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Statistical Analysis of Water Quality and Fish Population Dynamics in a Freshwater Lake Ecosystem

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Abstract: *This study investigates the relationship between selected water quality parameters and fish population dynamics in a freshwater lake ecosystem through statistical modelling techniques. Freshwater ecosystems are highly sensitive to physicochemical variations that directly influence aquatic biodiversity and ecological balance. The primary objective was to evaluate how environmental factors affect fish abundance and to demonstrate the utility of statistical tools in ecosystem assessment. Secondary monthly data collected over one year were analysed, including temperature, pH, dissolved oxygen (DO), biological oxygen demand (BOD), nitrate, and phosphate concentrations alongside corresponding fish population counts. Descriptive statistics summarised seasonal variability, Pearson correlation analysis assessed relationships between water quality parameters and fish populations, and multiple linear regression quantified the combined effects of environmental variables. Results revealed a strong positive association between dissolved oxygen and fish count, emphasising the ecological importance of oxygen availability. Conversely, BOD and elevated nutrient concentrations exhibited significant negative relationships with fish abundance, reflecting the impacts of organic pollution and eutrophication. Temperature and pH showed moderate seasonal influences. Overall, the findings highlight the importance of maintaining optimal water quality conditions to sustain freshwater fish populations. The integration of statistical and ecological approaches provides a robust framework for environmental monitoring, ecological assessment, and sustainable water resource management. Seasonal analysis indicated higher fish abundance during cooler months and a decline during summer due to reduced oxygen availability. The regression model showed significant predictive capability in explaining fish population variability. Anthropogenic activities such as runoff and wastewater discharge contributed to water quality degradation.*

Keywords: Water Quality Parameters, Fish Population Dynamics, Correlation Analysis, Multiple Regression, Seasonal Variation, Aquatic Ecosystem Health,

I. INTRODUCTION

Freshwater ecosystems, including lakes, rivers, and reservoirs, represent some of the most productive and ecologically significant natural systems on Earth. They provide essential services such as drinking water supply, fisheries production, irrigation, recreation, and biodiversity conservation. However, these environments are highly sensitive to physicochemical changes that can alter biological communities and disrupt ecosystem functioning. Water quality parameters such as temperature, pH, dissolved oxygen (DO), biological oxygen demand (BOD), and nutrient concentrations (nitrate and phosphate) play critical roles in regulating aquatic life. Fish populations, in particular, serve as reliable bioindicators of ecosystem health due to their sensitivity to environmental fluctuations [6,11].

Dissolved oxygen is widely recognised as a fundamental factor governing fish survival, growth, and reproduction, with reduced oxygen levels often inducing physiological stress and mortality. Organic pollution, measured through BOD, increases microbial respiration and oxygen consumption, thereby limiting oxygen availability [4]. Similarly, excessive nutrient inputs accelerate eutrophication processes, leading to algal blooms and subsequent oxygen depletion during decomposition [2,3]. Temperature and pH further influence fish metabolism, reproductive cycles, and species distribution, where even minor deviations from optimal ranges may adversely affect aquatic biodiversity and ecosystem stability [12].

Despite extensive research on freshwater ecosystems, many studies have primarily focused on individual water quality parameters or short-term observations, while integrated statistical assessments linking seasonal physicochemical variability with fish population dynamics remain comparatively limited. In particular, the combined evaluation of dissolved oxygen, nutrient enrichment, organic pollution, and temperature effects using multivariate statistical approaches is still insufficiently explored in freshwater lake ecosystems. Lake Victoria and its catchment an important study area for fish community observation[10]. Moreover, increasing anthropogenic pressures such as agricultural runoff, urban expansion, and wastewater discharge necessitate comprehensive analytical frameworks capable of identifying key environmental drivers influencing aquatic biodiversity. Therefore, incorporating statistical modelling techniques provides an opportunity to quantitatively understand ecosystem responses and improve predictive ecological assessments, thereby supporting evidence-based conservation and sustainable freshwater resource management. Recent advances in statistical and mathematical modelling have enhanced the analysis of complex ecological systems. Techniques such as descriptive statistics, correlation analysis, and multiple linear regression allow quantification of relationships between environmental variables and biological responses [9]. Given increasing pressures from urbanisation, industrialisation, and agricultural activities, understanding statistical relationships between water quality and fish populations is essential for effective ecosystem management. This study, therefore, aims to analyse these relationships using statistical modelling approaches applied to secondary environmental data, thereby contributing to ecological monitoring and sustainable freshwater resource management [7,13].

II. METHODOLOGY

This study utilised secondary data obtained from publicly available environmental monitoring repositories and previously published freshwater ecosystem assessments. The datasets were derived from peer-reviewed environmental monitoring records to ensure reliability and scientific consistency. Monthly observations covering one year included water temperature (°C), pH, dissolved oxygen (DO), biological oxygen demand (BOD), nitrate (NO_3^-) concentration, phosphate (PO_4^{3-}) concentration, and fish population counts. Data were screened for completeness and compiled into a structured Microsoft Excel database. Since the dataset consisted exclusively of open-access environmental records, ethical approval was not required.

Data quality was verified before analysis. The dataset comprised 12 complete monthly observations; therefore, no missing-value imputation was necessary. Descriptive measures, including mean, median, standard deviation, minimum, and maximum values, were computed to summarise variability. Seasonal grouping was performed as winter (December–February), spring (March–May), summer (June–August), and autumn (September–November), enabling assessment of limnological variability driven by climatic and biological processes. Statistical significance for all analyses was evaluated at a 95% confidence level ($p < 0.05$).

Normality assumptions were evaluated using histogram visualisation and distributional assessment to confirm suitability for parametric statistical analysis. Skewness and kurtosis statistics were additionally calculated to support visual normality assessment. The approximate normal distribution of variables justified the application of parametric statistical methods for subsequent analyses [9].

Correlation Analysis

Pearson product–moment correlation analysis was applied to assess linear relationships between environmental variables and fish population.

r value	Interpretation
0.00–0.19	Very weak

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0.20-0.39	Weak
0.40-0.59	Moderate
0.60-0.79	Strong
0.80-1.00	Very Strong

Table 1: Interpretation scale for Pearson correlation coefficient (r).

Multiple Linear Regression Analysis

A Multiple Linear Regression (MLR) model was developed

$Fish\ Count = \beta_0 + \beta_1(DO) + \beta_2(BOD) + \beta_3(Temperature) + \epsilon$,

where β_0 = intercept, $\beta_1, \beta_2, \beta_3$ = regression coefficients & ϵ = error term.

Parameters were estimated using Ordinary Least Squares (OLS). Model evaluation included the coefficient of determination (R^2), adjusted R^2, and residual diagnostics.

All analyses were conducted using Python, ensuring reproducibility, statistical accuracy, and graphical visualisation capability. Python-based statistical libraries were employed to enhance analytical reproducibility and transparency of the modelling workflow.

Graphical Representation: Graphical representations were used to visually interpret seasonal patterns, statistical relationships, and data distribution characteristics observed in the study.

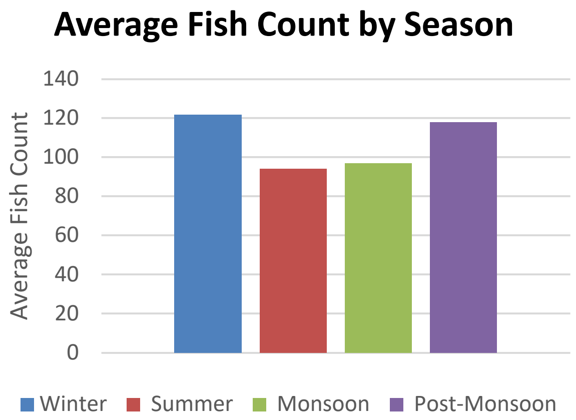

Fig 1: Seasonal variation in fish population density within the lake ecosystem. The bar chart illustrates a peak in fish abundance during the Winter season, with a noticeable decline during the Pre-Monsoon (Summer) period.

Fig-1

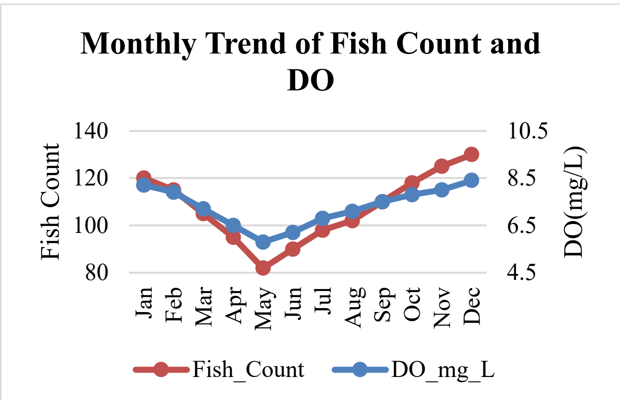

Fig 2: Monthly trends comparing Fish Count and Dissolved Oxygen (DO) levels over one year. The dual-axis plot illustrates a strong synchronised relationship, where fish population peaks during months with higher dissolved oxygen concentrations.

Fig-2

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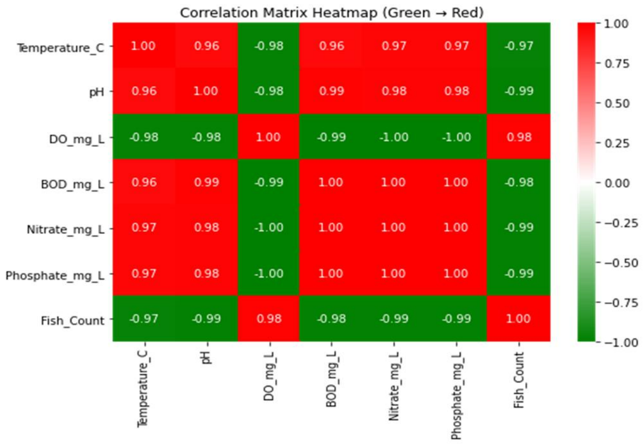

Fig 3: Correlation heatmap illustrating the interrelationships between physicochemical water quality parameters and fish population dynamics. The colour intensity represents the strength of the Pearson correlation coefficient (r), ranging from -1 to +1.

Fig-3

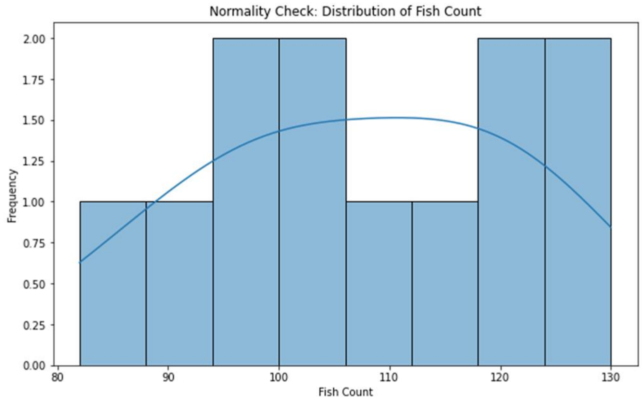

Fig. 4 To ensure the suitability of the data for parametric testing, a normality test was performed. The visual inspection of the Histogram and the values of Skewness and Kurtosis (calculated using Excel) indicated that the data follows a normal distribution, thereby justifying the use of Pearson Correlation and Multiple Linear Regression.

Fig-4

III. RESULTS AND DISCUSSION

Seasonal variability was evident across all physicochemical parameters. Dissolved oxygen levels were consistently higher during cooler months, whereas rising temperatures corresponded with reduced oxygen availability. Elevated BOD and nutrient concentrations were linked to runoff and organic loading events, reflecting anthropogenic influences on water quality. Fish abundance also varied seasonally, with higher populations recorded under favourable oxygen and temperature conditions.

Correlation analysis revealed several key environmental drivers of fish populations. Dissolved oxygen exhibited a strong positive correlation with fish count, confirming its role as a critical determinant of fish abundance [4,5]. In contrast, BOD showed a significant negative correlation, indicating that increased organic pollution adversely affects fish populations. Elevated nitrate and phosphate concentrations were also negatively associated with fish abundance, consistent with eutrophication processes described in [2,3]. Temperature exerted a moderate influence, while pH remained relatively stable near neutral, suggesting minimal impact on fish distribution under current conditions. These findings align with established ecological theory linking water quality degradation to reduced aquatic biodiversity [6,11].

The multiple linear regression analysis further highlighted the significant role of environmental predictors in shaping variability in fish populations. The model demonstrated strong explanatory power and was statistically significant according to the F-test, confirming the collective influence of environmental factors[8]. Dissolved oxygen emerged as a positive and significant determinant, while BOD exerted a negative and significant effect. Temperature showed a moderate influence, suggesting it contributes to variability but is less decisive compared to oxygen-related parameters. Overall, the regression model underscores the importance of water quality indicators in regulating fish populations within freshwater ecosystems [1,9].

Seasonal analysis revealed distinct ecological patterns. Winter conditions, characterised by high dissolved oxygen, supported increased fish abundance. Spring exhibited relatively stable ecological conditions, while summer was marked by elevated temperatures and reduced oxygen availability, leading to population decline. Autumn reflected partial ecological recovery, with gradual improvement in environmental balance following summer stress.

The ecological implications emphasise dissolved oxygen as the dominant driver of fish sustainability. Organic pollution and nutrient enrichment, largely stemming from agricultural runoff and wastewater discharge, were identified as major stressors compromising aquatic health. These findings reinforce the importance of managing anthropogenic impacts on water quality. Moreover, statistical modelling proved highly effective for ecosystem monitoring, offering predictive insights to guide environmental management and conservation strategies [7,13].

Comparison with previous studies shows strong alignment with established ecological research. The results reaffirm earlier work [2,4], which emphasised oxygen availability as a critical determinant of fish survival. Observed eutrophication impacts are consistent with frameworks, while the usefulness of regression modelling corresponds with established methodologies in statistical ecology [9].

Overall, the study highlights dissolved oxygen as the strongest positive driver of fish population growth, while BOD and nutrient enrichment contribute to ecological stress. Seasonal variations in temperature and pH further shaped population dynamics, though their effects were less pronounced compared to oxygen-related parameters. The regression model effectively captured ecological variability, demonstrating its value as a tool for understanding and predicting fish abundance.

IV. CONCLUSION

Water quality parameters play a decisive role in shaping fish population dynamics within freshwater ecosystems. Dissolved oxygen emerged as the most critical factor sustaining aquatic life, while organic pollution and nutrient enrichment negatively impacted ecological stability. By integrating statistical analysis with ecological theory, this research provides a robust framework for environmental monitoring and sustainable freshwater management. These findings support the implementation of pollution control measures and continuous water quality assessment to safeguard aquatic biodiversity. Future research incorporating longer datasets, additional biological indicators, and advanced predictive modelling techniques may further enhance ecosystem management strategies and strengthen conservation efforts.

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