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Evaluation of rate constant models on the performance of the integrated solar and hydraulic jump enhanced waste stabilization pond using quantitative statistics approach

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ABSTRACT

The quest for the improvement of the conventional waste stabilization pond (WSP) vis-à-vis enhancing its applicability and performance necessitated this study. The integrated solar and hydraulic jump enhanced waste stabilization pond (ISHJEWSP) incorporates solar reflectance and the occurrence of hydraulic jump through change in pond bed slope of the conventional waste stabilization pond. The effect of Saqqar and Pescod rate constant model and Chick's law in predicting coliform die-off, on the performance of the ISHJEWSP model was evaluated. The performance of the model at calibration and validation was analyzed using three quantitative statistics: Nash- Sutcliffe model efficiency coefficient (NSE), ratio of the root mean square error to the standard deviation of measured data (RSR), percent bias (PBIAS) and the coefficient of correlation (R). The research revealed that the use of Chick's law in the determination of the rate constant parameter for the ISHJEWSP model enhanced the accuracy of the prediction of the model. The average values of NSE, RSR, PBIAS obtained from the use of Chick's law rate constant parameter for the ISHJEWSP model and the Saqqar and Pescod rate constant were 0.837 ± 0.068, 0.398 ± 0.074, 1.688 ± 9.644 and 0.581 ± 0.209, 0.627 ± 0.169, 14.836 ± 10.788, respectively. The validation of the ISHJEWSP model yielded an average coefficient of correlation of R = 0.969 ± 0.016 between the measured and calculated N_e/N_o for Chick's law predicted coliform die-off and R = 0.924 ± 0.034 for the Saqqar and Pescod rate constant model. The normal small theory of test of hypothesis revealed that the predicted N_e/N_o of the Chick's law rate constant parameter for the ISHJEWSP are not lower than those of the Saqqar and Pescod rate constant parameter for the ISHJEWSP model at a significance level of 0.05.

Keywords: Evaluation;Performance; ISHJEWSP; Rate constant; Model

1. Introduction

Waste stabilization ponds (WSPs) have been very useful in the treatment of wastewater. However, WSPs are limited in application by their large area requirement [1]. The availability of land in addition to cost also poses another challenge. In search of solutions to the problem of large land area requirement of the WSP, researches have been carried out on the use of hydraulic jump for wastewater treatment [2]; using recirculating stabilization ponds in series [3]; step feeding [4]; incorporating an attached growth system [5]; using tapered WSP [6]. Solar radiation has been used for the treatment of chemically and biologically contaminated water [7–11]. Bunce [7] stated that the use of solar radiation to remove a wide range of organic chemicals and pathogenic organisms by direct exposure, is relatively inexpensive, and avoids generation of harmful by-products of chemically driven technologies.

In addition, different WSP performance prediction models have been developed. Marais [12] presented equations for pond design assuming faecal coliform

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removal by the first order kinetic model in a completely-mixed reactor. The resulting equation for a single pond is given by:

$$N_e = \frac{N_o}{1 + k\theta} \quad (1)$$

where N_e and N_o are the number of faecal coliform/100 ml in the effluent and influent, K is the first order rate constant for faecal coliform removal (d^{-1}), and θ is the retention time (d).

In objection to Marais model, Thirumurthi [13] 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 [14] for rectangular ponds as shown in Eq. (2).

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

where $a^2 = 1 + 4K\theta d$, d is the dispersion number, K is the die-off rate coefficient, θ is the detention time (days), N_e and N_o are the number of faecal coliform/100 ml in the effluent and influent, respectively.

In contrast to the conventional WSP, Ogarekpe [15] studied the ISHJEWSP. An integrated solar and hydraulic jump enhanced waste stabilization pond (ISHJEWSP) was introduced as a new technology that incorporates solar reflector and the introduction of hydraulic jump through change in pond bed slope of the conventional waste stabilization pond. The essence is for the purpose of increasing the treatment efficiency of the conventional WSP and consequently, the reduction in land area requirement [15]. Ogarekpe and Agunwamba [16] presented a new model for the prediction of the performance of the Integrated Solar and Hydraulic Jump Enhanced Waste Stabilization Pond (ISHJEWSP) as shown in Eq. (3). The theoretical development of the ISHJEWSP model proceeded from the combination of relevant existing equations that predicts the impacts of solar irradiation and the effect of turbulence on bacterial removal.

$$\frac{N_e}{N_o} = \left[\frac{\exp\left\{\frac{u_c\left(\frac{h}{\sin\sin\theta_s} + x\right)}{2\varepsilon}\left(1 - \left(1 + \frac{4\varepsilon.I}{u_c^2}\right)^{\frac{1}{2}}\right)\right\} + \frac{1}{20,000}}{1 + K\theta}\right] \quad (3)$$

where L is the characteristic length, which is the average distance travelled by the wastewater while under direct exposure to light (m), N_p represents the density associated with the particles, which shield the bacteria from being affected by irradiation light (organisms/100 ml), ε denotes the dispersion coefficient (m^2/s), u_c is the supercritical inlet velocity of wastewater before the occurrence of hydraulic jump (m/s), N_o is the initial and bacteria density, measured immediately before entry into the irradiated pond (organisms/100 ml), N_e is the bacteria density remaining after exposure to irradiation (organisms/100 ml), k is the first order rate constant for faecal 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 slope (°), h is the depth of the ISHJEWSP (m), x is the length of the horizontal section of the pond (m).

The use of Saqqar and Pescod [17] rate constant model in Eq. (3) yielded good average coefficients of correlation of R = 0.800 ± 0.173 between the measured and calculated N_e/N_o for the conventional model and R = 0.924 ± 0.034 for the ISHJEWSP, respectively [16]. The faecal coliform die-off rate coefficient (k) was determined using Eq. (4) as presented by Saqqar and Pescod [17].

$$k = 0.5(1.02)^{Tw-20}(1.15)^{pH-6}(0.99784)^{Ls-100} \quad (4)$$

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

The present study therefore seeks to determine the performance of the ISHJEWSP model when Chick's law is utilized in the prediction of the coliform overall die-off rate constant. Being that the ISHJEWSP model presented by Ogarekpe and Agunwamba [16] assumed the site-specific sensitivity of micro-organism to UV as unity, Chick's law [Eq. (5)] was chosen for the determination of overall die-off rate constant in order to account for the environmental conditions of temperature, solar radiation, sorption and sedimentation.

$$C_t = C_o e^{-k_o t} \quad (5)$$

where C_t, C_o, k_o and t are the concentration of organism at time (t) (organisms/100 ml), concentration of organism at time zero (organisms/100 ml), overall die-off rate constant at the environmental conditions (d^{-1}), elapsed time since time zero (d), respectively.

Data obtained from the ISHJEWSP (pilot scale experiments) were used for the evaluation and validation of the model presented in Eq. (3).

2. Materials and methods

2.1. Plant site description

The study was carried out at the University of Nigeria, Nsukka. Nsukka is a town and Local Government Area in South-East Nigeria in Enugu State. Nsukka urban is the home to the prestigious University of Nigeria. Located at the north-eastern end of the University campus about 800 m from the junior staff quarters, the sewage treatment plant consists of a screen followed by two imhoff tanks and two facultative waste stabilization ponds. Sludge discarded from the imhoff tank is placed in the drying beds. The process flow diagram of the sewage treatment plant is represented in Fig. 1.

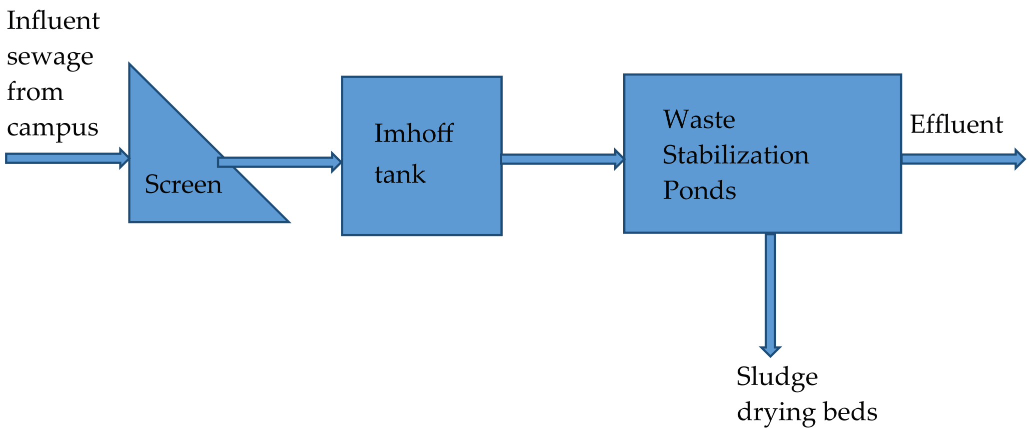

Fig. 1. Process flow diagram of the sewage treatment plant.

2.2. Description of experimental set-up

Three sets of these experimental ponds with varying locations of change in pond bed slope were constructed using metallic tanks. Tilt frames of size 1.0 m × 0.3 m was fixed at varying angles in accordance with the relative position of the sun per week. The surfaces of the tilt frames were wrapped with aluminum foil paper to enhance as solar reflectance. Care was taken to ensure that the solar reflectors were facing the west. Also, for each set of experiments, three flow conditions with Froude numbers 1.1, 1.2 and 1.3 were studied. Half inches diameter inlet and outlet pipes were fitted centrally to the experimental ponds. Also, flow control valves were fitted at the inlet and outlet pipes of the experimental ponds. Two storage tanks were usually filled to supply the pond 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 collected at the outlets after two days.

2.3. Data collection and laboratory analysis

Wastewater samples were collected before degradation and after degradation in the ISHJEWSP. The effluent samples were collected for varying inlet Froude numbers and varying locations of point of initiation of hydraulic jump. The samples were examined for physico chemical and biological characteristics for a period of nine months. Total coliform count (TCC) was examined alongside other parameters. All the laboratory analyses were carried out using appropriate water testing meters and in accordance with the standard methods [19].

2.4. Model evaluation

The performance of the model at calibration was analyzed using the following statistics: Nash-Sutcliffe model efficiency coefficient (NSE), ratio of the root mean square error to the standard deviation of measured data (RSR) and percent bias (PBIAS). At validation, the coefficient of correlation (R), was used for the model performance evaluation.

2.4.1. Nash-Sutcliffe efficiency (NSE)

The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information") [20]. NSE is computed as shown in Eq. (6):

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean} \right)^2} \right] \tag{6}$$

An NSE value of 1 corresponds to a perfect match between observed and simulated stream flow. An NSE value between 0 and 1 is considered an acceptable level of performance, whereas an NSE value ≤ 0 suggests that the observed mean is a better predictor than the model [21].

2.4.2. Ratio of the root mean square error to the standard deviation of measured data (RSR)

RSR is calculated as the ratio of the RMSE and standard deviation of measured data [22], as shown in Eq. (7):

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2}}{\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean} \right)^2}} \tag{7}$$

RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect model simulation, to a large positive value. The lower RSR, the lower the RMSE, and the better the model simulation performance [22].

2.4.3. Percent bias (PBIAS)

Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their corresponding observed counterparts [21]. The optimal value of

PBIAS is 0, while positive values indicate model underestimation and negative values indicate model overestimation [21]. PBIAS is computed as shown in Eq. (8):

$$PBIAS = \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) * 100}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)} \tag{8}$$

2.4.4. Coefficient of correlation (R)

The performance indicator at validation is determined by the coefficient of correlation or the coefficient of determination as shown in Eqs. (9) and (10). In the past, standard theories of regression analysis have been discussed [23–27].

$$Cor\left(Y_i^{obs}, Y_i^{sim}\right) = \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)\sum_{i=1}^{n}\left(Y_i^{sim} - Y_{sim}^{mean}\right)}{\sqrt{\sum_{i}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2 \sum_{i}^{n}\left(Y_i^{sim} - Y_{sim}^{mean}\right)^2}} \tag{9}$$

The coefficient of determination is also given as

$$R^2 = \left[Cor\left(Y_i^{obs}, Y_i^{sim}\right)\right]^2 \tag{10}$$

where i independent variable values from total set of n observations, is the observed variable depicting the observed $\frac{N_e}{N_o}$, Y_i^{sim} is the simulated variable depicting the calculated $\frac{N_e}{N_o}$, Y^{mean} is the mean of observed n values, Y_{sim}^{mean} is the mean of simulated n values, n is the number of observations, R^2 is the coefficient of determination

According to Moriasi et al. [22] model simulation judged as satisfactory if NSE > 0.5, RSR ≤ 0.70 and PBIAS = ±25% for flow and NSE > 0.5, RSR ≤ 0.70 and PBIAS = ± 55% for sediment. Model performance was deemed acceptable when $R^2 > 0.60$ (i.e R > 0.77), NSE > 0.50, and PBIAS was within 25% [22].

3. Results and discussion

3.1. Comparison of the performance of the ISHJEWSP model for different rate constant models

Adopting the guidelines presented by Moriasi et al. [22], and considering the various sets of experiments studied, the NSE results obtained when Chick's law was used in the determination of the rate constant parameter for the ISHJEWSP model showed very good model performance (i.e. 0.5 < NSE < 1). Also, the PBIAS and RSR values showed good model performance (PBIAS = ± 25%, RSR ≤ 0.70) for all the experimental sets studied as shown in Table 1.

The evaluation of the performance of the ISHJEWSP model when the Saqqar and Pescod [17] rate constant equation was used yielded good NSE (i.e. 0.5 < NSE < 1) and RSR (RSR ≤ 0.70) results for the various sets studied except Set 2, Fr = 1.1, Set 3, Fr = 1.2. Also, the RSR for Set 3 Fr = 1.3 showed unsatisfactory performance (RSR > 0.70) however, the value was close to the satisfactory model performance criteria (e.g., RSR = 0.704). The PBIAS values indicated satisfactory model performance (PBIAS = ± 25%) except for Set 2, Fr = 1.1. The unsatisfactory performance for some of the experiments is indicative of the inadequacy of the Saqqar and Pescod rate constant to account for the effect of solar radiation, sorption and sedimentation. Aside the solar radiation, the Saqqar and Pescod rate constant did not take into consideration the effect of detention time of which sorption and sedimentation are dependent on [28,29].

The average values of NSE, RSR, PBIAS obtained from the use of Chick's law rate constant parameter for the ISHJEWSP model and the Saqqar and Pescod rate constant were 0.837 ± 0.068, 0.398 ± 0.074, 1.688 ± 9.644 and 0.581 ± 0.209, 0.627 ± 0.169, 14.836 ± 10.788, respectively. Comparatively, all the results of the parameters of NSE, RSR, PBIAS show that the Chick's law rate constant parameter for the ISHJEWSP model were satisfactory with better skew to optimal vis-a-vis those obtained from the use of the Saqqar and Pescod rate constant.

Figs. 3–11 show the validation of the ISHJEWSP model (with k from Chick's law) with good average coefficients of correlation of R = 0.956 between the measured and calculated N_e/N_o for set 1. Similarly, average coefficients of correlation of 0.967 and 0.984 were obtained for sets 2 and 3, respectively.

The validation of the ISHJEWSP model yielded an average coefficient of correlation of R = 0.969 ± 0.016 between the measured and calculated N_e/N_o for Chick's law predicted coliform die-off. Similarly, the validation of the ISHJEWSP model yielded an average coefficient of correlation of R = 0.924 ± 0.034 for the Saqqar and Pescod rate constant model [16].

In general, the research revealed that the use of Chick's law in the determination of the rate constant parameter for the ISHJEWSP model enhanced the accuracy of the ISHJEWSP performance prediction.

3.2. Predicted efficiency of removal of fecal coliform

A comparison of the fecal coliform removal efficiencies using Chick's law rate constant parameter for the ISHJEWSP model and the Saqqar and Pescod rate constant was made. The appropriate null hypothesis (H_o) and alternate hypothesis (H_a) for the calibration of the Chick's law rate constant parameter for the ISHJEWSP model and Saqqar and Pescod rate constant parameter for the ISHJEWSP model thus:

H_o: There is no statistically significant difference between the mean of the N_e/N_o of Chick's law rate constant parameter for the ISHJEWSP model and Saqqar and Pescod rate constant parameter for the ISHJEWSP model

$\mu_{ISHJEWSP(C)} = \mu_{ISHJEWSP\,(S\,\&\,P)}$

where $\mu_{ISHJEWSP(C)}$ = Population mean of N_e/N_o of the Chick's law rate constant parameter for the ISHJEWSP model

$\mu_{ISHJEWSP(S\,\&\,P)}$ = Population mean of N_e/N_o of the Saqqar and Pescod rate constant parameter for the ISHJEWSP model

H_a: There is statistically significant difference between the mean of the N_e/N_o of Chick's law rate constant parameter for the ISHJEWSP model and Saqqar and Pescod rate constant parameter for the ISHJEWSP model

$\mu_{ISHJEWSP(C)} = \mu_{ISHJEWSP\,(S\,\&\,P)}$

Table 1
ISHJEWSP model evaluation using rate constants determined by Chick's law and Saqqar and Pescod Equation for different flow conditions

ISHJEWSP model evaluation (Set 1, Froude number = 1.1)		
	k from Chick's law	*k* from Saqqar and Pescod Equation
NSE	0.867	0.660
RSR	0.364	0.583
PBIAS	–2.858	17.212
R	0.944	0.897
ISHJEWSP model evaluation (Set 1, Froude number = 1.2)		
	k from Chick's law	*k* from Saqqar and Pescod Equation
NSE	0.892	0.689
RSR	0.329	0.558
PBIAS	–10.732	1.962
R	0.964	0.858
ISHJEWSP model evaluation (Set 1, Froude number = 1.3)		
	k from Chick's law	*k* from Saqqar and Pescod Equation
NSE	0.881	0.782
RSR	0.346	0.467
PBIAS	–2.322	6.152
R	0.961	0.930
ISHJEWSP model evaluation (Set 2, Froude number = 1.1)		
	k from Chick's law	*k* from Saqqar and Pescod Equation
NSE	0.667	0.186
RSR	0.577	0.902
PBIAS	19.767	33.498
R	0.979	0.928
ISHJEWSP model evaluation (Set 2, Froude number = 1.2)		
	k from Chick's law	*k* from Saqqar and Pescod Equation
NSE	0.848	0.534
RSR	0.390	0.683
PBIAS	8.624	21.548
R	0.948	0.933
ISHJEWSP model evaluation (Set 2, Froude number = 1.3)		
	k from Chick's law	*k* from Saqqar and Pescod Equation
NSE	0.855	0.895
RSR	0.380	0.324
PBIAS	–8.743	–0.814
R	0.974	0.954
ISHJEWSP model evaluation (Set 3, Froude number = 1.1)		
	k from Chick's law	*k* from Saqqar and Pescod Equation
NSE	0.857	0.561
RSR	0.378	0.662
PBIAS	7.968	17.844
R	0.983	0.965
ISHJEWSP model evaluation (Set 3, Froude number = 1.2)		
	k from Chick's law	*k* from Saqqar and Pescod Equation
NSE	0.805	0.416
RSR	0.442	0.764
PBIAS	5.607	20.899
R	0.982	0.925
ISHJEWSP model evaluation (Set 3, Froude number = 1.3)		
	k from Chick's law	*k* from Saqqar and Pescod Equation
NSE	0.859	0.505
RSR	0.376	0.704
PBIAS	–2.117	15.221
R	0.988	0.927

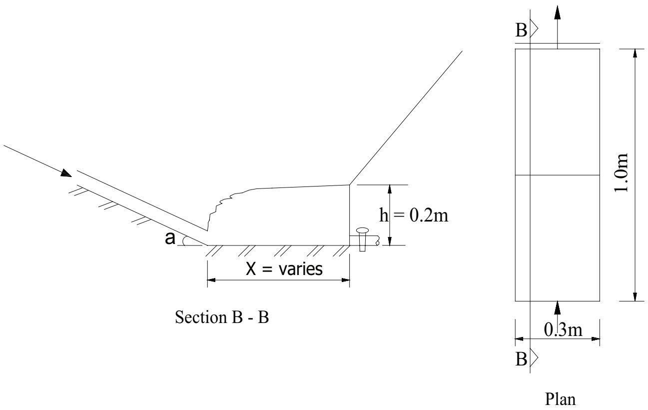

Fig. 2. Schematic digram of the ISHJEWSP [18].

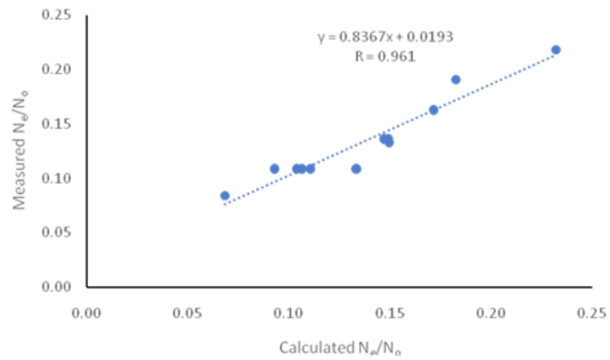

Fig. 5. Measured vs. calculated N_e/N_o ISHJEWSP (Set 1, Fr_3).

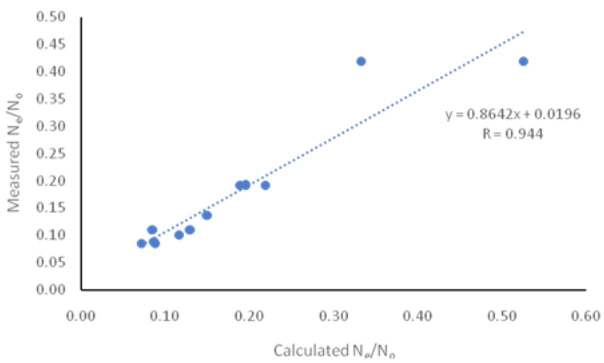

Fig. 3. Measured vs. calculated N_e/N_o ISHJEWSP (Set 1, Fr_1).

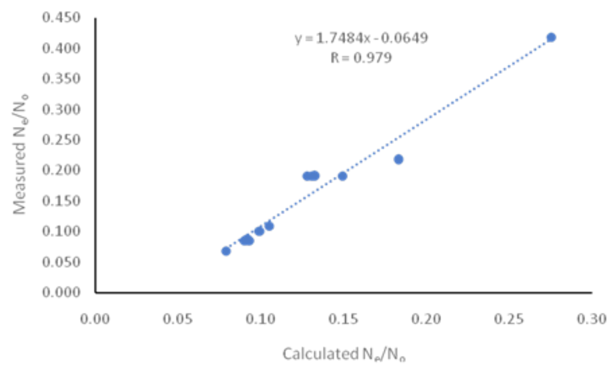

Fig. 6. Measured vs. calculated N_e/N_o ISHJEWSP (Set 2, Fr_1).

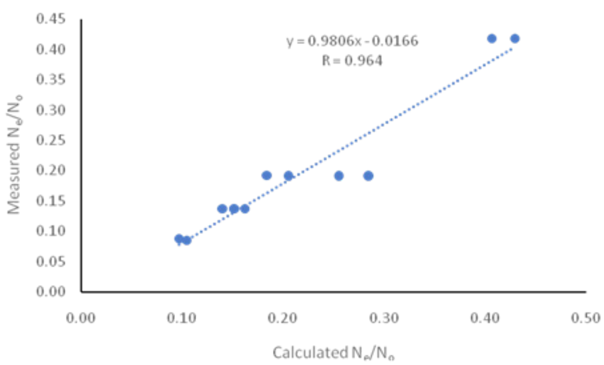

Fig. 4. Measured vs. calculated N_e/N_o ISHJEWSP (Set 1, Fr_2).

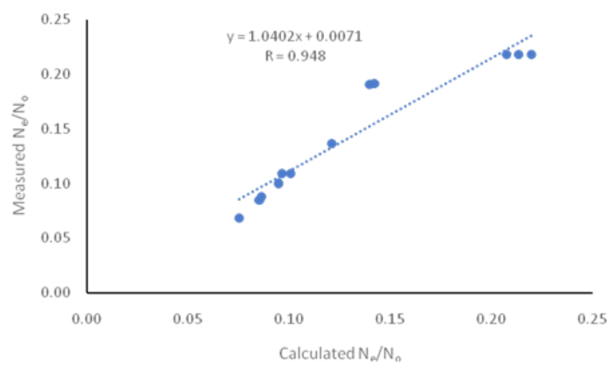

Fig. 7. Measured vs. calculated N_e/N_o ISHJEWSP (Set 2, Fr_2).

Applying the normal small theory of test of hypothesis, the student t-critical value at 22 degree of freedom and 5% level of significance is 1.717 while the computed t-values were 0.813, 0.647, 0.630, 1.194, 0.929, 0.592, 0.966, 1.049 and 1.040 corresponding to Set 1, Set 2 and Set 3 for Froude numbers Fr_1, Fr_2 and Fr_3, respectively. Hence, since the calculated t value does not exceed the critical t value, we accept the null hypothesis. We therefore conclude that at $\alpha = 5\%$ ($p < 0.05$) there is no statistically significant difference between the mean of N_e/N_o of the Chick's law rate constant parameter for the ISHJEWSP model and the mean of N_e/N_o of the Saqqar and Pescod rate constant parameter for the ISHJEWSP model. We infer that the N_e/N_o of the Chick's law rate constant parameter for the ISHJEWSP model are not lower than those of the Saqqar and Pescod rate constant parameter for the ISHJEWSP model at $\alpha = 5\%$.

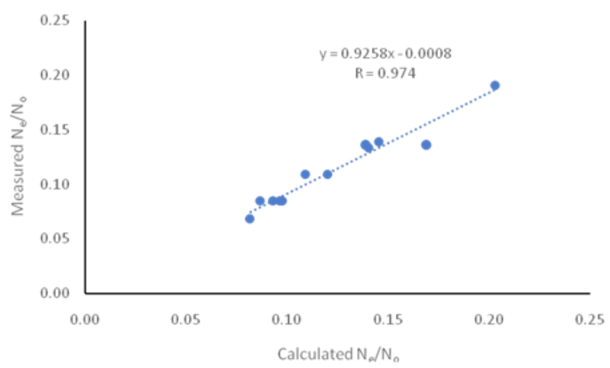

Fig. 8. Measured vs. calculated N_e/N_o ISHJEWSP (Set 2, Fr_3).

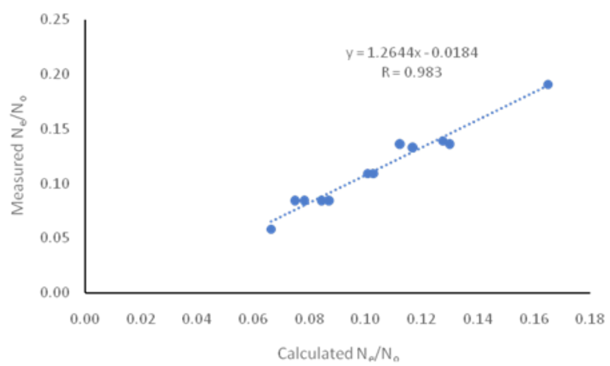

Fig. 9. Measured vs. calculated N_e/N_o ISHJEWSP (Set 3, Fr_1).

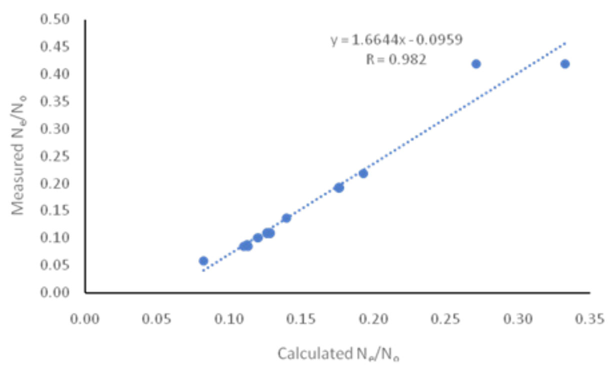

Fig. 10. Measured vs. calculated N_e/N_o ISHJEWSP (Set 3, Fr_2).

4. Conclusion

The effect of Saqqar and Pescod rate constant model and Chick's law in predicting coliform die-off, on the performance of the ISHJEWSP model was evaluated. The performance of the model at calibration and validation analyzed using three quantitative statistics namely: Nash-Sutcliffe model efficiency coefficient (NSE), ratio of the root mean square error to the standard deviation of measured data (RSR), percent bias (PBIAS) revealed that the use of Chick's law in the determination of the rate constant parameter for

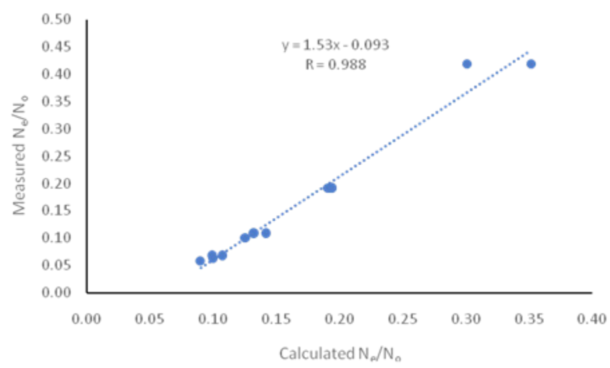

Fig. 11. Measured vs. calculated N_e/N_o ISHJEWSP (Set 3, Fr3).

the ISHJEWSP model enhanced the accuracy of the prediction of the model. The validation of the ISHJEWSP model yielded good average coefficients of correlation between the measured and calculated N_e/N_o for Chick's law predicted coliform die-off and the N_e/N_o for Saqqar and Pescod predicted rate constant model. The normal small theory of test of hypothesis revealed that the predicted N_e/N_o of the Chick's law rate constant parameter for the ISHJEWSP model are not lower than those of the Saqqar and Pescod rate constant parameter for the ISHJEWSP model at a significance level of 0.05.

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