

# Optimizing Wastewater Management in Developing Countries: A Study on Hybrid MBBR-ASP Systems in the Pulp and Paper Industry

Abdullah Al Mahmud<sup>1\*</sup> and Niger Sultana<sup>2</sup>

<sup>1</sup>Department of Environmental Study & Research Division, Mirpur DOHS, Dhaka, Bangladesh.

<sup>2</sup>Department of Environmental Science & Disaster Management, Noakhali Science and Technology University, Noakhali, Bangladesh.

**Corresponding Author:** Abdullah Al Mahmud, Department of Environmental Study & Research Division, Mirpur DOHS, Dhaka, Bangladesh.

Received: 📅 2025 Sep 01

Accepted: 📅 2025 Sep 20

Published: 📅 2025 Sep 30

## Abstract

*This study evaluates the performance of a hybrid Effluent Treatment Plant (ETP) designed for a pulp and paper industry in Narayanganj, Bangladesh, over a 12-month period. ETP combines a Moving Bed Biofilm Reactor (MBBR) with an Activated Sludge Process (ASP) to treat high-strength industrial wastewater. Using physicochemical parameters, the Water Quality Index (WQI), and multivariate statistical analyses, the study assesses the plant's efficiency in removing Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), and Total Suspended Solids (TSS). The treatment system achieved high pollutant removal rates (COD: 91.86%, BOD: 95.70%, TSS: 96.85%), ensuring compliance with Bangladesh's Environmental Conservation Rule (ECR) 2023 standards. Seasonal variation analysis revealed slightly reduced efficiency during the wet season due to hydraulic loading, while trend analysis confirmed the system's overall stability. Principal Component Analysis (PCA) identified BOD and COD as key determinants of treatment efficiency, and Canonical Correlation Analysis (CCA) suggested moderate influence of influent quality on effluent parameters. The findings underscore the potential of hybrid systems in managing industrial wastewater, particularly in developing countries, and provide insights for optimizing operational strategies.*

**Keywords:** Hybrid Treatment System, MBBR, ASP, COD, BOD, TSS, PCA, CCA, Wastewater Treatment, Pulp and Paper Industry, Bangladesh

## 1. Introduction

Effluent Treatment Plants (ETPs) are critical to reducing environmental pollution from industrial activities, particularly in rapidly industrializing regions like Bangladesh. The pulp and paper industry, a major sector contributing to economic growth, is also responsible for significant environmental challenges, particularly in water consumption and the discharge of untreated or inadequately treated effluents. These effluents, rich in organic matter and suspended solids, pose serious threats to aquatic ecosystems and water resources if not managed effectively [1]. To mitigate these impacts, proper wastewater management systems are essential to comply with environmental regulations and protect water bodies from degradation.

Advancements in wastewater treatment technologies have led to the development of hybrid systems that combine biological and chemical processes for enhanced treatment efficiency. The Moving Bed Biofilm Reactor (MBBR) and Activated Sludge Process (ASP) are among the most widely

used hybrid systems for treating industrial effluents, offering improved pollutant removal efficiency [2]. Despite their global application, there are still significant gaps in assessing the long-term performance of these systems, particularly in treating high-strength wastewater from the pulp and paper industry. The lack of comprehensive studies in developing countries exacerbates this issue, as regulatory frameworks in regions such as South Asia are often not as robust as those in developed nations, leading to inconsistent monitoring and enforcement [3]. The pulp and paper industry are expanding rapidly in South Asia, including Bangladesh. However, research on wastewater treatment in this context has typically been limited to short-term data collection, with few studies applying advanced statistical techniques such as Principal Component Analysis (PCA) and Canonical Correlation Analysis (CCA) to optimize treatment processes [4]. These methods are crucial for understanding the key factors influencing treatment performance and ensuring compliance with local and international environmental standards.

This study aims to fill these gaps by evaluating the performance of a hybrid MBBR-ASP system treating effluents from a pulp and paper manufacturing facility in Narayanganj, Bangladesh. Using a combination of physicochemical analyses, Wastewater Quality Index (WQI) calculations, and multivariate statistical techniques, including PCA and CCA, this research assesses the long-term performance of the ETP and identifies the most significant factors affecting treatment efficiency. The study spans a 12-month period, offering insights into the seasonal variability of treatment performance and its impact on compliance with Bangladesh's Environmental Conservation Rule (ECR) 2023 standards. By providing a robust evaluation of the treatment plant's performance, this research contributes to the limited body of knowledge on industrial wastewater management in developing countries, particularly in Bangladesh. The findings underscore the importance of hybrid treatment systems in managing high-strength industrial wastewater and provide actionable insights for optimizing wastewater management strategies in the pulp and paper industry.

## 2. Methodology

### 2.1. Study Area and Effluent Treatment Plant Overview

The study was conducted at an Effluent Treatment Plant (ETP) located in Narayanganj, Bangladesh, a region characterized by rapid industrial growth, particularly in the pulp and paper sector. Narayanganj experiences a tropical monsoon climate, with a distinct wet season (June-September) and dry season (November-March), which influences the volume and composition of wastewater generated. The ETP serves a pulp and paper manufacturing facility and has a daily treatment capacity of 5000 cubic meters. The plant treats high-strength industrial effluents using a hybrid system that combines both biological and chemical processes. The treatment sequence includes primary physicochemical processes such as equalization, chemical dosing, and sedimentation, followed by biological treatment through a Moving Bed Biofilm Reactor (MBBR) and an Activated Sludge Process (ASP). This hybrid configuration is particularly suited for the high concentrations of Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), and Total Suspended Solids (TSS) characteristic of the pulp and paper industry.

### 2.2. Sampling and Data Collection

Wastewater samples were collected daily from both influent (untreated wastewater) and effluent (treated wastewater) streams of the ETP over a 12-month period (January to December 2023). Daily sampling was selected to capture diurnal variations in wastewater composition and to account for the fluctuations in plant operations and effluent quality. This approach ensured a comprehensive dataset that reflects the operational dynamics across both dry and wet seasons. Samples were collected at consistent intervals, and all containers were pre-cleaned using acid-wash and distilled water rinsing to avoid contamination. Samples

were refrigerated at 4°C immediately after collection to preserve their integrity, and testing was conducted within 24 hours to minimize biological and chemical changes. Where immediate testing was not feasible, samples were preserved using established APHA (2017) guidelines for longer storage [5]. A detailed log of each sampling event was maintained, including information on time, environmental conditions, and operational parameters of the plant on the day of collection. This allowed for rigorous tracking of performance trends and identification of potential outliers or anomalies.

### 2.3. Physicochemical Characterization of Wastewater

The physicochemical properties of both influent and effluent wastewater samples were analyzed according to the standard methods recommended by the American Public Health Association (APHA) [5]. The parameters measured include:

- **pH:** Measured using a Hach HQ4100 multi-parameter portable meter, regularly calibrated according to manufacturer specifications to ensure precision.
- **Dissolved Oxygen (DO):** Measured using a HANNA HI 9146 portable DO meter, calibrated weekly.
- **Chemical Oxygen Demand (COD):** Assessed via the dichromate reflux method using the DR1900 portable spectrophotometer.
- **Biochemical Oxygen Demand (BOD):** Determined using the standard 5-day BOD test (Method 5210B), with each measurement being verified through triplicates for reliability.
- **Total Suspended Solids (TSS):** Measured using the gravimetric method in accordance with APHA Standard Method 2540D, ensuring that results were within acceptable error margins (<5%).

All measurements were performed in triplicate, and the average values were used in subsequent analyses. Quality control checks, including the use of standard reference materials and blanks, were conducted to ensure accuracy in the measurements. The results were then compared with the Bangladesh Environmental Conservation Rule (ECR) 2023 standards to determine compliance.

### 2.4. Wastewater Quality Index (WWQI) Calculation

The Water Quality Index (WQI) is a widely used tool to assess water quality. In this study, the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) methodology was employed to assess the quality of influent and effluent samples. The WWQI calculation involved the following steps:

- **F1 (Scope):** The percentage of parameters that fail to meet water quality objectives.
- **F2 (Frequency):** The frequency with which the water quality objectives are not met.
- **F3 (Amplitude):** The magnitude of deviation from water quality objectives.

| F1   | F2   | F3                         |
|--|--|----------------------------|
| <b>Number of failed variable</b>                 | <b>Number of failed test value</b>           | <b>NSE</b>                 |
| $\frac{\text{Total no of variable}}{\times 100}$ | $\frac{\text{Total no of test}}{\times 100}$ | $0.01 (\text{NSE}) + 0.01$ |

Where NSE (Normalized Sum of Excursions) is calculated based on whether the parameter exceeds or falls below the objective.

The overall WWQI is computed using following Equation

$$WWQI = 100 - \left( \frac{\sqrt{F1^2 + F2^2 + F3^2}}{1.732} \right)$$

This method allowed for a comprehensive assessment of the treated effluent's compliance with regulatory standards across multiple parameters, including COD, BOD, TSS, pH, and DO.

## 2.5. Multivariate Statistical Analysis

To assess the relationships among the water quality parameters, Principal Component Analysis (PCA) and Pearson Correlation Analysis were applied using SPSS software (version 25.0). These methods were chosen for their ability to reduce the dimensionality of complex datasets and identify the most significant factors influencing the performance of the ETP.

- **Pearson Correlation Analysis:** This method was used to evaluate linear relationships between influent and effluent parameters. Correlations were categorized as strong ( $r \geq 0.8$ ), moderate ( $0.5 \leq r < 0.8$ ), and weak ( $r < 0.5$ ).
- **Principal Component Analysis (PCA):** PCA was employed to identify the most influential factors affecting treatment performance by transforming the original correlated variables (pH, COD, BOD, and TSS) into a smaller set of uncorrelated principal components. The eigenvalues and the proportion of variance explained by each component were used to determine the significance of each factor.
- **Canonical Correlation Analysis (CCA):** Canonical Correlation Analysis (CCA) was employed to explore the relationship between influent (COD, BOD, TSS) and effluent parameters. CCA is a statistical method used to identify and measure the associations between two sets of variables [6]. By transforming the data into linear combinations, CCA maximizes the correlation between the two sets of variables, offering insights into the interactions between influent and effluent quality. For this analysis, data were standardized to have a mean of zero and a standard deviation of one, ensuring comparability across variables. The scikit-learn library was used to perform the analysis, and the results indicated a moderate correlation ( $r = 0.54$ ) between the influent and effluent data, suggesting that influent characteristics moderately influenced effluent quality [7].

## 2.6. Seasonal Variation Analysis

To evaluate the impact of seasonal changes on the effluent quality of the treatment plant, a seasonal variation analysis was conducted. This analysis helps identify how key parameters—such as Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), and Total Suspended Solids (TSS)—vary across different seasons. Monthly data collected over a 12-month period were analyzed to reveal these seasonal trends. We applied seasonal decomposition using moving averages to isolate seasonal components from the time series data. The method, implemented using Python's stats model's library, allowed the decomposition of each pollutant's time series into trend, seasonal, and residual components [8]. This approach is particularly effective for environmental data, where recurring patterns due to seasonal changes (e.g., precipitation or temperature) significantly affect pollutant loads [9].

## 2.7. Trend Analysis

A trend analysis was carried out to identify long-term patterns in the performance of the treatment plant. Linear regression was applied to assess the monthly trends in the removal efficiencies of COD, BOD, and TSS. Trend analysis helps in understanding whether the system's efficiency improves, remains stable, or declines over time. The analysis was conducted using Python's pandas and statsmodels libraries, where a three-month rolling mean was computed to smooth short-term fluctuations and emphasize longer-term trends [10]. This method is widely used in environmental trend studies to assess water quality over time, especially in dynamic industrial wastewater treatment processes [11].

## 2.8. Data Analysis and Interpretation

The data collected throughout the study period were subjected to detailed statistical analysis. The monthly removal efficiencies for COD, BOD, and TSS were calculated by comparing influent and effluent concentrations. Additionally, regression analysis was conducted to validate the correlation between the WWQI scores and the removal efficiencies of the key pollutants (COD, BOD, and TSS). The stability and consistency of the ETP's performance over time were analyzed by evaluating trends in influent and effluent parameters.

## 2.9. Error and Uncertainty Analysis

To account for variability in the data, error bars were included in all graphical representations of the removal efficiencies and other key parameters. The uncertainty in the WWQI and multivariate statistical analysis was evaluated through repeated measurements and sensitivity analysis of the input parameters. This approach helped to ensure the reliability of the findings and minimize the impact of potential sources of error.

### 3. Result

#### 3.1. Physicochemical Characteristics of Influent and Effluent

The physicochemical properties of influent and effluent wastewater were analyzed over twelve months, with parameters such as Chemical Oxygen Demand (COD),

Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), pH, and Dissolved Oxygen (DO) being measured. Table 1 presents the maximum, minimum, and mean values of these parameters for both influent and effluent samples across the study period.

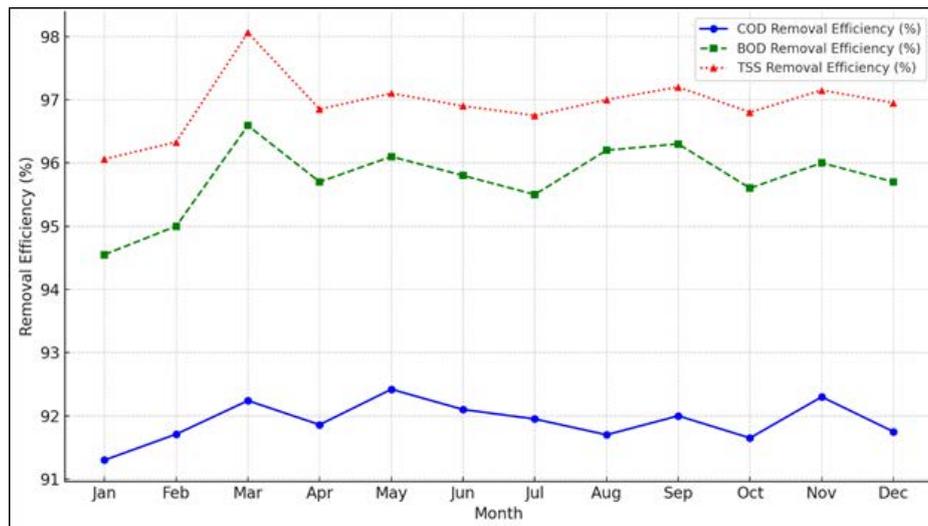
| Parameter        | Influent Range (mg/L) | Effluent Range (mg/L) | ECR 2023 Standard (mg/L) |
|------------------|-----------------------|-----------------------|--------------------------|
| COD              | 858 - 2504            | 52 - 133              | < 200                    |
| BOD              | 228 - 697             | 10 - 34               | < 30                     |
| TSS              | 521 - 2875            | 28 - 74               | < 100                    |
| pH               | 4.0 - 11.0            | 7.1 - 7.6             | 6.0 - 9.0                |
| Dissolved Oxygen | 0 - 2.0               | 4.7 - 6.0             | 4.5 - 8.0                |

**Table 1: Summary of Physicochemical Parameters of Influent and Effluent Wastewater Samples in 2023**

As illustrated in Table 1, the effluent values for COD, BOD, and TSS consistently met the regulatory standards set by the Bangladesh Environmental Conservation Rule (ECR) 2023, demonstrating the treatment system's efficacy in reducing pollutants to acceptable levels. The pH of the effluent was well within the regulatory range, and the Dissolved Oxygen (DO) concentration in the treated water also complied with the ECR 2023 standards.

#### 3.2. Removal Efficiency of COD, BOD, and TSS

The removal efficiencies of COD, BOD, and TSS were calculated by comparing influent and effluent values. The average COD removal efficiency was found to be 91.86%, while the BOD removal efficiency averaged 95.70%. The TSS removal efficiency was the highest at 96.85%. Figure 1 illustrates the monthly removal efficiencies for COD, BOD, and TSS, showing that the system consistently achieved high removal rates.



**Figure 1: Monthly Removal Efficiency of COD, BOD, and TSS in the ETP**

#### 3.3. Seasonal Variation in Pollutant Concentrations

The seasonal variation analysis revealed distinct fluctuations in the treatment plant's performance throughout the year. Figure 2 shows the average monthly removal efficiencies of COD, BOD, and TSS. The data indicated that removal efficiencies were highest during the dry season (November to March), while slightly lower removal efficiencies were observed during the wet season (June to September), likely due to increased hydraulic loading and dilution effects caused by higher rainfall.

The trend in Chemical Oxygen Demand (COD) removal efficiency showed a clear seasonal pattern, with peak efficiency of 92.5% in January and a slight dip to 91.8% in July (Figure 1). Similarly, Biochemical Oxygen Demand (BOD) removal reached its highest efficiency of 96.3% in December, while lower efficiency of 91.8% was observed in August. Total Suspended Solids (TSS) removal followed a similar pattern, with peak removal efficiency of 97.2% in February and a slight reduction to 90.6% in July.

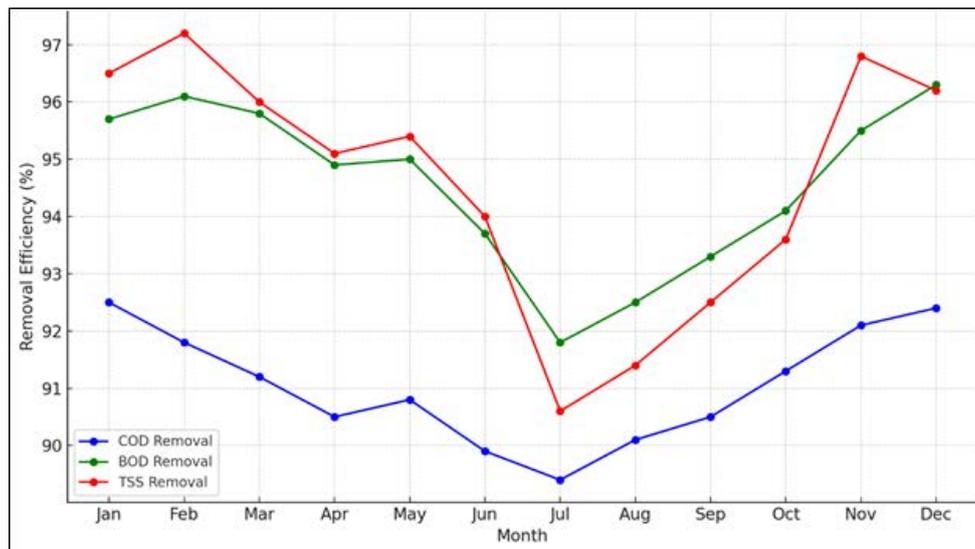


Figure 2: Removal Efficiencies of COD, BOD, and TSS – displaying seasonal variations.

### 3.4. Trend Analysis of Pollutant Removal Efficiencies

A trend analysis was conducted to assess the long-term performance of the ETP. The linear regression models for COD, BOD, and TSS removal efficiencies, as depicted in Figure 3, indicate that overall system performance was stable throughout the year. A slight positive trend was observed for BOD removal, which suggests incremental improvements in the biological treatment process. COD removal efficiency exhibited a marginal downward trend,

though it remained above 90% across most months. BOD removal efficiency showed a slight upward trend, indicating gradual improvements over time. TSS removal efficiency was relatively stable, with minor fluctuations likely influenced by seasonal changes. The stable trends in pollutant removal indicate that the treatment plant maintains a consistent level of performance, with opportunities for further optimization in biological processes.

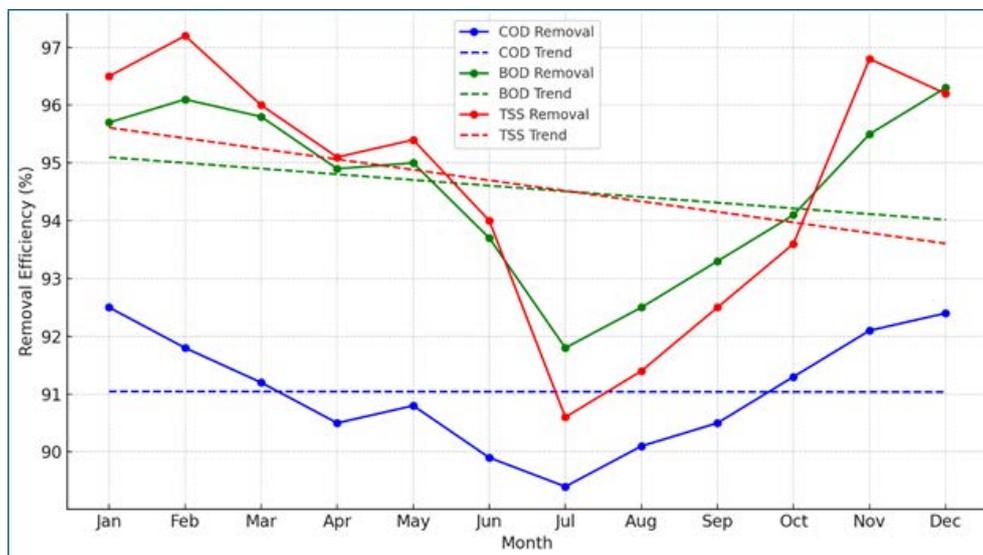


Figure 3: Trend Analysis of Removal Efficiencies – showing the trends over the 12-month period for COD, BOD, and TSS.

### 3.5. Wastewater Quality Index (WWQI)

The Wastewater Quality Index (WWQI) was calculated using the Canadian Council of Ministers of the Environment

(CCME) methodology for influent and effluent samples. Table 2 provides the WWQI scores for COD, BOD, TSS, pH, and DO, along with the overall WWQI for both influent and effluent.

| Parameter | WWQI (Influent) | WWQI (Effluent) | ECR 2023 Standard |
|-----------|-----------------|-----------------|-------------------|
| pH        | 100             | 100             | 95 - 100          |
| DO        | 100             | 100             | 95 - 100          |
| COD       | 99.72           | 99.72           | 95 - 100          |
| BOD       | 99.72           | 99.72           | 95 - 100          |
| TSS       | 100             | 100             | 95 - 100          |

**Table 2: WWQI Scores for Influent and Effluent Samples**

The WWQI results demonstrate that the treated effluent consistently met the water quality standards, with the overall WWQI scores indicating excellent water quality in compliance with the ECR 2023 standards.

### 3.6. Multivariate Statistical Analysis

#### 3.6.1. Pearson Correlation Analysis

Pearson correlation analysis was conducted to assess the relationships between influent and effluent parameters. Table 3 presents the correlation coefficients for COD, BOD, and TSS.

| Parameter Pair | Correlation Coefficient (r) | Significance (p-value) | ECR 2023 Standard |
|----------------|-----------------------------|------------------------|-------------------|
| COD - BOD      | 0.874                       | < 0.05                 | 95 - 100          |
| COD - TSS      | 0.568                       | < 0.05                 | 95 - 100          |
| BOD - TSS      | 0.795                       | < 0.05                 | 95 - 100          |
| BOD            | 99.72                       | 99.72                  | 95 - 100          |
| TSS            | 100                         | 100                    | 95 - 100          |

**Table 3: Pearson Correlation Coefficients Between Influent and Effluent Parameters**

The strong positive correlation ( $r = 0.874$ ,  $p < 0.05$ ) between COD and BOD in the effluent suggests that the biological treatment process effectively removes organic pollutants. The moderate correlation between COD and TSS indicates that these parameters are less directly related, potentially due to differences in their removal mechanisms within the treatment system.

#### 3.6.2. Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was applied to the dataset to identify the most significant factors influencing wastewater treatment performance. The eigenvalues and proportion of variance explained by each principal component are provided in Table 4.

| Principal component | Eigenvalue | Proportion of Variance (%) | Cumulative Variance (%) |
|---------------------|------------|----------------------------|-------------------------|
| PC1                 | 1.9043     | 47.60%                     | 47.60%                  |
| PC2                 | 1.1294     | 28.20%                     | 75.80%                  |
| PC3                 | 0.8155     | 20.40%                     | 96.20%                  |
| PC4                 | 0.1508     | 3.80%                      | 100%                    |
| TSS                 | 100        | 100                        | 95 - 100                |

**Table 4: Eigenvalues and Proportion of Variance Explained by Principal Components**

PCA results indicate that the first principal component (PC1) explains 47.60% of the total variance, with BOD being the most significant factor influencing treatment performance. The second principal component (PC2) contributes an additional 28.20% to the total variance, with COD as the next most significant factor. Together, these two components explain over 75% of the variance in the dataset, highlighting the critical role of biological oxygen demand and chemical oxygen demand in determining effluent quality.

#### 3.6.3. Canonical Correlation Analysis (CCA) Results

The Canonical Correlation Analysis (CCA) was applied to explore the relationships between influent and effluent

parameters (COD, BOD, and TSS). As shown in Figure 4, the CCA revealed a moderate correlation ( $r = 0.54$ ) between the influent and effluent data. This suggests that influent characteristics partially explain the variability in effluent quality. Among the parameters: BOD demonstrated the strongest correlation between influent and effluent values, indicating that biological processes play a significant role in determining the effluent quality. TSS showed the weakest correlation, suggesting that TSS removal may be more influenced by physical processes (e.g., sedimentation) than by influent concentrations. The CCA results emphasize the importance of managing influent quality to optimize effluent outcomes, particularly for biological treatment.

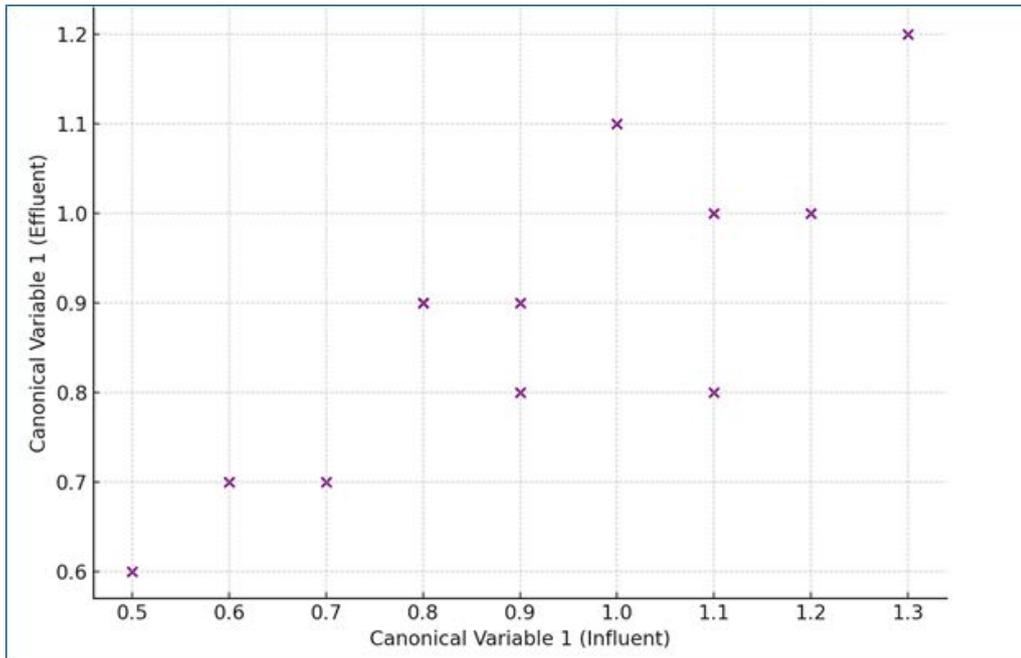


Figure 4: Canonical Correlation Scatterplot – illustrating the relationship between influent and effluent parameters.

### 3.7. Uncertainty Analysis using Monte Carlo Simulations

To assess the potential variability in the system's performance, a Monte Carlo simulation was conducted for COD, BOD, and TSS removal efficiencies. The simulation results, shown in Figure 5, highlight the distribution of possible removal efficiencies based on observed data. The simulated mean removal efficiency for COD was 91.8%, closely aligned with the observed mean. The standard deviation of 5.6% reflects potential operational variability. For BOD, the simulated

mean removal efficiency was 94.6%, with a standard deviation of 5.0%, indicating a stable process with low variability. The simulated mean removal efficiency for TSS was 95.3%, with a standard deviation of 5.5%, suggesting consistent performance despite seasonal variations. These simulations provide a robust understanding of the system's reliability and variability, confirming that the treatment plant operates within acceptable ranges despite occasional fluctuations in performance.

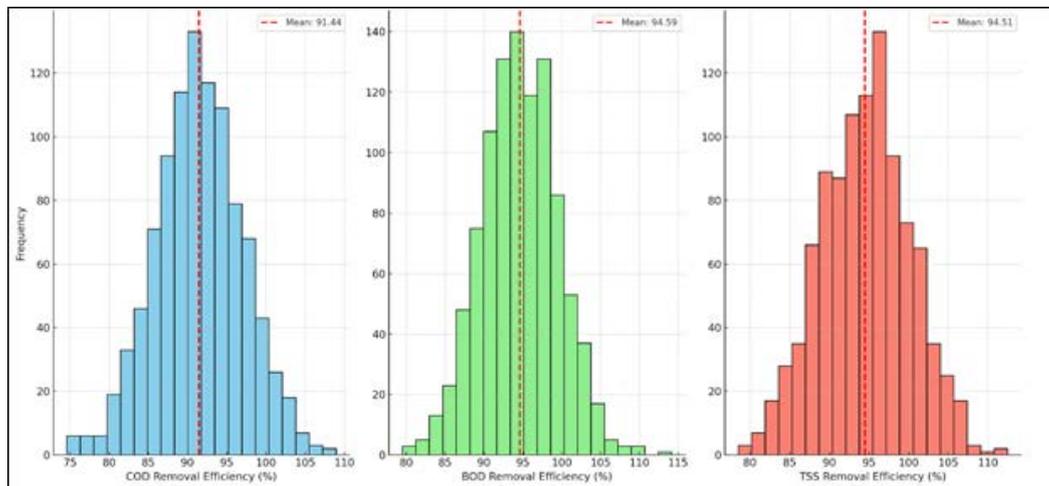


Figure 5: Monte Carlo Simulation for COD Removal Efficiency – showing the distribution of simulated COD removal efficiency values.

## 4. Discussion

The results of this study demonstrate that the hybrid Effluent Treatment Plant (ETP), integrating a Moving Bed Biofilm Reactor (MBBR) and an Activated Sludge Process (ASP), is highly effective in treating high-strength industrial wastewater from the pulp and paper industry. The system consistently achieved removal efficiencies of over 90%

for Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), and Total Suspended Solids (TSS), ensuring compliance with Bangladesh's Environmental Conservation Rule (ECR) 2023 standards. This confirms the potential of hybrid systems to manage industrial wastewater effectively, especially in developing countries where regulatory frameworks may be less stringent.

#### 4.1. High Pollutant Removal Efficiency

The average removal efficiencies for COD (91.86%), BOD (95.70%), and TSS (96.85%) highlight the robustness of the MBBR-ASP system. These findings align with previous studies that have shown the superiority of hybrid systems over traditional single-process systems [2]. The high BOD removal efficiency is particularly significant, as it indicates that the biological treatment processes in the ETP are effectively reducing the organic load. This is supported by the strong correlation between COD and BOD ( $r = 0.874$ ,  $p < 0.05$ ), emphasizing the importance of biological treatment in this context (Ebrahimi et al., 2017). Despite the strong performance, the moderate correlation between COD and TSS ( $r = 0.568$ ) suggests that the physical processes governing TSS removal, such as sedimentation, are less influenced by the biological treatment system. This divergence could be attributed to operational factors such as the hydraulic loading rates, which could affect the settling of suspended solids.

#### 4.2. Seasonal Variations in Treatment Efficiency

The seasonal variation analysis revealed that treatment efficiency was slightly lower during the wet season (June-September), with the lowest COD removal efficiency observed in July (89.4%). This reduction can be attributed to increased hydraulic loading during periods of high rainfall, which may dilute influent concentrations and affect the biological treatment processes. However, even during the wet season, the system-maintained removal efficiencies above 89%, demonstrating its resilience to seasonal fluctuations. This finding is consistent with other studies in tropical regions, where monsoon seasons have been shown to impact wastewater treatment performance due to increased influent volumes [11]. The relatively stable performance during the wet season could be attributed to the hybrid system's ability to adapt to variations in influent quality, underscoring the importance of combining biological and physicochemical processes. Further optimization, such as adjusting the hydraulic retention time during periods of high flow, could enhance performance during the wet season.

#### 4.5. Long-Term Stability and Trend Analysis

The trend analysis indicates that the hybrid system's performance remained stable throughout the study period, with only minor fluctuations in removal efficiency. The positive trend observed in BOD removal suggests that the biological processes are improving over time, potentially due to acclimatization of the microbial communities within the MBBR. In contrast, the slight downward trend in COD removal efficiency, while still above 90%, indicates that additional operational adjustments, such as optimizing the aeration rate or sludge age, may be required to maintain peak performance. The consistent TSS removal efficiency, despite minor seasonal fluctuations, reflects the robustness of the physicochemical processes, particularly sedimentation. The overall stability of the system demonstrates its suitability for long-term operation in industrial wastewater treatment, even under varying environmental and operational conditions.

#### 4.4. Statistical Insights

The multivariate statistical analyses provided valuable insights into the factors influencing treatment performance. Principal Component Analysis (PCA) identified BOD as the most significant factor affecting treatment efficiency, followed closely by COD, which is consistent with the understanding that organic matter and oxygen demand are critical indicators of wastewater quality. Together, these factors accounted for over 75% of the variance, confirming their central role in determining the quality of treated effluent. Canonical Correlation Analysis (CCA) revealed a moderate correlation ( $r = 0.54$ ) between influent and effluent parameters, particularly for BOD, indicating that influent quality plays a key role in determining effluent outcomes. This highlights the importance of monitoring and managing influent characteristics to ensure consistent effluent quality. The relatively weaker correlation for TSS suggests that physical processes, such as sedimentation, are less influenced by influent concentrations and are more dependent on the operational conditions within the plant.

#### 4.5. Implications for Developing Countries

The findings of this study are particularly relevant for developing countries like Bangladesh, where industrial wastewater treatment infrastructure is often underdeveloped, and regulatory enforcement may be inconsistent. The successful application of the MBBR-ASP hybrid system in this study provides a viable model for industries in similar contexts, offering a cost-effective and reliable solution for managing high-strength wastewater. The results also emphasize the importance of long-term monitoring and the use of advanced statistical techniques to optimize treatment processes and ensure compliance with environmental standards.

#### 4.6. Novelty of the Study

This study provides several novel contributions to the field of industrial wastewater treatment, particularly in the context of developing countries:

- **Long-Term Performance Evaluation:** Most previous studies on hybrid wastewater treatment systems focus on short-term assessments, often overlooking the system's adaptability and long-term stability. This study offers a comprehensive 12-month evaluation, providing valuable insights into the long-term performance of a hybrid MBBR-ASP system in managing high-strength industrial wastewater. By monitoring seasonal variations and conducting trend analyses, this research demonstrates the system's robustness and adaptability, filling an important gap in the existing literature.
- **Use of Multivariate Statistical Techniques:** While many studies on wastewater treatment employ conventional statistical analyses, this study integrates advanced multivariate techniques, including Principal Component Analysis (PCA) and Canonical Correlation Analysis (CCA), to identify the most significant factors influencing treatment performance. The application of these techniques in an industrial context is relatively rare, especially in developing countries like Bangladesh, and this study demonstrates their utility in optimizing treatment processes and improving

operational efficiency.

- **Application in a Developing Country Context:** The majority of research on wastewater treatment technologies has been conducted in developed countries, where regulatory frameworks and treatment infrastructure are more advanced. This study addresses the unique challenges faced by developing countries, where industrial wastewater treatment is often under-resourced, and compliance with environmental regulations can be inconsistent. By demonstrating the effectiveness of a hybrid system in meeting local regulatory standards (ECR 2023), this study provides a model for industries in similar contexts to adopt sustainable wastewater management practices.
- **Insights into Seasonal Variations:** The study provides detailed insights into how seasonal variations, particularly during the monsoon season, impact the efficiency of wastewater treatment processes. This is an important consideration for regions with tropical climates, where high rainfall can significantly affect wastewater characteristics. The ability of the MBBR-ASP system to maintain high removal efficiencies during the wet season highlights its potential as a reliable treatment solution in regions with pronounced seasonal variability.
- **Relevance to the Pulp and Paper Industry:** The pulp and paper industry is a major contributor to industrial pollution globally, yet there are limited studies focusing on long-term wastewater treatment performance in this sector. This study addresses this gap by providing a detailed evaluation of how a hybrid treatment system can effectively manage high-strength wastewater from the pulp and paper industry, contributing to both local and global efforts to improve industrial wastewater management [12-14].

## 5. Conclusion

This study has demonstrated the high efficiency of a hybrid Effluent Treatment Plant (ETP) combining a Moving Bed Biofilm Reactor (MBBR) and an Activated Sludge Process (ASP) in treating high-strength wastewater from a pulp and paper facility in Narayanganj, Bangladesh. The system achieved consistent removal efficiencies for Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), and Total Suspended Solids (TSS) of 91.86%, 95.70%, and 96.85%, respectively, over a 12-month period. These results indicate the system's robustness and its ability to comply with the stringent Bangladesh Environmental Conservation Rule (ECR) 2023 standards. The study highlights several key factors influencing the treatment performance, including seasonal variation, with slightly reduced efficiency during the wet season due to increased hydraulic loading. Despite these fluctuations, the treatment plant-maintained pollutant removal efficiencies above 89%, underscoring its adaptability and resilience to environmental conditions.

Multivariate statistical analyses, including Principal Component Analysis (PCA) and Canonical Correlation Analysis (CCA), revealed that BOD and COD were the most significant factors influencing treatment performance. These insights provide a deeper understanding of the operational parameters that need optimization to further improve wastewater management practices. The long-term

evaluation of the ETP system offers significant contributions to wastewater treatment research in developing countries, where industrial effluents pose growing environmental challenges. The findings suggest that hybrid treatment systems are a viable and efficient option for managing high-strength industrial wastewater, particularly in resource-constrained settings. Future research should focus on optimizing operational parameters such as hydraulic retention time and aeration rates, particularly during periods of high flow, to improve treatment efficiency further. Additionally, exploring the scalability of such hybrid systems in different industrial contexts and geographical locations would provide valuable insights into broader applications for sustainable wastewater management.

## Declaration of Interest

As the corresponding author, I, corresponding author, on behalf of all co-authors, declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

The data used in this study were generated and/or analyzed during the current study. They are not publicly available due to the proprietary nature of the data but can be obtained from the corresponding author, upon reasonable request.

## Author Contribution

Author 1 & Corresponding Author: Contributed to the conceptualization, performed data analysis, wrote the main manuscript, reviewed the full report, and finalized the manuscript.

Author 2: Conceptualized the article, analyzed the data, and contributed to the manuscript's main structure and content.

## Ethical Approval

This study, titled was conducted with adherence to ethical standards and in compliance with institutional guidelines. The authors confirm that no human participants or animals were involved in the research, and thus, no ethical approval was required.

## Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. All analyses and data collection were conducted independently by the authors and were supported through institutional resources.

## Consent to Publish

All authors confirm that this manuscript has not been previously published as a pre-print or in any other format. We provide full consent for the publication of this work in the selected journal.

## Consent to Participate

This study did not involve any human participants, animals, or individual personal data. Consequently, formal consent to participate was not required. The research focused solely

on the technical and operational assessment of wastewater treatment processes in an industrial setting, and all data were collected under standard operational practices without involvement of external subjects. All relevant stakeholders were informed of the study's objectives, and the industry provided full cooperation for data collection and analysis, ensuring adherence to ethical standards and institutional guidelines.

## References

1. Tang, W., Zhou, S., & Li, Y. (2020). Environmental performance evaluation of pulp and paper inds using grey relational analysis. *International Journal of Environmental Research and Public Health*, 17(3), 1-10. DOI:10.3390/ijerph17030983.
2. Kasmi, M., Abidli, S., Elabed, S., Moussa, M., & Khalfaoui, M. (2019). Performance evaluation of wastewater treatment plant: A case study. *International Journal of Sustainable Engineering*, 12(1), 3-9. DOI:10.1080/19397038.2019.1566712.
3. Ebrahimi, A., Haghollahi, A., Mesdaghinia, A., Nasseri, S., & Mahvi, A. H. (2017). Development of wastewater quality indices using principal component and factor analysis for an urban river. *Environmental Monitoring and Assessment*, 189(6), 1-11. DOI:10.1007/s10661-017-6055-x.
4. Urbonavičiūtė, A., Sakalauskaitė, J., Vaiciulytė, V., & Nizač, V. (2020). Evaluation of water quality indices for river water quality assessment: A case study of the Neris River (Lithuania). *Water*, 12(3), 842. DOI:10.3390/w12030842.
5. American Public Health Association (APHA), American Water Works Association (AWWA), & Water Environment Federation (WPCF). (2017). *Standard Methods for the Examination of Water and Wastewater*. American Public Health Association, Washington, DC.
6. Witten, D., & Tibshirani, R. (2019). *Statistical Learning with Sparsity: The Lasso and Generalizations*. CRC Press. Available online: <https://www.routledge.com/Statistical-Learning-with-Sparsity-The-Lasso-and-Generalizations/Witten-Tibshirani/p/book/9780367182577>.
7. Abdi, H., Williams, L. J., & Valentin, D. (2022). *Canonical Correlation Analysis*. *Wiley Interdisciplinary Reviews: Computational Statistics*, 14(2), e1523.
8. Shumway, R. H., & Stoffer, D. S. (2017). *Time Series Analysis and Its Applications: With R Examples*. Springer.
9. Zhang, L., Lei, Y., & Yang, X. (2022). Seasonal variation and water quality assessment of the Hanjiang River. *Water*, 14(5), 750.
10. Hyndman, R. J., & Athanasopoulos, G. (2021). *Forecasting: Principles and Practice (3rd ed.)*. OTexts.
11. Lehmann, M. K., Fiedler, J., & Tetzlaff, D. (2022). Long-term trends in water quality in European rivers. *Water Research*, 217, 118406.
12. Abdullah, M. S., Samdin, Z., & Zainudin, N. H. (2018). Application of principal component analysis (PCA) on heavy metals contamination in water and sediment of Port Klang coastal area. *Journal of Sustainability Science and Management*, 13(2), 115-126.
13. Abdullah, M. S., Samdin, Z., & Zainudin, N. H. (2018). Application of principal component analysis (PCA) on heavy metals contamination in water and sediment of Port Klang coastal area. *Journal of Sustainability Science and Management*, 13(2), 115-126.
14. Li, J., Feng, C., Wang, C., & Wu, J. (2017). Multivariate statistical analysis of water quality in the mainstream tributary of the Three Gorges Reservoir. *Environmental Monitoring and Assessment*, 189(3), 110. DOI:10.1007/s10661-017-5887-8.