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Regression-Based Insights into the Efficiency of Waste Stabilization Ponds

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Abstract: Waste Stabilization Ponds (WSPs) are a widely utilized wastewater treatment technology, known for efficiently removing organic pollutants and pathogenic microorganisms. Their performance is influenced by environmental factors such as solar radiation, air temperature, and wind speed. Despite its role as a primary mixing mechanism in WSPs, wind speed has been largely underexplored in predictive modeling studies. This study analyzed 30 pairs of samples collected over 5 months (April to September, 2023) from the inlet and outlet of a facultative pond at the University of Nigeria, Nsukka, to evaluate Biochemical Oxygen Demand (BOD) removal efficiency and Faecal Coliform (FC) log reduction value (LRV). Regression models were developed using various combinations of radiation intensity, air temperature, and wind speed as predictor variables. Results revealed that average air temperature alone provided the most robust models, explaining over 88% and 95% of the variability in BOD removal efficiency and FC LRV, respectively. Radiation intensity showed limited predictive significance, while wind speed was not significant in any model. These findings highlight the dominant role of temperature in WSP performance and support temperature-centric models for optimizing wastewater treatment across diverse climatic settings.

Keywords: BOD; faecal coliform; solar radiation; temperature; wind speed

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1. INTRODUCTION

Waste Stabilization Ponds (WSPs) are a prominent centralized wastewater treatment technology, valued for their ability to efficiently remove organic contaminants and pathogenic microorganisms [1]. These systems consist of expansive, shallow basins typically constructed from earthen materials, where prolonged retention of wastewater facilitates treatment through a combination of physical, chemical, and biological processes. Despite their straightforward infrastructure, WSPs foster a diverse ecological system comprising algae, bacteria, viruses, protozoa, fungi, and various aquatic organisms [2]. This intricate microbial and biological community plays a critical role in the degradation of organic matter and the inactivation of pathogens, thereby enhancing effluent quality [3]. Research has shown WSPs to achieve substantial reductions in intestinal [4], [5] and high removal efficiencies of organic pollutants and fecal bacteria [6], provided the system is appropriately designed and managed. Their economic viability [7], coupled with minimal technological complexity [8], makes WSPs particularly suited for implementation in regions with limited financial or technical resources. Furthermore, their low maintenance requirements [9] and complete reliance on natural energy inputs significantly reduce operational costs and logistical barriers, solidifying their reputation as an accessible and sustainable wastewater treatment solution for developing countries [10].

The effectiveness of stabilization in waste stabilization ponds (WSPs) is predominantly governed by microbial dynamics, with bacterial and algal populations serving as critical contributors [11]. These microbial systems are modulated by three principal environmental parameters: thermal conditions, solar radiation, and hydrodynamic mixing. Temperature exerts an exponential influence on bacterial metabolism [12], while light availability dictates algal biomass levels [13]. Mixing facilitates the uniform distribution of chlorophyll a and oxygen and non-motile algae such as Chlorella throughout the pond's vertical profile [14]. Mixing is achieved through the interplay of factors such as wind-induced turbulence, advective transport, and the natural sedimentation tendencies inherent to the organisms [15]. In WSPs, mixing is primarily driven by wind action and thermal stratification processes. The sun plays a pivotal role in this microbial synergy by elevating water temperature, which accelerates bacterial functions and induces thermal mixing, and by enhancing algal photosynthesis. The latter not only increases dissolved oxygen concentrations but also raises pond pH through intensified photosynthetic activity [16].

Based on the interactions among key parameters of waste stabilization ponds (WSPs), various studies have utilized regression techniques to derive design equations for optimizing WSP performance. Early efforts include the development of regression-based models for calculating the Surface Loading Rate (SLR) of facultative ponds, as proposed in the widely recognized equations by Arceivala [17], McGarry and Pescod [18], and Gloyna [19]. More recent studies, such as those by Ayres et al. [5] and Pearson et al. [20], expanded the application of regression methods to predict pathogen and nutrient removal efficiencies, respectively.

Other researches have applied regression analyses to uncover the intricate relationships between WSP parameters and pollutant removal performance. For instance, Tyagi et al. [21] used regression techniques to explore the associations between Biochemical Oxygen Demand (BOD), Suspended Solids (SS), and turbidity with fecal indicator bacteria concentrations in both influent and effluent streams. Their results demonstrated a strong link between improved microbiological water quality and the effective reduction of BOD and SS in wastewater. Ellis and Rodrigues [22] developed a multivariate regression model to assess WSP performance in the Cayman Islands, emphasizing the removal of BOD and Fecal Coliform (FC). Their model identified significant environmental factors influencing pollutant removal. In facultative ponds, FC removal was strongly associated with hydraulic loading rate, retention time, pond depth, and water conductivity, while BOD removal was primarily driven by solar radiation, sunshine duration, rainfall, and pond depth.

Notably, none of the previously mentioned studies accounted for wind, the primary mixing mechanism in waste stabilization ponds (WSPs), despite its critical role in enhancing pond capacity and improving pollutant removal efficiency. Therefore, the objective of this study is to develop a regression model for predicting pond efficiency, incorporating key environmental parameters such as solar radiation intensity, ambient temperature, and wind speed.

2. MATERIAL AND METHODS

2.1 Description of Experiment

Samples were collected from the inlet (influent) and outlet (effluent) of a waste stabilization pond system located on the Nsukka campus of the University of Nigeria, which consists of two secondary facultative ponds, each measuring 120 m × 30 m × 1.2 m, designed to treat domestic wastewater from an upstream Imhoff tank. Over a five-month period (April to September 2023), 30 sample pairs (influent and effluent samples) were analyzed in the Sanitary Engineering Laboratory of the University of Nigeria, Nsukka based Standard Methods [23], to evaluate Biochemical Oxygen Demand (BOD) removal efficiency and Faecal Coliform (FC) log reduction value (LRV).

2.2 Physicochemical Analysis

The parameters were assessed following the methodologies outlined in Standard Methods (APHA, 1985). Weekly sampling was conducted to measure pH, dissolved oxygen (DO), five-day biochemical oxygen demand (BOD_5) in both influent and effluent, as well as water temperature. DO levels were determined using a AZ8403 DO meter, while pH readings were obtained via a calibrated pH meter. Pond water temperatures were recorded using a standard mercury-in-glass thermometer.

2.3 Bacteriological Analysis

The efficiency of fecal coliform removal in the ponds was evaluated through weekly grab sampling of influent and effluent. The analysis employed the Most Probable Number (MPN) technique. Serial dilutions of samples were prepared using buffered dilution water and inoculated into lactose broth for presumptive testing, followed by incubation at 35°C for 24 hours. Positive tubes were subjected to confirmatory testing by subculturing into brilliant green lactose bile broth and incubating at 35°C for 48 hours. Final MPN counts for fecal coliforms were determined by transferring presumptive positives into an E. coli medium and incubating at 44.5°C for 24 hours.

2.4 Evaluation of Pond's Efficiency

The efficiency of BOD removal is typically represented as a percentage, describing the extent of reduction in BOD concentrations between the influent and effluent during the treatment process. It is calculated using the formula:

$$\text{BOD (\%)} \quad = \frac{BOD_{influent} - BOD_{effluent}}{BOD_{influent}} \times 100 \qquad (1)$$

Here, $BOD_{influent}$ denotes the initial biochemical oxygen demand (in mg/L) before treatment, and $BOD_{effluent}$ represents the concentration post-treatment.

Fecal coliform (FC) removal performance was assessed using the logarithmic reduction value (LRV), which measures concentration reductions on a logarithmic scale and is widely used in evaluating pathogen removal in water treatment systems. The LRV for FC removal is expressed as:

$$\text{LRV} \quad = \log_{10}\left(\frac{FC_{influent}}{FC_{effluent}}\right) \qquad (2)$$

A higher LRV signifies a greater reduction in FC concentrations, indicating a more effective treatment process. For example, an LRV of 1 corresponds to 90% removal, LRV 2 to 99% removal, and LRV 3 to 99.9% removal. This metric is particularly useful for evaluating processes involving highly variable contaminant levels or for quantifying high-efficiency removal.

2.5 Regression Method

Table 1 presents the regression equations evaluated in this study. Three predictor variables were considered: radiation intensity (R), ambient temperature (T), and wind speed (W), with either the percentage removal of BOD_5 or the log reduction value (LVR) of fecal coliforms (FC) serving as the response variable (Y). The regression coefficients β_o, β_R, β_T, and β_W were estimated using β_o the Ordinary Least Squares (OLS) method.

When the OLS assumptions of normality and homoscedasticity of residuals were violated, Box-Cox transformations were applied, and the optimal lambda (λ) for transforming the response variable was determined. Model performance was assessed using evaluation metrics such as adjusted R-square, root mean square error (RMSE), mean absolute error (MAE), and predicted residual sum of squares (PRESS). All regression analyses, including assumption diagnostics, were performed using the *Real Statistics Using Excel* add-in (version 8.9.1, released October 2, 2023).

Table 1. Model specification and denotation

SN	Regression method	Predictors	Regression Model
1	OLS	R, T, W	$Y = \beta_o + \beta_R R + \beta_T T + \beta_W W$
2	OLS	R, T	$Y = \beta_o + \beta_R R + \beta_T T$
3	OLS	R, W	$Y = \beta_o + \beta_{uv} R + \beta_W W$
4	OLS	T, W	$Y = \beta_o + \beta_T T + \beta_W W$
5	OLS	R	$Y = \beta_o + \beta_R R$
6	OLS	T	$Y = \beta_o + \beta_T T$
7	OLS	W	$Y = \beta_o + \beta_R R$

Y- response variable, which is either BOD removal efficiency (%) or log reduction value (LRV) of faecal coliform

3. RESULT AND DISCUSSIONS

3.1 Influent Characteristics

The influent wastewater characteristics were assessed weekly over a 5-month experimental period, evaluating parameters such as pH, BOD_5, fecal coliforms, total suspended solids, total nitrogen, ammonia, sulfide (Table 1). While pH met WHO standards for discharge into inland waters, BOD, fecal coliforms, and sulfide may require further treatment, such as maturation ponds, though other parameters pose minimal challenges for anaerobic and facultative pond systems. Sulfide, primarily produced by sulfate-reducing bacteria (e.g., Desulfovibrio), is a potential odor source but can precipitate heavy metals and inhibit Vibrio cholerae at low concentrations (10–12 mg/L) [24]. Odor is mitigated in well-designed anaerobic ponds where typical pH (~7.5) maintains sulfide as odorless bisulfide ions, with hydrogen sulfide gas release governed by Henry's law equilibrium, as detailed in Sawyer et al. [25].

Table 1. Influent characteristics

Parameter	Discharge limits	Influent values
pH	5.5 – 9.0	8.8
Free Ammonia-Nitrogen (mg N/L)	5	6.1
Biochemical Oxygen Demand (BOD) (mg/L)	30	288
Sulfide (mg/L)	2	9.0
Total Nitrogen (TN) (mg/L)	$<1 \times 10^3$	3×10^6
Fecal Coliforms (CFU/100 mL)	5	6.1
Total Suspended Solids (TSS) (mg/L)	100	256
Ammonia-Nitrogen (Total) (mg N/L	50	35

3.2 Evaluation and Comparison of Model Performance

Table 1 provides the descriptive statistics for the dataset used in the regression analyses, while Tables 2 and 3 summarize the regression outcomes for BOD and fecal coliform removal efficiencies, respectively. These tables include model coefficients, regression diagnostics, and hypothesis tests assessing factor significance and model adequacy. The Shapiro-Wilk (SW) test was employed to evaluate residual normality, while heteroscedasticity of residuals was confirmed via the Breusch-Pagan (BP) test using the F-statistic.

Regression models were developed for all possible combinations of the predictor variables examined in the study. For clarity, these predictor variables are designated as follows: R for maximum 30-minute radiation intensity, T for average daily temperature, and W for average wind speed. Consequently, BOD removal efficiency models are represented as BOD (R, T, W), BOD (R, T), BOD (R, W), BOD (T, W), BOD (R), BOD (T), and BOD (W), corresponding to the predictor variables incorporated. Similarly, fecal coliform removal models are denoted FC (R, T, W), FC (R, T), FC (R, W), FC (T, W), FC (R), FC (T), and FC (W).

Table 1. Descriptive statistics for regression data

	R (W/m^2)	T (ºC)	W (mph)	BOD removal (%)	LRV of FC
Mean	678.33	26.55	3.78	27.26	1.42
Standard Error	26.68	0.21	0.21	3.14	0.15
Median	726.5	26.2	3.6	32.08	1.39
Standard Deviation	146.15	1.16	1.13	17.2	0.82
Sample Variance	21359.2	1.35	1.28	295.85	0.67
Kurtosis	-0.3	-0.96	0.09	-1.48	-0.92
Skewness	-0.29	0.29	0.68	-0.08	0.28
Range	621	4.16	4.5	54.75	2.77
Minimum	381	24.46	2.2	0.53	0.21
Maximum	1002	28.62	6.7	55.29	2.97
Sum	20350	796.57	113.5	817.91	42.75
Count	30	30	30	30	30

The selection of the best models for BOD and FC removal efficiencies was performed through a systematic process. Initially, models with non-significant p-values were excluded. If only the intercept term was found to be non-significant, the model was refitted without the intercept. The remaining models were subsequently ranked based on adjusted R-square, RMSE, MAE, and PRESS, with the top-ranking model selected as the best.

To assess multicollinearity, the Variance Inflation Factor (VIF) was applied. Multicollinearity is a problematic condition in Ordinary Least Squares (OLS) regression, as it inflates the standard errors of coefficients and diminishes the statistical significance of predictor variables. A VIF value exceeding 5 is considered indicative of multicollinearity concerns [26].

From Table 2, it is evident that only the models BOD(T) and BOD(R) (no intercept) have all their regression coefficients statistically significant. A comparison of the two models indicates that BOD(T) outperforms BOD(R) across all performance metrics, with adjusted R² = 87.9%, RMSE = 2.602, MAE = 2.119, and PRESS = 223.3 for BOD(T) compared to adjusted R² = 78.8%, RMSE = 14.771, MAE = 12.87, and PRESS = 7587.67 for BOD(R). The R-square value (0.883) suggest that 88.3% of variance in BOD removal efficiency can be explained by average air temperature. Consequently, average ambient temperature is identified as the most effective predictor of BOD removal efficiency in waste stabilization ponds.

Similarly, as indicated in Table 3, only the models FC(T) and FC(R) (no intercept) produced statistically significant regression coefficients. Comparing their performance reveals that FC(T) outperformed FC(R) in all evaluation metrics. Specifically, FC(T) achieves an adjusted R² of 95.2%, RMSE of 0.174, MAE of 0.147, and PRESS of 1.029, whereas FC(R) (no intercept) attains an adjusted R² of 81.9%, RMSE of 0.697, MAE of 0.557, and PRESS of 16.819. The R-square value (0.953) suggest that 95.3% of variance in LRV of FC can be explained by average air temperature. Thus, average ambient temperature emerges as the most reliable predictor of log reduction value of faecal coliform in waste stabilization ponds.

The regression analysis for faecal coliform indicates that when all three predictor variables—radiation intensity, temperature, and wind speed—were included in a single least square regression model, radiation intensity was not statistically significant, whereas temperature emerged as the only significant predictor. Notably, radiation intensity became significant when combined individually with temperature or wind speed. Additionally, when radiation intensity was used as the sole predictor, the intercept term was not statistically significant. Wind speed was found not to be statistically significant in any of the models.

3.3 Impact of Air Temperature on the Efficiency of WSP

Numerous studies affirm the critical role of temperature in the efficiency of waste stabilization ponds. Research by Gloyna [19] and Arceivala [17] highlights significant drops in BOD removal efficiency during colder periods, even with prolonged hydraulic retention times (HRT). This reflects temperature's influence on microbial activity, which governs organic matter decomposition. Arceivala [17] and McGarry and Pescod [18] further emphasize that local climatic factors like temperature and sunlight dictate organic removal capacity, with warmer conditions enabling higher surface loadings.

Moreover, models like those by Sah et al. [27] integrate temperature and related environmental factors to predict pond efficiency more comprehensively. Comparative analyses, such as between the Gloyna and McGarry-Pescod equations, reveal that temperature-centric approaches often lead to more streamlined yet effective designs. Your findings, where temperature emerges as the sole significant predictor of BOD removal efficiency, are consistent with this literature, offering a simplified yet robust model for assessing pond performance. This reinforces the understanding that temperature is a primary determinant in the effective operation of stabilization ponds.

Table 2. Regression summary for BOD

Model	β_o	β_R	β_T	β_W	R^2	R_a^2	**RMSE**	**MAE**	**PRESS**	**BP F-test**	**SW test**
BOD (R, T, W)	-1424.8	-0.031	56.6	7.453	0.925	0.916	17.063	14.395	12003	0.017	0.264
p-value	<0.001	0.294	<0.001	0.027							
VIF	-	1.507	1.646	1.121							
BOD (R, T)	-176.4	-0.002	7.285	-	0.886	0.877	2.921	2.385	309.4	0.568	0.003
p-value	-0.002	0.005	-0.455	-							
VIF	-	1.504	1.504	-							
BOD (R, W)	-4.4	0.058	-2.077	-	0.284	0.231	14.306	12.17	7523	0.549	0.464
p-value	0.058	0.019	3.006	-							
VIF	-	1.024	1.024	-							
BOD (T, W)	-297.0	11.871	1.271	-	0.901	0.893	4.363	3.625	677.1	0.508	0.002
p-value	<0.001	<0.001	0.123	-							
VIF	-	1.118	1.118	-							
BOD (R)	-13.9	0.061	-	-	0.266	0.24	14.487	12.209	7366.3	0.369	0.589
p-value	0.301	0.004	-	-							
BOD (R) (no intercept)	-	0.041	-	-	0.888	0.788	14.771	12.87	7587.67	0.369	0.589
p-value	-	<0.001	-	-							
BOD (T)	-152.2	6.261	-	-	0.883	0.879	2.602	2.119	223.3	0.29	0.001
p-value	<0.001	<0.001	-	-							
BOD (W)	5.5	-0.353	-	-	0.072	0.039	1.411	1.308	69.3	0.164	0.003
p-value	<0.001	0.152	-	-							

VIF – variance inflation factor, R_a^2 – adjusted R-square, RMSE – root mean square error, MAE – mean absolute error, PRESS – predicted residual sum of squares, BP – Breusch-Pagan, SW - Shapiro-Wilk.

Table 3. Regression summary for LRV of faecal coliform

Model	β_o	β_R	β_T	β_W	R^2	R_a^2	**RMSE**	**MAE**	**PRESS**	**BP F-test**	**SW test**
FC (R, T, W)	-17.95	0.0004	0.733	0.047	0.96	0.955	0.161	0.134	1.057	0.017	0.264
p-value	<0.001	0.177	<0.001	0.128							
VIF	-	1.507	1.646	1.121							
FC (R, T)	-16.155	0.0003	0.669	-	0.956	0.952	0.159	0.13	0.938	0.962	0.029
p-value	<0.001	<0.001	-1.221	-							
VIF	-	1.504	1.504	-							
FC (R, W)	0.054	0.003	-0.135	-	0.307	0.256	0.671	0.528	16.426	0.289	0.399
p-value	0.003	0.001	3.051	-							
VIF	-	1.024	1.024	-							
FC (R, W) (no intercept)	-	0.003	-0.13	-	0.912	0.832	0.671	0.526	16.439	0.289	0.399
p-value	-	-0.13	5.686	-							
VIF	-	1.024	1.024	-							
FC (T, W)	-16.279	0.660	0.039	-	0.956	0.953	0.158	0.131	0.917	0.178	0.171
p-value	0.660	0.028	23.345	-							
VIF	-	1.118	1.118	-							
FC (R)	-0.564	0.003	-	-	0.273	0.247	0.687	0.529	16.495	0.185	0.482
p-value	0.375	0.003	-	-							
FC (R) (no intercept)	-	0.002	-	-	0.905	0.819	0.697	0.557	16.819	0.185	0.482
p-value	-	<0.001	-	-							
FC (T)	-16.899	0.69	-	-	0.953	0.952	0.174	0.147	1.029	0.906	0.021
p-value	<0.001	<0.001	-	-							
FC (W)	2.142	-0.189	-	-	0.068	0.035	0.778	0.701	20.829	0.601	0.015
p-value	<0.001	0.163	-	-							

VIF – variance inflation factor, R_a^2 – adjusted R-square, RMSE – root mean square error, MAE – mean absolute error, PRESS – predicted residual sum of squares, BP – Breusch-Pagan, SW - Shapiro-Wilk

4. CONCLUSIONS

This study investigated the influence of radiation intensity, ambient temperature, and wind speed on the removal efficiency of Biochemical Oxygen Demand (BOD) and Faecal Coliform (FC) in waste stabilization ponds (WSPs) using regression analysis. Results demonstrated that ambient temperature was the most significant and consistent predictor of removal efficiency for both BOD and FC, outperforming other variables across all performance metrics. Radiation intensity showed limited significance, primarily in scenarios influenced by oxygen availability, dissolved organic matter, and pH, while wind speed was not statistically significant in any model, aligning with literature that suggests its effects are largely indirect or context-dependent. These findings underscore the centrality of temperature in WSP performance and provide a foundation for temperature-focused predictive models to enhance the design and optimization of wastewater treatment systems across diverse climatic conditions.

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