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Modelling solar enhanced waste stabilization pond

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Abstract

Solar enhanced waste stabilization pond (SEWSP) was modeled in this research. In the analysis, SEWSPs of varying sizes, made of metallic tanks with inlet and outlet valves and solar reflectors, were constructed to increase the incident solar intensity. Wastewater samples collected from the inlet and outlet of the SEWSPs were examined for physico-chemical and biological characteristics for a period of twelve (12) months. The parameters examined were temperature, pH, detention time, total suspended solids, dissolved oxygen, biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), algae count, faecal coliforms and *E. coli*. The efficiencies of the SEWSPs with respect to these parameters fluctuated with depth, location of reflectors and variation in width. The SEWSP with a width of 0.2 m whose reflector was installed at the outlet position gave the highest treatment efficiency. The conventional model was modified to account for solar irradiation. The faecal bacteria removal was significantly higher in the enhanced pond than in the conventional pond at 0.10 level of significance. The verification of the conventional model gave a good correlation of $r = 0.882$ between the measured and calculated N_e/N_o with a low standard error of $s = 0.010$, while the irradiated pond gave a correlation and standard error of $r = 0.959$ and $s = 0.012$ respectively. The research revealed that with the incorporation of solar radiation in WSPs, a length/ width/depth ratio of 1:0.2:0.2 can be used in the design of SEWSPs for maximum treatment efficiency.

Key words: dispersion, efficiency, modelling, solar radiation, waste stabilization pond, wastewater

INTRODUCTION

The incorporation of solar reflectors in conventional waste stabilization ponds to effectively increase the efficiency of the pond and consequently reduce the land area requirement is an evolving technology termed the solar enhanced waste stabilisation pond (SEWSP) (Agunwamba *et al.* 2009).

Over the years, the severe shortage of water, primarily in arid and semi-arid regions, has promoted the search for extra sources currently not intensively exploited, especially in developing countries. Treated wastewater of domestic origin is now being considered and used in many countries throughout the world as an additional renewable and reliable source of water that can be used for numerous purposes (Angelakis *et al.* 2003). Treated wastewater reuse makes a contribution to water conservation and expansion of irrigated agriculture, taking on an economic dimension. It also solves disposal problems aimed at protecting the environment and public health and preventing surface water pollution (Papadopoulos & Savvides 2003). The benefits and the potential health and environmental risks resulting from wastewater reuse and the management measures aimed at using wastewater within acceptable levels of risk to public health and the environment are well documented (Hamzeh & Ponce 2002). Therefore, wastewater reuse requires effective treatment and measures to protect public health and the environment at a feasible cost (Anderson *et al.* 2001; Leite *et al.* 2009).

In the past, researches have been conducted to improve pond efficiency, thereby maximizing land use by optimization techniques (Agunwamba & Tanko 2005); using recirculating stabilization ponds in series (Leite *et al.* 2009); step feeding (Leite *et al.* 2009); incorporating an attached growth system (Abbas *et al.* 2006), and more accurate estimation of pond design parameters (Mara *et al.* 2001; Ihsan & Sunarsih 2018; Winchen *et al.* 2018).

Many authors have work in the area of pond geometry, the addition of other techniques and materials for the purpose of economy or enhancing waste stabilization pond efficiency. Higher pond depths have been investigated for reduction of pond surface area (Pearson *et al.* 2005; Coggins *et al.* 2017; Gopolany & Letshweny 2018; Winchen *et al.* 2018). Although solar inactivation of bacteria in wastewater is well established (Sinton *et al.* 2002; Benchokroun *et al.* 2003; Davies-Colley *et al.* 2005; Nwokolo 2017), high efficiency and economics of integration of solar reflectors in ponds have also been investigated. However, a model for the prediction and verification of solar enhanced WSP performance has not been reported.

METHODOLOGY

In the course of carrying out the research, different sets of solar ponds were constructed with dimensions as shown in Figures 1–6 below, with one sewage storage tank (1.2 m × 0.5 m × 0.5 m) that receives its influent from an overhead storage tank (1.2 m × 1.5 m × 1.5 m) constructed for the experiment. Detailed descriptions of the various ponds with respect to their different set-ups are shown in Tables 1–3. Five (5) out of the six ponds were constructed with tilt frames at 45° for installation of

Figure 1 | Experimental set-up of solar ponds with different widths.

Figure 2 | Inlet position of reflectors.

Figure 3 | Right position of reflectors.

Figure 4 | Left position of reflectors.

Figure 5 | Outlet position of reflectors.

polished aluminium sheets of size 0.2 m by 1.0 m each, which act as solar reflectors. The ponds were installed with one solar reflector each, first at the inlet position, subsequently at the outlet position, then lastly the two sides, for the purpose of increasing the incident radiation into the ponds. The solar ponds were filled with sewage from Nsukka sewage pond located within the University of

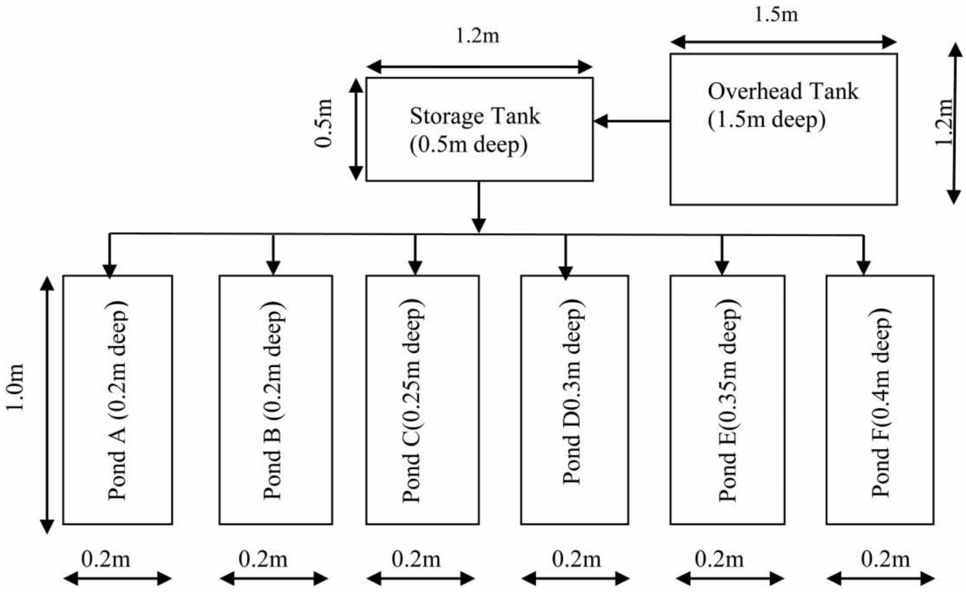

Figure 6 | Schematic diagram of experimental setup due to depth variation.

Table 1 | Description of the various ponds with different widths

Experimental ponds	Size (m) (l x w x d)	Characteristics	Purpose
A	1 × 0.4 × 0.2	No solar reflector	Control
B	1 × 0.4 × 0.2	Solar reflector	Measure the effect of solar reflector
C	1 × 0.3 × 0.2	Solar reflector	Measure the effect of solar reflector
D	1 × 0.5 × 0.2	Solar reflector	Measure the effect of solar reflector
E	1 × 0.2 × 0.2	Solar reflector	Measure the effect of width
F	1 × 0.6 × 0.2	Solar reflector	Measure the effect of solar reflector

Table 2 | Detailed experimental characteristics of the various ponds due to positioning

Experimental set-ups	No. of solar ponds	Characteristics	Purpose
Set 1	6	Inlet position	Effect of solar position ermiControl
Set 2	6	Right position reflector	Effect of solar position
Set 3	6	Left position	Effect of solar position
Set 4	6	Outlet position reflector	Effect of solar position

Table 3 | Description of the various ponds with different depths

Experimental ponds	Size (m) (l x w x d)	Characteristics	Purpose
A	1 × 0.2 × 0.20	No solar reflector	Control
B	1 × 0.2 × 0.20	Solar reflector	Measure the effect of depth
C	1 × 0.2 × 0.25	Solar reflector	Measure the effect of solar reflector
D	1 × 0.2 × 0.30	Solar reflector	Measure the effect of solar reflector
E	1 × 0.2 × 0.35	Solar reflector	Measure the effect of solar reflector
F	1 × 0.2 × 0.40	Solar reflector	Measure the effect of solar reflector

Nigeria, Nsukka campus. The two storage tanks were filled to supply the six sets of ponds with sewage wastewater; the overhead storage tank was at intervals filled with sewage from the facultative pond, through an underground pipe, with the aid of a water pump that was powered by a generator. The detailed descriptions of the various ponds are explained in the Tables below, where $(l \times w \times d)$ means (length: width: depth).

Sample analysis

Influent and effluent samples were collected weekly from the inlet and outlet of the solar ponds, and were examined for physio-chemical and biological characteristics for a period of twelve (12) months. The parameters examined were temperature, pH, detention time, suspended solids, dissolved oxygen, biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), algae concentration, coliforms and E. coli. All the analysis was done using appropriate water testing meters and in accordance with the standard methods (APHA 1999).

Flow measurement

The wastewater discharge was measured using a graduated discharge measurement tank because no flow meter and recorder were available. The discharge was obtained from the recorded volume divided by the time to reach that volume. The flow in the control ponds was adjusted with the control valves to achieve the same flow rate in the irradiated ponds. The ponds were continuously fed with waste water from the reservoir for two weeks to attain steady-state condition.

Tracer studies

Tracer studies were conducted to determine the dispersion characteristics of the six ponds for different detention times. Sodium chloride (NaCl) was used as the impulse tracer and the response tracer concentration was monitored at the exit stream at time intervals. The amount of input impulse tracer was about 60 g for each pond. The base amount of NaCl present in the wastewater was subtracted from the measured values. The calculation of the dispersion number (d) was made with the relationship, Polprasert & Bhattarai (1985),

$$\sigma^2 = 2d - 2d^2\left[1 - \exp\left(-\frac{1}{d}\right)\right] \tag{1}$$

where σ^2 is the normalized variance determined from the tracer concentration-time curves.

Model parameters

Ukpong *et al.* (2006) used the model developed by Saqqar & Pescod (1992) for the computation of K as:

$$K = 0.5(1.02)^{Tw-20}(1.15)^{(pH-6)2}(0.99784)^{(Ls-100)} \tag{2}$$

where K, $T_{w,}$ p^H and L_s are the faecal coliform die-off rate coefficient, water temperature, hydrogen ion concentration and concentration of soluble BOD_5 loading respectively.

The pond depth effect on K has been accounted for by the model developed by Sarikaya & Saatci (1987):

$$K = K_d + \frac{K_s S_o}{K_i H} \tag{3}$$

where K_d is rate of coliform mortality in the dark/d; $K_{s,}$ the rate constant for high mortality term, cm^2/cal; $K_{i,}$ the light attenuation coefficient; $S_{o,}$ light intensity, $cal/cm^2/s$ and H is the pond depth, m.

In Equation (3), all the other factors, except depth and solar radiation, are lumped into K_d and then represented as a constant (Neumaier 2004). However, K_d has been found to vary widely, which challenges the validity of representing it as a constant in the regression analysis. Equation (3) also failed to incorporate the effects of humic substances, pH and dissolved oxygen, which are important variables in the process by which light damages bacteria. From the experimental results reported in Table 4, the faecal coliform die-off rate coefficient (k) was determined using Equation (2). The effluent bacteria reduction ratio for the ponds was evaluated based on the completely mixed flow model.

Table 4 | Operational characteristics of the pond before irradiation

Parameters	Conventional pond
Hydraulic detention time, days	5.9–11.2
pH	7.5–8.2
Temperature, T^0C	23.0–25.8
Do, mg/1	5.1–7.8
Influent (MPN) × 10^6/100 ml	9–43
Influent BOD mg/l	19.3–25.8
K, day^{-1}	0.54–0.91

Mathematical model development

The derivation follows the procedure used by Agunwamba (2010) but differs in terms of the basic assumption made. Whereas Agunwamba (2010) assumed dispersed flow, a completely mixed flow regime is assumed in the present study. The completely mixed flow model for one pond is expressed as

$$\frac{N_e}{N_o} = \frac{1}{1 + k_o \theta} \tag{4}$$

where N_e and N_0 are the effluent and influent bacteria concentrations; k_o, the bacteria die-off rate coefficient without solar radiation enhancement and θ is the detention time.

The relation between pond area and the detention time is

$$Q\theta = HA \tag{5}$$

where Q is discharge, m^3/day; θ, detention time, days; and A is pond area, m^2.

For simplicity, Equation (4), is used in the analysis. Considering the total die-off coefficient, K given in Equation (3), then differentiating Equations (3)–(5),

$$dk = dS_o \frac{K_s}{K_1 H} \tag{6}$$

$$\theta \mathrm{dk} = -\mathrm{kd}\theta \tag{7}$$

and

$$d\theta = \frac{H}{Q} dA \tag{8}$$

Eliminating dk and dθ from Equations (6)–(8),

$$\frac{\theta K_s}{K_1 H} dS_o = -\frac{KHdA}{Q} \tag{9}$$

Substituting for θ and K using Equations (3) and (4)

$$\frac{dA}{dS_o} = \frac{-K_s Q}{K_1 H^2}\left(\frac{N_o}{N_e} - 1\right)\frac{1}{\left(K_d + \frac{K_s S_o}{K_i H}\right)^2} \tag{10}$$

The negative sign in Equation (10), expresses that the higher S_o is the smaller the pond area A.

Kinetics of the solar enhanced WSP system

If the radiation is directed at only a small portion before the pond outlet, then the system can be considered to behave like two dispersed flows in series. The first is a conventional pond with no artificial solar enhancement, while a solar reflector is connected to the second.

The impact of light on bacterial removal is given by Scheible (1987) as

$$N_2 = N_1 \exp\left[\frac{ux}{2D}\left\{1 - \left(1 + \frac{4K_1 ID}{u^2}\right)^{\frac{1}{2}}\right\}\right] + N_p \tag{11}$$

where x is the characteristic length, which is the average distance travelled by the wastewater while under direct exposure to light; N_p represents the density associated with the particles, which shield the bacteria from being affected by irradiated light; D denotes the dispersion coefficient, which accounts for deviation of hydraulic behavior from that of perfect plug flow; and U is the flow velocity of the fluid; N_1 and N_2 are the bacteria concentrations before and after irradiation, respectively; I represents the density of irradiation while K_1 stands for the inactivation rate constant.

Combining Equations (4) and (11),

$$\frac{N_2}{N_o} = \frac{\left[\exp\left\{\frac{ux}{2D}\left\{1 - \left(1 + \frac{4K_1 ID}{u^2}\right)^{\frac{1}{2}}\right\}\right\} + N_p\right]}{1 + K_o \theta} \tag{12}$$

Data obtained from the pilot scale experiments were used to calibrate and verify Equation (3).

RESULTS AND DISCUSSION

The results of the variability in efficiency of parameter removal for the different widths, solar positioning, depth and solar intensity with respect to pH, temperature, coliform, E. coli, BOD, COD, suspended solids, algal concentration and DO are presented in Figures 7–16. While, Figures 17–19

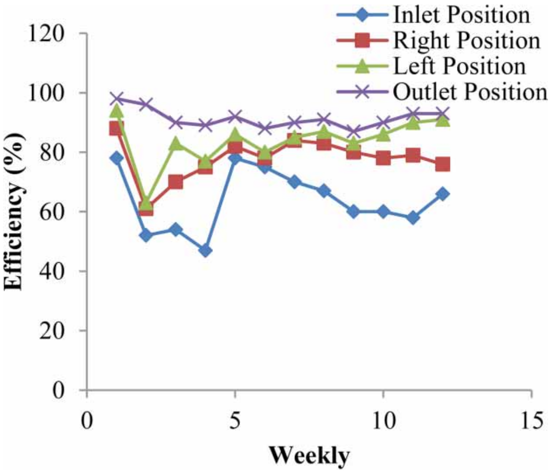

Figure 7 | Efficiency of coliform removal with time.

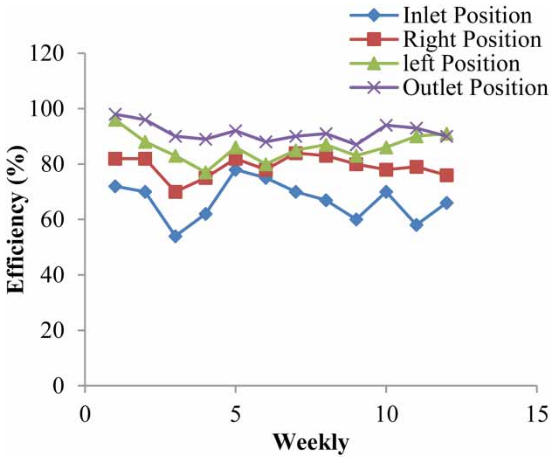

Figure 8 | Efficiency of E. coli removal with time.

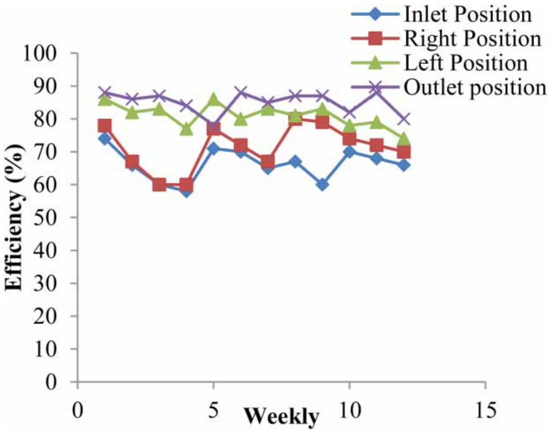

Figure 9 | Efficiency of BOD removal with time.

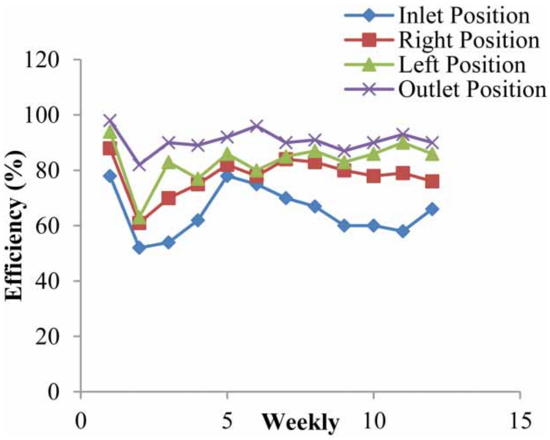

Figure 10 | Efficiency of COD removal with time.

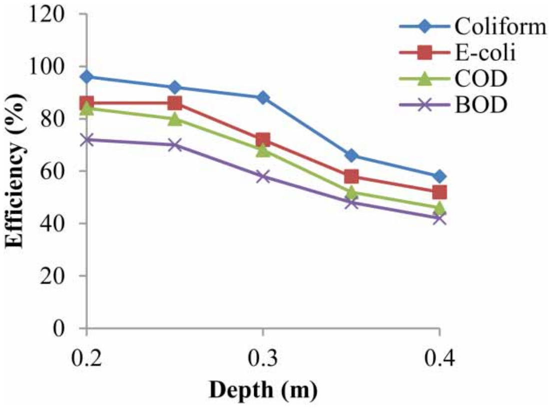

Figure 11 | Efficiency of treatment with depth.

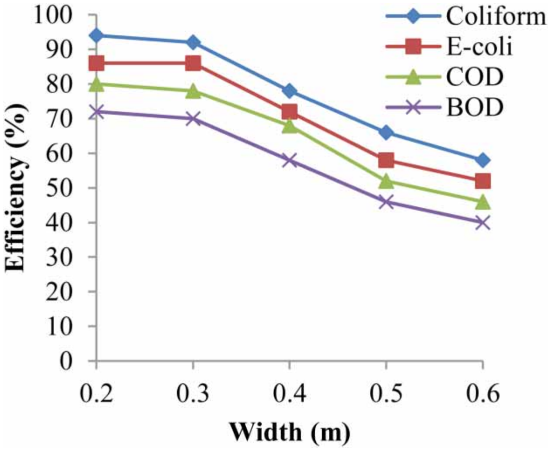

Figure 12 | Efficiency of treatment with width.

illustrates the variations of N_e/N_o with θ and k for both control and irradiated ponds and model verification respectively. Figure 7 shows the efficiency of coliform removal time as a function of the position of the solar reflectors. The outlet position gave the highest coliform removal in the SEWSPs. When biological activities take place in the pond, some level of treatment is said to have taken place. Hence, the reflectors gain momentum for efficient wastewater treatment if placed at

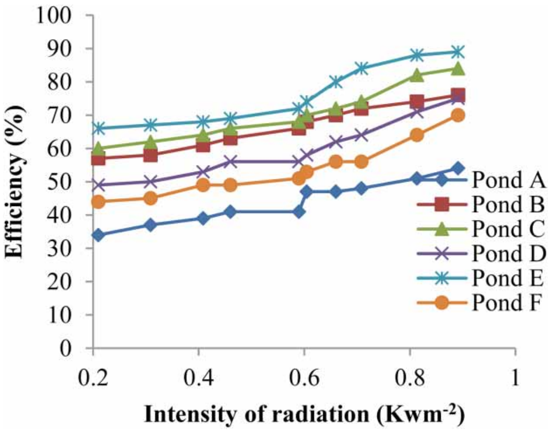

Figure 13 | Efficiency of BOD removal versus solar intensity.

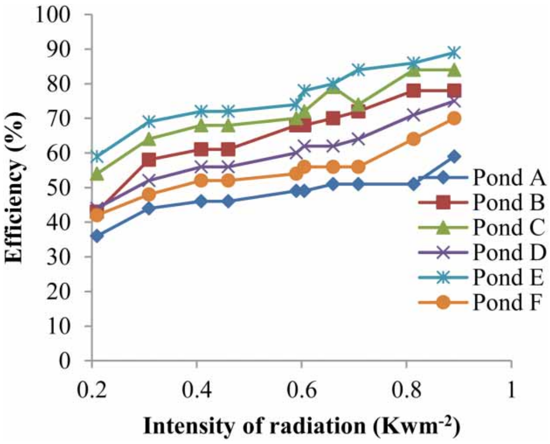

Figure 14 | Efficiency of COD removal versus solar intensity.

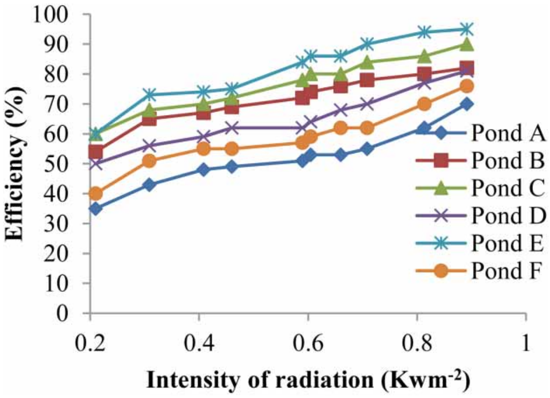

Figure 15 | Efficiency of coliform removal versus solar intensity.

the outlet (Utsev & Agunwamba 2012). The same was noticed for E. coli, BOD, and COD removal in Figures 8–10 respectively. Figures 11 and 12 show the efficiency of treatment with depth and width respectively. The efficiency of coliform removal amongst E. coli, COD and BOD was highest when depth and width were considered. Figure 13 demonstrated the efficiency of BOD removal for the different type of ponds considered. Pond E gave the highest BOD removal as all the ponds A, B, C, D, E, and F were subjected to the same intensity of radiation. This is also similar for COD, coliform, and E. coli removal as presented in Figures 14–16 respectively.

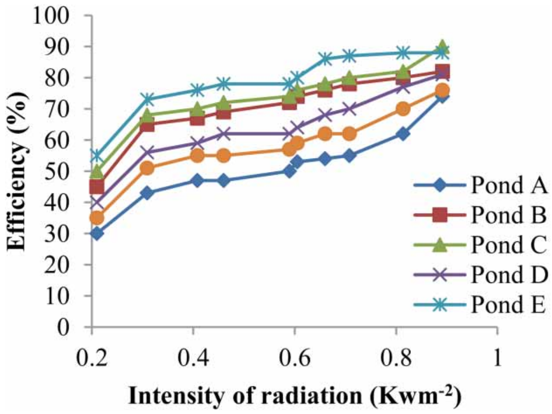

Figure 16 | Efficiency of E. coli removal versus solar intensity.

Experimental comparison ponds

Efficiency/model calibration

Generally, the average bacteria removal efficiency of the irradiated ponds was higher than that of the control. Following the normal small theory of test of hypothesis, the Student's t-critical value (at 22° of freedom and 0.10 level of significance) is 1.35 while the computed t-value is 1.42. Hence, at this level, it is significant to infer that N_e/N_o for the irradiated pond is lower than that of the control pond. The variations of N_e/N_o with θ and k for both control and irradiated ponds are shown in Figures 17 and 18, respectively.

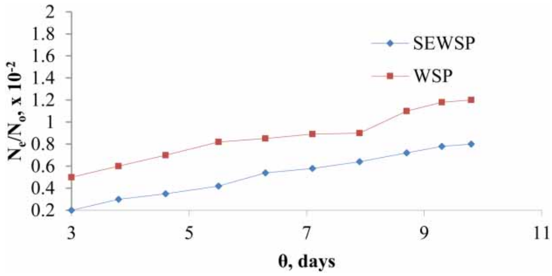

Figure 17 | Variation of bacteria reduction with detention time, θ for conventional and Solar Enhanced WSP.

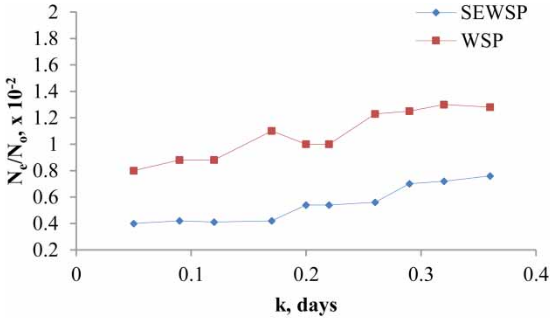

Figure 18 | Variation of bacteria reduction with die-off coefficient, k for conventional and Solar Enhanced WSP.

Verification of models

Figure 19 shows the verification of the conventional model with a good correlation of $r = 0.882$ between the measured and calculated N_e/N_o with a low standard error of $s = 0.010$. As for

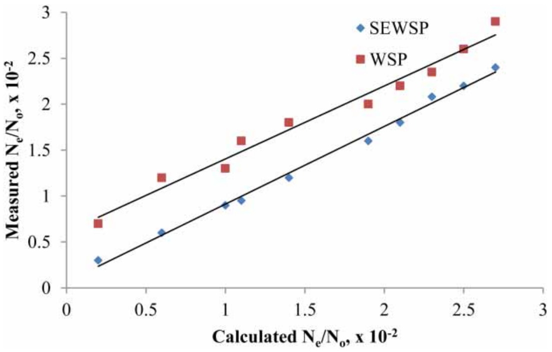

Figure 19 | Measured against calculated N_e/N_o in conventional and Solar Enhanced WSP.

the irradiated pond, the coefficient of correlation and standard error with the measure N_e/N_o are $r = 0.959$ and $s = 0.012$, respectively.

CONCLUSION

In the modification of the conventional waste stabilization pond, six sets of solar ponds with different widths, depths and installation of solar reflectors at different positions (i.e, left side, right side, inlet and outlet) were constructed to increase the incident radiation. Each set was comprised of six ponds (B, C, D, E and F) with pond A, without a reflector, as the control experiment. Laboratory analysis was carried out in order to examine some physico-chemical and biological parameters to ascertain the level of bacterial removal for a period of twelve (12) months. From the experimental results, a new model was derived, calibrated and verified for prediction of the solar enhanced WSP performance. The faecal bacteria removal was significantly higher in the enhanced pond than in the conventional pond at 0.10 level of significance. The verification of the conventional model gave a good correlation of $r = 0.882$ between the measured and calculated N_e/N_o with a low standard error of $s = 0.010$, while the irradiated pond gave a correlation and standard error of $r = 0.959$ and $s = 0.012$ respectively.

In conclusion, solar reflectors are recommended to be installed at the outlet position with a length/width/depth ratio of 1:0.2:0.2, in the design of solar enhanced waste stabilization ponds (SEWSPs) using the new model for optimum bacterial removal. However, further study is required to determine the efficiency of other types of solar reflecting materials and changing the position of the reflecting materials as the sun changes position for maximum treatment in SEWSPs.

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