

Seasonal Shifts in Microbial Communities and Physicochemical Quality of a Pristine Waterfall in Abuja, Nigeria

Ngozika Florence Okey-Ndeche

Veritas University

Nnamdi Henry Igwe

Veritas University

Chizoma Nwakego Adewumi

Veritas University

Frank Abimbola Ogundolie

fa.ogundolie@gmail.com

Baze University

Research Article

Keywords: Fresh water ecology, Heterotrophic microorganisms, Hydro-climate factor, Predictive modelling, Water quality surveillance

Posted Date: July 2nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9634275/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Environmental Monitoring and Assessment on August 20th, 2026. See the published version at <https://doi.org/10.1007/s10661-026-15811-2>.

SEASONAL SHIFTS IN MICROBIAL COMMUNITIES AND PHYSICOCHEMICAL QUALITY OF A PRISTINE WATERFALL IN ABUJA, NIGERIA

Okey-Ndeche, Ngozika Florence^{1*}; Igwe, Nnamdi Henry¹; Adewumi, Chizoma Nwakego², Ogundolie, Frank Abimbola^{3*}.

¹Department of Microbiology, Veritas University, Abuja, Nigeria. ngozikeyndech@gmail.com 0000-0002-4282-5575

¹Department of Microbiology, Veritas University, Abuja, Nigeria. henryigweacademy@gmail.com; 0009-0006-3436-885X

²Department of Pure and Applied Chemistry, Veritas University Abuja, Nigeria. ezechizoma24@gmail.com 0000-0002-9343-1031

³Department of Biotechnology, Baze University Abuja, Nigeria fa.ogundolie@gmail.com; 0000-0001-6112-1496

*Correspondence e-mail: ngozikeyndech@gmail.com; 08055466369; fa.ogundolie@gmail.com; 08035162818

SEASONAL SHIFTS IN MICROBIAL COMMUNITIES AND PHYSICOCHEMICAL QUALITY OF A PRISTINE WATERFALL IN ABUJA, NIGERIA

Abstract

The effects of seasonal changes on the physio-chemical properties and microbial populations of a Pristine waterfall stream located near Veritas University, Abuja, Nigeria, were evaluated. Water samples were collected monthly for twelve (12) months from three sampling locations (upstream, midstream, and downstream), during the dry and rainy seasons. Analytical determination of water physio-chemical parameters such as temperature, pH, conductivity, turbidity, and biochemical oxygen demand (BOD) was done by standard methods. The microbial content analysis included heterotrophic bacteria, fungi, and yeast. The interaction effect of temperature and pH on the abundance of microbial organisms and BOD was modelled using Response Surface Methodology (RSM) based on Central Composite Rotational Design (CCRD). Findings indicate that physico-chemical parameters such as conductivity (22.82 $\mu\text{S}/\text{cm}$), turbidity (0.96 NTU), and pH (8.23) were higher in the rainy season than in the dry season, but the values are still within the acceptable range of values for freshwater systems. Moreover, an increase in the number of microbial organisms occurred in the rainy season. The relationships between temperature, pH, and microbial counts were significantly explained through quadratic models ($p < 0.05$) that also show high fitness values ($R^2 = 0.7622\text{--}0.9728$). The significant quadratic effect of temperature on the proliferation of bacteria and fungi and significant influence of pH on yeast and BOD was noted. BOD, on the other hand, changed its model response from quadratic in the rainy season to linear in the dry season. The research demonstrates that even relatively Pristine freshwater ecosystems are vulnerable to seasonal physicochemical variations that influence microbial ecology and probable public health risks. These discoveries offer a predictive framework for monitoring freshwater ecosystems under increasing anthropogenic and climate-related pressures.

Keywords: Seasonal variation, Microbial communities, Pristine waterfall, Physicochemical parameters, Response Surface Methodology Optimization.

Key Highlights

- Seasonal variation significantly influenced physicochemical parameters, with higher conductivity, turbidity, and pH recorded during the rainy season.
- Microbial populations (bacteria, fungi, and yeast) increased markedly in the rainy season, indicating enhanced microbial activity.
- Temperature and pH interactions strongly affected microbial abundance and BOD, as demonstrated using Response Surface Methodology (RSM).

- Quadratic models showed high predictive accuracy ($R^2 = 0.7622\text{--}0.9728$), effectively describing microbial dynamics and environmental interactions.
- Even relatively pristine freshwater systems are vulnerable to seasonal changes, posing potential ecological and public health risks

Introduction.

Aquatic ecosystems constitute an important reservoir for supporting the rich diversity of living organisms. They are equally vital for sustaining human livelihoods. However, due to anthropogenic interference and environmental changes induced by climatic factors, such ecosystems experience alterations that affect their physical, chemical, and biological properties. In many instances, surface waters like streams and waterfalls act as recipients for agricultural runoff, municipal effluents, and environmentally dispersed pollutants. The latter contribute nutrients, organic matter, and even pathogenic microorganisms capable of modifying the properties of the water and the composition of its indigenous microbiota (Ayejoto et al., 2023)

The seasonal alternations between rainy and dry seasons form the most prominent driver of processes in tropical ecosystems (Bernardino et al., 2023). During rainfall, the influxes of nutrients, sediments, and microorganisms from terrestrial habitats into the aquatic environment become much stronger, whereas during the dry season, decreased surface runoff leads to increased concentrations of solutes in the water and changes in the water temperature regime (Akinawo, 2023). All these variables affect the major physicochemical properties of water (for example, temperature, pH, turbidity, conductivity) (Debassi et al., 2025) and subsequently impact the microbial metabolism, species' composition, and BOD of the water body. Although seasonal variations in highly polluted water bodies have been widely described in the literature comparatively, fewer studies have analyzed similar patterns in more pristine ecosystems e.g., waterfalls. The assumption about ecological equilibrium in minimally impacted lotic systems should be considered cautiously since such systems can undergo some degree of human intervention through small-scale agricultural production, animal grazing, and recreational activities. For example, the presence of opportunistic pathogens of the genera *Pseudomonas*, *Salmonella*, *Staphylococcus*, and *Streptococcus* has been proven in natural water systems (Huang et al., 2024). In addition, since untreated surface water is still used for drinking purposes in some communities, these pathogens pose a public health hazard that requires thorough analysis.

Although there is increasing awareness of the importance of seasonality in the determination of water quality, the majority of the existing literature is mainly descriptive or uses single-factor analysis. This approach does not sufficiently account for the intricate, non-linear relationship among the environmental factors involved. For instance, the interplay of temperature and pH, which are significant environmental determinants of microbial growth and metabolism, is poorly characterized in tropical freshwater habitats. This limits the possibility of developing predictive models that can determine the thresholds at which environmental variables stimulate or inhibit

microbial population growth. The current study attempted to address the above gaps by examining the seasonal variation in the composition of microbial communities and the physiochemical parameters of Pristine (a natural) waterfall stream in Abuja, Nigeria. The application of Response Surface Methodology (RSM) based on a Central Composite Rotational Design (CCRD) enables us to move beyond traditional methods of analyzing the interaction and quadratic effect of temperature and pH on microbial numbers and biological oxygen demand (BOD).

Our study focuses on three main objectives: (i) examining seasonal variations in physiochemical parameters, (ii) determining seasonal variation in the abundance of heterotrophic bacteria, fungi, and yeasts, and (iii) establishing the relationship between the environmental variables and microbial populations using mathematical models.

Materials and Methods

Study Area

The study was conducted on the stream sourced from a waterfall located within Veritas University, Bwari Area Council FCT, Abuja which is situated on a 49-acre campus in a rural setting and approximately 40 kilometers from the Abuja city center. The University is located on the Latitude of 9.2907° or 9° 17' 18" North and on the Longitude of about 7.41642° or 7° 24' 51" East. The local waterfall is situated on a hill and drops from about 30 meters height. The surrounding environment of the stream is characterized by temperate weather and influenced by some physical and chemical conditions. The waterfall under study experiences two weather conditions annually including a warm, humid rainy season and a hot dry season and is susceptible to pollution while receiving a considerable quantity of waste and effluents from different environmental sources.

Sample collection

In twelve months, covering both dry (April - September) and rainy seasons (October -March), three different water samples were collected from different points sources (upstream, midstream and downstream) given a representative sample of the stream. They were then transported in a sterile-screw-capped vials, placed in ice-filled bags, to the Microbiology Laboratory for analysis using the (APHA, 2020) approach. All field tools and equipment used were properly checked and calibrated before use according to the manufacturer's specifications.

Determination of Physicochemical Parameters

The BOD was evaluated using the Winkler titration method, a turbidimeter was used to measure turbidity in Nephelometric Turbidity Units (NTU), Conductivity was determined with conductivity meter and the values obtained were recorded in $\mu\text{S}/\text{cm}$, pH was evaluated using a pH meter while a digital thermometer was used to measure the temperature and values recorded in degree centigrade ($^{\circ}\text{C}$).

Microbial Count Evaluation

The types of microorganisms present in the waterfall stream, and their estimated populations were evaluated using the colony counts and biochemical tests. Groups of microorganisms isolated during the experiment include heterotrophic bacteria and fungi which included coliforms and yeasts respectively. The culture media used in this study were all prepared according to manufacturers' specifications and included Nutrient Agar, Sabouraud Dextrose Agar (SDA), MacConkey Agar, and peptone water. All analyses were aseptically executed in compliance with the Guidelines on Standard Operating Procedures for Microbiology as described by (Kumari and Ichhpujani, 2000)

Statistical Design for Seasonal Shift Evaluation

Central composite rotational design of Response Surface Methodology (RSM) was utilized for evaluating the optimal conditions for seasonal shifts in microbial communities and biological oxygen demand (BOD) quality of the Pristine Waterfall in Abuja, Nigeria. The dependent variables: bacteria count, fungal count, yeast count and BOD levels, were determined from the independent variables of Temperature (Rainy and Dry seasons in $^{\circ}\text{C}$) and pH. Three coded alpha levels ($-\alpha$, 0, $+\alpha$) of the Central Composite Rotational Design (CCRD), produced 13 experimental runs for each dependent variable. These conditions are shown in Table 1 and 2. Equation 1 represents the second-order model used to forecast the optimum position.

$$Y = \beta_0 + \sum \beta_1 X_1 + \sum \beta_2 X_2 + \sum \beta_{12} X_1 X_2 + \sum \beta_{11} X_1^2 + \sum \beta_{22} X_2^2 + e^2 \quad (1)$$

Where Y = Dependent variable (predicted response), X_1 and X_2 = variable factors (Temperature and pH), β_0 is a constant term. β_1 and β_2 are the coefficients of the linear terms, β_{12} is the coefficient of the cross term, β_{11} , and β_{22} are the coefficients of the quadratic term and e is the error term.

Table 1: Coded levels of variable for CCRD for Rainy Season

Variables	Units	Symbols	Coded Levels		
			- α	0	+ α
Temperature	°C	X ₁	23.0	23.55	24.1
pH		X ₂	7.5	8.15	8.8

Table 2: Coded levels of variable for CCRD for Dry Season

Variables	Units	Symbols	Coded Levels		
			- α	0	+ α
Temperature	°C	X ₁	24.23	25.42	26.6
pH		X ₂	5.5	7.0	8.5

Results and Discussions

The Physicochemical parameters of the waterfall were studied for a period of 12 months: rainy (April -September) and dry (October- March) seasons to establish the relationship between isolates and their microenvironments. The summary of the physicochemical parameters are as presented in Table 3. The result shows that all the selected parameters had higher values during the rainy season than during the dry season.

Table 3: Effects of Season shifts on Some Physicochemical Parameters of Pristine Waterfall.

Parameter	Mean/DS	Mean /RS	SD/DS	SD/RS	Variance
Temperature (°C)	25.611	23.533	0.856	0.474	0.96
Conductivity(μs/cm)	13.030	22.815	1.524	7.315	55.83
pH	6.967	8.233	1.211	0.450	1.67
Turbidity (NTU)	0.63	0.96	0.120	0.161	0.04

- SD= Standard deviation, RS = Rainy season, DS = Dry season

Investigating the physicochemical parameters of a pristine waterfall helps establish a baseline for water quality, supports biodiversity conservation, and provides data for future comparisons if environmental changes occur. The pH range obtained during this period of study is considered safe for all purposes since (NSDWQ, 2015) stated that pH of 6.5 to 8.5 is generally good for both aquatic life and drinking. However, the low conductivity range of 13.03-22.82 $\mu\text{S}/\text{cm}$ in pristine waterfall is assumed to be good for the water quality and typically indicates very low levels of dissolved ions or salts which suggests minimal impacts on aquatic survival and human health. Turbidity of the stream was between 0.63 to 0.96 NTU which agrees with the findings of NSDWQ, (2015) that a pristine waterfall with turbidity <1 NTU suggests very clear water, likely reflecting minimal sediment or disturbance.

RSM Modeling of Microbiota and BOD

The findings from this research work indicate a variation in the microbial population and BOD qualities of the waterfall during different seasons in Abuja influenced by the interaction of temperature and pH. Response Surface Methodology (RSM) using Central Composite Rotational Design (CCRD) proved effective in modeling such changes (Tables 4 and 9). It shows, above all, that quadratic interactions are responsible for such changes.

According to the ANOVA result (Tables 5-8 for rainy season, and Tables 10-13 for dry season), it is clear that the most appropriate mathematical model to describe the relation between environmental variables and microbial numbers was quadratic in both seasons, whereas there was a shift in BOD behavior from being quadratic (Table 8) in the rainy season to linear in the dry season (Table 13). Heterotrophic bacterial counts, fungal counts, and yeast counts exhibited significant quadratic relationships in both seasons ($p < 0.05$) indicating a non-linear relationship between microbial population and environmental drivers.

Table 4: Experimental Design for Rainy Season shift

		Factor 1	Factor 2	Response 1	Response 2	Response 3	Response 4
Std	Run	A: Temperature (Rainy Season)	B: pH	Heterotrophic Bacteria count	Heterotrophic Fungal count	Yeast count	BOD
		$^{\circ}\text{C}$		cfu/ml	cfu/ml	cfu/ml	mg/l
1	1	23.11	7.63	9.7	53.4	13.6	5.45
3	2	23.11	8.67	15	50.2	10.55	5.03
10	3	23.55	8.15	18	68.5	16	6.92
11	4	23.55	8.15	19	66.33	15.9	8.1
7	5	23.55	7.5	11.69	56.8	11.6	4.8
6	6	24.1	8.15	11.6	44.66	15.7	5.1

4	7	23.99	8.67	14	54.6	17.66	7.8
13	8	23.55	8.15	18.5	65.8	14.8	6.6
12	9	23.55	8.15	20	68.2	14.5	5.6
8	10	23.55	8.8	15.1	52	10.2	8.26
2	11	23.99	7.63	12.26	41	12	4.46
9	12	23.55	8.15	17.5	62.9	14.8	6
5	13	23	8.15	7.9	52.6	15.13	5.2

182

183 **Table 5. ANOVA for Quadratic model for Heterotrophic Bacteria count**

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	155.68	5	31.14	10.57	0.0037	Significant
A-Rainy Season	5.37	1	5.37	1.82	0.2190	
B-pH	17.93	1	17.93	6.09	0.0430	
AB	3.17	1	3.17	1.08	0.3341	
A²	102.87	1	102.87	34.93	0.0006	
B²	24.39	1	24.39	8.28	0.0237	
Residual	20.62	7	2.95			
Lack of Fit	16.92	3	5.64	6.10	0.0567	not significant
Pure Error	3.70	4	0.9250			
Cor Total	176.30	12				
Fit Statistics						
Std. dev	Mean	C.V(%)	R²	Adjusted R²	Predicted R²	Adeq. Precision
1.72	14.63	11.73	0.8831	0.7995	0.6818	8.6674

184 **Table 6. ANOVA for Quadratic model for Heterotrophic Fungal count**

Source	Sum Squares	of	Df	Mean Square	F-value	p-value	
Model	906.07		5	181.21	18.84	0.0006	Significant
A-Rainy Season	45.10		1	45.10	4.69	0.0671	
B-pH	2.72		1	2.72	0.2825	0.6115	
AB	70.56		1	70.56	7.34	0.0303	
A²	545.42		1	545.42	56.71	0.0001	
B²	228.52		1	228.52	23.76	0.0018	
Residual	67.32		7	9.62			
Lack of Fit	47.07		3	15.69	3.10	0.1516	not significant
Pure Error	20.25		4	5.06			
Cor Total	973.39		12				
Fit Statistics							
Std. dev	Mean		C.V(%)	R²	Adjusted R²	Predicted R²	Adeq. Precision
3.10	56.69		5.47	0.9308	0.8814	0.7084	11.6668

185

All microbial models (Bacteria, Fungi, and Yeast) displayed high significance ($p < 0.05$) during both seasons. The model for fungal population demonstrated the most reliability, with the value of R^2 of 0.9308 (rainy season) and 0.9728 (dry season). Adequate precision values were very high, ranging between 6.9 and 18.1, indicating that the signal-to-noise ratio is appropriate for exploring the design space. Furthermore, lack of fit for all was not significant ($p > 0.05$) indicating the model accurate representation of the experimental data.

Table 7. ANOVA for Quadratic model for Yeast count

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	55.00	5	11.00	9.69	0.0048	significant
A-Rainy Season	5.43	1	5.43	4.78	0.0649	
B-pH	0.1038	1	0.1038	0.0914	0.7712	
AB	18.97	1	18.97	16.70	0.0047	
A²	0.9921	1	0.9921	0.8735	0.3811	
B²	29.70	1	29.70	26.15	0.0014	
Residual	7.95	7	1.14			
Lack of Fit	6.01	3	2.00	4.13	0.1021	
Pure Error	1.94	4	0.4850			
Cor Total	62.95	12				
Fit Statistics						
Std. dev	Mean	C.V(%)	R²	Adjusted R²	Predicted R²	Adeq. Precision
1.07	14.03	7.59	0.8730	0.7835	0.5926	9.2761

Table 8. ANOVA for Quadratic model for BOD

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	15.62	5	3.12	4.49	0.0375	Significant
A-Rainy Season	0.3844	1	0.3844	0.5522	0.4816	
B-pH	7.37	1	7.37	10.58	0.0140	
AB	3.53	1	3.53	5.08	0.0589	
A²	4.31	1	4.31	6.20	0.0416	
B²	0.0115	1	0.0115	0.0164	0.9016	
Residual	4.87	7	0.6962			
Lack of Fit	1.17	3	0.3901	0.4214	0.7482	
Pure Error	3.70	4	0.9257			
Cor Total	20.49	12				
Fit Statistics						
Std. dev	Mean	C.V(%)	R²	Adjusted R²	Predicted R²	Adeq. Precision
0.83	6.10	13.67	0.7622	0.5924	0.4221	6.9045

In the rainy season, the variables pH and quadratic temperature (A^2) were found to be significant, with a high R^2 of 0.8831, at $p=0.0430$ and $p=0.0006$ respectively for bacterial count. This implies that there is an optimal temperature beyond which bacterial growth will rapidly increase during the rainy Season. Fungal and yeast growth, on the other hand, are strongly affected by the interaction between pH and temperature (AB, $p=0.0303$; AB, $p=0.0047$) respectively; with their quadratic values. This means that fungi have a certain optimal combination of both pH and temperature in order to multiply successfully. Biochemical Oxygen Demand (BOD) levels, an indication of organic matter contamination, showed a significant model in the rainy season ($p=0.0375$) with pH ($p=0.0140$) and the quadratic value of temperature being the most prominent predictors. This shows that the level of organic matter pollution increased in the rainy seasons, leading to faster microbial growth and subsequent depletion of oxygen.

Conversely, in the dry season, temperature remained a dominant driver displaying a significant quadratic effect on bacterial and fungal populations (bacteria $p = 0.0011$, fungi $p < 0.0001$). It is noteworthy that the model for fungi revealed an extraordinary fit level ($R^2 = 0.9728$), indicating that as the concentration of the waterfall ecosystem increases due to decreased flow, the effect of temperature fluctuations becomes more significant. On the other hand, in the case of yeast count, the importance of pH as a linear driving factor was established ($p = 0.0009$). This implies that either the acidity or alkalinity of the water is possibly affected by the concentrated anthropogenic runoff during the dry season and limits yeast proliferation. The BOD model (Table 13) transformed into a linear one ($R^2 = 0.6119$), whereby temperature ($p = 0.0112$) and pH ($p = 0.0326$) exerted direct and significant linear effects.

Figure 1 and 3 show the diagnostic plots (predicted vs. Actual plots), of the rainy and dry seasons respectively. The data points are located near the 45 °C line, which implies: 1) Model predictions fit well with the experimental data; and 2) there were no special patterns or outliers observed, which can be interpreted that errors are normally distributed and model is not biased. From the 3D response surfaces plots, it can visually be confirmed that seasonal responses: For the rainy Season (Figure 2) microbial count surfaces were generally "convex" or "mountain like" and show their maxima at an intermediate range of temperature and pH values (around 23.5C and pH 8.1); and also, for the dry season (Figure 4) bacteria and fungi surfaces were still curved (quadratic) and the BOD plot (Figure 4d) was a flat slanting plane showing a switch to linear modeling with a continuously rising slope over temperature and pH. The RSM analysis quantify successfully that while pH offers a steady linear effect, the quadratic effect of temperature became a decisive threshold-defining factor for microbial ecosystem in the pristine waterfall. The shift in modeling from quadratic (Rainy) to linear (Dry) for BOD additionally highlights the influence of seasonal runoff on the metabolic intricacy of the aquatic system. These observations are vital for predicting how tropical and sub-tropical freshwater ecosystems will respond to future climate-driven chemical and thermal shifts.

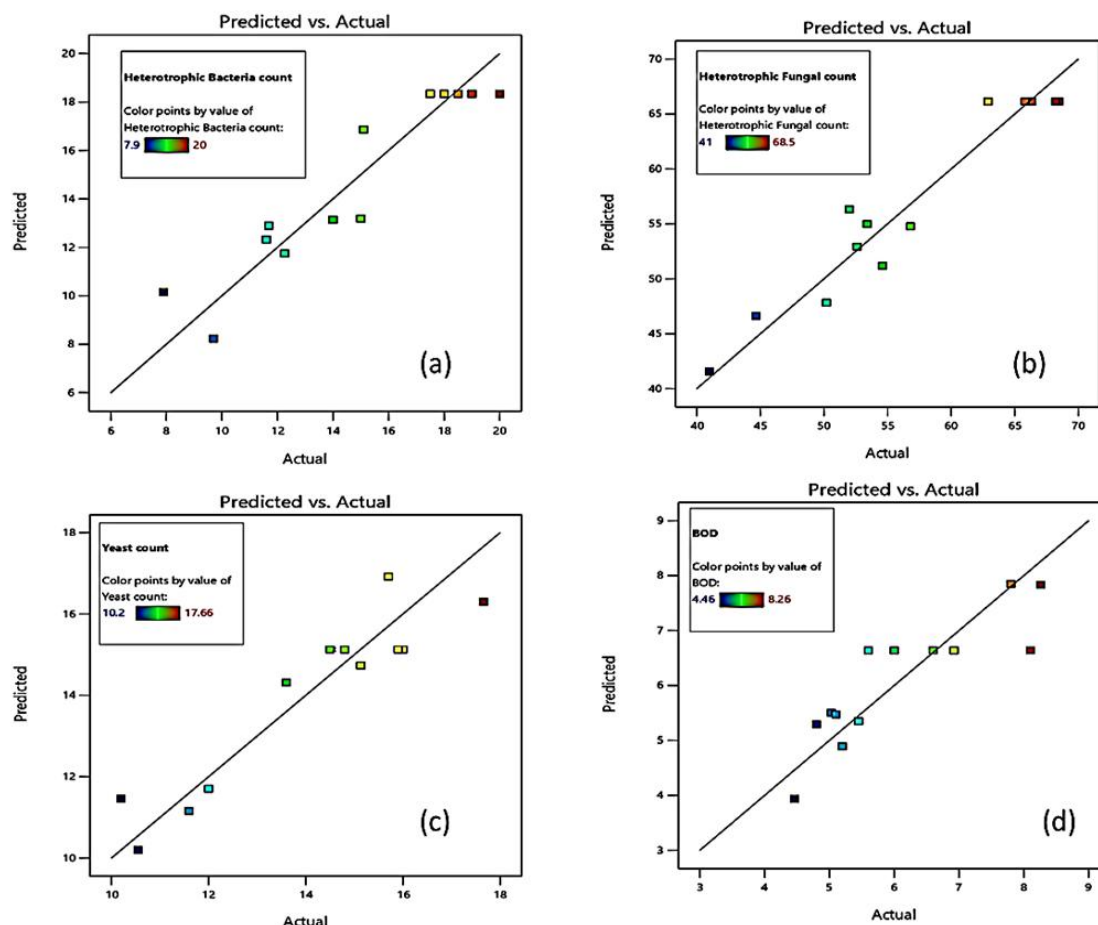


Figure 1: Predicted Vs actual yield of (a) Bacteria count (b) Fungal count (c) Yeast count (d) BOD in Rainy Season shift

The BOD levels determined in this study serve as a pointer of organic pollution. High levels of organic matter, driven by seasonal runoff and anthropological activity, reduce water quality thereby leading to an environment that encourage high concentrations of pathogens.

Results obtained from pristine waterfall align with and expand upon previously documented literature studies of tropical freshwater environment. Through comparison of the results with current findings, the implication of the seasonal fluctuations and pathogens menace have been recognized.

The microbial load was significantly increased seasonally as shown in this research and is similar with the research of Omoregie et al. (2025) in Ikpoba Okha Local Government Area of Edo state, Nigeria. The research established that waterborne pathogens were mainly induced by runoff which is correlated with rainy season. Contrary to the work of Omoregie et al. (2025) in which indicators of pollution are derived descriptively, in this work RSM proves that microbial load is not simply a

function of presence of seasons but a quadratic response to thermal and acidic/alkaline fluctuations simultaneously presents in water bodies. Daramola et al. (2019) worked on the Landzun Stream in Bida, Niger State is a great comparative background study to the Pristine waterfall in Abuja, where both of these studies investigated tropical Nigerian water bodies affected by seasonal variability however, each study identified different pollutant sources and health hazards. While Daramola et al. (2019) used Water Quality Index (WQI) and multivariate analysis (PCA/Cluster Analysis) to determine that during dry season there is an increased number of dissolved solids and metal levels attributing it to evaporation/concentration, thus increasing the non-carcinogenic risk from metal consumption. In this study, RSM identified increased microbial loads and greater BOD variability in Rainy Season from surface run-off that could lead to greater bacterial pathogenesis risk.

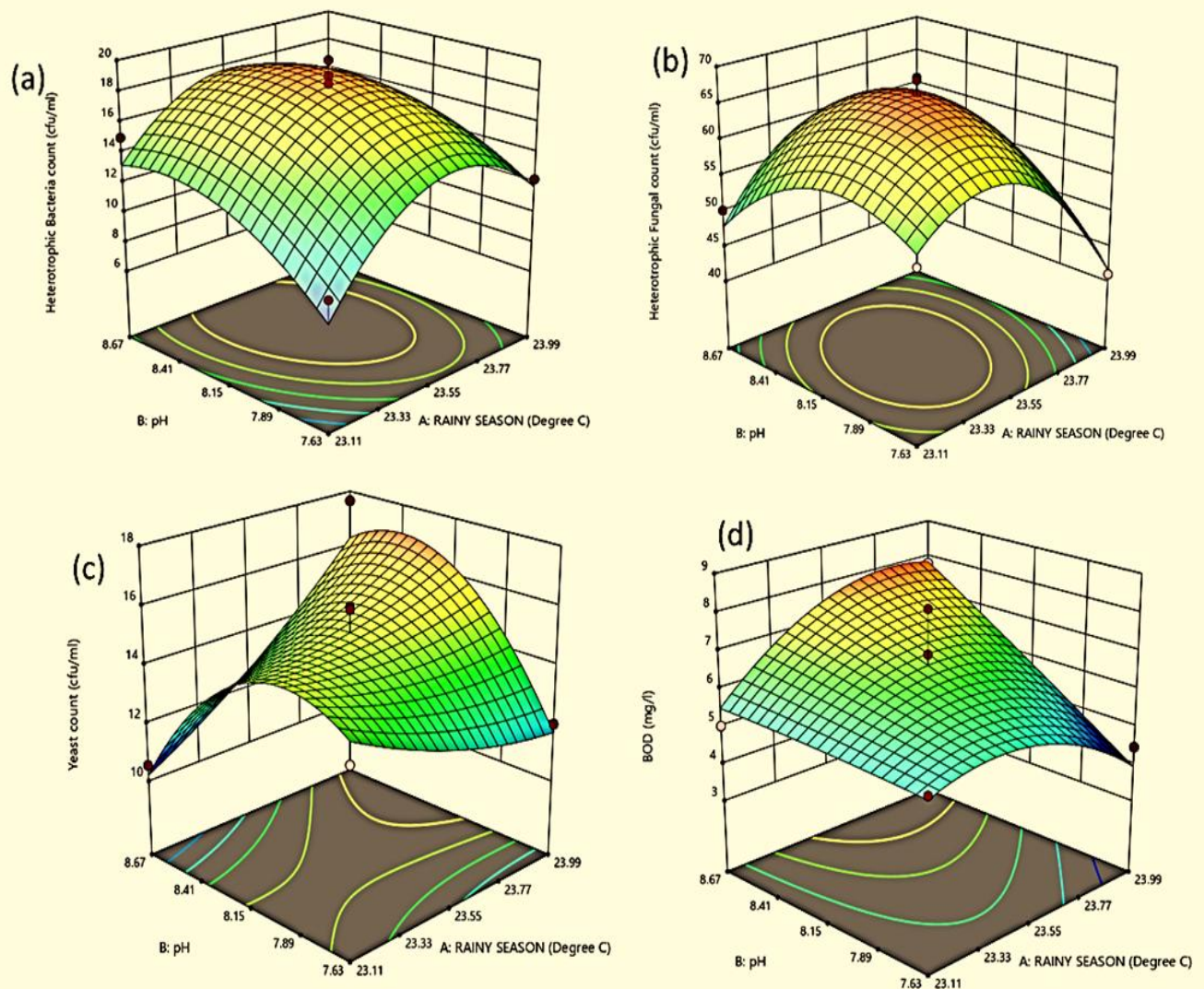


Figure 2: 3D Response Surface Plots of (a) Bacteria count (b) Fungal count (c) Yeast count (d) BOD in Rainy Season shift.

Table 9: Experimental Design for Dry Season shift

		Factor 1	Factor 2	Response 1	Response 2	Response 3	Response 4
Std	Run	A: Temperature (Dry Season) °C	B: Ph	Heterotrophic Bacteria count cfu/ml	Heterotrophic Fungal count cfu/ml	Yeast count cfu/ml	BOD mg/l
5	1	24.23	7	6.01	38	4.1	7.96
9	2	25.415	7	8.5	53.2	7	6.1
1	3	24.7379	6.14286	6.06	43.56	4	5.5
8	4	25.415	8.5	8.97	54.69	8.9	8.73
10	5	25.415	7	9.6	52.8	6.5	6.7
3	6	24.7379	7.85714	6.3	50.55	6.3	6.4
7	7	25.415	5.5	5.98	40	1.63	3.68
2	8	26.0921	6.14286	7	36.66	2.4	5
4	9	26.0921	7.85714	8.5	56	5	3.9
12	10	25.415	7	9.6	54.1	7.5	6.5
6	11	26.6	7	6.4	34.67	2.4	3.5
11	12	25.415	7	9.4	52.5	8	7.1
13	13	25.415	7	9	55.1	5.5	5.4

Table 10. ANOVA for Quadratic model for Heterotrophic Bacteria count

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	23.52	5	4.70	8.90	0.0061	significant
A-Dry Season	1.44	1	1.44	2.73	0.1425	
B-pH	4.80	1	4.80	9.08	0.0196	
AB	0.3969	1	0.3969	0.7507	0.4150	
A²	15.01	1	15.01	28.40	0.0011	
B²	5.43	1	5.43	10.28	0.0149	
Residual	3.70	7	0.5287			not significant
Lack of Fit	2.81	3	0.9377	4.22	0.0989	
Pure Error	0.8880	4	0.2220			
Cor Total	27.22	12				
Fit Statistics						
Std. dev	Mean	C.V(%)	R²	Adjusted R²	Predicted R²	Adeq. Precision
0.7271	7.79	9.33	0.8640	0.7669	0.5536	7.79

In a review by James and Joyce (2004), the authors emphasized that effective management of watershed contaminants must be shifted from static monitoring to dynamic multi-parameters modeling, to obtain a holistic view of the contaminants. In the similar manner, Agbasi et al. (2023) claim that seasonality of climatic changes is still the leading cause for degradation of water quality in Nigeria, noting great lack of predictive model in literature; in this regard, this study employs a response surface methodology (RSM) approach for developing a quadratic model to explore the dynamic and non-linear interplay of hydro-climatic parameters for microbial proliferation in pristine waterfall ecosystem. The discovery of the precise threshold values for bacterial and fungal

growth in this study ($p < 0.05$) is the fine-scale data required to apply the site-specific 'Best Management Practices' prescribed by James & Joyce (2004).

Table 11. ANOVA for Quadratic model for Heterotrophic Fungal count

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	742.09	5	148.42	50.06	< 0.0001	Significant
A-Dry Season	5.23	1	5.23	1.76	0.2257	
B-pH	267.45	1	267.45	90.21	< 0.0001	
AB	38.13	1	38.13	12.86	0.0089	
A²	427.45	1	427.45	144.18	< 0.0001	
B²	53.18	1	53.18	17.94	0.0039	not significant
Residual	20.75	7	2.96			
Lack of Fit	16.26	3	5.42	4.83	0.0812	
Pure Error	4.49	4	1.12			
Cor Total	762.84	12				
Fit Statistics						
Std. dev	Mean	C.V(%)	R²	Adjusted R²	Predicted R²	Adeq. Precision
1.72	47.83	3.60	0.9728	0.9528	0.8170	18.1966

A number of studies carried out by Laniyan et al. (2025) in Osun River Basin and its environs show that variability in climate is a dominant driver of changes in Nigerian surface water quality during the seasons. Though Laniyan et al. (2025) work identifies spatial-temporal degradation of water quality attributed to precipitation cycle in Nigeria. This study takes a step further by employing RSM to predict the specific thresholds under which Yersinia, and Salmonella have suitable conditions for rapid growth in the Pristine Waterfall in Abuja, while ANOVA indicates seasonal microbial bloom as noted by Laniyan et al. (2025) which are sustained not only by conveyance but also the synergistic quadratic relationship between temperature and pH values.

Table 12. ANOVA for Quadratic model for Yeast count

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	56.89	5	11.38	11.26	0.0030	significant
A-Dry Season	3.41	1	3.41	3.38	0.1088	
B-pH	30.67	1	30.67	30.37	0.0009	
AB	0.0225	1	0.0225	0.0223	0.8856	
A²	21.73	1	21.73	21.51	0.0024	
B²	4.89	1	4.89	4.84	0.0636	not significant
Residual	7.07	7	1.01			
Lack of Fit	3.37	3	1.12	1.21	0.4125	
Pure Error	3.70	4	0.9250			
Cor Total	63.96	12				
Fit Statistics						
Std. dev	Mean	C.V(%)	R²	Adjusted R²	Predicted R²	Adeq. Precision

1.01	5.33	18.87	0.8895	0.8105	0.6545	8.9220
------	------	-------	--------	--------	--------	--------

Table 13. ANOVA for Linear model for BOD

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	18.90	2	9.45	7.88	0.0088	Significant
A-Dry Season	11.53	1	11.53	9.62	0.0112	
B-pH	7.37	1	7.37	6.15	0.0326	
Residual	11.99	10	1.20			not significant
Lack of Fit	10.32	6	1.72	4.11	0.0962	
Pure Error	1.67	4	0.4180			
Cor Total	30.89	12				
Fit Statistics						
Std. dev	Mean	C.V(%)	R ²	Adjusted R ²	Predicted R ²	Adeq. Precision
1.09	5.88	18.61	0.6119	0.5343	0.3691	7.3018

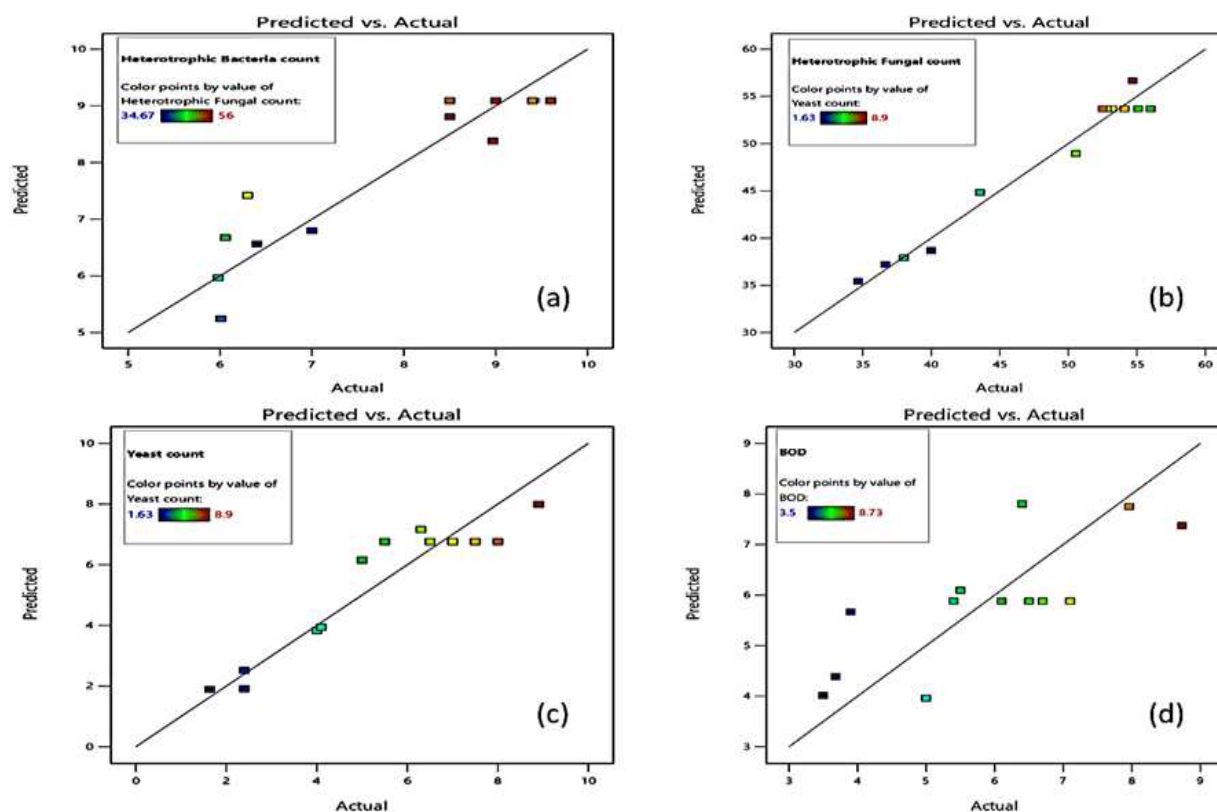


Figure 3: Predicted Vs actual yield of (a) Bacteria count (b) Fungal count (c) Yeast count (d) BOD in Dry Season shift

The modes of contamination observed in the Pristine Waterfall are consistent with the latest approach by Aleruchi et al. (2025), which showed distinct microbial signature of urban and agricultural runoffs. Aleruchi et al. (2025) found that agricultural input significantly raised zoonotic pathogen concentration during high rainfall period; and this study measured this threat with quadratic modeling. The result of ANOVA for rainy season in this study shows that survival and proliferation of these introduced pathogens is highly governed by combined interaction between temperature and pH ($p < 0.05$), indicating that 'pathogen load' reported by Aleruchi et al. (2025) is guided by specific optimum conditions. Even though the seasonal change observed in the Pristine Waterfall is similar to the nationally occurring pattern reported by Agbasi et al. (2023) and Laniyan et al. (2025), this study reported mathematical evidence to demonstrate these changes with quadratic interactions. From observation to optimization with RSM provided a more rigorous scientific insight to save the lotic pristine habitats from constant assault by agricultural runoffs and changing climate. A detailed review in comparison to latest research papers has been provided in Table 14.

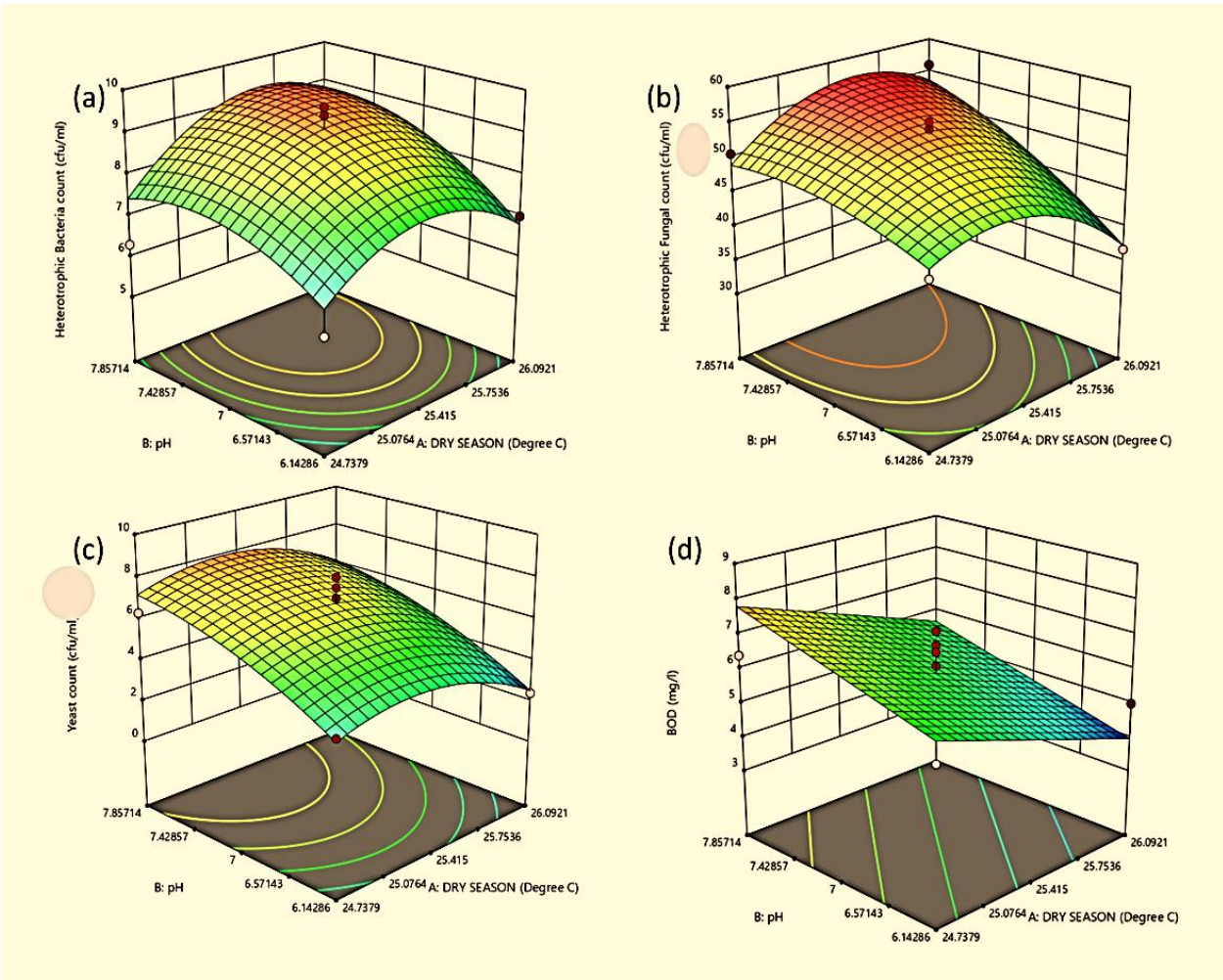


Figure 4: 3D Response Surface Plots of (a) Bacteria count (b) Fungal count (c) Yeast count (d) BOD in Dry Season shift

307

308 The identification of *Salmonella* and *Yersinia* (frequently associated with gastrointestinal
 309 infections), *Staphylococcus* (traced to wide range of skin infections) and *Pseudomonas*, (an
 310 opportunistic pathogen that weakens the immune system) in the Pristine waterfall is an important
 311 finding that challenges the "pristine" ecosystem. Therefore, stringer measures should be applied to
 312 by the Government to mitigate the effects of these pathogens on the health of the flora and fauna
 313 within the ecosystem. Such measures include; regular water quality surveillance, regulation
 314 mitigating agricultural activities around the waterfall, community awareness programs that
 315 emphasize link between human wellness and environmental sanitation. In addition, where
 316 communities depend on the waterfall for basic consumption, point-of-use treatment is highly
 317 recommended to ensure public health safety.

318

319 **Table 14: Comparative Analysis of Seasonal Microbial Dynamics and Environmental Risks**

Author & Study Area	Methodology & Modeling	Key Findings	Comparison with Current Study
Current Study (2026) <i>(Pristine Waterfall, Abuja)</i>	RSM (CCRD); Quadratic modeling of Temp/pH interactions.	Significant quadratic responses (A^2 , B^2) for Bacteria and Fungi. BOD dynamics shift from quadratic (Rainy) to linear (Dry).	Baseline: Identifies non-linear "optimization thresholds" for pathogens that traditional linear studies overlook.
Aleruchi et al. (2025) <i>(Rivers State)</i>	Comparative analysis of Urban vs. Agricultural runoff.	Agricultural runoff significantly elevates zoonotic pathogens (Enterobacteriaceae) during peak rains.	Supports the finding of <i>Salmonella</i> and <i>Staphylococcus</i> in the Pristine waterfall as results of agricultural encroachment.
Laniyan et al. (2025) <i>(Osun River Basin)</i>	Spatial-temporal WQI and climate variability assessment.	Water quality degrades during seasonal transitions due to "first-flush" pollution events.	Laniyan defines the "when" (transition periods); our RSM models define the "how" (the exact Temp/pH niche that sustains the flush).
Agbasi et al. (2023) <i>(Southeastern Nigeria)</i>	Critical Review of regional seasonal trends.	Noted a major data gap in predictive modeling; highlights national trends of fecal contamination.	This study fills the gap identified by Agbasi by providing the mathematical framework (RSM) for future predictive monitoring.
Omoriegie et al. (2025) <i>(Ikpoba Okha LGA)</i>	"Contamination to Prevention" framework; descriptive statistics.	Identified septic seepage and flood runoff as primary rainy season risks.	Extends Omoriegie's prevention strategy by using 3D surface plots to visualize "safe vs. risk" environmental zones.
Daramola et al. (2019) <i>(Landzun Stream, Bida)</i>	Multivariate states and Water Quality Index (WQI).	Dry season concentration effect leads to higher mineral/metal toxicity risks.	Both studies show North-Central risks, but our work shows biological risk peaks in the wet season.

James & Joyce (2004) <i>(Global Review)</i>	Watershed-scale management and Critical Source Areas (CSAs).	Advocates for multi-parameter modeling to replace "one-off" static sampling.	Our study applies James & Joyce's theoretical CSA concept by empirically identifying the "Chemical Stress CSA" in the dry season.
---	--	--	---

Conclusion.

The findings obtained from this study highlighted the importance of seasons in determining both the physicochemical parameters and the microbial community structure of the pristine waterfall stream in Abuja. Despite having acceptable physicochemical conditions overall, there were distinct seasonal variations observed, with the water body demonstrating higher levels of conductivity, turbidity, pH, microbial populations, and BOD content during the rainy season. Most likely, the reasons for these increased measurements were more pronounced surface runoff, nutrient, and organic content due to nearby human activities.

The use of Response Surface Methodology made it clear that bacterial growth and BOD in the water body were highly dependent on interactions between temperature and pH parameters. In other words, a quadratic relationship was found for heterotrophic bacteria, fungi, and yeast, which suggests that microbial growth occurs when there are optimal environmental conditions. As to BOD, its linear behavior in the dry season contrasts with its quadratic behavior in the rainy season.

Notably, it has been shown that even in a relatively pristine ecosystem, microbial and environmental alterations due to seasonality and possibly anthropogenic factors occur. Specifically, the increase in microbial abundance in the rainy season raises the probability of waterborne diseases caused by pathogenic microorganisms and makes the water unsafe for human consumption. Overall, the statistical analysis conducted helped create a predictive model that describes seasonal ecological shifts for the investigated area. This model could be applied to monitor water body conditions and develop management practices to maintain sustainable ecosystem operation for tropical freshwater environments similar to that of Abuja, Nigeria.

Data availability

All data used in this study are available on request from the corresponding authors

Contribution

ONF -Conceptualization, supervision, manuscript writing, INH- conceptualization, methodology, manuscript Draft, ACN-Data analysis, manuscript writing and revision, OFA-Data interpretation, Manuscript writing and revision. All coauthors have revised and contributed to the manuscript.

Funding

The authors received no funding for this study, all expenses are out-of-pocket expenses

Ethics declarations

Ethics approval

Not Applicable

Consent to participate

Not Applicable

Competing Interests

The authors declare no financial or non-financial competing interests, including any personal, professional, or family relationships that could have influenced this work.

Clinical trial number

Not Applicable

References

- Agbasi, J. C., Egbueri, J. C., Ayejoto, D. A., Unigwe, C. O., Omeka, M. E., Nwazelibe, V. E., & Fakoya, A. A. (2023). The impact of seasonal changes on the trends of physicochemical, heavy metal and microbial loads in water resources of Southeastern Nigeria: a critical review. *Climate change impacts on Nigeria: environment and sustainable development*, 505-539.
- Akinnawo, S. O. (2023). Interactive effect of anthropogenic activities and seasonal changes on the biophysicochemical properties and heavy metal status of tropical surface water resources. *Scientific African*, 21, e02495. <https://doi.org/10.1016/j.sciaf.2023.e02495>.
- Aleruchi, O., Ogbuleka, N. A. C., Ogbonna, S. I., Robinson, V. K., Ajie, P. C., & Harold, I. (2025). Impact of agricultural and urban runoff on waterborne pathogen contamination. *Eur. J. Sci. Res. Rev*, 2, 104.
- APHA (American Public Health Association) American Water Works Association, & Water Environment Federation. Year: (2020) Standard methods for the examination of water and wastewater (24th ed). American Public Health Association, Washington, DC. 1792.
- Ayejoto, D. A., Egbueri, J. C., Agbasi, J. C., Omeka, M. E., Unigwe, C. O., Nwazelibe, V. E., & Pande, C. B. (2023). Influence of seasonal changes on the quality of water resources in southwestern Nigeria: a review. *Climate change impacts on Nigeria: environment and sustainable development*, 423-447.
- Bernardino, P. N., Brandt, M., De Keersmaecker, W., Fensholt, R., Law, B. E., & Verstraeten, W. W. (2023). Global-scale characterization of turning points in the rainfall–vegetation relationship. *Global Ecology and Biogeography*, 32(9), 1613–1626.
- Daramola, J., Ekhwan, T. M., Adepehin, E. J., Mokhtar, J., Lam, K. C., & Er, A. C. (2019). Seasonal quality variation and environmental risks associated with the consumption of surface water: implication from the Landzun Stream, Bida Nigeria. *Heliyon*, 5(7).
- Huang, Y., Liu, Y., Shang, X., Shi, Y., Wang, D., Wei, Y., & Chen, S. (2024). Seasonal metagenomic survey of pathogenic microorganisms in non-human primates in Mayanghe National

387 Nature Reserve, China. Pathogens, 13(12), Article 1237.
 388 <https://doi.org/10.3390/pathogens13121237>.
 389 James, E., & Joyce, M. (2004). Assessment and management of watershed microbial contaminants.
 390 Critical reviews in environmental science and technology, 34(2), 109-139.
 391 Laniyan, A. B., Olugbenga, O. M., Odjegba, E. E., & Ademeno, W. O. (2025). Seasonal Climate
 392 Variability and Water Quality Dynamics in the Osun River Basin, Southwestern Nigeria.
 393 Journal of Environment, Climate, and Ecology, 2(2), 114-129.
 394 Nigerian Standard for Drinking Water Quality (NSDWQ), Standards Organisation of Nigeria
 395 (SON), 2015.
 396 Omoregie, A. E., Omoregie, A. P., & Okoro, E. O. (2025). Contamination to Prevention:
 397 Addressing Microbial Pollution in Water Sources across Rainy and Dry Seasons in Ikpoba
 398 Okha Local Government Area, Nigeria. Matrix Science Pharma, 9(2), 38-42.
 399 Kumari S. and Ichhpujani R. L., 2000 World Health Organization, Guidelines on Standard
 400 Operating Procedures for Microbiology, Sudarshan Kumari, Ed. Geneva, Switzerland:
 401 WHO, 2020.
 402 Debassi, B., Allaoua, N., Ghanem, N., Hafid, H., Benacherine, M., & Chenchouni, H. (2025).
 403 Assessment of water quality of groundwater, surface water, and wastewater using
 404 physicochemical parameters and microbiological indicators. Science Progress, 108(2),
 405 00368504251348544.

