Assessment of Ahmadu Bello University, Zaria Waste Stabilization Pond Efficiency through Principal Component Analysis with R Programming

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Abstract
In this study, the performance of the ABU (Ahmadu Bello University) waste stabilisation pond system was evaluated, with a primary focus on its efficiency of organic loading remover, and the interplay of key physicochemical parameters. Principal Component Analysis (PCA) application reveals strong correlations between BOD and selected parameters, notably turbidity and total suspended solids (TSS), highlighting their significance in water quality dynamics. The findings affirmed the system's effectiveness in organic loading reduction having a removal efficiency of 62.05% and the stability of physicochemical parameters within acceptable limits. Recommendations include measures to control turbidity, manage pH and dissolved oxygen (DO) levels, implement real-time monitoring, and conduct periodic assessments to optimise treatment capacities. Beyond practical applications, the study's impact extends to potential policy implications, environmental conservation, and the dissemination of knowledge in the field of wastewater treatment, contributing to sustainable wastewater management and the safeguarding of aquatic ecosystems.

Keywords: *Principal component analysis, Waste stabilization pond*

1.0 Introduction

Wastewater treatment is a pivotal aspect of environmental management and the preservation of aquatic ecosystems (Hung et al., 2021). One of the primary objectives of wastewater treatment systems is the removal of organic contaminants, such as Biochemical Oxygen Demand (BOD), which plays a critical role in maintaining the health and sustainability of water bodies ("CASE STUDY ON SEWAGE TREATMENT PLANT," 2023). Among the various methods employed for wastewater treatment, waste stabilization ponds have emerged as cost-effective and ecologically sound alternatives (Dos Santos & Van Haandel, 2021).

The ABU (Ahmadu Bello University) waste stabilization pond, situated at $11^{o}09^{1}04.20^{11}$N; $7^{o}39^{1}16.53^{11}$E, stands as a testament to the potential of such systems in addressing the escalating challenges of wastewater treatment. This study embarks on exploring the ABU waste stabilization pond, moving into its capacity to effectively mitigate BOD levels and scrutinizing the dynamics of key water quality parameters throughout the pond treatment stages.

Waste stabilization ponds are regarded for their treatment efficiency and their harmony with natural processes (Alfa et al., 2022). The ABU waste stabilization pond, like many others of its kind, attest to the potential of these ecologically driven systems to mitigate the environmental impact of organic contaminants in wastewater. To apprehend the complexities of wastewater management and the pressing need for its treatment and sustainable water resources management, understanding the intricate workings of waste stabilization ponds becomes paramount.

In this research, we present the analysis of the ABU waste stabilization pond's treatment efficiency with respect to ABU waste Stabilization Pond. The research studies the wastewater treatment system, exploring the transformations that occur as wastewater traverses from the inlet to the facultative and maturation ponds. Additionally, we employ Principal Component Analysis (PCA) to unravel the intricate interplay of water quality parameters and their implications for BOD removal.

The insights garnered from this study are not only instrumental in optimizing the performance of the ABU waste stabilization pond but also offer broader implications for the advancement of sustainable wastewater treatment practices. The research provides a nuanced perspective on the reciprocal relationship between organic contaminants and the natural processes harnessed by waste stabilization ponds.

2. Methods

2.1 Sample Collection

2.2.1 Sampling Sites Selection:

The sample collection site was the ABU waste stabilization pond, whose efficiency in organic loading remover was of concern due to the increase in the pond's hydraulic loading and organic loading. The selected sites include:

1. **Influent Point**: This represents where influent enters the treatment system. Samples were collected at point A, which is the point just after the screens.
2. **Facultative Ponds**: Sampling points were established at the outlet of the pond(B) as shown in Figure 1.
3. **Maturation Ponds**: Sampling locations were strategically placed within the maturation ponds, allowing for the assessment of water quality at the final stages of treatment. The point of sampling at this stage is represented as C in Figure 1.

2.2.2 Sampling Frequency:

The sampling frequency was determined based on magnitude of flow during the Wet and Dry seasons. To determine the seasonal fluctuations and the efficacy of the waste stabilization pond system, a sampling frequency of weekly intervals was recommended for this study.

The Rationale for Sampling Frequency:

1. **Seasonal Fluctuations**: The selection of weekly intervals allows for the capture of variations in water quality. Wastewater characteristics can vary throughout the year, and frequent sampling ensures that these fluctuations are adequately documented.
2. **Operational Conditions**: The sampling frequency aligns with the operational circumstances of the ABU waste stabilization pond system. It enables research to assess the system's performance under different conditions, such as varying influent loads or climatic changes.
3. **Study Objectives**: The chosen sampling frequency aligns with the goals of the study, which include evaluating the efficiency of the treatment system over both the wet and dry seasons. Frequent sampling ensures a detailed assessment of changes in water quality parameters.

Map of the Study Area

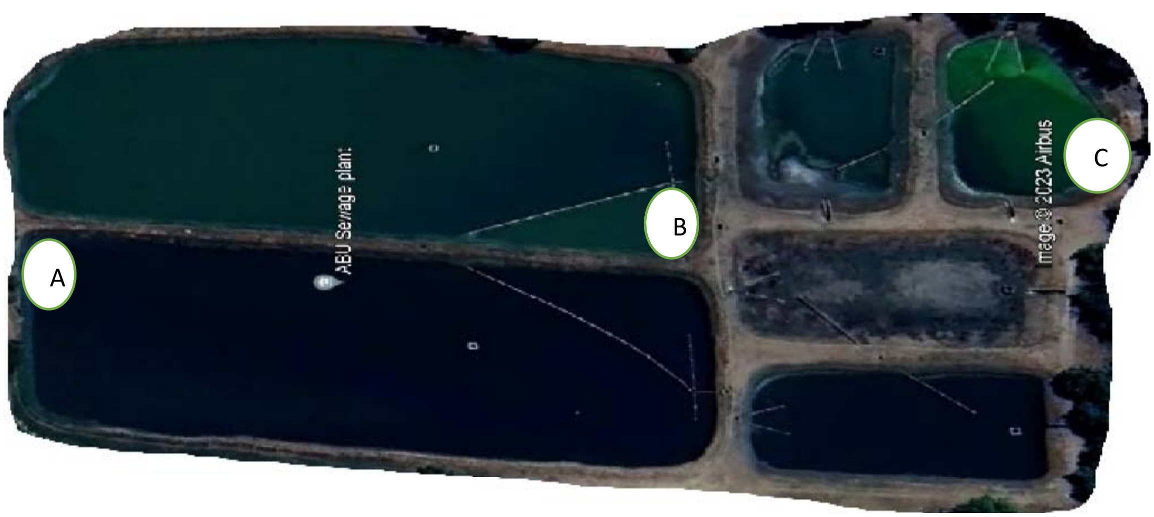


Figure 1: ABU waste stabilization pond (label the pond and show sample collection points)

2.2 Water Quality Parameter Measurements

The samples were taken to the Environmental Laboratory of the Department of Water Resources and Environmental Engineering, ABU, Zaria, and the physiochemical parameters of the samples were measured and recorded.

2.3 Data Analysis

The data analysis for this study involved a multi-step process, combining both descriptive and statistical approaches to assess the performance of the ABU waste stabilization pond and understand the interrelationships between various water quality parameters. The key steps in the data analysis process are detailed below:

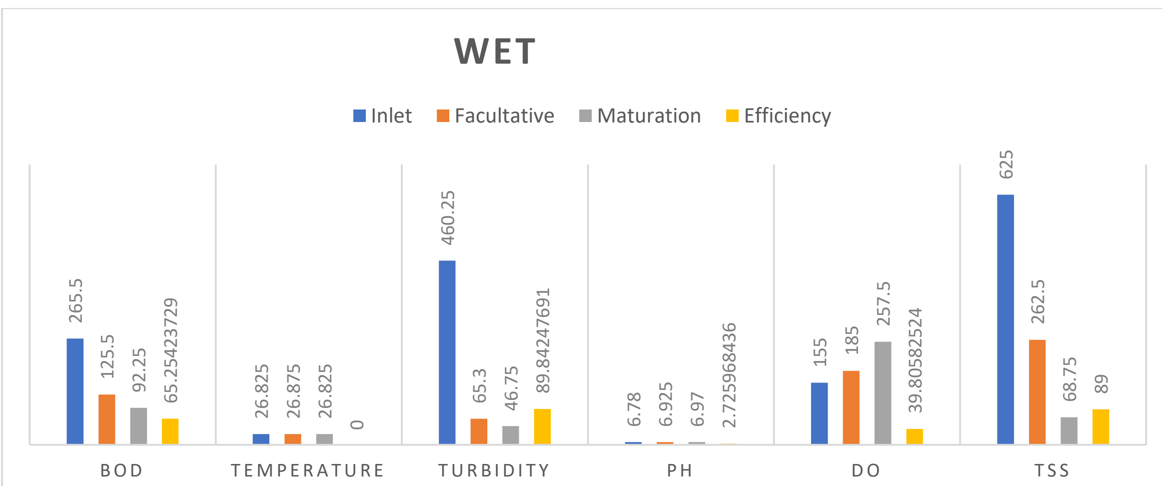
1. Data Collection:
Data on water quality parameters, including Biochemical Oxygen Demand (BOD), temperature, turbidity, pH, dissolved oxygen (DO), and suspended solids (TSS), obtained from the laboratory were used. These measurements were recorded at regular intervals during the dry season and wet season to capture temporal fluctuations in water quality.

2. Data Preprocessing:
Before conducting any analysis, it is essential to preprocess the collected data. This typically involves cleaning, filtering, and organizing the dataset to ensure data accuracy and consistency. Any outliers or missing values were addressed during this phase to prevent potential biases in the analysis.

3. Principal Component Analysis (PCA):
The primary analytical technique employed in this study was Principal Component Analysis (PCA). PCA is a multivariate statistical method that simplifies complex datasets by reducing dimensionality and identifying patterns and correlations among variables. In this context, PCA was applied to the dataset consisting of the various water quality parameters.

3. Results
The findings of this study are as follows:

- **BOD Reduction**: The ABU waste stabilization pond effectively reduced BOD levels from the inlet to the maturation pond, indicating its efficiency in removing organic contaminants. During the wet season, BOD has a removal efficiency of 65.3%, turbidity 89.8%, TSS 89% DO 39%, while during the dry season, BOD has a removal efficiency of 55%, Turbidity=87%, DO=21.2%, and TSS= 78.3%.



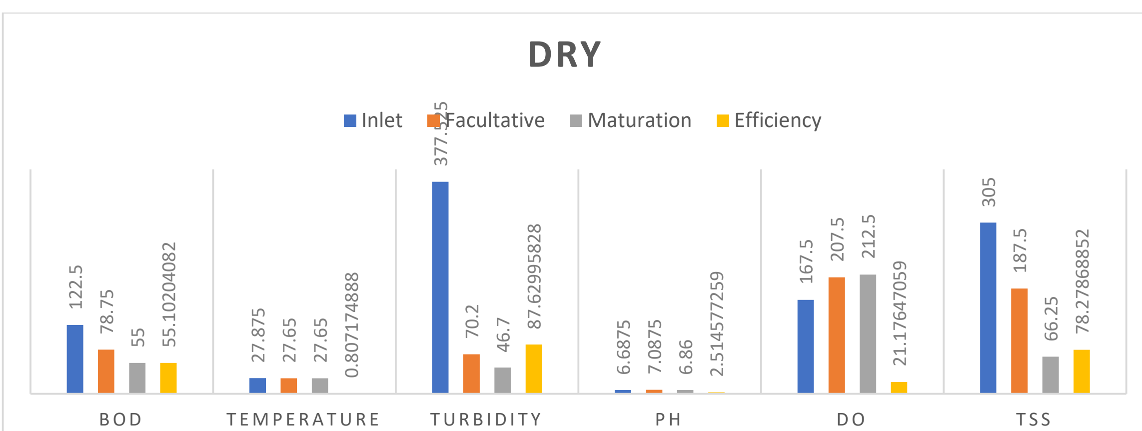


Fig. 2: Results of Physiochemical Tests

- **Stable Physicochemical Parameters**: Physicochemical parameters, such as temperature, turbidity, pH, DO, and TSS, remained relatively stable and within acceptable ranges. This demonstrates favorable conditions for biological processes.
- **PCA Correlations**: PCA analysis identified strong correlations between BOD and certain parameters, particularly turbidity and TSS. This indicated that changes in these parameters were closely related to variations in BOD levels.
- **Significance of PC1**: PC1 explained a substantial portion of the data variance, highlighting the importance of BOD, turbidity, and TSS in influencing water quality dynamics within the pond.

Table 1: Principal Components

	PC1	PC2	PC3	PC4	PC5	PC6
BOD (mg/L)	0.523317	0.268713	-0.02062	-0.19585	-0.56977	0.538994
Temperature (°C)	-0.09183	-0.67146	0.440673	-0.44998	-0.36398	-0.10749
Turbidity (NTU)	0.513632	-0.1376	0.17676	-0.35681	0.718389	0.206426
pH	-0.15878	0.461388	0.859241	0.137509	0.043544	0.05301
DO (mg/L)	-0.32547	0.466883	-0.17601	-0.78264	0.027955	-0.17833
TSS (mg/L)	0.56811	0.164764	0.069733	0.020321	-0.15531	-0.78785

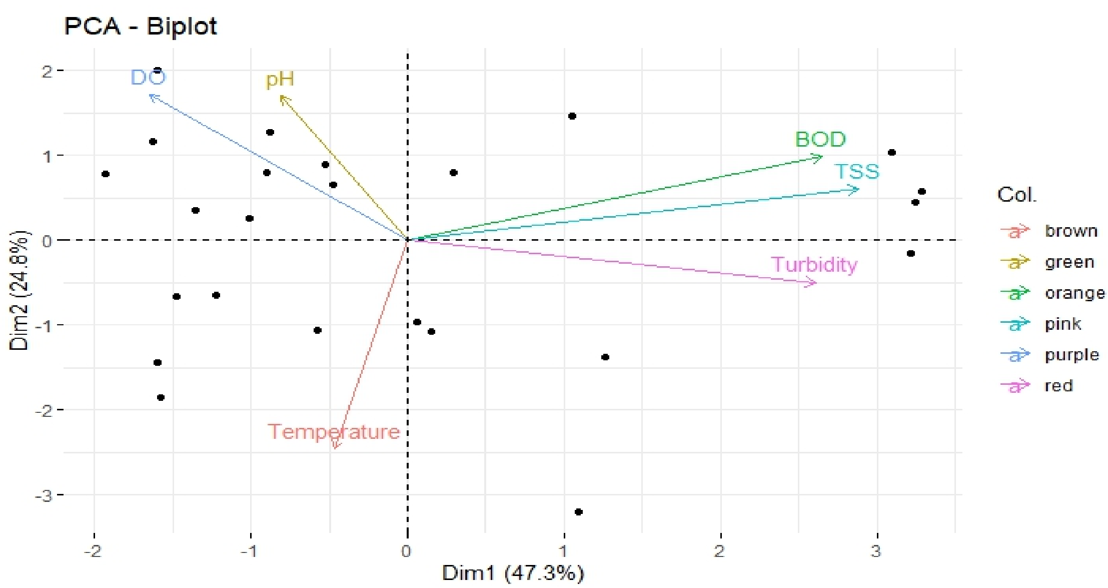


Fig 3: Biplot

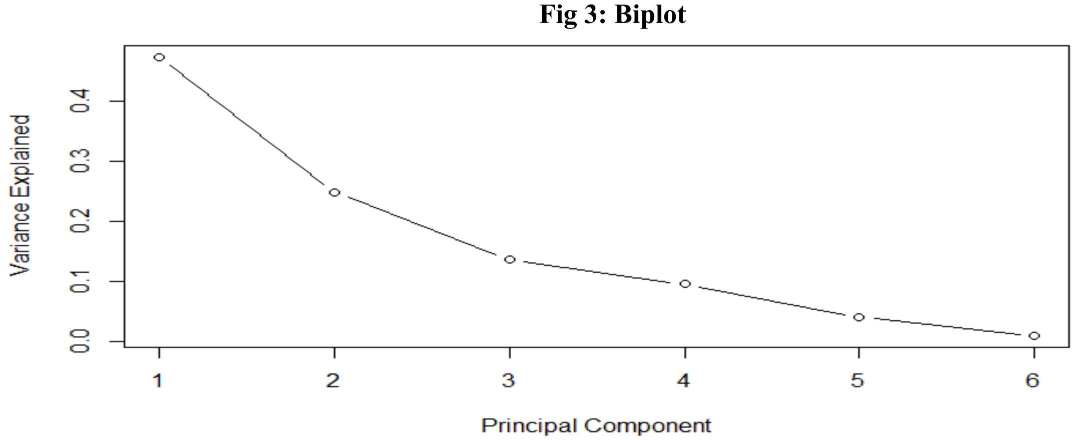


Fig 4: Scree plot

4. Discussion

Implications of the Findings:
The findings of this study have significant implications for wastewater treatment, particularly in the context of the ABU waste stabilization pond system. Elaborating on these implications and comparing them with existing literature, and provide a deeper analysis of the observed correlations:

1. **BOD Reduction and Treatment Efficiency:**
   Implication: The effective reduction of BOD levels from the inlet to the maturation pond signifies the efficiency of the ABU waste stabilization pond in removing organic contaminants. This achievement aligns with the primary goal of wastewater treatment, which is to mitigate the environmental impact of organic pollutants.

   Comparison with Existing Literature: These results are consistent with the broader literature on waste stabilization ponds. Research indicates that well-designed and properly operated stabilization ponds can significantly reduce BOD levels in wastewater, highlighting their effectiveness in organic pollutant removal. (*James*, 1987)

2. **Stable Physicochemical Parameters:**
   Implication: The stable physicochemical parameters, including temperature, turbidity, pH, DO, and TSS, within acceptable ranges, indicate favorable conditions for biological processes within the treatment system. This stability supports the growth of beneficial microorganisms responsible for organic matter degradation.

   Comparison with Existing Literature: The maintenance of stable physicochemical parameters is a critical factor in the success of waste stabilization ponds (Islami et al., 2022). Consistency in these parameters supports the growth of algae and aerobic bacteria, which contribute to organic pollutant removal through photosynthesis and biological degradation (Shetty et al., 2019).

3. **PCA Correlations:**
   Implication: The strong correlations identified between BOD and specific parameters, notably turbidity, and TSS as shown in Fig. 2, emphasize the interconnectedness of these variables. Changes in turbidity and TSS are closely linked to variations in BOD levels, indicating that alterations in these parameters have a direct impact on organic pollutant removal.

   Comparison with Existing Literature: Existing research supports the idea that turbidity and TSS are indicative of the concentration of suspended and particulate organic matter in wastewater. High turbidity and TSS levels can hinder the penetration of sunlight and the activities of microorganisms, potentially reducing the efficiency of waste stabilization ponds in organic matter removal (Munien et al., 2023).

4. **Significance of PC1:**
   Implication: PC1, which explained a substantial portion of the data variance and was strongly associated with BOD, turbidity, and TSS, highlights the primary factors influencing water quality dynamics within the pond. This emphasizes the need to focus on these parameters to optimize the treatment system's performance.

   Comparison with Existing Literature: The dominance of a single principal component, such as PC1, in explaining data variance is not uncommon in PCA studies of water quality. It underscores the importance of specific variables in driving variations in water quality and can guide efforts to enhance treatment system efficiency (Pandit et al., 2023); (Obiri et al., 2021).

Analysis and Significance in Wastewater Treatment:
The observed correlations between BOD, turbidity, and TSS suggest that controlling and optimizing turbidity and TSS levels may lead to more effective BOD reduction in the ABU waste stabilization pond system. Strategies to reduce turbidity and TSS, such as improved sedimentation, settling, or filtration processes, should be explored and implemented.

Furthermore, the study's findings indicate the need for continuous monitoring and management of turbidity and TSS levels in the treatment system. Periodic assessments and adjustments can help maintain stable conditions favorable for biological processes and, subsequently, efficient organic pollutant removal.

The implications of the findings underscore the importance of a holistic approach to wastewater treatment, focusing on not only BOD reduction but also the control of turbidity and TSS levels. These findings align with existing literature and provide valuable insights into optimizing waste stabilization pond systems for enhanced organic pollutant removal and environmental protection.

5. Conclusion

This study provides valuable insights into the performance of the ABU waste stabilization pond in removing organic contaminants, with a specific focus on BOD reduction. The results suggest that the pond is effective in reducing BOD, with strong correlations identified between BOD and parameters like turbidity and TSS. Recommendations for enhancing the treatment process include optimizing facultative and maturation ponds, maintaining stable pH and DO levels, and implementing additional measures to enhance turbidity and TSS removal. Continuous monitoring and periodic assessments will be essential for maintaining the treatment system's effectiveness and protecting the environment.

6. Recommendations (find a way of incorporating these recommendations in your discussion of results)

Based on the findings of this study, several specific recommendations are provided to optimize the wastewater treatment process within the ABU waste stabilization pond system. These recommendations aim to enhance the removal of organic contaminants, particularly Biochemical Oxygen Demand (BOD), and maintain favourable conditions for biological processes:

6.1. Turbidity and TSS Control:

1. **Sedimentation and Clarification:** Implement efficient sedimentation and clarification processes within the treatment system to reduce turbidity and total suspended solids (TSS). This can include the installation of settling tanks or lamella clarifiers to facilitate the removal of particulate matter.
2. **Enhanced Filtration:** Consider incorporating advanced filtration techniques, such as sand filters or microfiltration, to further reduce turbidity and TSS levels before wastewater enters the facultative and maturation ponds.
3. **Regular Maintenance:** Establish a routine maintenance schedule to clean and maintain sedimentation and filtration components. Regular inspections and cleaning will help ensure their continued effectiveness.

6.2. pH and DO Management:

1. **pH Adjustment:** Monitor and adjust pH levels as needed to maintain a stable pH range within the ponds. Control pH using appropriate chemicals or natural methods, such as carbon dioxide injection or algal growth.
2. **Dissolved Oxygen Enhancement:** Promote the oxygenation of wastewater within the ponds by enhancing aeration mechanisms, such as mechanical aerators or surface splashing. Ensure sufficient dissolved oxygen (DO) levels to support aerobic biological processes.

6.3. Monitoring and Data Collection:

1. **Continuous Monitoring:** Implement a real-time monitoring system to continuously track water quality parameters, including BOD, turbidity, pH, DO, and TSS, at key points within the treatment system. This allows for immediate detection of deviations from desired conditions.
2. **Data Analysis and Feedback:** Analyze the real-time data to identify trends and correlations. Use this information to adjust operational parameters and respond proactively to maintain optimal treatment conditions.

6.4. Regular System Evaluation:

1. **Periodic Assessments:** Conduct periodic comprehensive assessments of the waste stabilization pond system's performance. These assessments should include detailed water quality analysis, hydraulic assessments, and biological evaluations.
2. **Capacity Optimization:** Explore opportunities to optimize the capacity of each pond stage based on observed performance and influent load fluctuations. Adjusting pond sizes or the number of parallel units can improve treatment efficiency.

6.5. Research and Development:

1. **Research Initiatives:** Encourage research initiatives to investigate advanced technologies and innovative approaches in wastewater treatment. Stay informed about emerging trends and best practices in pond-based treatment systems.

6.6. Stakeholder Engagement:

1. **Engage Stakeholders:** Foster collaboration and communication with relevant stakeholders, including regulatory agencies, environmental organizations, and local communities. Promote transparency in reporting and compliance with regulatory standards.

6.7. Training and Capacity Building:

1. **Personnel Training:** Provide training and capacity-building programs for operational staff involved in the management and maintenance of the waste stabilization pond system. Ensure they have the necessary skills and knowledge to operate the system effectively.

These recommendations aim to address the specific challenges identified in the study and enhance the ABU waste stabilization pond system's performance in removing organic contaminants and maintaining favorable treatment conditions. Implementing these practical steps will contribute to the continuous improvement of wastewater treatment processes and environmental protection

7. Utilizing the Findings

The findings of this study offer valuable insights that can be applied in practice, potentially impacting policy decisions, and contributing to broader wastewater treatment and environmental conservation efforts:

7.1. Practical Applications:

1. **Enhanced Treatment Efficiency:** Implementing the recommendations outlined in the study, such as controlling turbidity and TSS, optimizing pH and DO levels, and establishing real-time monitoring systems, can lead to improved treatment efficiency within the ABU waste stabilization pond system. These practical applications are critical for meeting regulatory standards and ensuring the treated effluent's environmental safety.
2. **Cost Savings:** By optimizing the capacity of each pond stage based on observed performance and influent load fluctuations, wastewater treatment facilities can potentially reduce operational costs. Efficient pond design and size adjustments can lead to cost savings in terms of maintenance and resource consumption.
3. **Data-Driven Decision-Making:** The use of continuous monitoring and data analysis can enable data-driven decision-making in real time. Treatment plant operators and managers can respond promptly to deviations from desired treatment conditions, reducing the risk of non-compliance with environmental regulations.

7.2. Policy Implications:

1. **Environmental Regulations:** The study's findings may have implications for environmental regulations and policies governing wastewater treatment. Policymakers and regulatory agencies can use the results to inform and update regulations related to water quality standards, treatment system design, and monitoring requirements.
2. **Best Practices:** The study's recommendations can serve as a reference for establishing best practices in wastewater treatment. Policymakers can consider incorporating these best practices into guidelines and regulations to promote consistent and effective wastewater treatment nationwide.

7.3. Broader Impact:

1. **Knowledge Dissemination:** The dissemination of the study's findings through academic publications, conferences, and industry forums can contribute to knowledge dissemination in the field of wastewater treatment. Researchers and professionals in the wastewater industry can learn from the study's methodology and outcomes, potentially leading to further research and innovation.
2. **Technology Transfer:** The findings can serve as a basis for technology transfer to other wastewater treatment facilities facing similar challenges. Lessons learned from the ABU waste stabilization pond system can be applied to various treatment contexts, both regionally and globally, facilitating the adoption of efficient and sustainable practices.
3. **Environmental Conservation:** By improving the performance of the ABU waste stabilization pond system and enhancing the removal of organic contaminants, the study indirectly contributes to environmental conservation. The treated effluent's improved quality reduces the potential environmental impact on receiving water bodies, protecting aquatic ecosystems and public health.
4. **Sustainability:** The study aligns with broader sustainability goals by promoting efficient wastewater treatment practices. Sustainable wastewater management is essential for conserving water resources, reducing pollution, and mitigating the environmental footprint of human activities.

In summary, the findings of this study have practical applications in wastewater treatment, potential policy implications for regulatory agencies, and a broader impact on environmental conservation and sustainability efforts. By implementing the study's recommendations and sharing knowledge with the wider community, the study contributes to the advancement of wastewater treatment practices and the protection of natural ecosystems.

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