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Modeling Faecal Coliform Inactivation Time in Waste Stabilization Ponds Using Cox Proportional Hazards Regression

Ekene Jude Nwankwo

Civil Engineering Department University of Nigeria, Nsukka, Enugu State, Nigeria

ABSTRACT: This study applies Cox proportional hazards regression to model faecal coliform inactivation in a pilot-scale waste stabilization pond (WSP) system, focusing on the influence of environmental covariates, including solar radiation, air temperature, and wind speed, on retention time required for complete disinfection. Experimental data were collected over a five-month period from a treatment facility located in southeastern Nigeria, and faecal coliform counts of the pilot pond were analyzed using the Most Probable Number (MPN) technique. A series of Cox models were fitted to determine the statistical significance and predictive strength of each environmental factor. The results show that air temperature was the most significant predictor of survival time ($p < 0.0001$), with a Nagelkerke pseudo R^2 of up to 0.972, indicating high explanatory power. Survival curves derived from the model reveal that retention times required for >99% confidence of complete faecal coliform inactivation range from 5.4 days at 24°C to 2.4 days at 29°C, illustrating the critical role of ambient temperature in driving disinfection efficiency. Solar radiation and wind speed, while individually significant in some models, exhibited inconsistent effects when combined with temperature. These findings align with previous literature emphasizing temperature-dependent microbial activity and highlight the practical value of integrating survival analysis into WSP design. The study underscores the need to consider local climate conditions in optimizing pond retention time and improving public health protection through wastewater treatment.

KEYWORDS: BOD, faecal coliform, solar radiation, temperature, wind speed

1. INTRODUCTION

Waste Stabilization Ponds (WSPs) are a widely recognized and cost-effective method for centralized wastewater treatment, particularly valued for their ability to remove organic pollutants and pathogenic microorganisms [1]. These systems consist of large, shallow basins—often built using locally sourced materials—where wastewater is retained long enough to undergo treatment through a combination of physical, chemical, and biological processes. Despite their structural simplicity, WSPs host a diverse and active ecosystem of algae, bacteria, protozoa, fungi, and other aquatic organisms that are essential to breaking down organic matter and inactivating pathogens [2], [3]. Properly designed and managed WSPs can achieve high removal efficiencies for fecal bacteria and intestinal pathogens [4], [5], [6]. Their low construction and operational costs, ease of maintenance, and minimal technical requirements [7], [8] make them especially suited to developing regions with limited financial and technical resources [9], [10].

The performance of WSPs depends heavily on microbial activity, especially from bacteria and algae, which are strongly influenced by environmental factors such as temperature, sunlight, and mixing within the pond [11]. These factors regulate key biological processes, including bacterial metabolism and algal photosynthesis, which in turn affect oxygen production and pH levels in the water [12], [13], [14]. Internal mixing, driven by wind and thermal gradients, ensures uniform distribution of oxygen and nutrients [15], [16]. Given the complex interactions within these systems, researchers have applied regression analysis to better understand and predict WSP performance. Early models by Arceivala [17], McGarry and Pescod [18], and Gloyna [19] focused on estimating surface loading rates, while later studies, including those by Ayres et al. [4], Pearson et al. [20], and Tyagi et al. [21], explored relationships between pollutant removal and operational variables like biochemical oxygen demand (BOD), suspended solids, and turbidity. Multivariate models, such as the one developed by Ellis and Rodrigues [22], have identified key predictors of fecal coliform and BOD removal, highlighting the potential of statistical modeling to guide site-specific and performance-driven WSP design.

Despite the inherently stochastic nature of environmental factors that influence the retention time in WSPs, existing studies have largely overlooked the application of probability-based regression models to account for the uncertainty inherent in these systems. Traditional deterministic approaches often fail to capture the variability introduced by fluctuating environmental conditions such as temperature, solar radiation, and hydrodynamics. To address this gap, the present study aims to model the pond's retention time using the Cox proportional hazards regression—a survival analysis technique that enables the estimation of time-to-event outcomes under varying conditions. By applying this method, the study introduces a probabilistic framework for evaluating how environmental parameters impact the likelihood of faecal bacteria remaining in the system over time, thus offering a more nuanced and adaptable approach to WSP performance modeling.

1.2 Survival Analysis Theory

Survival analysis examines the time until an event (e.g., death, failure, or bacterial persistence) using two key concepts: survival probability and hazard. Survival Function $S(t)$ is the probability that an individual remains event-free beyond time t. It is given by the formula:

$$S(t) = P(T > t) \qquad (1)$$

The function declines over time as the event becomes more likely. For further reading on survival analysis theory, see Clark et al. [23], Kartsonaki [24], and Jenkins [25].

Hazard Function $h(t)$ is the instantaneous risk of the event occurring at time t, given survival up to that point. It is given by the formula:

$$h(t) = \lim_{\Delta t \to 0} \frac{P(t \le T < t + \Delta t | \, T \ge t)}{\Delta t} \qquad (2)$$

Unlike survival probability, hazard focuses on the event's immediate risk. The cumulative hazard $H(t)$ sums up risk over time:

$$H(t) = \int_0^t h(t)\, dt \qquad (3)$$

Survival and cumulative hazard are related by:

$$S(t) = \exp(-H(t)) \qquad (4)$$

1.3 Cox Proportional Hazards Model

Cox regression model assesses how variables influence survival time without requiring knowledge of the baseline hazard. Cox model form is given as:

$$h(t; X) = h_o(t) e^{\beta^T X}; \qquad X: x_1, .., x_p; \qquad \beta: \beta_1, .., \beta_p \qquad (5)$$

Where $h_o(t)$ denotes the baseline hazard (risk when all predictors are zero or at their means); X is matrix of predictor variables (e.g., environmental factors); β represents regression coefficients showing each predictor's effect. The key assumption of Cox regression is that hazard ratios remain constant over time (proportional hazards). Coefficients are estimated using partial likelihood (Equation 6), avoiding the need to specify the $h_o(t)$. The model performance is assessed by Nagelkerke R^2, which is a modified version of Cox-Snell R^2 for better interpretability:

$$PL(\beta) = \prod_{i=1}^{n} \frac{exp(\beta^T X_i)}{\sum_{j \in R_{(t_i)}} exp(\beta^T X_j)} \qquad (6)$$

where $R^2_{Cox-Snell} = 1 - \left(\frac{L_1}{L_0}\right)^{\frac{2}{n}}$. While L_1 is the likelihood of the full model, L_0 denote the likelihood of the null model (no predictors).

2. MATERIAL AND METHODS

2.1 Setup and Estimation of Faecal Coliform Survival Duration

The experimental system involved a small-scale pilot pond measuring 1 m × 0.3 m × 0.2 m, which was operated in batch mode. This pond received secondary influent directly from an upstream Imhoff tank situated at the University of Nigeria, Nsukka's wastewater treatment facility. Each experimental run began by collecting an initial water sample for faecal coliform enumeration before allowing the secondary effluent into the pond. Subsequent samples were taken daily until faecal coliform levels dropped below the detection limit of <1.8 MPN/100 mL.

All experimental activities were conducted between April and September 2023. The analysis of faecal coliforms was performed using the Multiple Tube Fermentation Technique—also known as the Most Probable Number (MPN) method—at the Sanitary Engineering Laboratory, University of Nigeria, Nsukka. This procedure adhered to the guidelines outlined in the Standard Methods for the Examination of Water and Wastewater [26]. Samples were serially diluted in buffered dilution water and inoculated into lactose broth for presumptive testing, followed by incubation at 35°C for 24 hours. Tubes that showed positive results were subjected to confirmatory tests by transferring aliquots into brilliant green lactose bile broth and incubating at 35°C for an additional 48 hours. Final confirmation of faecal coliforms involved transferring presumptive positives into *E. coli* medium and incubating at 44.5°C for 24 hours. The rate at which faecal coliforms were inactivated was estimated using a first-order kinetic model, as described in Equation (7).

$$N_t = N_o\, e^{-kt} \qquad (7)$$

Here, k denotes the inactivation rate constant per day, N_t represents the faecal coliform population at time t (day), N_o is the starting population, and e is the base of the natural logarithm. Equation (7) can be expressed in its linearized form:

$$\log_e N_t = \log_e N_o - kt \qquad (8)$$

Faecal coliform survival time (t_s, i.e time taken for $N_t = 0$) was estimated by applying a regression line to the paired data [log $N(t)$, t] before evaluating t_s as t at $N_t = 0$.

2.2 Physicochemical analysis

The quality of wastewater from the Imhoff tank was assessed on a weekly basis using standard procedures outlined in APHA [26]. The parameters measured included pH, dissolved oxygen (DO), five-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), free ammonia-nitrogen, total nitrogen, ammonia-nitrogen, sulfide, and temperature. Dissolved oxygen levels were measured using an AZ8403 DO meter, while pH readings were obtained with a properly calibrated pH meter. Water temperature was monitored using a conventional mercury-in-glass thermometer.

3. RESULTS AND DISCUSSION

3.1 Characteristics of Imhoff Tank Effluent

The effluent quality of the Imhoff tank was monitored weekly throughout the five-month experimental period, focusing on key parameters such as pH, BOD_5, faecal coliforms, total suspended solids, total nitrogen, ammonia, and sulfide (see Table 1). While the pH values complied with WHO discharge standards for inland water bodies, concentrations of BOD, faecal coliforms, and sulfide may necessitate further treatment—potentially through additional units like maturation ponds. Other measured parameters are generally within acceptable ranges for treatment by anaerobic and facultative ponds. Sulfide, mainly generated by sulfate-reducing bacteria such as *Desulfovibrio*, poses a potential odor issue. However, it can also offer some benefits by precipitating heavy metals and inhibiting pathogens like *Vibrio cholerae* at relatively low concentrations (10–12 mg/L) as noted by Oragui et al. [27]. In well-functioning anaerobic ponds, odor problems are typically controlled. At the typical pond pH of around 7.5, sulfide exists mainly as odorless bisulfide ions, minimizing the release of hydrogen sulfide gas. The extent of gas release is governed by Henry's law equilibrium, as explained by Sawyer et al. [28].

Table 1. Characteristics of Imhoff tank effluent

Quality parameters	Discharge Standard	Influent values
Biochemical Oxygen Demand (BOD_5) (mg/L)	30	232
Fecal Coliforms (CFU/100 mL)	$<1 \times 10^3$	5×10^5
Total Suspended Solids (TSS) (mg/L)	100	211
Sulfide (mg/L)	2	9.0
Free Ammonia-Nitrogen (mg N/L)	5	6.1
Total Nitrogen (TN) (mg/L)	10	48.0
Ammonia-Nitrogen (Total) (mg N/L	50	41.0
pH	5.5 – 9.0	8.1

3.2 Evaluation and Comparison of Model Performance

The descriptive statistics shown in Table 2 reveal distinct patterns across the variables used in the Cox regression analysis. Radiation intensity showed moderate variability (mean = 604.87 W/m², SD = 121.77) and a left-skewed distribution, while air temperature was relatively stable (mean = 26.55°C, SD = 1.16) with a near-normal shape. Wind speed had a moderate spread (mean = 3.78 mph, SD = 1.13) and was slightly right-skewed. Retention time, the key outcome variable, exhibited greater variability (mean = 4.33 days, SD = 1.3) and was notably right-skewed and leptokurtic, indicating the presence of longer survival times in some cases. Overall, these statistics suggest that retention time is the most dispersed and asymmetrical variable, potentially influenced by the more variable environmental factors like radiation and wind speed. However, non-normality, skewness, and kurtosis in the predictor variables do not violate the assumptions of the Cox proportional hazards model. The Cox model is semi-parametric, and it does not require the covariates to be normally distributed [29].

Cox regression analysis was carried out to examine the influence of radiation intensity, air temperature, and wind speed on wastewater retention time in stabilization ponds.

Among all model combinations, temperature consistently emerged as the most significant predictor. In the full model including all three covariates (radiation, temperature, and wind speed), temperature had a highly significant effect ($p < 0.001$), while radiation and wind speed were not statistically significant. The model demonstrated an excellent fit, with a chi-square of 105.39 (df = 3, $p < 0.0001$) and a Nagelkerke pseudo R-squared of approximately 0.977, indicating that nearly 98% of the variability in hazard was explained.

When the models were reduced to two or one covariate, the significance of temperature remained consistent. The model with only temperature and radiation also yielded a strong fit (Nagelkerke $R^2 \approx 0.977$), with temperature remaining significant ($p < 0.0001$) and radiation remaining non-significant ($p \approx 0.11$). The temperature-only model still explained about 97.3% of the variability (Nagelkerke $R^2 \approx 0.973$), confirming that temperature alone is a powerful predictor. In contrast, models including only radiation or wind speed yielded relatively low explanatory power (Nagelkerke $R^2 \approx 0.181$ and 0.156, respectively), even though both variables were individually significant at the 5% level. These results strongly support the dominant role of temperature in determining retention time, while radiation and wind speed play more context-dependent or marginal roles.

Table 2. Descriptive statistics for regression data

	R (W/m^2)	T (°C)	W (mph)	Retention time
Mean	604.87	26.55	3.78	4.33
Standard Error	22.23	0.21	0.21	0.24
Median	653.5	26.2	3.60	3.81
Standard Deviation	121.77	1.16	1.13	1.30
Sample Variance	14828.19	1.35	1.28	1.69
Kurtosis	-0.72	-0.96	0.09	4.64
Skewness	-0.69	0.29	0.68	2.22
Range	419	4.16	4.50	5.00
Minimum	762	28.62	6.70	8.38
Maximum	343	24.46	2.20	3.38
Sum	18146	796.57	113.5	129.92
Count	30	30	30	30

R – mean of the average 6-hour midday solar radiation intensities, T – average daily temperature, W – average wind speed.

Table 2: Result of Cox regression

Covariates Included	χ^2 (df)	p-value	Nagelkerke R^2	Covariate	Coefficient (β)	SE	p-value	exp(β)
R, T, W	105.39 (3)	<0.0001	0.977	R	-0.0052	0.0037	0.1545	0.995
				T	11.6906	2.9025	<0.0001	119440.2
				W	-0.1813	0.3283	0.5809	0.834
R, T	105.08 (2)	<0.0001	0.977	R	-0.0057	0.0035	0.1088	0.994
				T	11.3763	2.7507	<0.0001	87,229.66
T, W	103.15 (2)	<0.0001	0.956	T	10.9966	2.6933	<0.0001	59,670.25
				W	-0.3273	0.3129	0.2957	0.721
R, W	10.22 (2)	0.006	0.156	R	0.0039	0.0017	0.0256	1.004
				W	-0.3732	0.1885	0.0478	0.689
R only	5.95 (1)	0.0147	0.086	R	0.0039	0.0016	0.0167	1.004
T only	102.03 (1)	<0.0001	0.973	T	10.2041	2.3762	<0.0001	27,014.35
W only	5.03 (1)	0.0248	0.07	W	-0.3852	0.1804	0.0327	0.68

R – radiation intensity, T – temperature, W – wind speed

3.3 Impact of Air Temperature on Retention Time in Waste Stabilization Ponds (WSPs)

The results of the Cox proportional hazards regression revealed that air temperature was the most significant covariate influencing the survival time of faecal coliforms

WSPs. In all models where temperature was included, it showed a strong, statistically significant effect on the hazard function ($p < 0.0001$), with Nagelkerke pseudo R^2 values reaching as high as 0.972, indicating excellent model fit and predictive accuracy. Figure 1 illustrates the adjusted survival curves of faecal coliforms at varying average air temperature levels. The model predicts that to achieve a >99% probability of complete inactivation, retention times of approximately 5.4, 4.8, 3.7, 3.6, 3.5, and 2.4 days are required at air temperatures of 24°C, 25°C, 26°C, 27°C, 28°C, and 29°C, respectively. This temperature range reflects the prevailing ambient conditions in southeastern Nigeria, where the study was conducted. These results confirm that higher temperatures are associated with faster bacterial die-off, aligning with expectations from survival theory and prior empirical studies.

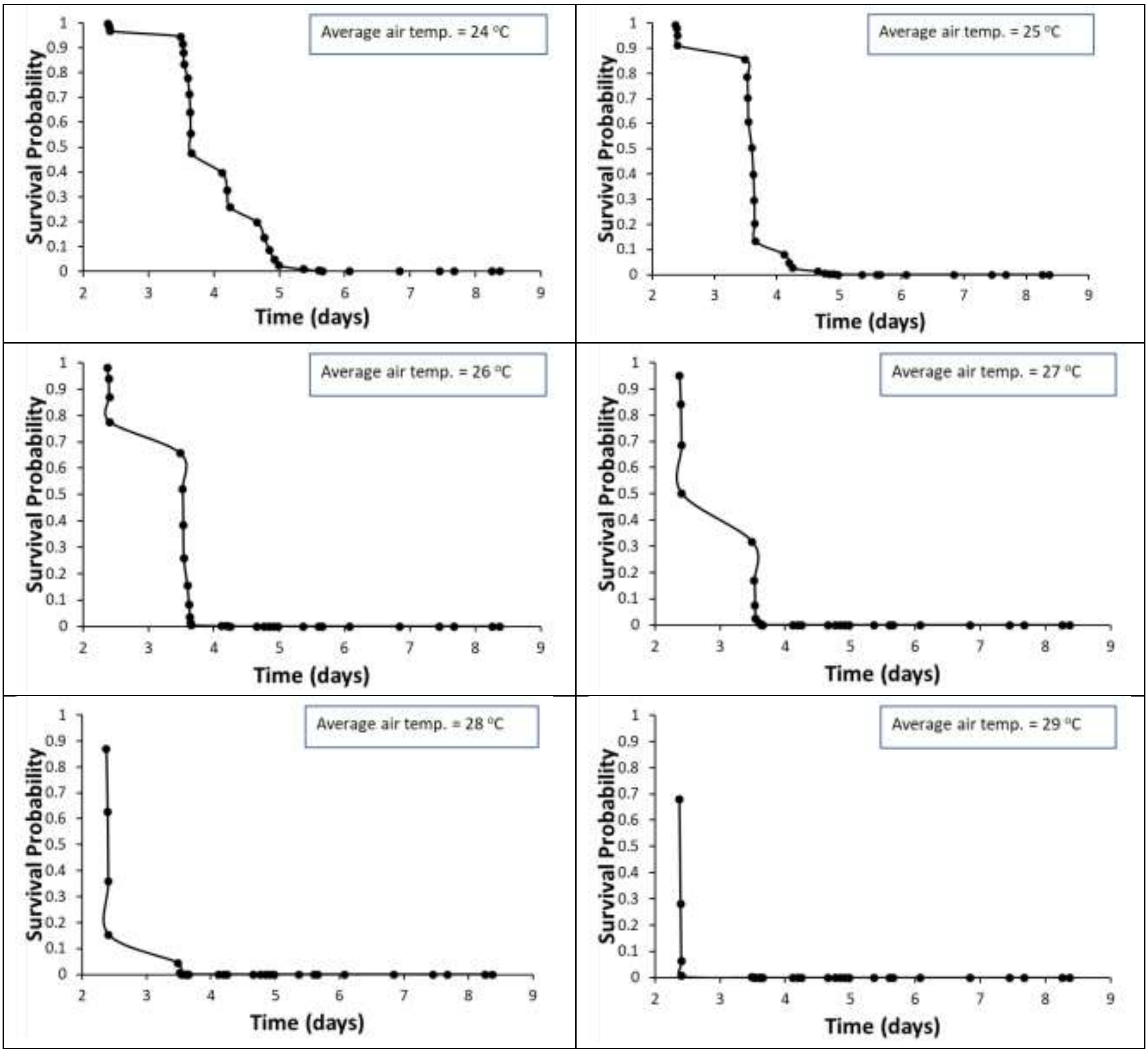

Figure 1: Predicted survival curves of faecal coliforms adjusted for varying average air temperature levels

The strong temperature dependence of faecal coliform inactivation observed here supports foundational findings by Gloyna [19] and Arceivala [17], who noted decreased BOD removal during colder seasons despite extended hydraulic retention times, attributable to diminished microbial metabolic activity. Arceivala [17] as well as McGarry and Pescod [18] also emphasized the role of temperature and sunlight in enhancing treatment efficiency at higher organic loadings. More recently, Sah et al. [30] incorporated temperature into pond performance models to improve prediction reliability. The current study adds to this body of evidence by demonstrating that temperature alone can serve as a robust predictor of microbial inactivation and retention time. The survival curves clearly demonstrate that under lower temperatures, maturation ponds may require significantly longer retention periods, up to six days, to achieve effective disinfection. These findings highlight the need to account for regional climate variability in pond design and operation, and they underscore the utility of survival analysis methods like the Cox model for integrating environmental variables into more realistic wastewater treatment models.

3.4 Wind Effects on Pond Mixing and Efficiency

The result showing that wind speed was not a statistically significant predictor of retention time in the Cox regression models is consistent with existing literature, which often portrays wind as a secondary and highly variable factor in the performance of WSPs. Although wind can enhance surface reaeration and facilitate vertical mixing—helping to distribute oxygen, nutrients, and algae throughout the pond—its influence is highly context-dependent. As noted by Davis and Cornwell [31] and EPA [32], wind-driven mixing can support aerobic microbial activity, particularly near the surface. However, studies by Aldana et al. [33] and Banks [34] show that the impact of wind depends heavily on its speed, prevailing direction, local geography, and the physical geometry of the pond itself.

Moreover, the dual role of wind—as both a potential enhancer of circulation and a disruptor of hydraulic stability—further complicates its predictive utility. Shilton and Harrison [35] argues that hydraulic behavior in ponds is more significantly influenced by inlet configuration and flow momentum than by wind action. Wind-induced turbulence may promote short-circuiting or stratification disruption, which can reduce mean retention time and undermine treatment performance [33]. These complex and often competing mechanisms likely explain why wind speed did not emerge as a significant variable in the regression models. Additionally, because wind effects are episodic and difficult to isolate in natural settings—often interacting with solar radiation, rainfall, and loading patterns—they are challenging to quantify consistently in statistical models. This underscores the findings that while wind can contribute to mixing under specific conditions, it lacks the steady, measurable influence that air temperature exerts on microbial activity and, by extension, on bacterial survival and pond efficiency.

3.5 Impact of Radiation Intensity on Faecal Coliform Removal Efficiency

The Cox regression analysis showed that solar radiation intensity was not statistically significant when modeled together with temperature and wind speed but became significant when examined alongside either temperature or wind individually. This outcome reflects the complex and context-dependent role of solar radiation in faecal coliform inactivation within waste stabilization ponds (WSPs). As shown in the foundational work by Curtis et al. [36], sunlight contributes to bacterial die-off primarily through oxygen-mediated, photosensitized reactions. These processes involve humic substances that absorb solar energy and transfer it to molecular oxygen, generating reactive oxygen species capable of disrupting bacterial membranes. This mechanism can extend into the visible light spectrum (up to 700 nm), which is especially relevant in shallow, clear water systems where such wavelengths can penetrate deeply.

However, in the naturally turbid environments of WSPs—often laden with algae and organic matter—direct sunlight penetration can be limited. High concentrations of suspended solids and dissolved organic compounds absorb or scatter shorter wavelengths, reducing the intensity of bactericidal UV and visible light reaching microbial cells [36]. Moreover, the presence of algae, though contributing to turbidity, also plays a beneficial indirect role. Enhanced algal photosynthesis under high solar radiation increases dissolved oxygen concentrations and elevates pH levels, both of which create unfavorable conditions for faecal coliform survival [37], [38]. This dual pathway—direct photoinactivation and indirect environmental modification—means the net effect of solar radiation is influenced by the pond’s biological and optical characteristics. The fact that radiation intensity was only conditionally significant in the regression models highlights the importance of interaction effects and suggests that future modeling efforts should consider nonlinear or moderated relationships among light, turbidity, and algal dynamics to better capture radiation’s full impact on microbial inactivation.

4. CONCLUSIONS

This study highlights the effectiveness of using Cox proportional hazards regression to model retention time in waste stabilization ponds (WSPs), offering a probabilistic approach that accounts for environmental variability. Among the covariates examined—radiation intensity, air temperature, and wind speed—temperature consistently emerged as the most significant and influential predictor of retention time and faecal coliform inactivation, aligning with established knowledge on its impact on microbial activity. While radiation and wind showed some effects, their predictive power was comparatively limited and context-dependent. The high Nagelkerke R^2 values, especially in temperature-inclusive models, affirm the model’s strong explanatory capability. Overall, the findings emphasize the centrality of temperature in WSP performance and advocate for its integration into design and operational planning for more adaptive, data-driven wastewater treatment in variable climatic conditions.

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REFERENCES

1. J. C. Agunwamba, “Effect of tapering on the performance of waste stabilization ponds,” *Water Res*, vol. 35, no. 5, pp. 1191–1200, 2001.

2. L. Dharani, R. Umapriya, J. Rohan, G. Surendran, and P. Deepak, “Microbes and wastewater treatment,” in *Clean Technologies Toward a Sustainable Future*, P. Verma and M. P. Shah, Eds., London, UK: IWA Publishing, 2023, ch. 1, pp. 1–17. doi: 10.2166/9781789063783_0001.
3. O. Kehl, M. Wichern, M. Lübken, and H. Horn, “Analysis of design approaches for stabilization ponds under different boundary conditions—A comparison,” *Ecological Engineering - ECOL ENG*, vol. 35, pp. 1117–1128, Aug. 2009, doi: 10.1016/j.ecoleng.2008.12.022.
4. R. M. Ayres, G. P. Alabaster, D. D. Mara, and D. L. Lee, “A design equation for human intestinal nematode egg removal in waste stabilization ponds,” *Water Res*, vol. 26, no. 6, pp. 863–865, 1992, doi: 10.1016/0043-1354(92)90019-Z.
5. R. Stott, E. May, and D. D. Mara, “Parasite removal by natural wastewater treatment systems: performance of waste stabilisation ponds and constructed wetlands,” *Water Science and Technology*, vol. 48, no. 2, pp. 97–104, 2003, doi: 10.2166/wst.2003.0095.
6. V. K. Tyagi, A. A. Kazmi, and A. K. Chopra, “Removal of fecal indicators and pathogens in a waste stabilization pond system treating municipal wastewater in India,” *Water environment research*, vol. 80, no. 11, pp. 2111–2117, 2008, doi: 10.2175/106143008X296433.
7. M. Von Sperling, *Waste stabilisation ponds*. London: IWA publishing, 2007.
8. S. Mahapatra, K. Samal, and R. R. Dash, “Waste Stabilization Pond (WSP) for wastewater treatment: A review on factors, modelling and cost analysis,” *J Environ Manage*, vol. 308, p. 114668, 2022, doi: 10.1016/j.jenvman.2022.114668.
9. N. Mburu, S. M. Tebitendwa, J. J. A. van Bruggen, D. P. L. Rousseau, and P. N. L. Lens, “Performance comparison and economics analysis of waste stabilization ponds and horizontal subsurface flow constructed wetlands treating domestic wastewater: A case study of the Juja sewage treatment works,” *J Environ Manage*, vol. 128, pp. 220–225, 2013, doi: 10.1016/j.jenvman.2013.05.031.
10. A. Mirzoev *et al.*, “A countrywide assessment of tuberculosis among health-care workers in tuberculosis health-care facilities in Tajikistan, 2009–2014,” *Public health panorama*, vol. 02, no. 01, pp. 74–80, 2016, [Online]. Available: https://apps.who.int/iris/handle/10665/325439
11. M. N. F. Shaheen *et al.*, “Evaluation of physical, chemical, and microbiological characteristics of waste stabilization ponds, Giza, Egypt,” *Environ Sci Eur*, vol. 36, no. 1, p. 170, 2024, doi: 10.1186/s12302-024-00965-y.
12. N. K. Shammas, L. K. Wang, and Z. Wu, “Waste Stabilization Ponds and Lagoons BT - Biological Treatment Processes,” L. K. Wang, N. C. Pereira, and Y.-T. Hung, Eds., Totowa, NJ: Humana Press, 2009, pp. 315–370. doi: 10.1007/978-1-60327-156-1_8.
13. S. Kayombo, T. S. A. Mbwette, A. W. Mayo, J. H. Y. Katima, and S. E. Jørgensen, “Diurnal cycles of variation of physical–chemical parameters in waste stabilization ponds,” *Ecol Eng*, vol. 18, no. 3, pp. 287–291, 2002, doi: 10.1016/S0925-8574(01)00086-6.
14. D. D. Mara, *Design manual for waste stabilization ponds in India*. IWA, 2003.
15. C. G. R. Meneses, L. B. Saraiva, H. N. de S. Melo, J. L. S. de Melo, and H. W. Pearson, “Variations in BOD, algal biomass and organic matter biodegradation constants in a wind-mixed tropical facultative waste stabilization pond,” *Water Science and Technology*, vol. 51, no. 12, pp. 183–190, 2005, doi: 10.2166/wst.2005.0458.
16. R. Marcé, C. Feijoó, E. Navarro, J. Ordoñez, J. Gomà, and J. Armengol, “Interaction between wind-induced seiches and convective cooling governs algal distribution in a canyon-shaped reservoir,” *Freshw Biol*, vol. 52, no. 7, pp. 1336–1352, 2007, doi: 10.1111/j.1365-2427.2007.01771.x.
17. S. J. Arceivala, *Simple waste treatment methods: aerated lagoons, oxidation ditches, stabilisation ponds in warm and temperate climates*. Middle East Technical University, 1973.
18. M. G. McGarry and M. B. Pescod, “Stabilization pond design criteria for tropical Asia,” *Environmental Enginnering Division, Asian Institute of Technology Babkok, Thailan*, 1970.
19. E. F. Gloyna, *Waste stabilization ponds*. World Health Organization, 1971.
20. . W. Pearson, S. T. S. Athayde, G. B. Athayde, and S. A. Silva, “Implications for physical design: the effect of depth on the performance of waste stabilization ponds,” *Water Science and Technology*, vol. 51, no. 12, pp. 69–74, 2005, doi: 10.2166/wst.2005.0429.
21. V. K. Tyagi, B. K. Sahoo, A. Khursheed, A. A. Kazmi, Z. Ahmad, and A. K. Chopra, “Fate of coliforms and pathogenic parasite in four full-scale sewage treatment systems in India,” *Environ Monit Assess*, vol. 181, no. 1, pp. 123–135, 2011, doi: 10.1007/s10661-010-1818-4.
22. K. V Ellis and P. C. C. Rodrigues, “Multiple regression design equations for stabilization ponds,” *Water Res*, vol. 29, no. 11, pp. 2509–2519, 1995, doi: 10.1016/0043-1354(95)00081-U.

23. T. G. Clark, M. J. Bradburn, S. B. Love, and D. G. Altman, "Survival Analysis Part I: Basic concepts and first analyses," *Br J Cancer*, vol. 89, no. 2, pp. 232–238, 2003, doi: 10.1038/sj.bjc.6601118.
24. C. Kartsonaki, "Survival analysis," *Diagn Histopathol*, vol. 22, no. 7, pp. 263–270, 2016, doi: 10.1016/j.mpdhp.2016.06.005.
25. S. P. Jenkins, "Survival analysis," *Unpublished manuscript, Institute for Social and Economic Research, University of Essex, Colchester, UK*, vol. 42, pp. 54–56, 2005.
26. APHA, *Standard Methods for the Examination of Water and Wastewater*, 23rd ed. Washington DC, USA: American Public Health Association (APHA), 2017. doi: 10.2105/SMWW.2882.192.
27. J. I. Oragui, H. Arridge, D. D. Mara, H. W. Pearson, and S. A. Silva, "Vibrio cholerae O1 (El Tor) removal in waste stabilization ponds in northeast Brazil," *Water Res*, vol. 27, no. 4, pp. 727–728, 1993, doi: 10.1016/0043-1354(93)90183-I.
28. C. N. Sawyer, P. L. McCarty, and G. F. Parkin, *Chemistry for Environmental Engineering*, 4th ed. New York: McGraw Hill Book Co., 1994.
29. D. R. Cox, "Partial likelihood," *Biometrika*, vol. 62, no. 2, pp. 269–276, 1975.
30. L. Sah, D. P. L. Rousseau, C. M. Hooijmans, and P. N. L. Lens, "3D model for a secondary facultative pond," *Ecol Modell*, vol. 222, no. 9, pp. 1592–1603, 2011, doi: 10.1016/j.ecolmodel.2011.02.021.
31. M. L. Davis and D. A. Cornwell, *Introduction to environmental engineering*. McGraw-Hill, 1991.
32. U. Epa, "Principles of design and operations of wastewater treatment pond systems for plant operators, engineers, and managers," *Cincinnati: United States Environmental Protection Agency, Office of Research and Development*, 2011.
33. G. J. Aldana, B. J. Lloyd, K. Guganesharajah, and N. Bracho, "The impact of wind on waste stabilisation pond performance," in *8 TH IWA SPECIALIST GROUP CONFERENCE ON WASTE STABILISATION PONDS (IWA Pond's 2009)*, 2009.
34. R. B. Banks, "Some Features of Wind Action on Shallow Lakes," *Journal of the Environmental Engineering Division*, vol. 101, no. 5, pp. 813–827, Oct. 1975, doi: 10.1061/JEEGAV.0000404.
35. A. Shilton and J. Harrison, "Development of guidelines for improved hydraulic design of waste stabilisation ponds," *Water Science and Technology*, vol. 48, no. 2, pp. 173–180, 2003, doi: 10.2166/wst.2003.0114.
36. T. P. Curtis, D. D. Mara, and S. A. Silva, "Influence of pH, Oxygen, and Humic Substances on Ability of Sunlight To Damage Fecal Coliforms in Waste Stabilization Pond Water," *Appl Environ Microbiol*, vol. 58, no. 4, pp. 1335–1343, Apr. 1992, doi: 10.1128/aem.58.4.1335-1343.1992.
37. A. Ouali, H. Jupsin, J. L. Vasel, and A. Ghrabi, "Removal of E. coli and enterococci in maturation pond and kinetic modelling under sunlight conditions," *Desalination Water Treat*, vol. 53, no. 4, pp. 1068–1074, Jan. 2015, doi: 10.1080/19443994.2013.856350.
38. D. F. C. Dias, R. G. Passos, and M. von Sperling, "A review of bacterial indicator disinfection mechanisms in waste stabilisation ponds," *Rev Environ Sci Biotechnol*, vol. 16, no. 3, pp. 517–539, 2017, doi: 10.1007/s11157-017-9433-2.