,443

Table 8 Experimental data of TDS removal for all the reactor configurations

Parameter **TDS (ppm)**	**Six-baffle 70% pond width reactor**	**Four-baffle 70% pond width transverse reactor**	**Four-baffle 70% pond width longitudinal reactor**	**Simplex optimized design**	**MOGA-II optimized design**
Influent TDS	342	340	340	343	343
Anaerobic Effluent TDS	340	334	333	338	338
Facultative Effluent TDS	326	313	309	315	318
Maturation Effluent TDS	302	273	285	275	293
Percentage Removal (%)	12	20	16	20	15
Cumulative Cost (N)	14, 592	14, 234	15,658	13,609	13,443

Table 9 Conductivity experimental data for all the reactor configurations

Parameter Conductivity (µS)	Six-baffle 70% pond width reactor	Four-baffle70% pond width transverse reactor	Four-baffle 70% pond- width longitudinal reactor	Simplex optimized design	MOGA-II optimized design
Influent conductivity	700	690	690	697	697
Anaerobic Effluent conductivity	693	682	662	689	691
Facultative Effluent conductivity	656	627	642	653	639
Maturation Effluent conductivity	625	557	581	562	598

Percentage Removal (%)	11	19	16	19	14
Cumulative cost (N)	14, 592	14, 234	15,658	13,609	13,443

The result of the effluent quality tested for pH, conductivity and TDS showed that the WSPs performed well with different levels of pollutant removal. The model results of the fecal coliform log removal at the low end rate constant compared well with the experimental results that were carried out in the entire set of reactors in the laboratory-scale WSPs. The significance of the CFD validation is that regulators and designers can use CFD confidently both as a reactor model and as a hydraulic tool to develop an optimal design that meets the treatment efficiency of baffled WSPs at a reduced cost. The results of this research will directly impact the possible design decisions that wastewater treatment engineers must make related to WSPs design in developing nations.

5. Conclusions

Characteristics of a CFD-based model that incorporates the effects of different foot print size, baffle configuration, and baffle length on the treatment performance of the WSP has been explored. The use of CFD has proven to be a powerful tool to facilitate the design and evaluation of new and existing WSP systems. However, the modeling performed in this study did not include potential physics and biodegradable build-up that may occur in field WSPs such as surface wind shear, variable flow rate, variable climatic condition, and sludge deposits that may impact WSP design decisions. It was also observed that even though hydraulic similarity was achieved in the laboratory scale model which is intended to represent a full scale pond, other physical and biochemical phenomena such as sunlight penetration along the depth, temperature gradients, gas transfer and removal of other nutrient parameters could not be incorporated into this CFD model because the removal of these parameters depends on various processes such as algae uptake, sedimentation, vaporization and denitrification, which are more complex to model as several sub-models and empirical measurement would be required. In addition, it would also be difficult to test and verify the results of such complex models. The optimized solution was based only on the disinfection process, the kinetics of fecal coliform, and an explicit cost objective function along with the associated constraints. The realization of this practical limitation of CFD modeling is a very important consideration for practicing engineers applying CFD result to full-scale pond design. However, since designs can be compared with each other, then it might be possible to determine the best design among a possible list of alternatives. Therefore, CFD/optimization technique is seen as a sign tool or protocol to achieving a cost effective designs that will not jeopardize the treatment efficiency.

Rigorous assessment of WSPs that account for cost in addition to treatment efficiency utilizing CFD coupled with an optimization program to efficiently optimize the selection of the best WSP configuration has been performed. In addition, a sensitivity analysis with the first order rate constant (k) and the temperature (T) parameters was carried out. The most important result of this study has been that a cost effective designs was produced by the simplex and MOGA II optimization techniques that do not jeopardize the treatment efficiency of the three stage reactors. While each design seemed to have produced similar results, the CFD optimized designs were significantly lower in cost. Therefore, this approach to developing a cost effective design has been validated.

In view of the experimental data obtained from the laboratory-scale waste stabilization ponds and the CFD modeling, further work is required:
1. Verification of results achieved from the laboratory-scale to a full-scale construction of waste stabilization pond. This type of experience would provide valuable insight on the real investment and operational costs as well as the real requirements of operation and management for this technology.
2. The data obtained from the full-scale construction of WSP would allow the sustainability of the technology to be assessed under real conditions. The result of the full-scale experimentation would serve as guide to physical planning units of institutions for the design of treatment systems that will enhance environmental quality and protection.

The results of this study have indicated that the WSP geometry can be optimized to achieve a target effluent contaminant reduction using CFD coupled with an optimization algorithm. Finally, this work has demonstrated the use of CFD coupled with an optimization algorithm to provide an efficient assessment of alternative pond configurations, thereby, addressing a potential knowledge gap in waste stabilization pond design.

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