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A new model for the prediction of the performance of integrated solar and hydraulic jump enhanced waste stabilization pond

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ABSTRACT

This paper presents a model which incorporates: characteristic length, dispersion coefficient, supercritical inlet velocity, initial and final bacteria density before and after irradiation, first-order rate constant for fecal coliform removal, retention time, dispersion number, solar radiation, depth of the integrated solar and hydraulic jump enhanced waste stabilization pond (ISHJEWSP), length of the horizontal section of ISHJEWSP, and angle of slope of the ISHJEWSP. A comparison of the conventional waste stabilization pond and the ISHJEWSP showed that the bacteria removal was significantly higher in the enhanced pond than the conventional pond at a significance level of 0.05. The verification of the conventional model gave good average coefficients of correlation of $R = 0.800 \pm 0.173$ between the measured and calculated N_e/N_o and $R = 0.924 \pm 0.034$ for the ISHJEWSP, respectively.

Keywords: Model; Performance; Prediction; ISHJEWSP

1. Introduction

A waste stabilization pond (WSP) is a basin dug on the earth for removal of organic and pathogenic organism [1]. It has been found to be 1,000 times better in destroying pathogenic organism. However, the large land area requirement of WSPs has limited their application [2]. The limitations of the conventional WSP have necessitated the need for new technologies in order to improve the treatment efficiency of wastewater. The integrated solar and hydraulic jump enhanced waste stabilization pond (ISHJEWSP) is introduced as a new technology that incorporates solar reflector and the introduction of hydraulic jump through change in pond bed slope of the conventional WSP. The essence is for the purpose of increasing the treatment efficiency of the conventional WSP and consequently, the reduction in land area requirement [3].

Some researchers have assumed that a pond is best represented as a completely mixed reactor [4,5].

Marais [6] presented equations for pond design assuming fecal coliform removal by the first order kinetic model in a completely mixed reactor. The resulting equation for a single pond is given by:

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

where N_e and N_o are the numbers of fecal coliform/100 ml in the effluent and influent, k is the first-order rate constant for fecal coliform removal (d^{-1}), and θ is

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the retention time (d). For a series of anaerobic, facultative, and maturation ponds.

$$N_e = \frac{N_o}{(1 + k\theta_a)(1 + k\theta_f)(1 + k\theta_m)^n} \tag{2}$$

where the subscripts a, f, and m refer to anaerobic, facultative, and maturation ponds and n is the number of maturation ponds.

Arguing that WSP cannot be modeled accurately as a completely mixed reactor as Marais did, Thirumurthi [7] recommended that ponds be designed as dispersed flow reactor since they are not in fact completely mixed. He therefore proposed the use of dispersion number and the first-order equation of Wehner and Wilhelm [8]. For rectangular ponds, Wehner and Wilhelm [8]; Agunwamba [9], obtained Eq. (3).

$$\frac{N_e}{N_o} = \frac{4a^2}{(1 + a)^2} \exp\left(\frac{1 - a}{2d}\right) \tag{3}$$

where $a^2 = 1 + 4\,k\theta d$.

As an alternative, a number of researchers support the use of the Wehner–Wilhelm equation for non-ideal flow, which incorporates the use of a dispersion number [7,10–15].

Predictive equations for the dispersion number have been proposed [13–18] but some of these have then been criticized when evaluated by others. The drawback of this approach is that the dispersion number is a single factor that is expected to account for the wide range of influences on the fluid flow through the pond system [19]. Shilton and Harrison [20] stated that hydraulic parameters, such as the mean hydraulic retention time or dispersion number, do not give a direct measure of treatment efficiency.

In the past, different performance predictive models for WSPs have been presented; however, no model has been presented for the prediction of the performance of ISHJEWSP. The specific objective is to derive, calibrate, and verify a new model for the prediction of the performance of the ISHJEWSP and compare with existing conventional model.

2. Materials and methods

2.1. Description of area of study

Located at the northeastern end of the University campus about 800 m from the junior staff quarters, the treatment plant at Nsukka consists of a screen (6 mm bar racks set at 12 mm centers) followed by two Imhoff tanks, each measuring about 6.667 m × 4.667 m × 10 m, and two facultative WSPs. Sludge is discarded from the Imhoff tank once every 28 d onto the drying beds, so that the beds are loaded at 40 d interval. The beds have a total area of 417 m^2. Although its efficiency has deteriorated, its effluent is used for uncontrolled vegetable irrigation by some village dwellers. The poor effluent quality is also partly attributable to overloading because of population growth.

2.2. Description of experimental setup

Experimental research and design was adopted. The experimental setup consisted of one sewage storage tank (1.2 m × 1.2 m × 0.6 m) and an overhead storage tank (1.5 m × 1.5 m × 1.2 m) as shown in Tables 1–3 and Fig. 1. Three sets of experimental ponds with varying locations of change in pond bed slope were constructed using metallic tanks with each set consisting of eight experimental ponds (A, B, C, D, E, F, G and H) with varying width. Six out of the eight ponds were constructed with tilt frames of size 1.0 m × 0.3 m, fixed at varying angles in accordance with the relative position of the sun per week. The tilt frames were made of flat wooden board wrapped with aluminum foil paper to serve as solar reflectors. The foil paper was to act as solar reflector, with each of the six ponds having one reflector each at the outlet position (west facing). One out of the eight ponds was constructed without a change in slope and solar reflector to serve as control experiment, while the other though without change in slope however was fitted with solar reflector in order to investigate the effect of solar radiation on the conventional WSP. For each set studied, ponds C, D, E, F, G, and H were constructed with varying locations of point of initiation of hydraulic jump. Half inches diameter inlet pipes were fitted centrally to the experimental ponds. The outlet pipes were centrally fitted to the experimental ponds. To control the inflow and outflow, valves were fitted at the inlet and outlet pipes of the experimental ponds. The two storage tanks were usually filled to supply the eight ponds with sewage effluent from the Imhoff tank of the University of Nigeria, Nsukka sewage treatment plant through a hose with the aid of an electromechanical water pump. The influent samples for the laboratory analysis were obtained from the storage tank immediately after being filled. Also, the experimental ponds were immediately filled and samples were collected at the outlets after 2 d.

Table 1
Detailed description of various ponds due to width effect [3]

Experimental ponds	Size	Characteristics	Purpose
A	1 × 0.3 × 0.2	No solar reflector, no change in slope	Control
B	1 × 0.3 × 0.2	No change in slope with reflector	Measure the effect of solar reflector
C	1 × 0.3 × 0.2	Change in slope without reflector	Measure the effect hydraulic jump
D	1 × 0.3 × 0.2	Solar reflector and change in slope	Measure the effect of solar reflector and hydraulic jump
E	1 × 0.4 × 0.2	Solar reflector and change in slope	Measure the effect of width
F	1 × 0.2 × 0.2	Solar reflector and change in slope	Measure the effect of width
G	1 × 0.5 × 0.2	Solar reflector and change in slope	Measure the effect of width
H	1 × 0.6 × 0.2	Solar reflector and change in slope	Measure the effect of width

Table 2
Detailed experimental characteristics of the various ponds due to variations in location of jump [3]

Experimental setup	Number of experimental ponds	Characteristics (location of point of initiation of hydraulic jump from the inlet, m)	Purpose
Set 1	8	0.5	Effect of location of point of initiation of hydraulic jump
Set 2	8	0.4	Effect of location of point of initiation of hydraulic jump
Set 3	8	0.3	Effect of location of point of initiation of hydraulic jump

All the analyses were carried out using appropriate water testing meters and in accordance with the standard methods [21].

2.3. Design of the ISHJEWSP

2.3.1. Hydraulic jump consideration

Inlet Froude number (F_r) of 1.1 was used in order to ensure the occurrence of air bubble entrainment in the ISHJEWSP [22–24]. The relationship between Froude number and velocity is shown in Eq. (4).

$$F_r = \frac{v}{\sqrt{gy_1}} \tag{4}$$

Similarly, inlet Froude numbers of 1.2 and 1.3 were studied. The obtained velocities corresponding to the Froude number of 1.1, 1.2, and 1.3 were 0.39, 0.42, and 0.46 m/s, respectively.

Table 3
Detailed experimental characteristics of the various ponds due to varying inlet velocity (inlet discharge) [3]

Experimental setups	Number of experimental ponds	Characteristics (velocity, m/s)	Purpose
Set 1	8	0.39	Effect of inlet velocity
	8	0.42	Effect of inlet velocity
	8	0.46	Effect of inlet velocity
Set 2	8	0.39	Effect of inlet velocity
	8	0.42	Effect of inlet velocity
	8	0.46	Effect of inlet velocity
Set 3	8	0.39	Effect of inlet velocity
	8	0.42	Effect of inlet velocity
	8	0.46	Effect of inlet velocity

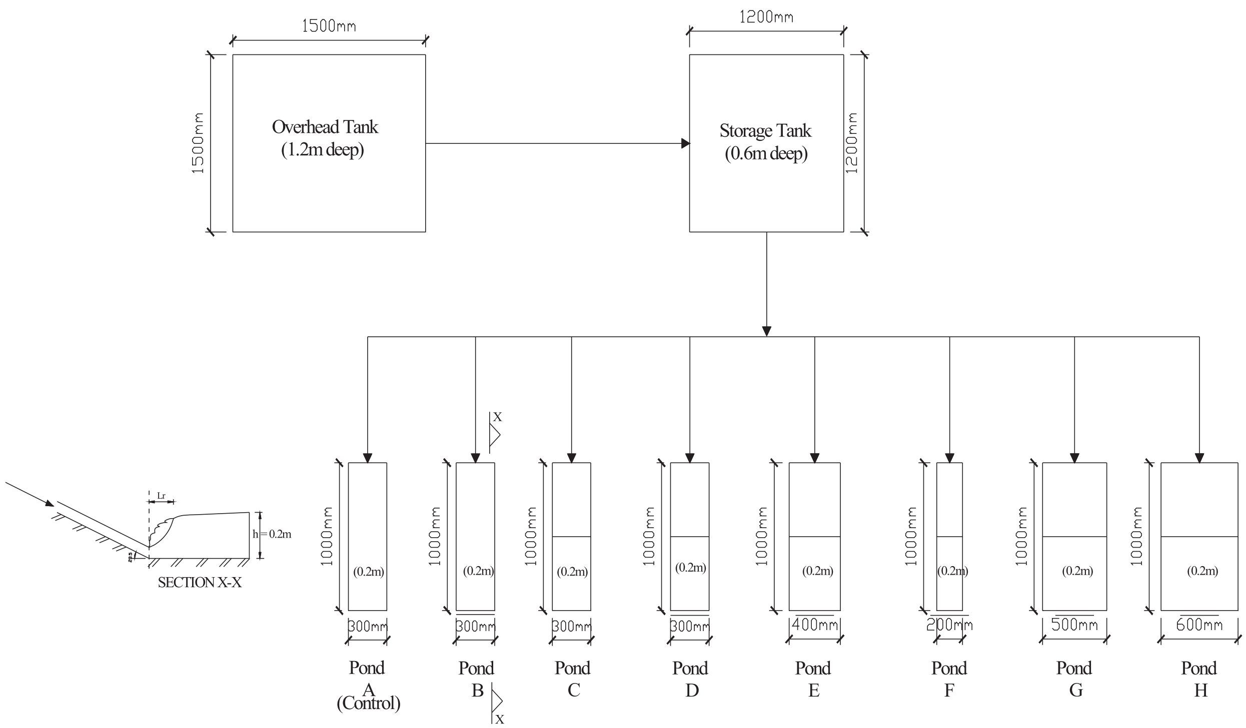

Fig. 1. Schematic diagram of experimental setup due to width variation [3].

2.3.2. Solar reflector consideration

The use of a plane reflector can increase the quantity of solar radiation energy by about 30–40% and sometimes even 50–60% [25–28].

The solar reflectors were constructed to increase the incident sunlight intensity. Agbiji [29] reported high efficiency of treatment of the WSP by the use of foil paper as solar reflector. This is coupled with its low cost and ease of maintenance. Utsev and Agunwamba [30] stated that the distribution and variation of both the physiochemical and biological characteristics inside the water body were found to be influenced by maximum temperature, DO, pH, algae count, as well as minimum BOD_5, COD, fecal coliform and *E. coli* were observed when the solar reflectors were placed at the outlet position.

The optimal angle between the WSPs and the solar reflector was determined by considering two factors namely: the optimum solar energy and the law of reflection. The quantity of solar energy depends on geographical position, the trajectory of the sun, on the intensity of solar radiation energy, sunlight duration per day and per year, the reflection coefficient of sun-ray concentrator–reflector etc. [31]. Therefore, due to the earth's tilt about its axis, the rotation of the earth about its axis, and the revolution of the earth around the sun various optimal angles for solar reflectors were obtained for the days of this study at solar noon. The solar elevation angles were determined using the equations obtained from the National Aeronautics and Space Administration Technical Memorandum, [32], shown below in Eqs. (5)–(8).

$$\sin\alpha = \sin\emptyset\sin D + \cos\emptyset\cos D\cos h \tag{5}$$

$$d = \frac{\left[(\text{Number of day in year}) - 1\right] \times 360}{365.242} \tag{6}$$

$$h = 15(T - M) - L \tag{7}$$

$$\begin{aligned} M = {} & 12 + 0.123570\sin d - 0.004289\cos d \\ & + 0.153809\sin 2d + 0.060783\cos 2d \end{aligned} \tag{8}$$

The solar declination was obtained as shown in Eq. (9). This equation has been widely used by researchers including Ezeilo [33].

$$D = 23.45^\circ \sin\left[360^\circ\left(\frac{284 + n}{365}\right)\right] \tag{9}$$

where α is solar elevation angle, Ø represent latitude, D is solar declination, d is the angular fraction of a year (°), h is solar hour angle (°), n is the day number in the year, with 1 January as 1, T is time in GMT, M (h) is the time of meridian passage or true solar noon, and L is the longitude.

2.4. Formulation and model development

The impact of light on bacterial removal is given by Scheible [34] as shown in Eq. (10):

$$N = N_o \exp\left\{\frac{uL}{2\varepsilon}\left(1-\left\{1+\frac{4\varepsilon\cdot aI^b}{u^2}\right\}^{\frac{1}{2}}\right)\right\} + N_P \quad (10)$$

Since Froude number governs the dynamic similarity of the flow situations where gravitational force is most significant [35], therefore velocity, u becomes u_c.

The density associated with the particles N_P is as shown in Eq. (11) [36].

$$N_P = \frac{1}{20{,}000}N_o \quad (11)$$

Substituting Eq. (11) and $u = u_c$ into Eq. (10), we have,

$$N = N_o\left[\exp\frac{u_c L}{2\varepsilon}\left\{1-\left(1+\frac{4\varepsilon\cdot aI^b}{u_c^2}\right)^{\frac{1}{2}}\right\}\right] + \frac{1}{20{,}000}N_o \quad (12)$$

Due to the mixing effect created by the hydraulic jump and to account for the site-specific sensitivity of the micro-organisms to UV, Eq. (12) is therefore factored by Eq. (1), we have,

$$\frac{N}{N_o} = \left[\frac{\exp\left\{\frac{u_c L}{2\varepsilon}\left(1-\left\{1+\frac{4\varepsilon I}{u_c^2}\right\}^{\frac{1}{2}}\right)\right\} + \frac{1}{20{,}000}}{1+k\theta}\right] \quad (13)$$

where a is assumed to be 1 m^2/kWs and b = 1.

Considering the change in slope causing the occurrence of the hydraulic jump, we have the length of channel L to be,

$$L = \frac{h}{\sin\theta_s} + x \quad (14)$$

Substituting Eq. (14) into Eq. (13), we have,

$$\frac{N}{N_o} = \left[\frac{\exp\left\{\frac{u_c\left(\frac{h}{\sin\theta_s}+x\right)}{2\varepsilon}\left(1-\left\{1+\frac{4\varepsilon I}{u_c^2}\right\}^{\frac{1}{2}}\right)\right\} + \frac{1}{20{,}000}}{1+k\theta}\right] \quad (15)$$

where L is the characteristic length, which is the average distance travelled by the wastewater while under direct exposure to light; ε denotes the dispersion coefficient (m^2/s); u_c is the supercritical inlet velocity (m/s); N_o and N represent the initial and final bacteria densities before and after irradiation (organisms/100 ml); k is the first-order rate constant for fecal coliform removal (d^{-1}); θ is the retention time (d); I is the intensity of solar radiation (KW/m^2); θ_s is the angle denoting change in pond bed slope (°); h is the depth of the ISHJEWSP (m); x is the length of the horizontal section of the pond (m).

The fecal coliform die-off rate coefficient (k) was determined with the formula [37].

$$k = 0.5(1.02)^{T_w\text{-}20}(1.15)^{\text{pH-6}}(0.99784)^{L_s\text{-}100} \quad (16)$$

where T_w, pH, and L_s are the water temperature, hydrogen ion concentration, and concentration of soluble BOD_5 loading, respectively.

Data obtained from the ISHJEWSP (pilot-scale experiments) were used to calibrate and verify Eq. (15) while Eq. (3) was used to verify data obtained from the conventional WSP.

Please note that subscript e is subsequently added to the N in Eq. (15) for uniformity of nomenclature i.e. N_e/N_o.

2.5. Comparison between the conventional pond (pond A) and ISHJEWSP (pond D) model calibration

The appropriate null hypothesis (H_0) and alternate hypothesis (H_a) for the calibration of the conventional (pond A) and ISHJEWSPs (pond D) are stated thus:

> H_0: There is no statistically significant difference between the mean of the N_e/N_o of the ISHJEWSP and the mean of the N_e/N_o of the conventional WSP.

$$\mu_{\text{ISHJEWSP}} = \mu_c$$

where μ_{ISHJEWSP} = population mean of N_e/N_o of the ISHJEWSP;

μ_c = population mean of N_e/N_o of the conventional WSP;

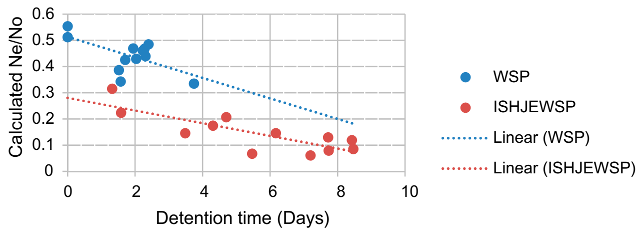

Fig. 2. Effect of detention time on N_e/N_o for velocity V_1 (Set 1).

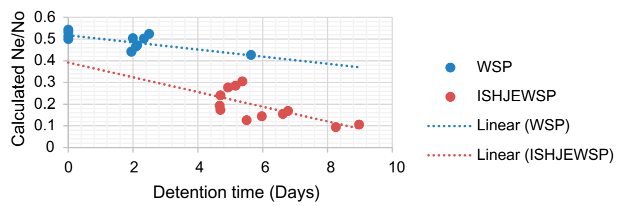

Fig. 3. Effect of detention time on N_e/N_o for velocity V_2 (Set 1).

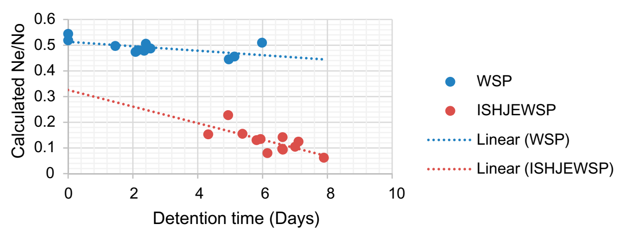

Fig. 4. Effect of detention time on N_e/N_o for velocity V_3 (Set 1).

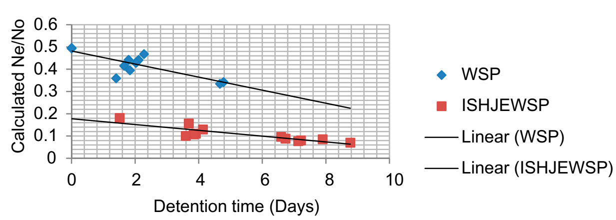

Fig. 5. Effect of detention time on N_e/N_o for velocity V_1 (Set 2).

H_a: There is statistically significant difference between the mean of the N_e/N_o of the ISHJEWSP and the mean of the N_e/N_o of the conventional WSP.

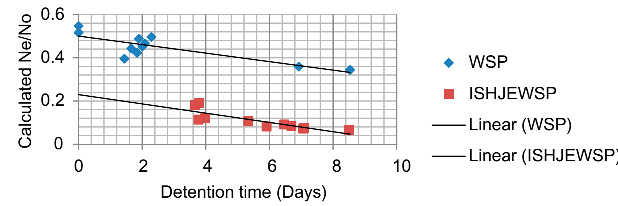

Fig. 6. Effect of detention time on N_e/N_o for velocity V_2 (Set 2).

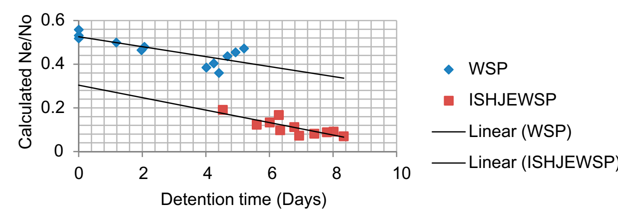

Fig. 7. Effect of detention time on N_e/N_o for velocity V_3 (Set 2).

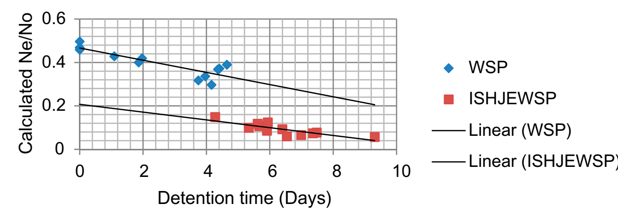

Fig. 8. Effect of detention time on N_e/N_o for velocity V_1 (Set 3).

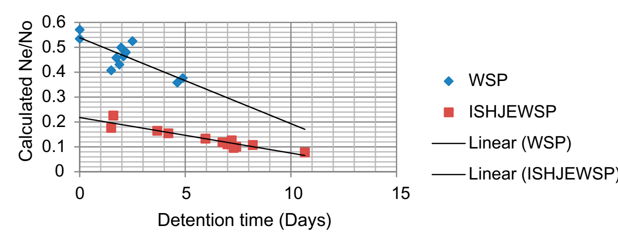

Fig. 9. Effect of detention time on N_e/N_o for velocity V_2 (Set 3).

$\mu_{\text{ISHJEWSP}} \neq \mu_c$

Applying the normal small theory of test of hypothesis [38], the student t-critical value at 22 degree of freedom and 5% level of significance is 1.72, while the computed t-values were 4.308, 4.299, 4.483, 4.105, 4.121, 3.683, 3.690, 3.865, and 3.752 corresponding to

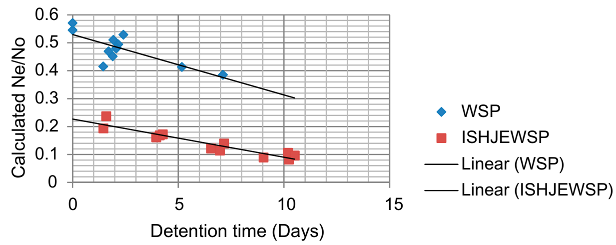

Fig. 10. Effect of detention time on N_e/N_o for velocity V_3 (Set 3).

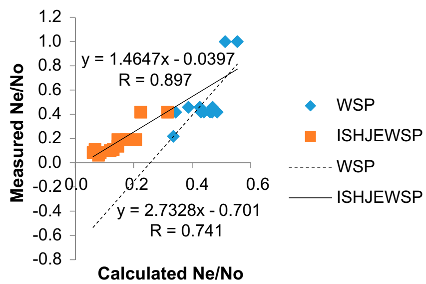

Fig. 11. Measured vs. calculated N_e/N_o in conventional and ISHJEWSP (Set 1, V_1).

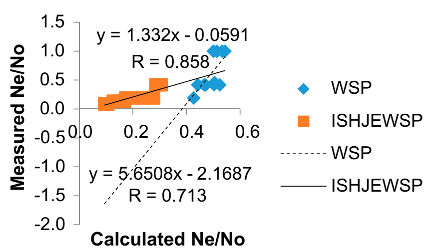

Fig. 12. Measured vs. calculated N_e/N_o in conventional and ISHJEWSP (Set 1, V_2).

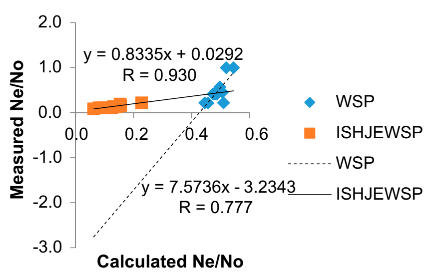

Fig. 13. Measured vs. calculated N_e/N_o in conventional and ISHJEWSP (Set 1, V_3).

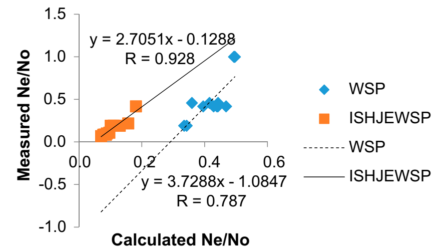

Fig. 14. Measured vs. calculated N_e/N_o in conventional and ISHJEWSP (Set 2, V_1).

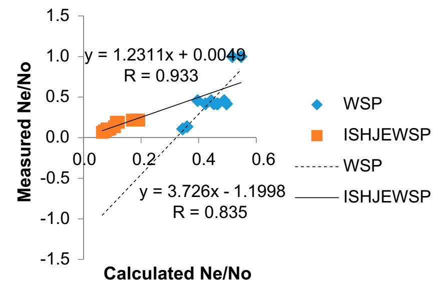

Fig. 15. Measured vs. calculated N_e/N_o in conventional and ISHJEWSP (Set 2, V_2).

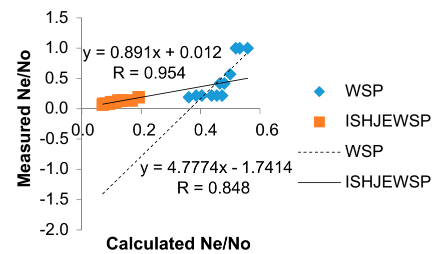

Fig. 16. Measured vs. calculated N_e/N_o in conventional and ISHJEWSP (Set 2, V_3).

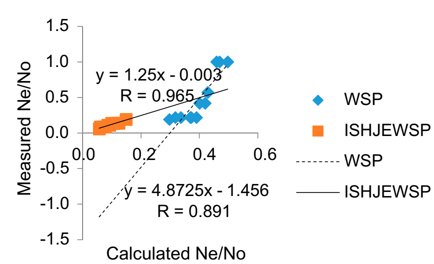

Fig. 17. Measured vs. calculated N_e/N_o in conventional and ISHJEWSP (Set 3, V_1).

Set 1, Set 2 and Set 3 for velocities V_1, V_2, and V_3, respectively. Therefore, because the calculated t value exceeds the critical t value, the null hypothesis is rejected. Hence, at $\alpha = 5\%$ ($p < 0.05$) it is significant to infer that there is statistically significant difference between the mean of the N_e/N_o of the ISHJEWSP and

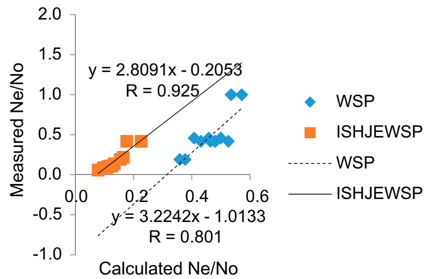

Fig. 18. Measured vs. calculated N_e/N_o in conventional and ISHJEWSP (Set 3, V_2).

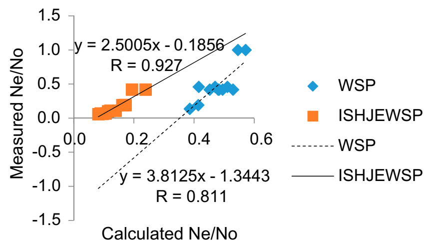

Fig. 19. Measured vs. calculated N_e/N_o in conventional and ISHJEWSP (Set 3, V_3).

the mean of the N_e/N_o of the conventional WSP. We infer that the N_e/N_o of the irradiated ISHJEWSPs are lower than those of the conventional pond at aforementioned level of significance.

2.6. Effect of detention time on the performance of the ISHJEWSP

The variations of N_e/N_o with detention time for both the conventional and ISHJEWSP are shown in Figs. 2–10.

Figs. 2–10 reveal that the N_e/N_o reduce with increase in detention time [39,40].

2.7. Verification of models

Figs. 11–19 shows the verification of the conventional model with good average coefficients of correlation of $R = 0.744$ (0.713–0.777) between the measured and calculated N_e/N_o with an average standard error of 0.189 (0.168–0.175) for Set 1. Similarly, average coefficients of correlation of $R = 0.823$ (0.787–0.848), average standard error of 0.170 (0.157–0.188), $R = 0.834$ (0.782–0.814), average standard error of 0.1613, (0.161–0.162) were obtained for Set 2 and 3, respectively. Also, for the ISHJEWSP, the average coefficients of correlation of $R = 0.890$ (0.843–0.897) between the measured and calculated N_e/N_o with an average standard error of 0.031 (0.015–0.056) for Set 1. Similarly, average coefficients of correlation of $R = 0.938$ (0.928–0.954), standard error of 0.023 (0.011–0.038), $R = 0.939$ (0.925–0.965), standard error of 0.033 (0.010–0.049) were obtained for Set 2 and 3, respectively. In the past, similar correlation coefficients have been obtained by different authors [9,41].

3. Conclusion

A new model was derived, calibrated and verified for the prediction of the performance of the ISHJEWSP. The fecal bacteria removal was significantly higher in the enhanced pond than in the conventional pond at 5% level of significance. The verification of the conventional model gave an average coefficient of correlation of $R = 0.744$ (0.713–0.777) between the measured and calculated N_e/N_o with an average standard error of 0.189 (0.168–0.224) for Set 1. Similarly, average coefficients of correlation of $R = 0.823$ (0.787–0.848), average standard error of 0.170 (0.157–0.188), $R = 0.834$ (0.801–0.891), average standard error of 0.1613, (0.161–0.162) were obtained for Set 2 and 3, respectively. Also, the ISHJEWSP gave an average coefficient of correlation of $R = 0.895$ (0.843–0.897) between the measured and calculated N_e/N_o with an average standard error of 0.031 (0.015–0.056) for Set 1. Similarly, average coefficients of correlation of $R = 0.938$ (0.928–0.953), standard error of 0.023 (0.011–0.038), and $R = 0.939$ (0.925–0.965), standard error of 0.033 (0.010–0.049) were obtained for Set 2 and 3, respectively.

Acknowledgments

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